Interim storage facility, encapsulation plant and final repository for spent nuclear fuel

Background material for consultations according to the Espoo (EIA) Convention

Updated January 2008

SKB

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Preface

If an activity is likely to have a significant environmental impact in another country, the Swedish Environmental Protection Agency shall, according to the Convention on Environmental Impact Assessment in a Transboundary Context (Espoo, 1991), known as the Espoo (EIA) Convention, "inform the competent authority in that country about the planned activity or measure and give the country concerned and the citizens who are affected the opportunity to take part in a consultation procedure concerning the application and the environmental impact assessment" (Environmental Code Chap. 6 Sec. 6).

Svensk Kärnbränslehantering AB, SKB (the Swedish Nuclear Fuel and Waste Management Co.), has been assigned the task of managing and disposing of the radioactive waste from the Swedish nuclear power plants. In order to dispose of the spent nuclear fuel, SKB plans to build an encapsulation plant, where the spent nuclear fuel is encapsulated in copper canisters, and a final repository at a depth of about 500 metres in the bedrock.

The encapsulation plant is planned to be built adjacent to the existing interim storage facility for spent nuclear fuel (Clab) in Oskarshamn. Investigations have been conducted in Forsmark and Oskarshamn to explore the prospects for siting of the final repository. Data from the investigations are at present compiled and analysed. Both Oskarshamn and Forsmark are situated on the Baltic Sea coast in southern Sweden.

The purpose of this document is to provide an overview of SKB's plans for disposal of the spent nuclear fuel and the consequences this activity is likely to have. Detailed information about: safety and radiation protection, the long term safety for a KBS-3 repository and the general structure of the EIS document for the final repository system are enclosed as appendences. Additional information can be found on SKB's website and in SKB's reports, the most important of which are available in English.

Introduction

Nuclear power in Sweden

Sweden has twelve nuclear power reactors at four sites, ten of which are in operation. At Ringhals there are three pressurized water reactors and one boiling water reactor with a combined capacity of 3,600 MW, at Forsmark three boiling water reactors with a combined capacity of 3,200 MW, at Oskarshamn three boiling water reactors totalling 2,200 MW, and at Barsebäck two boiling water reactors of 600 MW each.

The plants were commissioned between 1972 and 1985. The Riksdag (Swedish parliament) has decided to begin a phase-out of nuclear power. One of the two reactors in Barsebäck was shut down in 1999. The other reactor was shut down on 31 May 2005.

Dates for closure of the remaining reactors have not been fixed. The plans for disposal of the radioactive waste are based on a scenario with 50 years of operation of the reactors in Forsmark and Ringhals and 60 years of operation for the reaktors in Oskarshamn.

SKB's mission

The radioactive waste in Sweden comes mainly from nuclear power. Under Swedish law the reactor owners bear full technical and financial responsibility for the waste from nuclear power. Together, they have formed Svensk Kärnbränslehantering AB, SKB (the Swedish Nuclear Fuel and Waste Management Co), which has been given the task of managing the country's spent nuclear fuel so that both the environment and human health are protected, in both the short and long term.

The Nuclear Activities Act requires that SKB prepare a programme for the comprehensive research and development and whatever other measures are needed to manage and dispose of the waste in a safe manner. In keeping with the requirements of the law, SKB submits reports to the regulatory authorities and the Government on the progress of this work. This is done every three years in RD&D programmes (Research, Development and Demonstration). So far SKB has presented ten RD&D programmes, including two supplements requested by the Government. The most recent report was submitted in September 2007.

Existing waste system

The radioactive waste from nuclear power can be divided into different categories based on life and activity level. With reference to requirements on management and final disposal, the Swedish waste is divided into three main categories. The first is *short-lived low- and intermediate-level waste (LILW)*. This category includes spent components, filters etc. from operation, maintenance and decommissioning of the nuclear power plants. The second category consists of *high-level waste (HLW)* in the form of spent nuclear fuel. It comprises a smaller fraction of the volume, but contains most of both the short- and long-lived radionuclides. The third main category, *long-lived LILW*, consists of e.g. spent components from the reactor core.

The short-lived LILW is disposed of in SFR in Forsmark (Final repository for radioactive operational waste). The spent nuclear fuel is interim-stored in Clab in Oskarshamn (Central interim storage facility for spent nuclear fuel). Furthermore, there is a system for transportation of the various waste types from the nuclear power plants to the waste facilities, see Figure 1.

What remains to be done in order to dispose of the waste from the nuclear power plants is:

- to build an encapsulation plant and a final repository for spent nuclear fuel
- to build a final repository for long-lived LILW

Long-lived LILW is generated mainly when the nuclear power plants are decommissioned. It is planned to be disposed of at a depth of several hundred metres in the bedrock. Siting and construction will not begin for another 30 years. SKB's current efforts are focused on final disposal of the spent nuclear fuel.

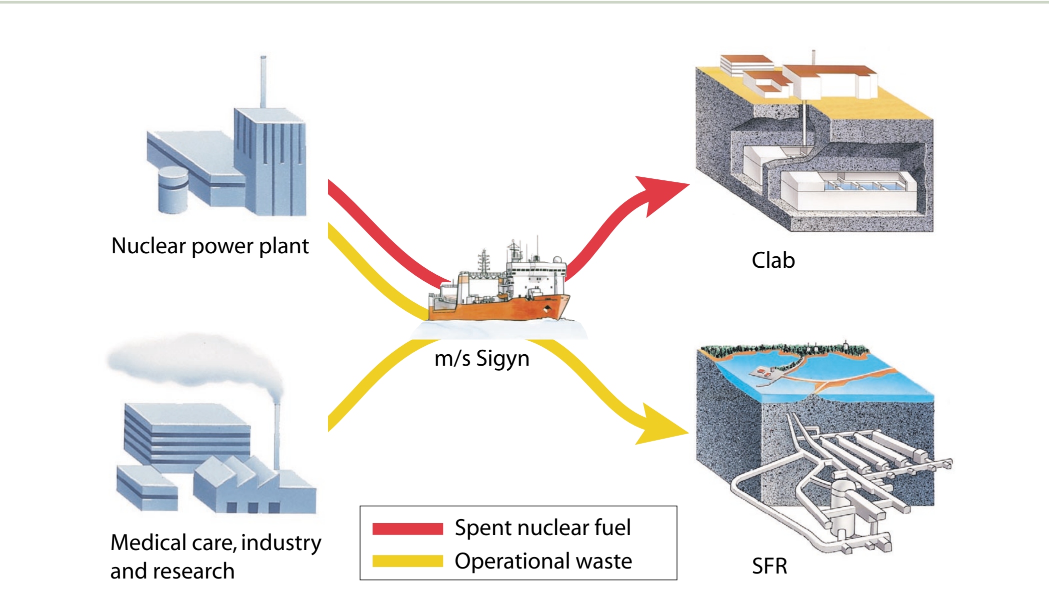


***Figure 1**. Existing facilities for management and disposal of radioactive waste.*

Final disposal of spent nuclear fuel

Choice of strategy and method

The general requirements governing disposal of spent nuclear fuel are found in international agreements and Swedish legislation. Reviews of different strategies and methods for disposal of spent nuclear fuel have been presented on a number of occasions, including in connection with the supplement to RD&D-Programme 1998, (Integrated account of method, site selection and programme prior to the site investigation phase. SKB report TR-01-03. Svensk Kärnbränslehantering AB, 2000.)

Internationally, a broad consensus exists that geological disposal is the strategy that is best suited to disposal of long-lived radioactive waste. The method which SKB proposes for final disposal is called KBS-3, where KBS stands for KärnBränsleSäkerhet (Nuclear Fuel Safety), see Figure 2.

The method entails that:

- the spent nuclear fuel is encapsulated in copper canisters with cast iron inserts
- the canisters are emplaced at a depth of approximately 500 metres in the bedrock
- the canisters are surrounded by a buffer of bentonite clay

The KBS-3 method requires construction of two new nuclear installations: an encapsulation plant and a final repository. Both facilities require permits under both the Nuclear Activities Act and the Environmental Code.

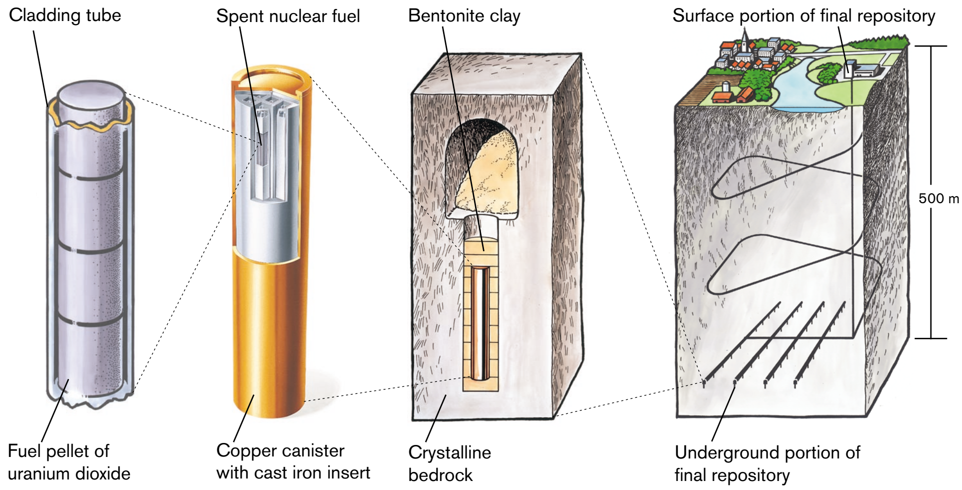


Figure 2. *The KBS-3 method is based on multiple barriers (canister, buffer and rock) that prevent the radionuclides in the fuel from harming man and the environment.*

Long-term safety

Safety aspects are of vital importance in connection with the management of spent nuclear fuel. Safety must be ensured both during repository operation and long after repository closure. The Swedish crystalline bedrock is between one and two billion years old and comprises a stable environment, where changes take place very slowly.

The spent nuclear fuel is hazardous (radiotoxic) for a very long time, and imposes special demands on management and disposal. The goal is to minimize the risks by isolating the fuel from man and the environment as long as it is hazardous. The short-lived substances (nuclides) with high radioactivity decay within the course of a few decades. Subsequently, cesium-137 and strontium-90 dominate the radiotoxicity of the fuel. After a thousand years, radiotoxicity is dominated by a few nuclides, the actinides and their decay products. After around 100,000 years, the radiotoxicity of the spent fuel has declined to the same level as the quantity of uranium ore from which the fuel was fabricated. The radiotoxicity of such uranium minerals, as well as eventually that of the spent fuel, is dominated by radiation from decay products of the uranium (radium, radon, polonium, etc).

Radiological *long-term safety* after closure of the final repository are dealt with in a special safety report, in which various scenarios are presented describing the evolution of the repository one million years into the future.

The safety report is regulated and reviewed by the regulatory authorities: the Swedish Radiation Protection Authority (SSI) and the Swedish Nuclear Power Inspectorate (SKI).

The most recent safety assessment, SR-Can, was submitted in November 2006. SR-Can is a preparatory step for the SR-Site safety assessment, which is planned to be published in 2009.

Important aspects to be described are:

- methodology of the assessment
- the repository system at closure – fuel, canister, buffer, rock and biosphere
- processes that alter the repository over time
- external impact in the event of a release of radionuclides due to canister damage

Radiological *safety during operation* of the encapsulation plant and the final repository is described and examined in preliminary safety reports. Before the facilities are taken into operation, the safety reports are supplemented by analyses and experience from the design phase, construction and commissioning.

The siting work

A step-by-step siting process for *the final repository* according to the KBS-3 method began in 1992, see Figure 3. By means of general siting studies, SKB explored the general siting prospects in different parts of the country. The feasibility studies comprised evaluation of the siting prospects in a total of eight municipalities: Storuman, Malå, Östhammar, Nyköping, Oskarshamn, Tierp, Älvkarleby and Hultsfred. In 2000, SKB proposed sites and program for geological investigations. In 2002, site investigations began in the Forsmark area in Östhammar Municipality and the Simpevarp area in Oskarshamn Municipality, see Figure 4, after supportive decisions by the Government and the municipalities. The site investigations have recently been finished. Data from the investigations are at present compiled and analysed.

Forsmarks Kraftgrupp AB, FKA, has three light-water nuclear power reactors in the Forsmark area. SFR (Final repository for radioactive operational waste), which was commissioned in 1987 and is owned by SKB, is also located in Forsmark.

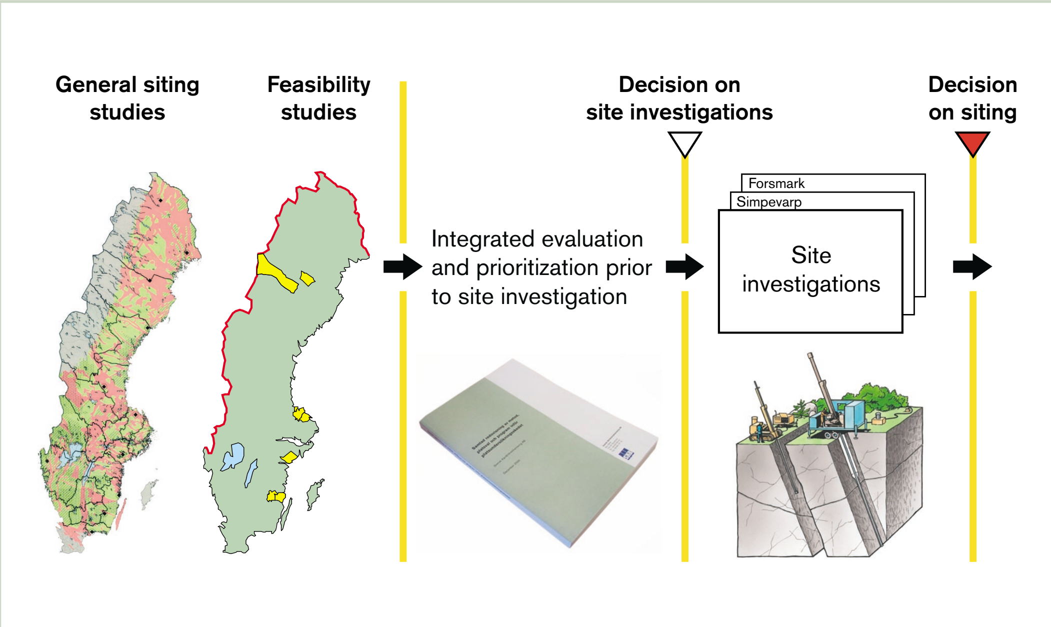


Figure 3. *The siting work for a final repository for spent nuclear fuel is being conducted through general siting studies, feasibility studies and site investigations.*

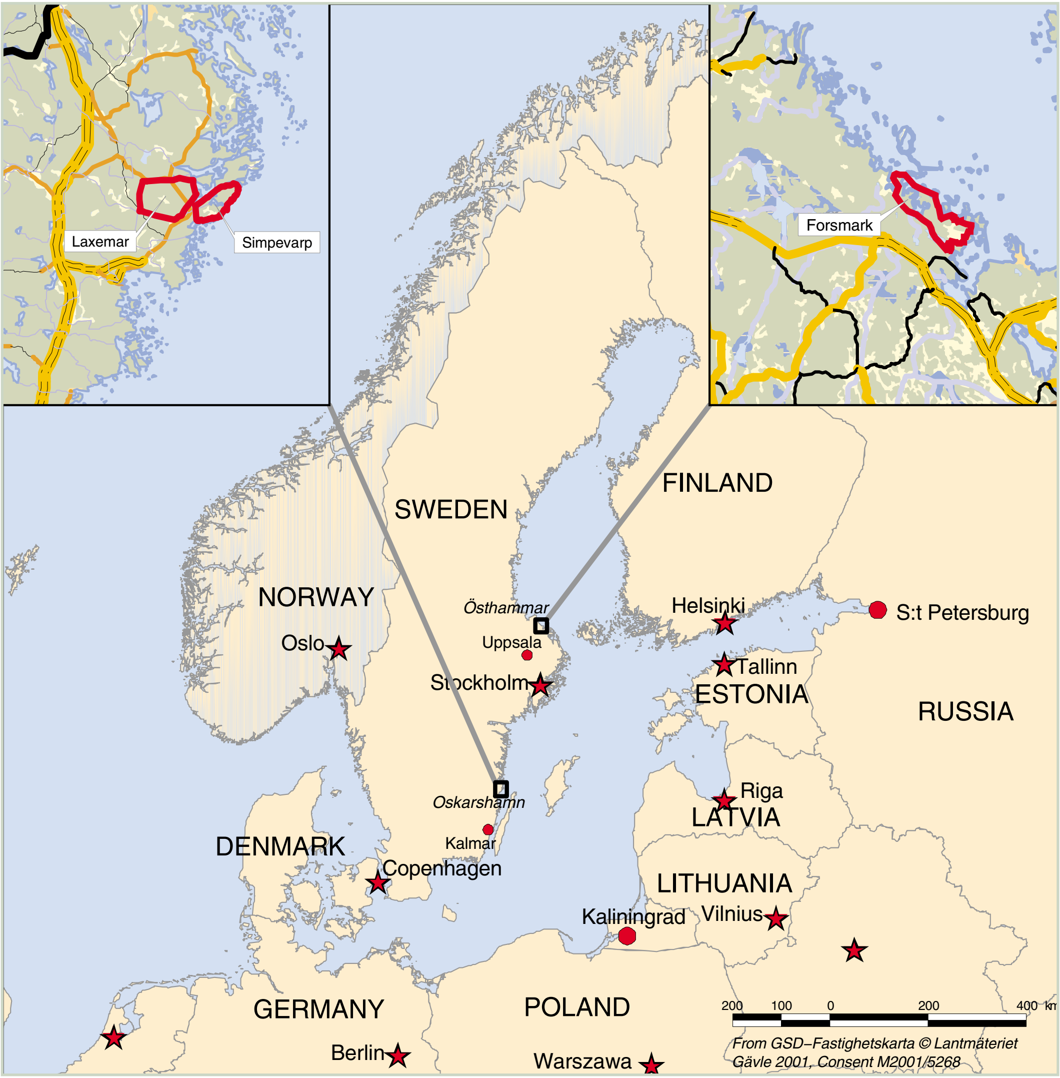
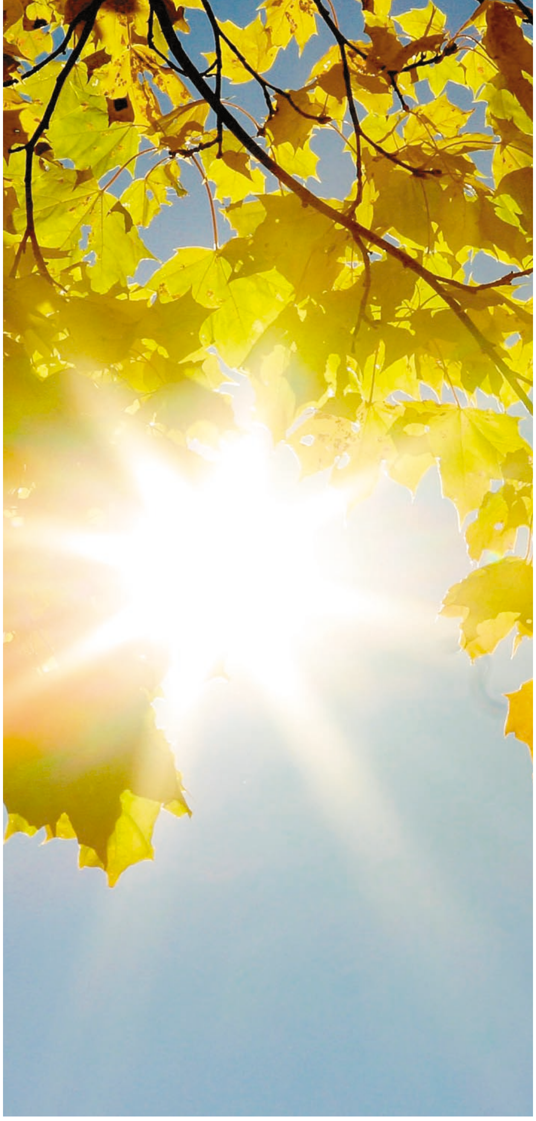


Figure 4. *Two sites – Forsmark in Östhammar Municipality and Simpevarp/Laxemar in Oskarshamn Municipality – are being investigated for siting of the final repository.*

The site investigations in Oskarshamn were initially focused on two candidate areas: Simpevarp and Laxemar. The investigations were later focused on the south-west part of Laxemar. Oskarshamns Kraftgrupp AB, OKG, which has three light-water nuclear power reactors, is located on the Simpevarp Peninsula. Clab (Central interim storage facility for spent nuclear fuel), which is owned by SKB, is also situated on the Simpevarp Peninsula. Clab, which was commissioned in 1985, receives spent nuclear fuel from all of Sweden's nuclear power plants. The descent tunnel to the Äspö HRL (Hard Rock Laboratory) is also located on the Simpevarp Peninsula. The Äspö HRL is SKB's research facility for a final repository and is situated at a depth of 460 metres in the bedrock.

SKB has also studied and compared different alternatives for siting of the *encapsulation plant*. Our proposal is to build it adjacent to Clab in Oskarshamn Municipality. The alternative for siting of the encapsulation plant is adjacent to the nuclear installations in Forsmark. This alternative will only be considered if the final repository is also sited at Forsmark.



Timetable

Consultations

Early consultations in accordance with the Environmenatal Code on the final repository and the encapsulation plant were carried out during the period 2002 – 2003. The extended consultations began in 2003. Joint meetings for the encapsulation plant and the final repository are being held in both Oskarshamn and Forsmark. The extended consultations will continue until a few months before the applications are submitted in 2009.

The application process

The current timetable for the application process is in short as follows:

2006 SKB applied for a permit under the Nuclear Activities Act for the encapsulation plant. An EIS (environmental impact statement) was appended to the application. At the same time, a safety assessment focusing on the performance of the canister in the final repository (SR-Can) was submitted to SKI, along with a system analysis focusing on the encapsulation plant's role in the KBS-3 system and an account of the planned canister shipments.

2009 SKB applies for a permit under the Nuclear Activities Act for the final repository and for permits under the Environmental Code for the interim storage facility, the encapsulation plant and the final repository, i.e. the entire KBS-3 system.

This proposal gives the Government an opportunity to make simultaneous decisions on permits under the Nuclear Activities Act and the Environmental Code for all parts of the KBS-3 system.

Construction and operation of the facilities

The scenario on which SKB's planning is based is that the ten reactors that are still in operation, i.e. all except Barsebäck 1 and 2, are shut down after 50–60 years of operation. This gives a total quantity of spent fuel of about 12,000 tonnes of uranium, which is equivalent to about 6,000 canisters of the type that will be used according to the current reference design. The programme permits both larger and smaller fuel quantities to be managed, the main consequences being modifications on the total operating time and the space require of the final repository.

The plan is that construction of the encapsulation plant and the final repository will start in 2012 and trial operation in 2020. The whole final repository programme is expected to be completed in 2070. By that time the final repository will have been backfilled and sealed, the above-ground facilities dismantled and the land restored. SKB's general planning is illustrated by Figure 5.

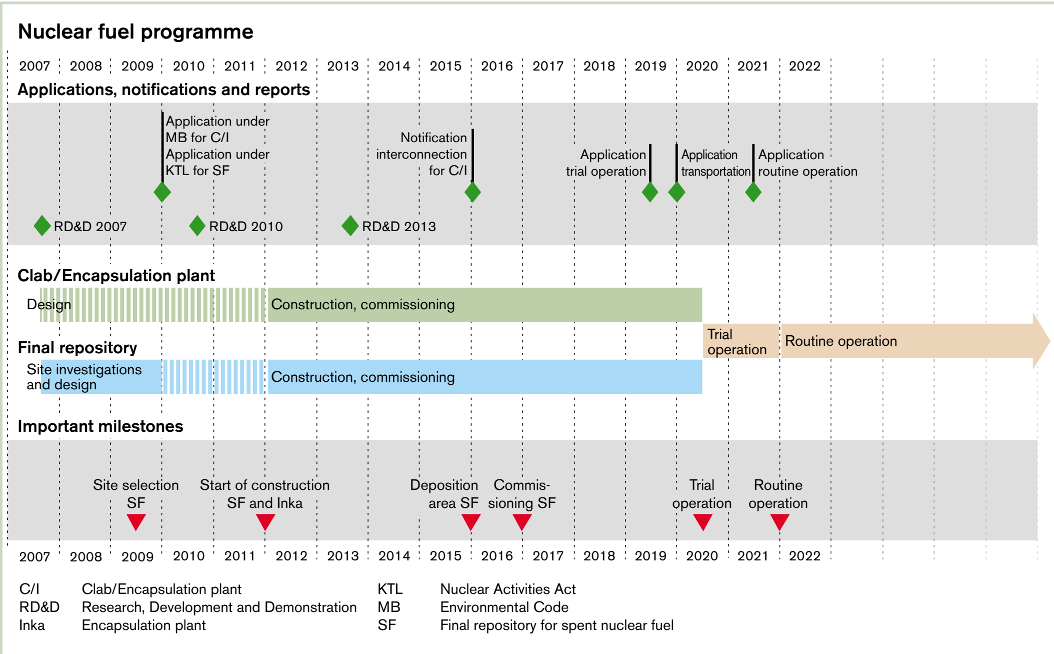
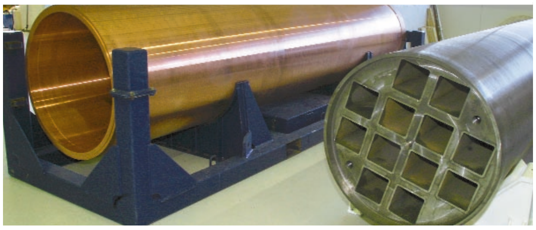


Figure 5. *Main features of SKB's long-term plan.*



Encapsulation plant

Siting

The encapsulation plant can be sited either at Clab (Central interim storage facility for spent nuclear fuel) in Oskarshamn, at the final repository, at another existing nuclear installation, or at a brand new site. SKB suggests that the encapsulation plant should be built adjacent to Clab, regardless of where the final repository is built. However, it is also possible to build a free-standing encapsulation plant, and a siting at Forsmark is being investigated as an alternative. There is plenty of space to build the encapsulation plant next to the nuclear power plant at Forsmark

Facility and activities

In Oskarshamn, the encapsulation plant can be built directly adjacent to Clab. The encapsulation plant will be about 70 x 100 metres and consist of three storeys below and seven above ground level, see Figure 6. The facility will be designed to allow integration with the systems and organization at Clab.

Prior to encapsulation the fuel is transported from the storage pools in Clab via a fuel elevator to a pool in the encapsulation plant, where the radiation is measured and the fuel is sorted. The fuel is then lifted up out of the water and into a radiation-shielded handling cell, where it is vacuum-dried. After drying it is placed in the canister. When a canister has been filled with fuel assemblies, the canister insert's lid is fitted. The copper lid is then placed on the canister and the canister is sealed by welding. The reference welding method for the encapsulation plant is Friction Stir Welding (FSW).

The encapsulated fuel is placed in a transport cask for shipment to the final repository. If the final repository is located at Oskarshamn, the transport cask will be shipped the short distance from the encapsulation plant to the repository by road.

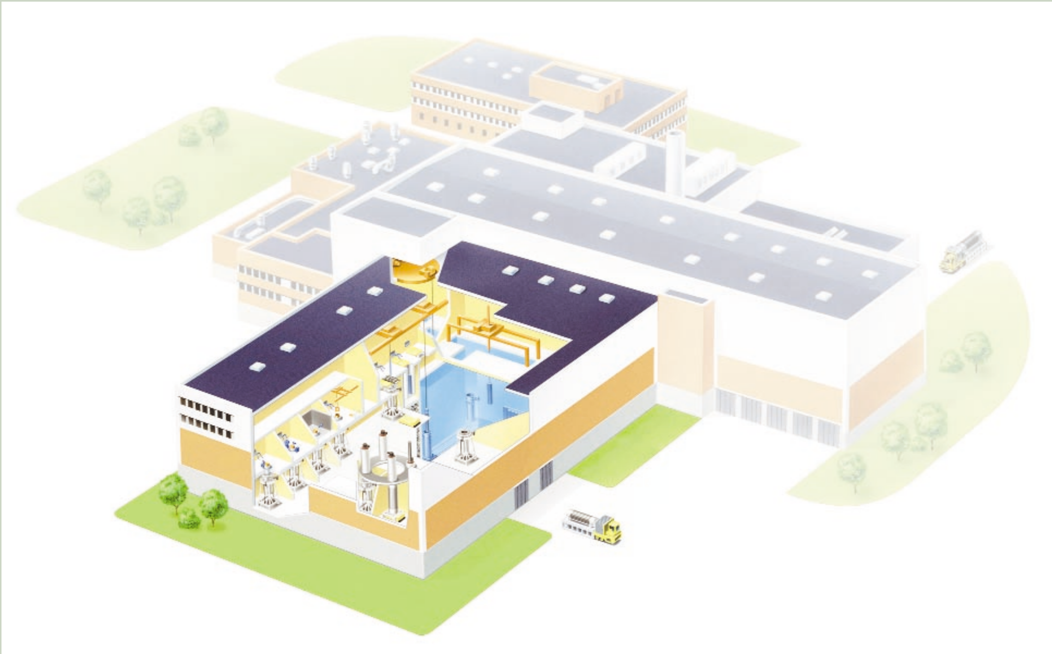


Figure 6. Possible layout of the encapsulation plant located adjacent to Clab.

If the encapsulation plant is located in Forsmark, all spent nuclear fuel will be sorted, measured and dried at Clab prior to shipment. The fuel will be transported to the final repository by the specially designed ship m/s Sigyn (or an equivalent other/new ship), which transports the fuel from the nuclear power plants to Clab today. The shipments will go from the harbour at Simpevarp to the Forsmark nuclear power plant's harbour. Encapsulation of the fuel will then take place in roughly the same way as described above.

Figure 7. Copper canister with spent nuclear fuel.

The canister

The canister that will contain the spent nuclear fuel is nearly five metres long and has a diameter of over one metre, see Figure 7. It weighs between 25 and 27 tonnes when filled with fuel. The outer shell is five centimetres thick and made of copper, which protects against corrosion. Inside the copper shell, an insert of cast iron provides the necessary strength.

Final repository

Siting

SKB has recently finished site investigations in Forsmark and Oskarshamn in order to determine the prospects for siting of the final repository. Alpresent, data from the investigations are compiled and analysed. SKB's objective is that one of the sites will constitute the main alternative for siting of the final repository in the permit application.

There is ample space to accommodate the final repository's above-ground buildings in both Forsmark and Oskarshamn. If the final repository is located at Forsmark, the main alternative is siting it close to the power plant; there is also suitable space there for a possible rock heap.

The site investigations in the Oskarshamn area were focusing on two subareas: the Simpevarp Peninsula with environs and the Laxemar area. The investigations were later focused on the south-west part of Laxemar. There are suitable land areas for the buildings and for the rock heap in this part of Laxemar.

Facility and activities

Design of the facility

The final repository's underground part must be located in an area with suitable geological properties considering the repository's long-term safety. The above-ground parts of the facility should be located as close to the underground part as possible to ensure good coordination between the above-ground operations area and the central area under ground, see Figures 8 and 9.

The connections between the ground surface and the repository consist of a ramp for canister transport and shafts for rock spoil and bentonite and for elevator and ventilation.

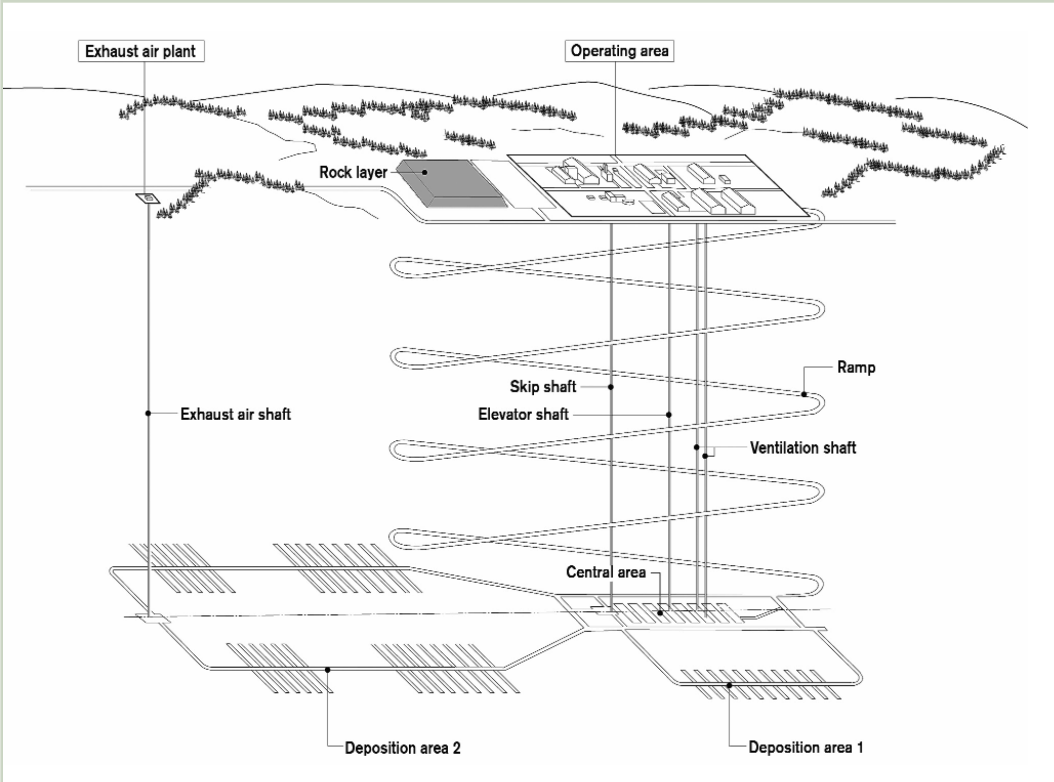


***Figure 8**. Schematic design of the final repository.*

Buildings, roads, the tunnel portal and the rock heap will occupy 0.2–0.4 km^2. The deposition area extends over an area of 2–4 km^2, at a depth of approximately 500 metres below the surface.

Construction and operation

The construction phase amounts to about 7 years and is divided into two sub-phases consisting of different building activities. During the construction phase, the shafts and ramp will be driven down to repository level, about 500 metres, and the excavation of the repository area will begin. The work in the form of blasting, rock haulage and construction activities will be most intensive during the latter half of the period**.**

The operating phase extends over approximately 45 years and consists of sequences of construction of deposition tunnels, deposition of canisters and backfilling of tunnels. During the operating phase, the speed of the excavation work will be determined by the desired rate of deposition, which means that the intensity will be much lower than during the construction phase.

The operating phase is also divided into two phases, trial operation and routine operation. When the encapsulation plant and the first part of the final repository are finished, *trial operation* will take place during a period of a few years.

Trial operation will be evaluated before a decision is made to proceed with *routine operation*, when up to 200 canisters per year will be deposited. A total of about 6,000 canisters will be deposited during trial and routine operation

After deposition is concluded, the buildings on the surface can be dismantled and the land restored or prepared for other activities. There are no restrictions on the use of the restored site, except for the fact that deep drilling is prohibited.

Figure 9. *In this sketch, the final repository's surface facilities are placed in the industrial area, where the Forsmark plant's residential area is located today.*

Handling of rock spoil

In the construction of the tunnels needed for the final repository, a total of about 3 million m^3 of rock (loose measure) will be excavated and hauled to the ground surface.

Approximately one-third of the total volume of rock spoil will be taken out during the construction phase. This spoil is not needed for backfilling of the final repository, but can be used as a resource for other construction activities, for example roadbuilding or other civil engineering projects. The spoil can be placed in a temporary heap pending removal from the area by truck.

The second one-third of the total volume of the rock spoil is taken to the production building to be crushed and mixed with bentonite. It is then transported down into the underground facility to be used as backfill in the deposition tunnels.

The remaining one-third of the rock spoil is used for backfilling of tunnels and shafts in the final repository. The rock spoil is stored temporarily in a rock heap.

Another possibility is to use Friedland clay, instead of rock spoil and bentonite, for the backfilling. In this case, a larger amount of rock spoil can be used as a resource for other construction activities.

Transportation

During regular operation, one canister can be deposited per day. How the canisters are transported from the encapsulation plant depends on where the final repository is located.

Furthermore, the traffic will include shipments of bentonite, rock spoil, backfill materials and building materials, as well as personell transport.

The transport activity will be most noticeable during the latter half of the construction phase, a period of approximately 3.5 years, when 1 million m^3 of rock spoil will be shipped out. The increase in traffic during the operation of the facility will be marginal in relation to the situation today.

Environmental impact

Environmental impact assessment

The applications for permits under the Nuclear Activities Act and the Environmental Code will be accompanied by an environmental impact statement (EIS). This document will describe the environmental impact of the encapsulation plant and the final repository with associated activities. The EIS covers the entire period of time from the start of construction of the facilities up to and including backfilling and closure of the underground tunnels and cleanup and restoration of the surface site.

The establishment of the encapsulation plant and the final repository for spent nuclear fuel will affect the people who live and work in the area. In addition to environmental impact, effects on human health and the community will therefore also be studied.

Impacts and consequences

The *radiological impact* of the encapsulation plant in the form of releases to water and air will be very small, on the order of a few ten-thousandths of what is permitted from a nuclear installation. No releases with radiological impact are expected to take place in connection with the shipments of encapsulated fuel to the final repository or the deposition of canisters in the final repository.

The main environmental impact is expected to be of a non-radiological character and is caused by handling and transport of the rock spoil, giving rise to local pollution of air and water.

During construction of the facilities, increased traffic to and within the area gives rise to *atmospheric emissions*. Furthermore, the blasting work and rock crushing at the final repository give rise to particulate emissions. Both the increased traffic and the blasting contribute locally to emissions of nitrogen oxides and carbon monoxide.

Drainage water from the rock works during construction of the encapsulation plant and the final repository will contain particles, oil and contaminants. The water will be cleaned before being discharged to the Baltic Sea. The *leachate* from rock heaps will be tested and cleaned if necessary.

Construction of tunnels, shafts and the underground part of the final repository causes a local lowering (drawdown) of the *groundwater level*. After repository closure, the natural groundwater level will be restored, but this may take several decades.

Noise and vibration are caused mainly by rock works, transport and the ventilation fans. Elevated sound levels will be noticed a few kilometres from the facilities and along the roads.

Safety and radiation protection

The safety work for SKB's nuclear facilities is based on legislation and regulatory requirements. SKB performs several different types of assessments and reports regarding safety and radiation protection for the encapsulation plant, Clab, the final repository and the transportation system.

A facility's safety analysis report describes how safety and radiation protection in a nuclear facility are arranged to protect human health and the environment.

Since transportation of spent nuclear fuel is classified as a nuclear activity, special permits are required from SKI and SSI according to the Nuclear Activities Act.

Development of the KBS-3 method for final disposal of spent nuclear fuel has been going on since the late 1970s. Over the course of the years SKB has carried out several analyses of the long-term safety of the final repository.

Transboundary environmental impact

The main environmental impacts due to the Encapsulation plant and the Final repository for spent nuclear fuel will be non-radiological consequences related to increase in traffic, transportations (noise, light, vibrations) due to handling of rock spoil and impact on groundwater level. Noise is judged to be the aspect that can have an impact furthest away. Elevated sound levels will be noticed a few kilometres from the facilities and along the roads.

The only possible activities or measures that might have an impact in other countries are related to release of radionuclides from the final repository. SR-Can is a safety analysis focusing on a first evaluation of the long-term safety for KBS-3 repositories at Forsmark and Laxemar.

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ENAInfo, CM Digitaltryck 2008-01

Mellanlagring, inkapsling och slutförvaring av använt kärnbränsle

Underlag för samråd enligt Esbo-konventionen

Svensk Kärnbränslehantering AB
Uppdaterad januari 2008

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Innehållsförteckning

Förord

Om en verksamhet kan antas medföra en betydande miljöpåverkan i ett annat land ska Naturvårdsverket enligt ”Konvention om miljökonsekvensbeskrivningar i ett gränsöverskridande sammanhang” – Esbo-konventionen, informera det landets ansvariga myndighet om den planerade verksamheten eller åtgärden och ge den berörda staten och den allmänhet som berörs där möjlighet att delta i ett samrådsförfarande om ansökan och miljökonsekvensbedömningen” (miljöbalken 6 kap 6 §).

Svensk Kärnbränslehantering AB, SKB, har i uppdrag att ta hand om avfallet från de svenska kärnkraftverken. För att slutligt omhänderta det använda kärnbränslet planerar SKB att bygga en inkapslingsanläggning, där det använda kärnbränslet kapslas in i koppar, och ett slutförvar på cirka 500 meters djup i berggrunden.

Inkapslingsanläggningen planeras att byggas intill det befintliga mellanlagret för använt kärnbränsle (Clab) i Oskarshamn. Undersökningar har genomförts i Forsmark och Oskarshamn för att utreda möjligheterna till lokalisering av slutförvaret. För närvarande sammanställs och analyseras informationen från undersökningarna. Både Oskarshamn och Forsmark ligger vid kusten till Östersjön, i södra delen av Sverige.

Syftet med detta dokument är att ge en översiktlig beskrivning av SKB:s planer för omhändertagande av det använda kärnbränslet och de konsekvenser den verksamheten kan antas medföra. Detaljerad information vad gäller säkerhet och strålskydd, långsiktig säkerhet för ett KBS-3-förvar och översiktlig struktur av MKB-dokumentet för slutförvarssystemet bifogas. Ytterligare information finns att tillgå på SKB:s webbplats samt i SKB:s rapporter.

1 Introduktion

1.1 Kärnkraft i Sverige

Sverige har tolv kärnkraftsreaktorer på fyra platser, varav tio är i drift. I Ringhals finns tre tryckvattenreaktorer och en kokarreaktor med en sammanlagd effekt på 3 600 MW, i Forsmark tre kokarreaktorer på sammanlagt 3 200 MW, i Oskarshamn tre kokarreaktorer på tillsammans 2 200 MW och i Barsebäck två kokarreaktorer på vardera 600 MW.

Anläggningarna togs i drift mellan 1972 och 1985. Sveriges riksdag har fattat beslut om att påbörja en avveckling av kärnkraften. År 1999 stängdes en av de båda reaktorerna i Barsebäck. Den andra reaktorn stängdes 31 maj 2005.

Det finns inga beslut om datum för stängning av de återstående reaktorerna. Planeringen för omhändertagandet av det radioaktiva avfallet bygger på ett scenario med totalt 50 års drift av reaktorerna i Forsmark och Ringhals och 60 års drift av reaktorerna i Oskarshamn.

1.2 SKB:s uppdrag

Det radioaktiva avfallet i Sverige kommer främst från kärnkraften. Enligt svensk lag har reaktorinnehavarna det fulla tekniska och ekonomiska ansvaret för kärnkraftens avfall. Dessa har tillsammans bildat Svensk Kärnbränslehantering AB, SKB, med uppdraget att ta hand om avfallet från de svenska kärnkraftverken så att miljön och människors hälsa skyddas, både på kort och på lång sikt.

Kärntekniklagen kräver att SKB upprättar ett program för den allsidiga forskning och utveckling, samt övriga åtgärder, som behövs för att hantera och slutförvara avfallet på ett säkert sätt. I enlighet med kärntekniklagens krav, redovisar SKB för myndigheter och regering hur arbetet fortskrider. Det sker vart tredje år i så kallade Fud-program (Forskning, Utveckling och Demonstration). Hittills har SKB presenterat tio Fud-program, inklusive två kompletteringar som regeringen begärt. Den senaste redovisningen kom i september 2007.

1.3 Befintligt avfallssystem

Det radioaktiva avfallet från kärnkraftverken kan delas in i olika kategorier grundat på livslängd och aktivitetsnivå. Med hänsyn till kraven på hantering och slutförvaring grupperas avfallet i Sverige i tre huvudkategorier. Den första utgörs av *kortlivat låg- och medelaktivt avfall*. Hit hör förbrukade komponenter, filter med mera från drift, underhåll och rivning av kärnkraftverken. Den andra består av *högaktivt avfall* i form av använt kärnbränsle. Det utgör en mindre andel av volymen, men innehåller både kort- och långlivade radioaktiva ämnen. Den tredje huvudkategorin, *långlivat låg- och medelaktivt avfall,* omfattar bland annat förbrukade komponenter från reaktorinneslutningen.

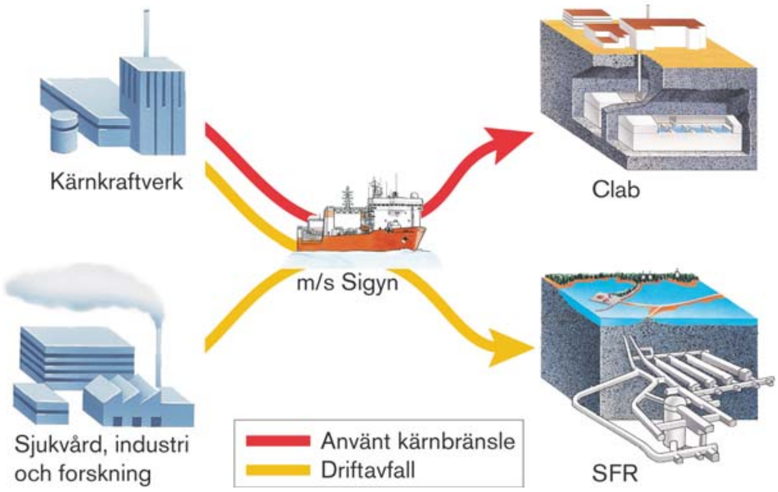
Det kortlivade låg- och medelaktiva avfallet slutförvaras i SFR i Forsmark (Slutförvar för radioaktivt driftavfall). Det använda kärnbränslet mellanlagras i Clab i Oskarshamn

(Centralt mellanlager för använt kärnbränsle). Dessutom finns ett system för transporter av de olika avfallstyperna från kärnkraftverken till avfallsanläggningarna, se *figur 1*.

Det som återstår att genomföra för att slutligt omhänderta avfallet från kärnkraftverken är:

- att uppföra en inkapslingsanläggning och ett slutförvar av använt kärnbränsle
- att uppföra ett slutförvar för långlivat låg- och medelaktivt avfall.

Långlivat låg- och medelaktivt avfall uppstår framför allt vid rivning av kärnkraft-verken. Det kommer enligt planerna att slutförvaras på några hundra meters djup i berggrunden. Lokalisering och byggande kommer att bli aktuellt först om cirka 30 år. SKB:s nuvarande arbete är fokuserat på att slutligt omhänderta det använda kärnbränslet.



Figur 1. *Befintliga anläggningar för omhändertagande av radioaktivt avfall.*

2 Slutligt omhändertagande av använt kärnbränsle

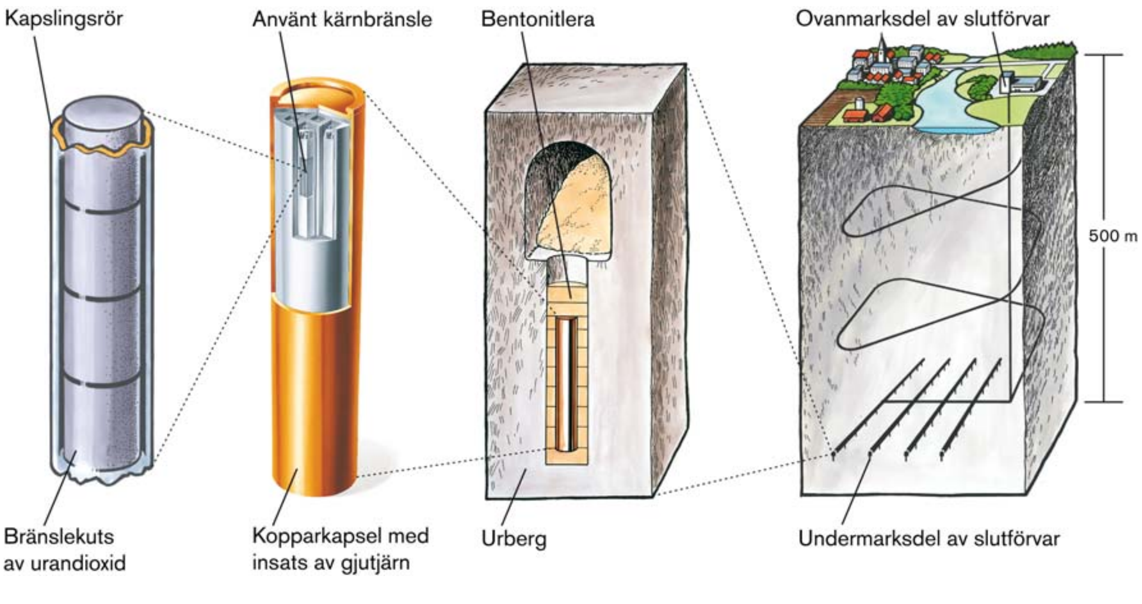
2.1 Val av strategi och metod

De övergripande kraven på omhändertagandet av använt kärnbränsle finns i internationella överenskommelser och svensk lagstiftning. Genomgångar av olika strategier och metoder för omhändertagande av använt kärnbränsle har presenterats vid ett flertal tillfällen, bland annat i samband med kompletteringen till Fud-program 1998, (Samlad redovisning av metod, platsval och program inför platsundersökningsskedet. Svensk Kärnbränslehantering AB, 2000.)

Internationellt råder det ett brett samförstånd om att geologisk deponering är den strategi som bäst lämpar sig för att ta hand om långlivat radioaktivt avfall. Den metod som SKB föreslår för slutförvaring kallas KBS-3, där KBS står för KärnBränsleSäkerhet, se *figur 2*.

Metoden innebär att:

- det använda kärnbränslet kapslas in i kopparbehållare med gjutjärnsinsats
- kapslarna placeras på cirka 500 meters djup i berggrunden
- kapslarna omges av en buffert av bentonitlera.



***Figur 2**. KBS-3-metoden bygger på att olika barriärer (kapseln, bufferten och berget) hindrar de radioaktiva ämnena i bränslet från att skada människa och miljö.*

KBS-3-metoden kräver att två nya kärntekniska anläggningar byggs, en inkapslingsanläggning och ett slutförvar. Båda anläggningarna kräver tillstånd enligt både kärntekniklagen och miljöbalken.

2.2 Långsiktigt säker metod

Kännetecknande för hanteringen av använt kärnbränsle är säkerhetsaspekterna. Säkerheten måste kunna upprätthållas både under drifttiden och på lång sikt – efter förslutningen av förvaret. Det svenska urberget har funnits i mellan en och två miljarder år och utgör en stabil miljö, där förändringar sker mycket långsamt.

Det använda kärnbränslet är farligt under mycket lång tid och ställer speciella krav på omhändertagandet. Målet är att minimera riskerna genom att göra bränslet otillgängligt för människa och miljö så länge det är farligt. De kortlivade ämnena med hög radioaktivitet sönderfaller inom loppet av några hundra år. Därefter dominerar cesium-137 och strontium-90 farligheten. Efter tusen år domineras farligheten av ett fåtal ämnen, de så kallade aktiniderna och deras sönderfallsprodukter. Efter omkring 100 000 år är radioaktiviteten i det använda bränslet nere i samma nivåer som den mängd uranmalm bränslet tillverkades av. Farligheten hos sådana uranmineral, liksom på sikt hos det använda bränslet, domineras av strålning från uranets sönderfallsprodukter (radium, radon, polonium med flera).

Den radiologiska *långsiktiga säkerheten* efter slutförvarets förslutning redovisas i säkerhetsanalyser. I dessa presenteras olika utvecklingsscenarier för slutförvaret som sträcker sig i storleksordningen en miljon år framåt i tiden.

Säkerhetsanalyser regleras och granskas av myndigheterna Statens strålskyddsinstitut (SSI) och Statens kärnkraftinspektion (SKI).

Den senaste säkerhetsanalysen, SR-Can, publicerades i november 2006. SR-Can är ett förberedande steg inför säkerhetsanalysen SR-Site (av engelskans site = plats) som planeras att publiceras år 2009.

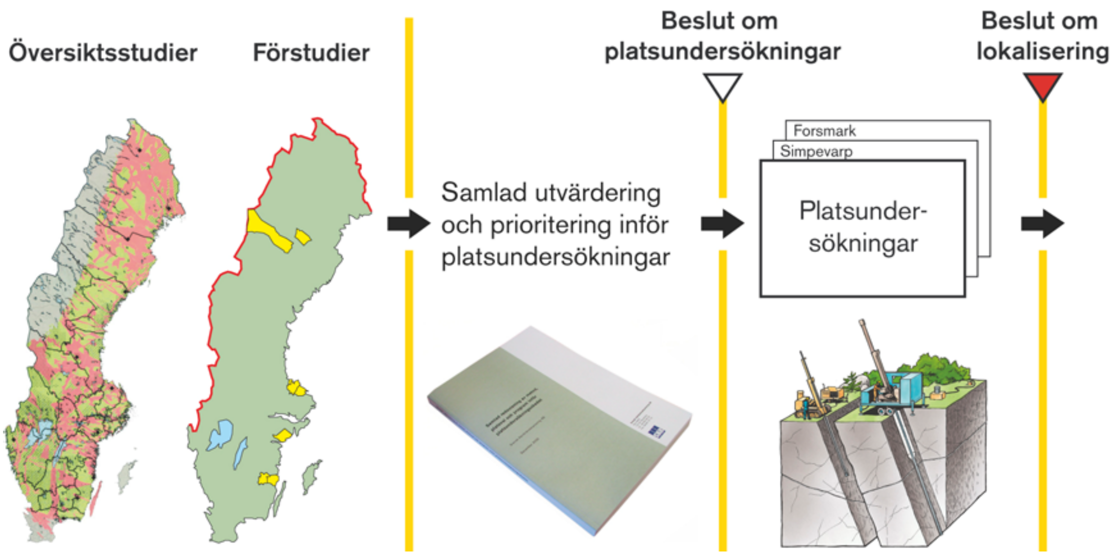
Viktiga moment är redovisningar av:

- metodik för analysen
- förvarssystemets utformning vid förslutning – bränsle, kapsel, buffert, berg och biosfär
- kunskapen kring de processer som förändrar förvaret över tiden
- yttre påverkan vid ett eventuellt utsläpp av radionuklider om någon kapsel skadas.

Den radiologiska *säkerheten under driften* av inkapslingsanläggningen och slutförvaret redovisas och granskas först i preliminära säkerhetsredovisningar. Innan anläggningarna tas i drift kompletteras säkerhetsredovisningarna med analyser och erfarenheter från konstruktionsskedet, uppförandet och driftsättningen.

2.3 Lokaliseringsarbetet

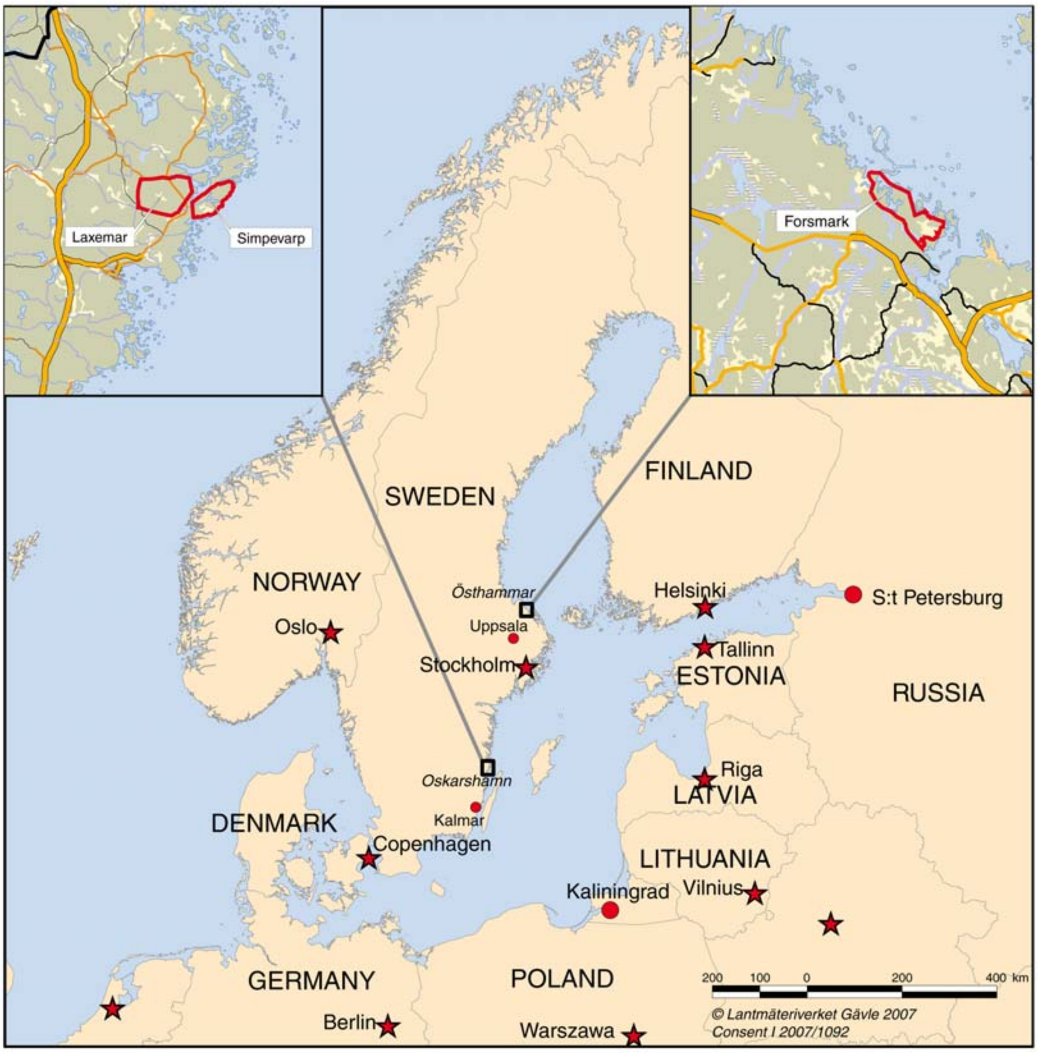
För *slutförvaret* enligt KBS-3-metoden pågår sedan år 1992 ett stegvis upplagt lokaliseringsarbete, se *figur 3*. Genom översiktsstudier kartlade SKB de generella lokaliseringsförutsättningarna i olika delar av landet. I förstudierna utvärderade vi sedan förutsättningarna i totalt åtta kommuner: Storuman, Malå, Östhammar, Nyköping, Oskarshamn, Tierp, Älvkarleby och Hultsfred. År 2000 presenterades platsval och program inför platsundersökningsskedet. År 2002 påbörjades platsundersökningar i Forsmarksområdet i Östhammars kommun och Simpevarpsområdet i Oskarshamns kommun, se *figur 4*. Platsundersökningarna har nyligen avslutats. För närvarande sammanställs och analyseras informationen från undersökningarna.



Figur 3. *Lokaliseringsarbetet för ett slutförvar för använt kärnbränsle bedrivs genom översiktsstudier, förstudier och platsundersökningar.*

I Forsmarksområdet finns i dag Forsmarks Kraftgrupp AB, FKA som omfattar tre kärnkraftsreaktorer av lättvattentyp. I Forsmark finns även SFR – Slutförvar för radioaktivt driftavfall – som togs i drift 1987 och som ägs av SKB.

Platsundersökningarna i Oskarshamn inriktas inledningsvis på två kandidatområden: Simpevarp och Laxemar. Undersökningarna fokuserade senare på den syd-västra delen av Laxemar. På Simpevarpshalvön ligger Oskarshamns Kraftgupp AB, OKG som omfattar tre kärnkraftsreaktorer av lättvattentyp. På Simpevarpshalvön finns även Clab – Centralt mellanlager för använt kärnbränsle – som ägs av SKB. Clab, som togs i drift 1985, tar emot använt kärnbränsle från Sveriges samtliga kärnkraftverk. Även nedfartstunneln till Äspölaboratoriet finns på Simpevarpshalvön. Äspölaboratoriet är SKB:s forskningsanläggning för ett slutförvar i berggrunden och är beläget på 460 meters djup.



Figur 4. *För lokalisering av slutförvaret för använt kärnbränsle undersöks två platser, Forsmark i Östhammars kommun och Simpevarp/Laxemar i Oskarshamns kommun.*

SKB har även utrett och jämfört olika alternativ för lokalisering av *inkapslingsanläggningen*. Vårt förslag är att bygga den i anslutning till Clab i Oskarshamns kommun. Alternativet för lokalisering av inkapslingsanläggningen är i anslutning till de kärntekniska anläggningarna i Forsmark. Detta alternativ är endast aktuellt om även slutförvaret lokaliseras till Forsmark.

3 Tidsplan

3.1 Samråd

Tidiga samråd om slutförvaret och inkapslingsanläggningen genomfördes under åren 2002 – 2003. De utökade samråden påbörjades under år 2003. I både Oskarshamn och Forsmark hålls gemensamma möten för inkapslingsanläggningen och slutförvaret. De utökade samråden kommer att pågå fram till några månader innan ansökningarna lämnas in år 2009.

3.2 Ansökningsprocessen

Nuvarande tidsplan för ansökningsprocessen innebär i korthet följande:

2006 SKB ansökte om tillstånd enligt kärntekniklagen för inkapslingsanläggningen. Till ansökan bifogas en MKB. Samtidigt lämnades till SKI en säkerhetsanalys med fokus på kapselns funktion i slutförvaret (SR-Can), en systemanalys med fokus på inkapslingsanläggningens roll i KBS-3-systemet samt en redovisning av de planerade kapseltransporterna.

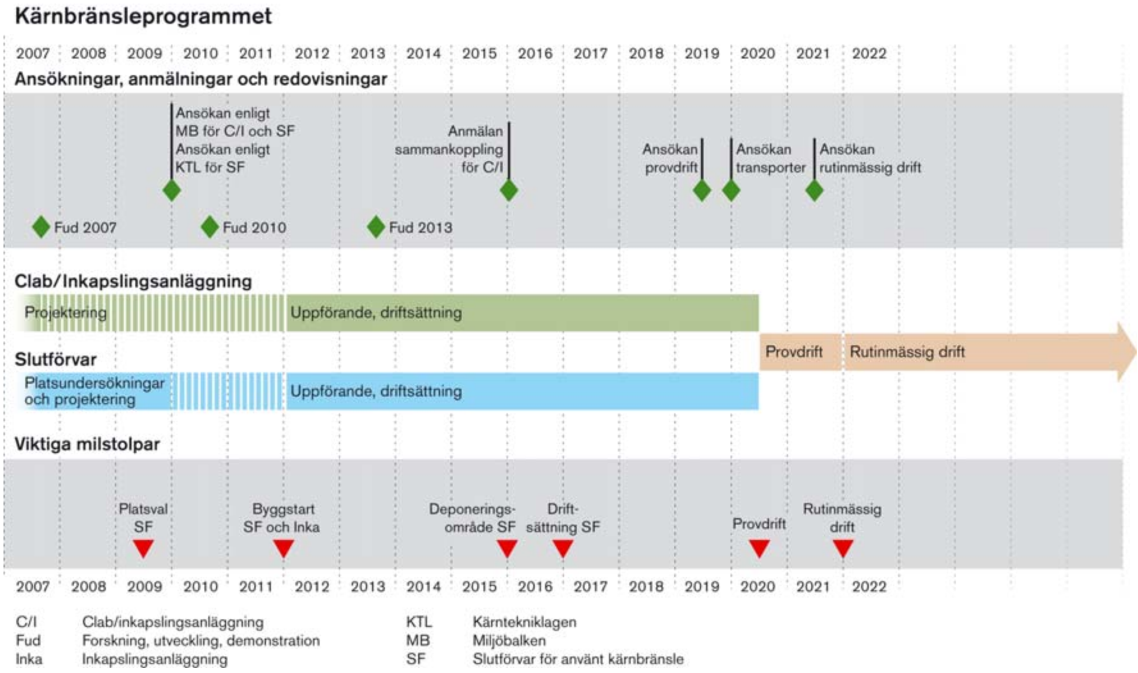
2009 SKB ansöker om tillstånd enligt kärntekniklagen för slutförvaret samt om tillstånd enligt miljöbalken för mellanlagret, inkapslingsanläggningen och slutförvaret, det vill säga hela KBS-3-systemet.

Detta förslag ger regeringen möjlighet att vid ett och samma tillfälle fatta beslut om tillstånd enligt kärntekniklagen och tillåtlighet enligt miljöbalken för alla ingående delar i KBS-3-systemet.

3.3 Byggnation och drift av anläggningarna

Det scenario som ligger till grund för SKB:s planering är att de tio reaktorer som fortfarande är i drift, det vill säga alla utom Barsebäck 1 och 2, stängs efter 50 – 60 års drift. Detta ger en total bränslemängd på cirka 12 000 ton uran, vilket motsvarar cirka 6 000 kapslar av den typ som enligt gällande referensutformning kommer att användas. Programmet medger att såväl mindre som större bränslemängder hanteras, i huvudsak utan andra konsekvenser än att den totala drifttiden, samt utrymmesbehovet i slutförvaret, påverkas.

Enligt plan beräknas byggandet av inkapslingsanläggning och slutförvar börja år 2012 och provdrift år 2020. Hela slutförvarsprogrammet beräknas vara avslutat år 2070. Då är slutförvaret återfyllt och förslutet, anläggningarna på markytan rivna och marken återställd. SKB:s översiktliga planering framgår av *figur 5*.



***Figur 5**. Huvuddragen i SKB:s långsiktiga plan.*

4 Inkapslingsanläggning

4.1 Lokalisering

Inkapslingsanläggningen kan antingen lokaliseras vid Clab (Centralt mellanlager för använt kärnbränsle) i Oskarshamn, vid slutförvaret, vid någon annan befintlig kärnteknisk anläggning eller på en helt ny plats. SKB föreslår att inkapslingsanläggningen byggs i anslutning till Clab, oavsett var slutförvaret byggs. Rent tekniskt finns det dock förutsättningar att uppföra en fristående inkapslingsanläggning och som alternativ lokalisering utreds en förläggning till Forsmark. Utrymmesmässigt finns det goda möjligheter att bygga inkapslingsanläggningen intill kärnkraftverket i Forsmark.

4.2 Anläggning och verksamhet

I Oskarshamn kan inkapslingsanläggningen byggas i direkt anslutning till Clab. Inkapslingsanläggningen kommer att bli cirka 70 x 100 meter och bestå av tre våningsplan under och sju över marknivån, se *figur 6.* Anläggningen kommer att utformas så att samordning med system och organisation vid Clab blir möjlig.

Vid inkapslingen transporteras bränslet från förvaringsbassängerna i Clab, med hjälp av en bränslehiss, till en bassäng i inkapslingsanläggningen, där mätningar och sortering av bränslet utförs. Därefter lyfts bränslet upp ur vattnet och in i en strålskärmad hanteringscell, där det torkas med vakuumtorkning. Efter torkning placeras det i förvaringskapseln. När en kapsel fyllts med bränsleelement monteras kapselinsatsens lock. Kopparlocket läggs på och kapseln försluts med en typ av friktionssvetsning, Friction Stir Welding.

Figur 6. *Möjlig layout av inkapslingsanläggningen placerad intill Clab.*

Det inkapslade bränslet placeras i en transportbehållare för transport till slutförvaret. Om slutförvaret placeras i Oskarshamn kommer transporten från inkapslingsanläggningen att ske en kort sträcka på väg.

Om inkapslingsanläggningen placeras i Forsmark kommer allt använt kärnbränsle att sorteras, mätas och torkas vid Clab före transport. Transporten sker med det special-konstruerade fartyget m/s Sigyn (eller motsvarande annat/nytt fartyg) som transporterar bränslet från kärnkraftverken till Clab idag. Transporten går från hamnen i Simpevarp till Forsmarksverkets hamn. Därefter sker inkapslingen av bränslet i stort sätt på samma sätt som beskrivs ovan.

4.3 Kapseln

Kapseln som ska innesluta det använda kärnbränslet är nästan fem meter lång och har en diameter på drygt en meter, se *figur 7*. Den väger mellan 25 och 27 ton när den är fylld med bränsle. Ytterhöljet består av fem centimeter tjock koppar, som skyddar mot korrosion. Inuti finns en insats av gjutjärn för att ge tillräckligt hög hållfasthet.

Figur 7. *Kopparkapsel med använt kärnbränsle.*

5 Slutförvar

5.1 Lokalisering

SKB har nyligen avslutat platsundersökningar i Forsmark och Oskarshamn för att utreda möjligheterna till lokalisering av slutförvaret. För närvarande sammanställs och analyseras informationen från undersökningarna. SKB:s målsättning är att en av platserna ska kunna utgöra huvudförslaget för lokalisering av slutförvaret i tillstånds-ansökan.

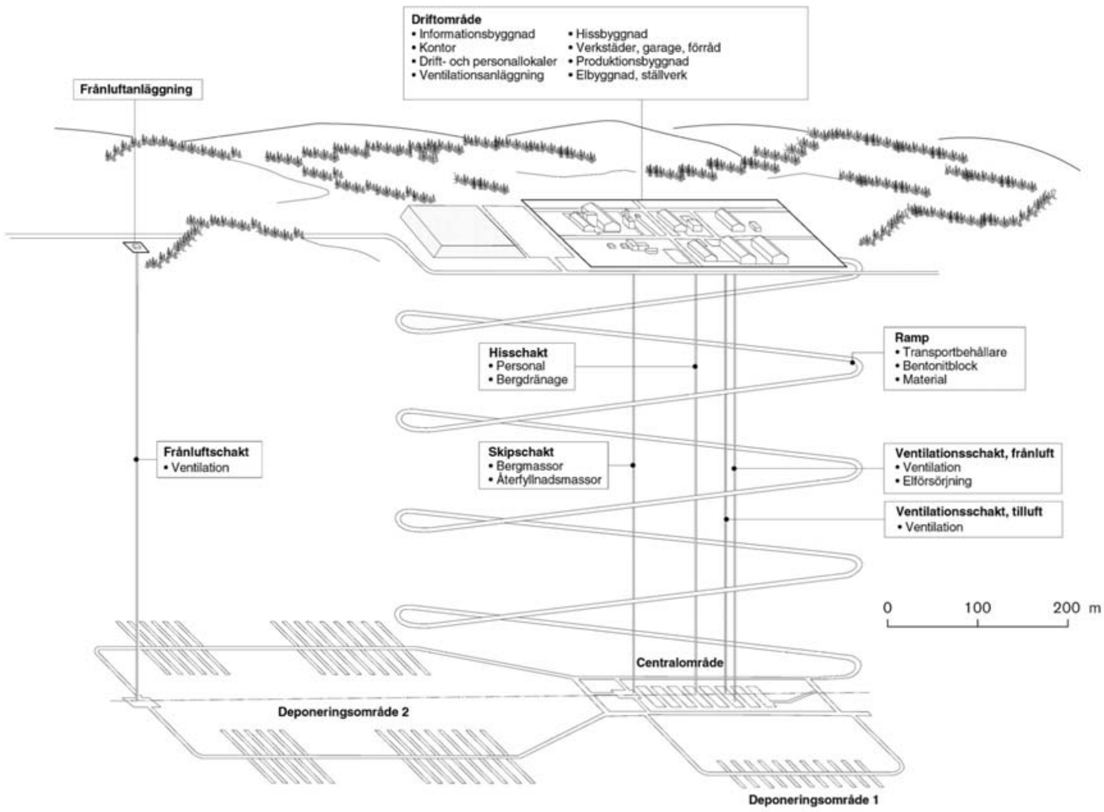
Det finns goda möjligheter att få plats med slutförvarets byggnader på markytan både i Forsmark och i Oskarshamn. Om slutförvaret lokaliseras till Forsmark är huvudalternativet en placering i närheten av kärnkraftverket; där finns det också plats som bedöms som lämplig för eventuella bergupplag.

Platsundersökningarna i Oskarshamnsområdet inriktades inledningsvis mot två delområden: Simpevarpshalvön med omnejd och Laxemarområdet. Undersökningarna fokuserade senare på den syd-västra delen av Laxemar. Det finns markytor som är lämpliga för både byggnader och bergupplag i denna del av Laxemar.

5.2 Anläggning och verksamhet

Anläggningens utformning

Lokaliseringen av slutförvarets undermarksdel ska ske till ett område som har lämpliga geologiska egenskaper med tanke på förvarets långsiktiga säkerhet. Anläggningsdelarna på markytan bör placeras så nära undermarksdelen som möjligt för att få en bra samordning mellan driftområdet på markytan och centralområdet under mark, se *figur 8 och 9*.



Figur 8. *Exempel på förvarsutformning.*

Förbindelserna mellan markytan och förvaret består av en ramp för kapseltransporter och schakt – för bergmassor och bentonit samt för hiss och för ventilation. Anläggandet av byggnader, vägar, tunnlelpåslag och bergupplag kommer att ta 0,2 – 0,4 km^2 i anspråk. Deponeringsområdet breder ut sig på en area av 2 – 4 km^2, cirka 500 meter under markytan.

Figur 9. *Exempel på utformning av slutförvarets utformning på markytan. Fotomontage.*

Bygge och drift

Byggskedet uppgår till cirka 7 år och är indelat i två faser efter hur byggverksamheten förändras under byggtiden. Under byggskedet kommer schakt och ramp att drivas ned till förvarsnivå, cirka 500 meter, och utbyggnaden av förvarsområdet kommer att påbörjas. Arbetet i form av sprängning, bergtransporter och byggverksamhet kommer att vara intensivast under den senare hälften.

Driftskedet uppgår till cirka 45 år och består av växelvis utbyggnad av deponeringstunnlar, deponering av kapslar och återfyllnad av tunnlar. Under driftskedet bestäms tempot i bergarbetena av önskad deponeringstakt, vilket innebär att intensiteten blir betydligt lägre jämfört med under byggskedet.

Även driftskedet är indelat i två faser, provdrift och rutinmässig drift. När inkapslingsanläggningen och första delen av slutförvaret är klara inleds provdrift, då deponering av kapslar i begränsad omfattning sker under en period av några år.

Provdriften utvärderas innan beslut tas om fortsatt, rutinmässig, drift då upp till 200 kapslar per år kommer att deponeras. Totalt kommer cirka 6 000 kapslar att deponeras under provdrift och rutinmässig drift.

Efter avslutad deponering kan byggnaderna ovan jord rivas och marken återställas eller iordningställas för annan verksamhet. Det behövs inga restriktioner för hur den återställda platsen används, med undantag för förbud mot djupborrning.

Hantering av bergmassor

För att bygga de tunnlar som behövs för slutförvaret kommer totalt cirka 3 miljoner m^3 berg (löst mått) att frigöras, transporteras upp till markytan och hanteras i anslutning till driftområdet.

Under byggskedet tas cirka en tredjedel av den totala volymen bergmassor ut. Dessa massor behövs inte för återfyllnaden i slutförvaret, utan kan användas som resurs för annan byggverksamhet, till exempel för vägbygge eller andra anläggningsbyggen. Massorna kan läggas i ett tillfälligt upplag i väntan på att transporteras iväg från området med lastbil.

Den andra tredjedelen bergmassor av den totala volymen, förs till produktionsbyggnaden för att krossas och blandas med bentonit. Därefter transporteras de ned i berganläggningen för att används som återfyllnad i deponeringstunnlarna.

Den resterande tredjedelen bergmassor används till återfyllning av tunnlar och schakt i slutförvaret. Bergmassorna mellanlagras i bergupplag.

En annan möjlighet är att använda Friedlandlera, istället för bergmassor och bentonit, för återfyllningen. I detta fall kommer en större mängd bergmassor att kunna användas för andra konstruktionsarbeten.

Transporter

Under reguljär drift ska en kapsel per dag deponeras. Hur transporten sker från inkapslingsanläggningen beror på var slutförvaret lokaliseras.

Trafiken kommer dessutom att omfatta transporter av bentonit, bergmassor, återfyllnadsmassor och byggnadsmaterial samt personaltransporter.

Transporterna kommer att vara mest märkbara under byggskedets senare hälft, cirka 3,5 år, då 1 miljon m^3 bergmassor ska avyttras. Vid driften av anläggningen blir ökningen av trafiken marginell i förhållande till dagens situation.

6 Miljökonsekvenser

6.1 Miljökonsekvensbeskrivning

Ansökningarna om tillstånd enligt kärntekniklagen och miljöbalken kommer att åtföljas av ett MKB-dokument. Där kommer miljöpåverkan från inkapslingsanläggningen och slutförvaret med tillhörande verksamheter att redovisas. Beskrivningen omfattar hela tidsperioden från att byggandet av anläggningarna startar till och med återfyllning och förslutning av tunnlar under jord samt avveckling och återställande på markytan.

Etableringen av inkapslingsanläggningen och slutförvaret för använt kärnbränsle kommer att påverka de människor som bor och är verksamma i området. Förutom miljöpåverkan utreds därför även effekter på människors hälsa och samhället.

6.2 Påverkan och konsekvenser

För inkapslingsanläggningen bedöms den *radiologiska påverkan* i form av utsläpp till vatten och luft bli mycket liten, i storleksordningen några tiotusendelar av vad som tillåts från en kärnteknisk anläggning. Inga utsläpp med radiologisk påverkan förutsätts ske vare sig vid transporten av inkapslat bränsle till slutförvaret eller vid deponeringen i slutförvaret.

Den huvudsakliga miljöpåverkan bedöms vara av icke-radiologisk karaktär och förorsakas av hantering och transporter av bergmassorna och medföra lokal påverkan på luft och vatten.

Under byggandet av anläggningarna sker *utsläpp till luften* från den ökade trafiken till och inom området. Vidare påverkas luften av stoft från sprängningsarbetena och för slutförvaret även från krossning av berg. Såväl den tillkommande trafiken som sprängningarna bidrar lokalt till utsläpp av kväveoxider och kolmonoxid.

Länsvattnet från bergarbeten vid byggandet av inkapslingsanläggningen och slutförvaret kommer att innehålla partiklar, olja och kväveföreningar. Innan vattnet släpps ut till Östersjön kommer det att renas. Även *lakvattnet* från bergupplag kommer att kontrolleras och vid behov åtgärdas.

Tunnlar, schakt och slutförvarets underjordsdel orsakar en lokal sänkning av *grund-vattennivån*. Efter förslutningen av förvaret kommer den naturliga grundvattennivån att återställas, men det kan ta några decennier.

Buller och vibrationer uppkommer främst på grund av bergarbeten, transporter samt, under drifttiden, från anläggningarnas fläktar. Förhöjda ljudnivåer kommer att märkas några kilometer ut från respektive anläggning och längs det lokala vägnätet.

Säkerhet och strålskydd

Säkerhetsarbetet för SKB:s kärntekniska anläggningar bygger på lagstiftning och myndighetsföreskrifter. SKB genomför flera olika typer av analyser och redovisningar av säkerheten och strålskyddet för inkapslingsanläggningen, Clab, slutförvaret och transportsystemet.

Hur säkerheten och strålskyddet i en kärnteknisk anläggning är anordnad för att skydda människors hälsa och miljön beskrivs i anläggningens säkerhetsredovisning.

Eftersom transport av använt kärnbränsle klassas som kärnteknisk verksamhet, krävs särskilda tillstånd från SKI och SSI enligt kärntekniklagen.

Utvecklingen av KBS-3-metoden för slutförvaring av använt kärnbränsle har pågått sedan slutet av 1970-talet. SKB har under årens lopp gjort flera genomgångar av slutförvarets långsiktiga säkerhet.

Gränsöverskridande miljöpåverkan

Den huvudsakliga miljöpåverkan som kommer att orsakas av inkapslingsanläggningen och slutförvaret för använt kärnbränsle kommer att bli icke-radiologiska konsekvenser relaterade till ökningen av trafiken, transporter (buller, ljussken, vibrationer) relaterade till hanteringen av bergmassor samt påverkan på grundvattennivån. Buller bedöms bli den aspekt som kommer att resultera i påverkan längst bort. Förhöjda bullernivåer kommer att uppstå inom några kilometer från anläggningarna och längs vägarna.

Det enda som skulle kunna påverka andra länder är om radionuklider sprids från slutförvaret. Säkerhetsanalysen SR-Can ger en första värdering av den långsiktiga säkerheten för ett slutförvar för använt kärnbränsle vid Forsmark och Laxemar.

Käytetyn ydinpolttoaineen väliaikainen varastointi, kapselointi ja loppusijoitus

Espoon yleissopimuksen (YVA) mukainen tausta-aineisto neuvotteluihin

Päivitetty tammikuussa 2008

Sisällysluettelo

Esipuhe

Jos jollain toiminnolla on todennäköisesti merkittävä ympäristövaikutus toiseen maahan, Ruotsin luonnonsuojeluvirasto aikoo valtioiden rajat ylittävien ympäristövaikutusten arviointia koskevan yleissopimuksen (Espoo, 1991), eli Espoon yleissopimuksen (YVA), mukaisesti "ilmoittaa kyseisen maan toimivaltaiselle viranomaiselle suunnitellusta toiminnosta tai toimenpiteestä, ja antaa kyseessä olevalle maalle ja niille kansalaisille, joihin asia vaikuttaa, mahdollisuuden osallistua hakemusta ja ympäristövaikutusten arviointia koskevaan neuvottelumenettelyyn" (ympäristölaki, 6 luku, 6 pykälä).

Svensk Kärnbränslehantering AB, SKB (Ruotsin ydinpolttoaine- ja ydinjäteyhtiö), huolehtii Ruotsin ydinvoimalaitosten radioaktiivisen jätteen käsittelystä ja loppusijoituksesta. SKB suunnittelee kapselointilaitoksen rakentamista käytetyn ydinpolttoaineen käsittelemiseksi. Käytetty ydinpolttoaine kapseloidaan laitoksessa kuparisäiliöihin, jonka jälkeen kapselit loppusijoitetaan kallioperään noin 500 metrin syvyyteen.

Kapselointilaitos on tarkoitus rakentaa Oskarshamnissa sijaitsevan käytetyn ydinpolttoaineen välivaraston (Clab) viereen. Forsmarkissa ja Oskarshamnissa on tehty tutkimuksia, joissa on selvitetty loppusijoituslaitoksen paikan valintaa. Tutkimustietoja kootaan ja analysoidaan parhaillaan. Oskarshamn ja Forsmark sijaitsevat molemmat Itämeren rannalla Etelä-Ruotsissa.

Tämä asiakirja on tarkoitettu yleiskatsaukseksi SKB:n suunnitelmista käytetyn ydinpolttoaineen loppusijoituksesta ja sen todennäköisistä seurauksista. Asiakirja sisältää yksityiskohtaista tietoa turvallisuudesta ja säteilysuojelusta. Lisätietoa KBS-3-menetelmän pitkäaikaisesta turvallisuudesta ja loppusijoitusjärjestelmästä laadittavan EIS-asiakirjan yleisrakenne ovat mukana liitteinä. Lisätietoja saa SKB:n Internet-sivustolta ja SKB:n laatimista raporteista, joista tärkeimmät ovat saatavana myös englanniksi.

Johdanto

Ruotsin ydinvoimalat

Ruotsilla on kaksitoista neljässä eri laitoksessa sijaitsevaa ydinreaktoria. Näistä kymmenen on käytössä. Ringhalsissa on kolme painevesireaktoria ja yksi kiehutusvesireaktori, joiden yhteiskapasiteetti on 3 600 MW, Forsmarkissa on kolme kiehutusvesireaktoria, joiden yhteiskapasiteetti on 3 200 MW, Oskarshamnissa on kolme kiehutusvesireaktoria, joiden yhteiskapasiteetti on 2 200 MW ja Barsebäckissa on kaksi kiehutusvesireaktoria, joiden kummankin kapasiteetti on 600 MW.

Voimalat on otettu käyttöön vuosina 1972–1985. Riksdag (Ruotsin valtiopäivät) on päättänyt poistaa ydinvoimalat vaiheittain käytöstä. Toinen Barsebäckin reaktoreista suljettiin vuonna 1999, ja toinen suljettiin 31. toukokuuta 2005.

Jäljellä olevien reaktoreiden sulkemispäiviä ei ole vielä päätetty. Radioaktiivisen jätteen loppusijoitussuunnitelmat perustuvat siihen, että Forsmarkin ja Ringhalsin reaktoreita käytetään 50 vuotta ja Oskarshamnin reaktoreita käytetään 60 vuotta.

SKB:n tavoite

Ruotsin radioaktiivinen jäte tulee pääosin ydinvoimalaitoksista. Ruotsin lain mukaan reaktorin omistajalla on täysi tekninen ja taloudellinen vastuu ydinvoimalaitoksen jätteistä. Omistajat ovat perustaneet Svensk Kärnbränslehantering AB:n, eli SKB:n (Ruotsin ydinpolttoaine- ja ydinjäteyhtiö), joka huolehtii käytetyn ydinpolttoaineen käsittelystä siten, että ympäristö ja ihmisten terveys eivät vaarannu lyhyellä eivätkä pitkällä aikavälillä.

Ydinvoimalatoimintalain (Nuclear Activities Act) mukaan SKB:n on laadittava perusteellinen ohjelma, joka kattaa tutkimuksen, kehittämisen ja muut mahdolliset toimenpiteet, joita tarvitaan jätteiden turvallisessa käsittelyssä ja loppusijoituksessa. SKB toimittaa lain vaatimusten mukaisesti raportit työn etenemisestä valvontaviranomaisille ja hallitukselle. Tämä tapahtuu joka kolmas vuosi RD&D-ohjelmien (tutkimus, kehitys ja esittely) muodossa. Tähän mennessä SKB on esittänyt kymmenen RD&D-ohjelmaa, mukaan lukien kaksi hallituksen pyytämää lisäystä. Uusin raportti annettiin syyskuussa 2007.

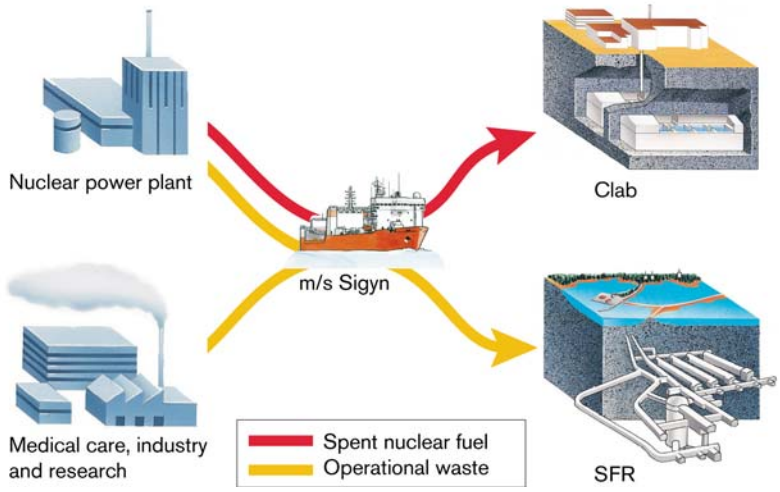
Nykyinen jätejärjestelmä

Ydinvoimalaitosten radioaktiivinen jäte voidaan jakaa eri luokkiin iän ja aktiivisuuden mukaan. Ruotsissa jätteet jaetaan kolmeen pääluokkaan käsittelyyn ja loppusijoitukseen liittyvien vaatimusten mukaisesti. Ensimmäiseen luokkaan kuuluu lyhytikäinen matala- ja keskiaktiivinen jäte. Tähän luokkaan kuuluvat esimerkiksi käytetyt osat ja suodattimet ydinvoimalaitoksen käyttö-, huolto- ja käytöstäpoistovaiheiden ajalta. Toiseen luokkaan kuuluu korkea-aktiivinen jäte eli käytetty ydinpolttoaine. Tätä jätettä syntyy vähemmän, mutta se sisältää suuren osan sekä lyhyt- että pitkäikäisistä radionuklideista. Kolmas pääluokka eli pitkäikäinen matala- ja keskiaktiivinen jäte koostuu esimerkiksi reaktorin sydämen käytetyistä osista.

Lyhytikäinen matala- ja keskiaktiivinen jäte käsitellään SFR:ssä Forsmarkissa (radioaktiivisen voimalaitosjätteen loppusijoituslaitos). Käytetyn ydinpolttoaineen välivarastointi tapahtuu Clabissa Oskarshamnissa (käytetyn ydinpolttoaineen keskusvälivarasto). Tämän lisäksi eri jätetyypeille on erilaiset kuljetusjärjestelmät jätteiden kuljettamiseksi ydinvoimalaitoksista jätteen vastaanottolaitoksiin (katso kuva 1).

Seuraavat asiat on hoidettava, jotta ydinvoimalaitosten jätteet voidaan käsitellä oikein:
- käytetyn ydinpolttoaineen kapselointi- ja loppusijoituslaitoksen rakentaminen
- pitkäikäisen matala- ja keskiaktiivisen jätteen loppusijoituslaitoksen rakentaminen.

Pitkäikäinen matala- ja keskiaktiivinen jäte syntyy pääosin ydinvoimalaitoksen käytöstäpoistovaiheessa. Se loppusijoitetaan kallioperään usean sadan metrin syvyyteen. Paikan valintaprosessia ja rakentamista ei aloiteta vielä 30 vuoteen. SKB keskittyy tällä hetkellä käytetyn ydinpolttoaineen loppusijoitukseen.



Kuva 1. Radioaktiivisen jätteen nykyiset käsittely- ja loppusijoituslaitokset.

Nuclear power plant - Ydinvoimalaitos

Medical care, industry and research - Sairaanhoito, teollisuus ja tutkimus

Spent nuclear fuel - Käytetty ydinpolttoaine
Operational waste - Voimalaitosjäte

Käytetyn ydinpolttoaineen loppusijoitus

Strategian ja menetelmän valinta
Käytetyn ydinpolttoaineen loppusijoituksessa tulee noudattaa kansainvälisten sopimusten ja Ruotsin lain vaatimuksia. Käytetyn ydinpolttoaineen loppusijoituksen eri strategioita ja menetelmiä on esitelty useissa tilanteissa, muun muassa vuoden 1998 RD&D-ohjelman lisäyksen yhteydessä ("Yhteinen selvitys menetelmästä, paikan valinnasta ja ohjelmasta ennen maastotutkimusvaihetta." SKB:n raportti TR-01-03. Svensk Kärnbränslehantering AB, 2000.)

Kansainvälisesti ollaan yksimielisiä siitä, että geologinen loppusijoitus on paras strategia pitkäikäisen radioaktiivisen jätteen loppusijoitukseen. SKB:n ehdottama loppusijoitusmenetelmä on nimeltään KBS-3. KBS on lyhenne sanasta KärnBränsleSäkerhet (ydinpolttoaineen turvallisuus) (katso kuva 2).

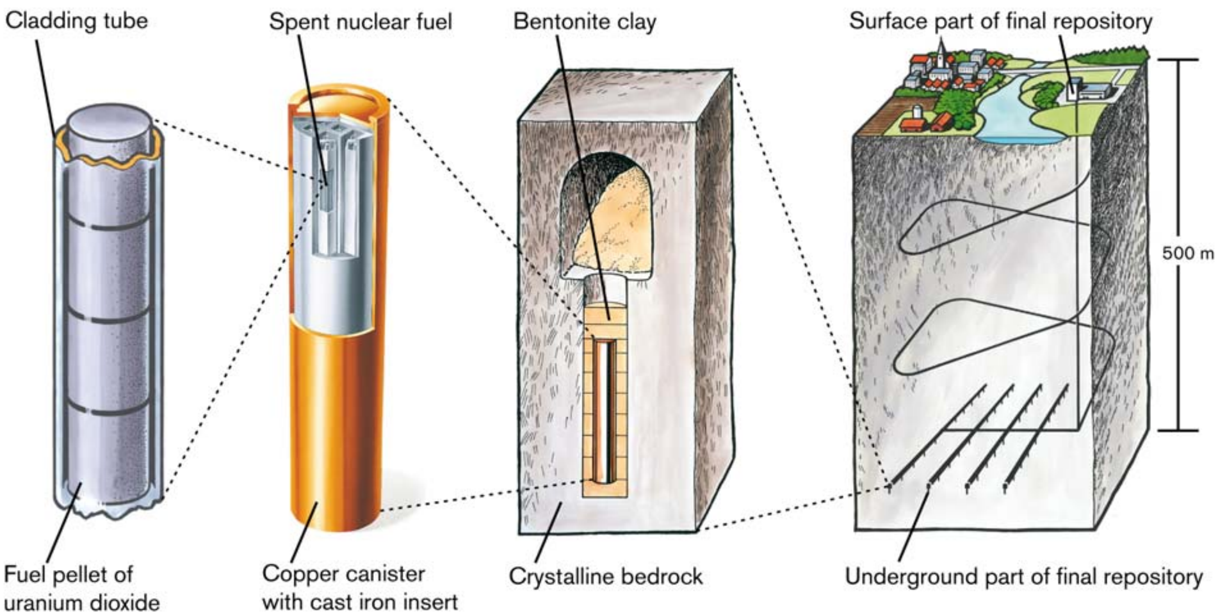
Tässä menetelmässä:
- käytetty ydinpolttoaine kapseloidaan kuparisäiliöihin, joissa on valurautasisus
- säiliöt sijoitetaan kallioperään noin 500 metrin syvyyteen
- säiliöt ympäröidään bentoniittisavella.

KBS-3-menetelmä edellyttää kahden uuden ydinvoimalaitoksen, kapselointi- ja loppusijoituslaitoksen, rakentamista. Molempien laitosten rakentaminen vaatii luvan ydinvoimalatoimintalain (Nuclear Activities Act) ja ympäristölain (Environmental Code) mukaisesti.

Pitkäaikainen turvallisuus
Turvallisuusnäkökohdat ovat ratkaisevan tärkeitä käytetyn ydinpolttoaineen käsittelyssä. Turvallisuus on taattava niin loppusijoitusvaiheessa kuin vielä kauan loppusijoituksen jälkeenkin. Ruotsin kiteinen peruskallio on 1–2 miljardia vuotta vanha, joten se muodostaa vakaan ympäristön, jossa muutokset tapahtuvat hyvin hitaasti.

Käytetty ydinpolttoaine on vaarallista (säteilevää) erittäin pitkän ajan, joten sen käsittelyssä ja loppusijoituksessa on huomioitava erityisvaatimukset. Tavoitteena on minimoida riskit eristämällä polttoaine ihmisistä ja ympäristöstä niin kauan kuin se on vaarallista. Lyhytikäiset aineet (nuklidit), jotka ovat korkeasti radioaktiivisia, hajoavat muutamassa vuosikymmenessä. Sen jälkeen polttoaineen radioaktiiviset aineet ovat cesium-137 ja strontium-90. Tuhannen vuoden jälkeen eräät nuklidit, aktinidit ja niiden hajoamistuotteet, ovat edelleen radioaktiivisia. Noin 100 000 vuoden jälkeen käytetyn polttoaineen radioaktiivisuus on laskenut samalle tasolle kuin uraanimalmin, josta polttoaine on valmistettu. Uraanimalmin, sekä käytetyn polttoaineen, radioaktiivisuus johtuu uraanin hajoamistuotteiden (esim. radium, radon, polonium) säteilystä.
Pitkäaikaista loppusijoituksen jälkeistä säteilyturvallisuutta käsitellään erityisessä turvallisuusselosteessa, jossa esitellään erilaisia skenaarioita loppusijoituksen kehityksestä miljoonan vuoden ajan.

Valvontaviranomaiset tarkastavat turvallisuusselosteen. Valvontaviranomaisia ovat Ruotsin säteilysuojeluviranomainen (SSI) ja Ruotsin ydinvoima-asiain tarkastuslaitos (SKI). Uusin turvallisuusselvitys, SR-Can, annettiin marraskuussa 2006. SR-Can on SR-Site-turvallisuusselvityksen valmisteluvaihe. SR-Site julkaistaan vuonna 2009.



Kuva 2. KBS-3-menetelmä perustuu useisiin esteisiin (säiliö, suojakerros ja peruskallio), jotka estävät polttoaineen radionuklideita vahingoittamasta ihmisiä ja ympäristöä.

Cladding tube - Suojakuori

Spent nuclear fuel - Käytetty ydinpolttoaine

Bentonite clay - Bentoniittisavi

Surface portion of final repository - Loppusijoituspaikan maanpäällinen osa

Fuel pellet of uranium dioxide - Polttoainetabletti, uraanidioksidi

Copper canister with cast iron insert - Kuparisäiliö, jossa valurautasisus

Crystalline bedrock - Kiteinen peruskallio

Underground portion of final repository - Loppusijoituspaikan maanalainen osa

Tärkeitä käsiteltäviä seikkoja ovat:
- selvitysmenetelmä
- loppusijoitusjärjestelmä sulkemisen jälkeen – polttoaine, säiliöt, suojakerros, peruskallio ja biosfääri
- prosessit, jotka muuttavat loppusijoitusta ajan myötä
- säiliön vahingoittumisesta johtuva ulkoinen vaikutus radionuklidien vapautuessa.

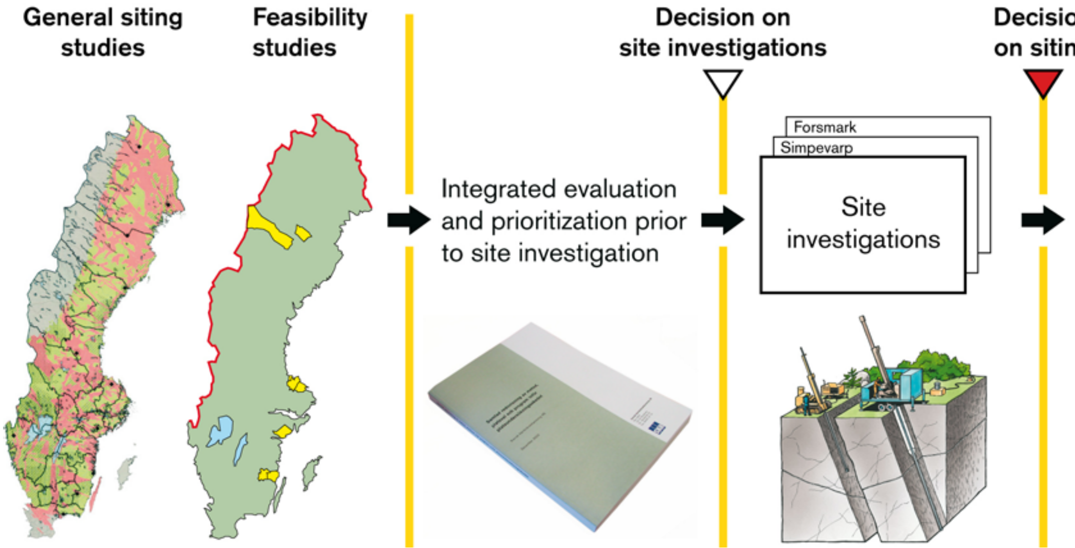
Kapselointilaitoksen ja loppusijoituslaitoksen käytön aikaista säteilyturvallisuutta käsitellään ja tutkitaan alustavissa turvallisuusselosteissa. Ennen laitosten käyttöä turvallisuusselosteita täydennetään selvityksillä ja suunnittelu-, rakennus- ja käyttöönottovaiheessa saadulla käytännön kokemuksella.

Paikan valinta
KBS-3-menetelmää käyttävän loppusijoituspaikan vaiheittainen valintaprosessi alkoi vuonna 1992 (katso kuva 3). SKB teki yleisiä sijoituspaikkatutkimuksia ja tutki sopivia paikkoja maan eri osissa. Toteutettavuustutkimuksissa arvioitiin sopivia paikkoja yhteensä kahdeksassa kunnassa, jotka olivat Storuman, Malå, Östhammar, Nyköping, Oskarshamn, Tierp, Älvkarleby ja Hultsfred. Vuonna 2000 SKB teki ehdotuksensa sijoituspaikoista ja geologisten tutkimusten ohjelmasta. Vuonna 2002 maastotutkimukset alkoivat Forsmarkin alueella Östhammarin kunnassa ja Simpevarpin alueella Oskarshamnin kunnassa (katso kuva 4), sen jälkeen kun hallitus ja kunnat olivat tehneet hyväksyvät päätökset. Maastotutkimukset päättyivät äskettäin. Tutkimustietoja kootaan ja analysoidaan parhaillaan.

Forsmarks Kraftgrupp AB:llä (FKA) on kolme kevytvesireaktoria Forsmarkin alueella. Myös vuonna 1987 käyttöönotettu, SKB:n omistama SFR (radioaktiivisen voimalaitosjätteen loppusijoituslaitos) sijaitsee Forsmarkissa.

Oskarshamnin maastotutkimukset keskittyivät aluksi kahteen vaihtoehtoon, jotka olivat Simpevarp ja Laxemar. Tutkimukset keskittyivät myöhemmin Laxemarin lounaisosaan. Oskarshamns Kraftgrupp AB:llä (OKG) on kolme kevytvesireaktoria, ja se sijaitsee Simpevarpin niemellä. SKB:n omistama Clab (käytetyn ydinpolttoaineen keskusvälivarasto) sijaitsee myös Simpevarpin niemellä. Vuonna 1985 käyttöönotettu Clab vastaanottaa kaikkien Ruotsin ydinvoimalaitosten käytetyn ydinpolttoaineen. Myös tunneli Äspön HRL:ään (kalliolaboratorio) lähtee Simpevarpin niemeltä. Äspön HRL on SKB:n loppusijoitustutkimuslaitos, joka sijaitsee 460 metrin syvyydessä kallioperässä.

SKB on myös tutkinut ja vertaillut eri vaihtoehtoja kapselointilaitoksen paikaksi. Se ehdottaa laitoksen rakentamista Clabin viereen Oskarshamnin kuntaan. Toisena vaihtoehtona on rakentaa kapselointilaitos Forsmarkin ydinvoimalaitoksen viereen. Tämä vaihtoehto tulee kyseeseen vain siinä tapauksessa, että myös loppusijoituslaitos rakennetaan Forsmarkiin.



Kuva 3. Käytetyn ydinpolttoaineen loppusijoituslaitoksen paikka valitaan yleisten sijoituspaikkatutkimusten, toteutettavuustutkimusten ja maastotutkimusten avulla.

General siting studies - Yleiset sijoituspaikkatutkimukset

Feasibility studies - Toteutettavuustutkimukset

Decision on site investigations - Päätös maastotutkimuksista

Decision on siting - Päätös sijoituspaikasta

Integrated evaluation and prioritization prior to site investigation - Maastotutkimuksia edeltävä arviointi ja prioriteettien asettaminen

Site investigations - Maastotutkimukset

Oskarshamnin maastotutkimukset keskittyivät aluksi kahteen vaihtoehtoon, jotka olivat Simpevarp ja Laxemar. Tutkimukset keskittyivät myöhemmin Laxemarin lounaisosaan. Oskarshamns Kraftgrupp AB:llä (OKG) on kolme kevytvesireaktoria, ja se sijaitsee Simpevarpin niemellä. SKB:n omistama Clab (käytetyn ydinpolttoaineen keskusvälivarasto) sijaitsee myös Simpevarpin niemellä. Vuonna 1985 käyttöönotettu Clab vastaanottaa kaikkien Ruotsin ydinvoimalaitosten käytetyn ydinpolttoaineen. Myös tunneli Äspön HRL:ään (kalliolaboratorio) lähtee Simpevarpin niemeltä. Äspön HRL on SKB:n loppusijoitustutkimuslaitos, joka sijaitsee 460 metrin syvyydessä kallioperässä.

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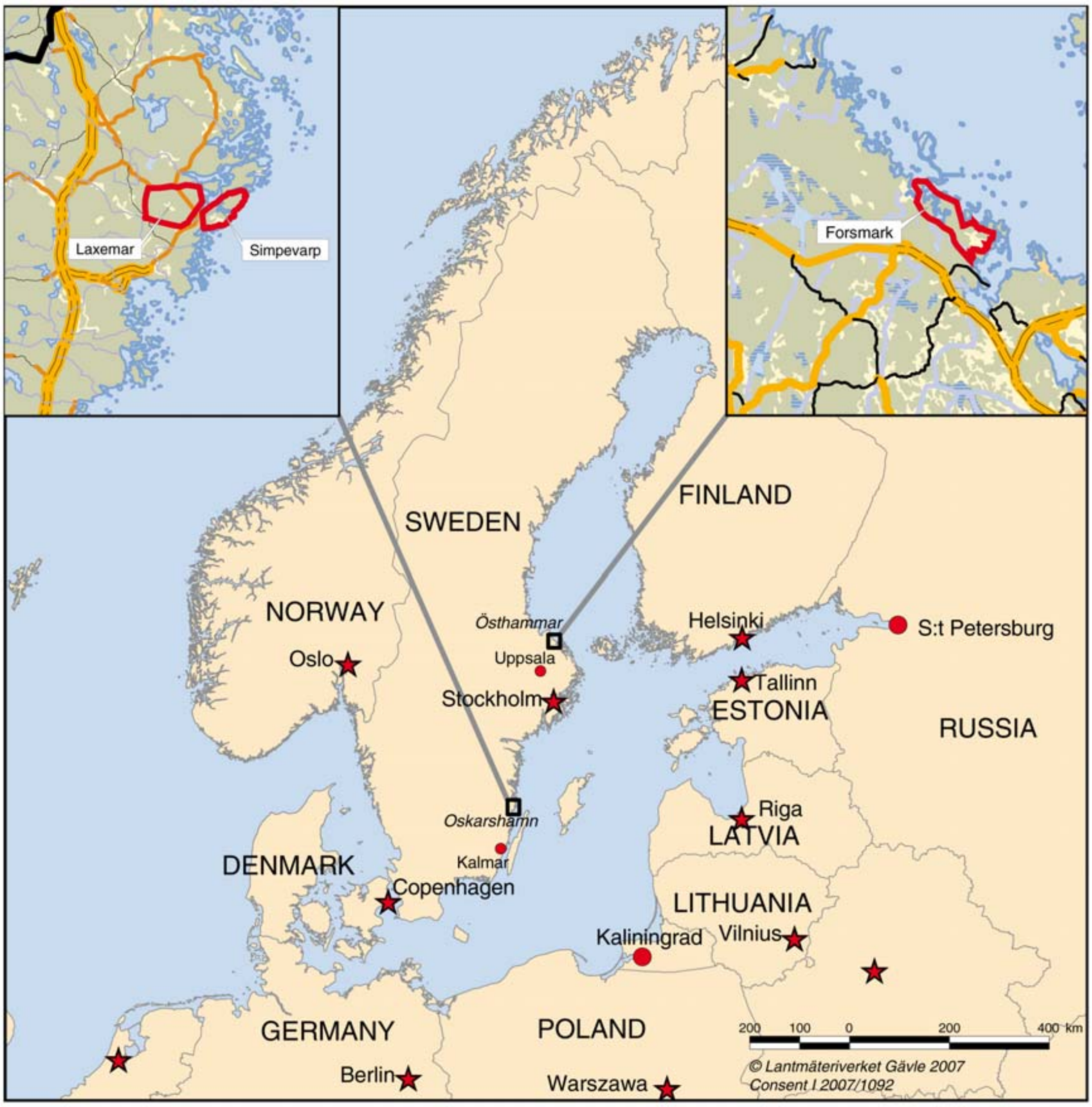


Kuva 4. Kahta paikkaa (Forsmark Östhammarin kunnassa ja Simpevarp/Laxemar Oskarshamnin kunnassa) harkitaan loppusijoituslaitoksen paikaksi.

Aikataulu

Neuvottelut

Ympäristölain (Environmental Code) mukaiset ensimmäiset neuvottelut loppusijoitus- ja kapselointilaitoksesta käytiin vuosina 2002–2003. Jatkoneuvottelut alkoivat vuonna 2003. Yhteiset kokoukset kapselointilaitoksesta ja loppusijoituslaitoksesta pidetään sekä Oskarshamnissa että Forsmarkissa. Jatkoneuvottelut päättyvät muutama kuukausi ennen hakemusten jättämistä vuonna 2009.

Hakemusprosessi
Hakemusprosessin tämänhetkinen aikataulu on lyhyesti seuraava:

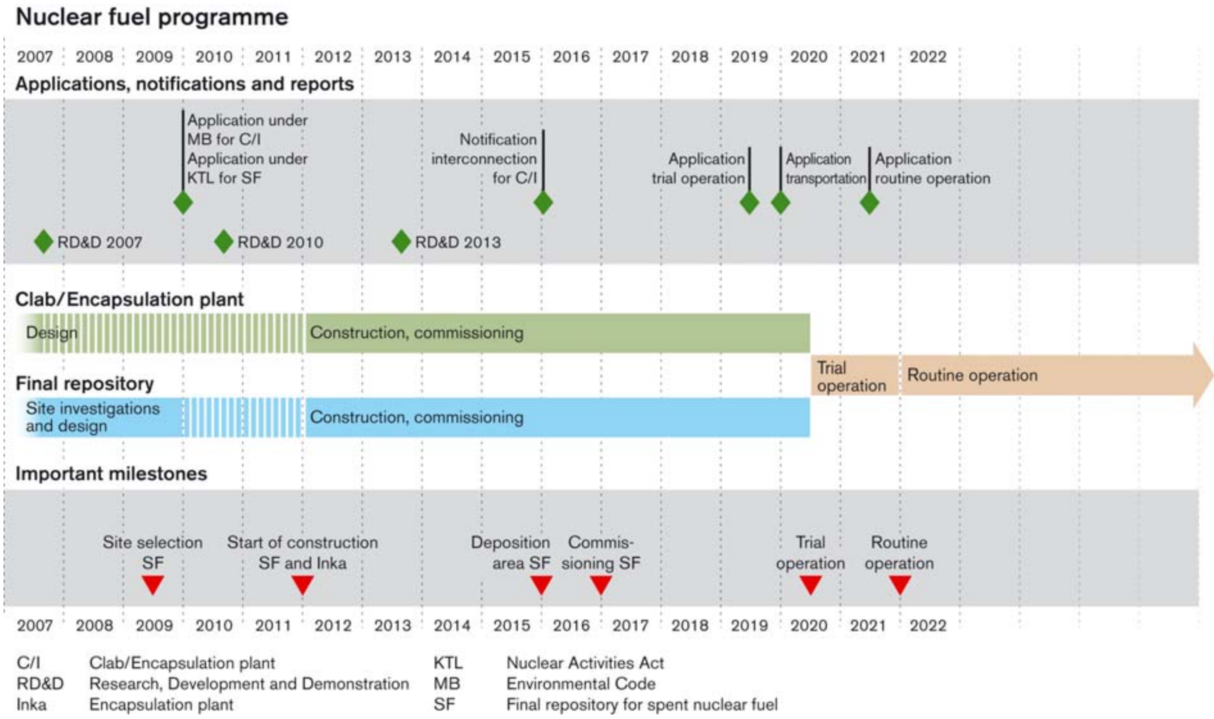
2006 SKB haki ydinvoimalatoimintalain (Nuclear Activities Act) mukaista lupaa kapselointilaitokselle. EIS (ympäristövaikutusten arviointiselostus) liitettiin hakemukseen. Samaan aikaan SKI:lle annettiin turvallisuusselvitys, jossa keskitettiin säiliöiden toimintaan loppusijoituksessa (SR-Can), ja systeemianalyysi, jossa keskitettiin kapselointilaitoksen tehtävään KBS-3-järjestelmässä, sekä selvitys suunnitellusta säiliöiden siirtämisestä.

2009 SKB hakee ydinvoimalatoimintalain (Nuclear Activities Act) mukaista lupaa loppusijoituslaitokselle ja ympäristölain (Environmental Code) mukaisia lupia keskusvälivarastolle, kapselointilaitokselle ja loppusijoituslaitokselle, eli koko KBS-3-järjestelmälle.

Tämä esitys antaa hallitukselle mahdollisuuden tehdä samanaikaisia päätöksiä ydinvoimalatoimintalain (Nuclear Activities Act) ja ympäristölain (Environmental Code) mukaisista luvista koko KBS-3-järjestelmälle.

Laitosten rakentaminen ja käyttö
SKB:n suunnitelmat perustuvat siihen skenaarioon, että kaikki kymmenen käytössä olevaa reaktoria (eli kaikki muut paitsi Barsebäck 1 ja 2) suljetaan 50–60 käyttövuoden jälkeen. Tällöin käytetyn polttoaineen kokonaismäärä olisi noin 12 000 tonnia uraania, joka vastaa noin 6 000:tta tämänhetkisten suunnitelmien mukaista säiliötä. Suunnitelma mahdollistaa myös suurempien ja pienempien polttoainemäärien käsittelyn, mutta tällöin loppusijoituslaitoksen kokonaistoiminta-aika ja tilavaatimukset muuttuvat.

Kapselointilaitoksen ja loppusijoituslaitoksen rakentaminen alkaisi suunnitelman mukaan vuonna 2012, ja koekäyttö alkaisi vuonna 2020. Koko loppusijoitusohjelma päättyisi suunnitelman mukaan vuonna 2070. Siihen mennessä loppusijoituslaitos olisi peitetty ja suljettu, ja maanpäälliset laitokset purettu ja maa-alueet entisöity. SKB:n suunnitelmien aikataulu ilmenee kuvasta 5.



Kuva 5. SKB:n pitkäaikaissuunnitelman pääpiirteet.

Nuclear fuel programme - Ydinpolttoaineohjelma

Applications, notifications and reports - Hakemukset, ilmoitukset ja raportit

Application under MB for C/I - MB:n mukainen hakemus C/I:lle
Application under KTL for SF - KTL:n mukainen hakemus SF:lle

Notification interconnection for C/I - Ilmoitus C/I:n yhteenliittämisestä

Application trial operation - Koekäyttöhakemus

Application transportation - Kuljetushakemus

Application routine operation - Rutiinitoimintahakemus

Clab/Encapsulation plant - Clab/kapselointilaitos

Design - Suunnittelu

Construction, commissioning - Rakentaminen, käyttöönotto

Trial operation - Koekäyttö
Routine operation - Rutiinitoiminta

Final repository - Loppusijoitus

Site investigations and design - Maastotutkimukset ja suunnittelu

Important milestones - Tärkeät välitavoitteet

Site selection SF - Paikan valinta, SF

Start of construction SF and Inka - Rakentamisen aloitus, SF ja Inka

Deposition area SF - Loppusijoitusalue, SF

Commissioning SF - Käyttöönotto, SF

C/I - Clab/Encapsulation plant - C/I - Clab/kapselointilaitos
RD&D - Research, Development and Demonstration - RD&D - Tutkimus, kehitys ja esittely
Inka - Encapsulation plant - Inka - Kapselointilaitos
KTL - Nuclear Activities Act - KTL - Ydinvoimalatoimintalaki (Nuclear Activities Act)
MB - Environmental Code - MB - Ympäristölaki (Environmental Code)
SF - Final repository for spent nuclear fuel - SF - Käytetyn ydinpolttoaineen loppusijoitus

Kapselointilaitos

Paikan valinta

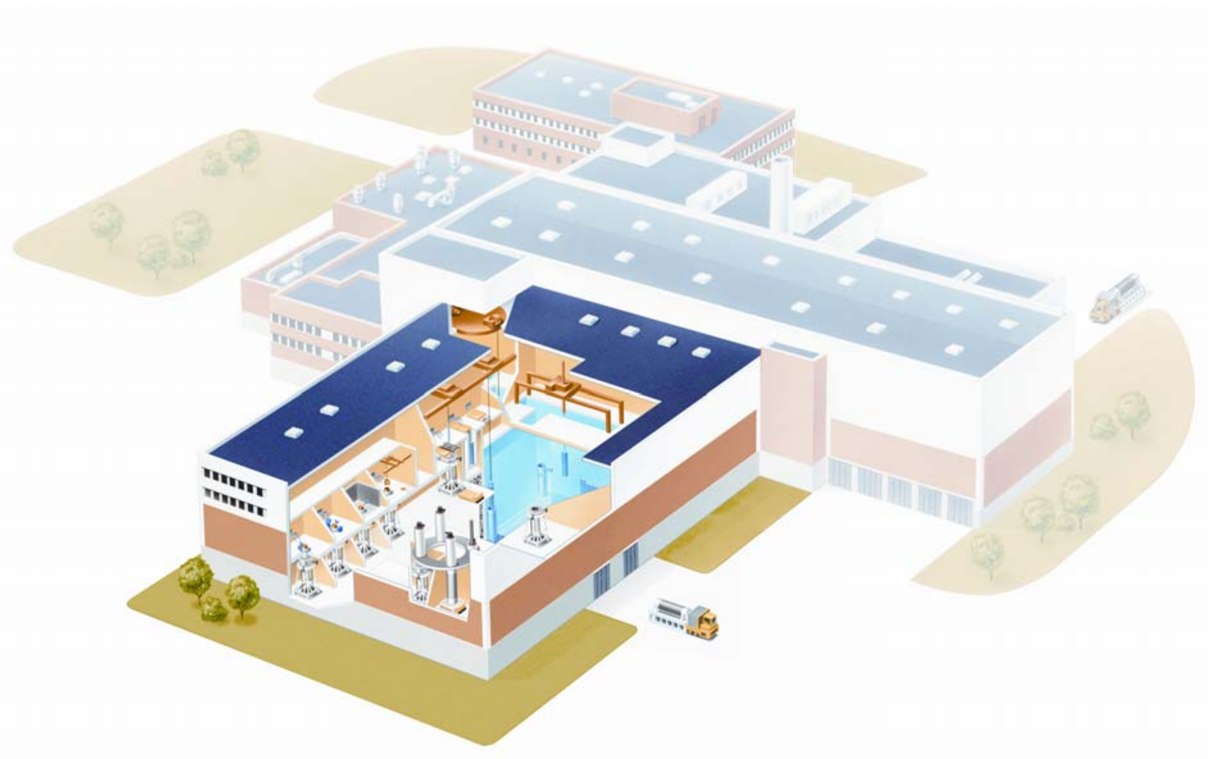
Kapselointilaitos voidaan sijoittaa Oskarshamnissa sijaitsevaan Clabiin (käytetyn ydinpolttoaineen keskusvälivarasto), loppusijoituslaitoksen yhteyteen, johonkin muuhun nykyiseen ydinvoimalaitokseen tai kokonaan uuteen paikkaan. SKB ehdottaa kapselointilaitoksen rakentamista Clabin viereen huolimatta siitä, mihin loppusijoituslaitos rakennetaan. On kuitenkin myös mahdollista rakentaa erillinen kapselointilaitos, joten laitoksen rakentamista Forsmarkiin pidetään toisena vaihtoehtona. Forsmarkin ydinvoimalaitoksen vieressä on runsaasti tilaa kapselointilaitoksen rakentamista varten.

Laitos ja sen toiminta

Oskarshamnissa kapselointilaitos voidaan rakentaa aivan Clabin viereen. Kapselointilaitoksen pinta-ala tulee olemaan noin 70 x 100 metriä, ja siinä on kolme maanalaista ja seitsemän maanpäällistä kerrosta (katso kuva 6). Laitos rakennetaan siten, että sen toiminta voidaan yhdistää Clabin järjestelmiin.

Ennen kapselointia polttoaine siirretään polttoainekuljettimella Clabin säilytysaltaista kapselointilaitoksen altaaseen, jossa säteily mitataan ja polttoaine lajitellaan. Polttoaine nostetaan sen jälkeen vedestä ja siirretään säteilysuojattuun käsittelykennoon, jossa se tyhjiökuivataan. Kuivaamisen jälkeen polttoaine siirretään kapseliin. Kun kapseli on täytetty polttoainenipuilla, kapselin sisäkansi kiinnitetään. Sen jälkeen kapselin kuparikansi asetetaan paikalleen, ja kapseli hitsataan kiinni. Kapselointilaitoksessa käytettävää hitsaustapaa kutsutaan kitkahitsaukseksi (FSW).

Kapseloitu polttoaine siirretään loppusijoituslaitokseen kuljetussäiliössä. Jos loppusijoituslaitos sijaitsee Oskarshamnissa, kuljetussäiliöt kuljetetaan tietä pitkin lyhyen matkan kapselointilaitoksesta loppusijoituslaitokseen.



Kuva 6. Clabin vieressä sijaitsevan kapselointilaitoksen mahdollinen pohjapiirros.

Jos kapselointilaitos sijaitsee Forsmarkissa, kaikki käytetty ydinpolttoaine lajitellaan, mitataan ja kuivataan Clabissa ennen kuljetusta. Polttoaine kuljetetaan loppusijoituslaitokseen erikoisrakenteisella aluksella, m/s Sigynillä (tai muu/uusi vastaava alus), jolla polttoaine nykyään kuljetetaan ydinvoimalaitoksista Clabiin. Polttoaine kuljetetaan Simpevarpin satamasta Forsmarkin ydinvoimalan satamaan. Polttoaine kapseloidaan suunnilleen samalla tavalla kuin edellä kerrottiin.

Kapselit

Käytettyä ydinpolttoainetta sisältävä kapseli on lähes viisi metriä pitkä, ja sen halkaisija on yli metrin (katso kuva 7). Kapseli painaa 25–27 tonnia, kun se on täytetty polttoaineella. Ulkokuori on viisi senttimetriä paksu, ja se on kuparia. Tämä suojaa kapselia korroosiolta. Kuparikuoren alla on valurautasisus, joka vahvistaa kapselia.

Kuva 7. Käytettyä ydinpolttoainetta sisältävä kuparikapseli.

Loppusijoitus

Paikan valinta
SKB on äskettäin päättänyt maastotutkimukset Forsmarkissa ja Oskarshamnissa. Tutkimuksissa on selvitetty loppusijoituslaitoksen paikan valintaa. Tutkimustietoja kootaan ja analysoidaan parhaillaan. SKB:n tavoitteena on, että toinen näistä paikoista on lupahakemuksen päävaihtoehto loppusijoituslaitoksen paikaksi.

Sekä Forsmarkissa että Oskarshamnissa on riittävästi tilaa loppusijoituslaitoksen maanpäällisille rakennuksille. Jos loppusijoituslaitos rakennetaan Forsmarkiin, päävaihtoehtona on rakentaa se ydinvoimalaitoksen viereen. Siellä on riittävästi tilaa myös mahdollisille kaivauskasoille.

Oskarshamnin alueen maastotutkimukset keskittyivät kahteen vaihtoehtoon, jotka olivat Simpevarpin niemi ympäristöineen ja Laxemarin alue. Tutkimukset keskittyivät myöhemmin Laxemarin lounaisosaan. Tässä Laxemarin osassa on riittävästi maata rakennuksille ja kaivauskasoille.

Laitos ja sen toiminta
Laitoksen suunnittelu
Loppusijoituspaikan maanalaisen osan on sijaittava sellaisella alueella, jossa on sopivat geologiset olosuhteet loppusijoituksen pitkäaikaista turvallisuutta ajatellen. Laitoksen maanpäällisten osien tulisi olla mahdollisimman lähellä maanalaisia osia, jotta maanpäälliset

toiminnot voidaan yhdistää sujuvasti maanalaisen keskusalueen toimintoihin (katso kuvat 8 ja 9).

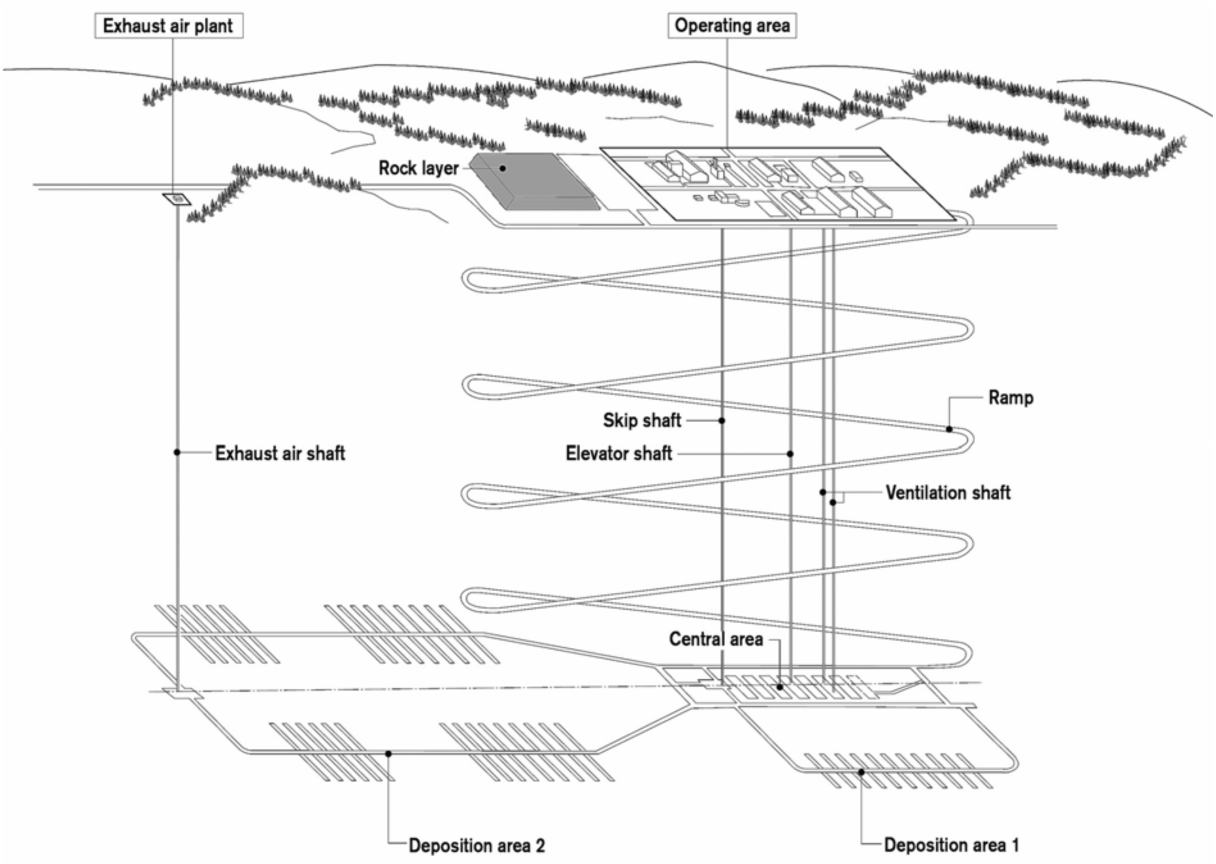
Maanpäällinen osa ja loppusijoituspaikka yhdistetään toisiinsa kapseliluiskalla ja kuiluilla, joita pitkin ilma, ihmiset, kaivumaa ja bentoniitti kulkevat. Rakennukset, tiet, tunnelin suu ja kaivauskasat vievät tilaa noin 0,2–0,4 km^2. Loppusijoitusalueen suuruus on noin 2–4 km^2, ja se on noin 500 metrin syvyydessä maanpinnan alla.

Rakentaminen ja käyttö
Rakennusvaihe kestää noin seitsemän vuotta, ja se jakautuu kahteen erilaiseen rakennustoimintaosaan. Rakennusvaiheen aikana kuilut ja luiska johdetaan loppusijoituspaikkaan, noin 500 metrin syvyyteen, ja loppusijoituspaikan kaivaminen alkaa. Räjäytystyöt, kaivumaan kuljetukset ja rakennustyöt ajoittuvat etenkin vaiheen loppupuoliskolle.

Käyttövaihe kestää yli 45 vuotta, ja siihen kuuluu loppusijoitustunneleiden rakentaminen, kapseleiden loppusijoitus ja tunneleiden täyttäminen. Käyttövaiheen aikana kaivutöiden nopeus määräytyy loppusijoitusasteen mukaan, eli työt eivät ole niin raskaita kuin rakennusvaiheessa.

Myös käyttövaihe jakautuu kahteen osaan: koekäyttöön ja rutiinitoimintaan. Kun kapselointilaitos ja loppusijoituslaitoksen ensimmäinen osa ovat valmiit, koekäyttö alkaa ja jatkuu muutaman viikon ajan.

Koekäytön tulokset arvioidaan ennen siirtymistä rutiinitoimintaan, jonka aikana käsitellään jopa 200 kapselia vuosittain. Koekäyttö- ja rutiinitoimintavaiheiden aikana käsitellään yhteensä noin 6 000 kapselia.
Kun loppusijoitus päättyy, maanpäälliset rakennukset voidaan purkaa ja maa-alueet entisöidä tai kunnostaa muuhun tarkoitukseen. Entisöidyn maa-alueen käytölle ei ole mitään muita rajoituksia kuin se, että syväporaaminen on kielletty.



Kuva 8. Loppusijoituslaitoksen suunnittelukaavio.

Exhaust air plant - Poistoilmalaitteet

Rock layer - Kalliokerros

Operating area - Toiminta-alue

Exhaust air shaft - Poistoilmakuilu

Skip shaft - Säiliökuilu

Elevator shaft - Hissikuilu

Ventilation shaft - Tuuletuskuilu

Central area - Keskusalue

Deposition area 2 - Loppusijoitusalue 2
Deposition area 1 - Loppusijoitusalue 1

Kaivumaan käsittely
Loppusijoitustunneleita rakennettaessa yhteensä noin 3 000 000 m³ (arvio) kaivumaata poistetaan ja kuljetetaan maanpinnalle.

Noin kolmasosa kaivumaan kokonaismäärästä tulee rakennusvaiheessa. Tätä kaivumaata ei tarvita loppusijoitustunneleiden täyttämiseen, vaan sitä voidaan käyttää muihin rakennuskohteisiin, kuten tienrakennukseen tai muihin rakennusteknisiin töihin. Kaivumaa voidaan sijoittaa väliaikaisiin kasoihin, jotka siirretään pois alueelta kuorma-autoilla.

Toinen kolmasosa kaivumaan kokonaismäärästä tulee tuotantorakentamisesta, ja se murskataan ja sekoitetaan yhteen bentoniitin kanssa. Sen jälkeen se kuljetetaan maanalaisiin tiloihin, jossa sitä käytetään loppusijoitustunneleiden täyttämiseen.

Viimeinen kolmasosa kaivumaata käytetään loppusijoituslaitoksen tunneleiden ja kuilujen täyttämiseen. Kaivumaata säilytetään väliaikaisesti kasoissa.

Täyttämiseen voi käyttää myös Friedland-savea kaivumaan ja bentoniitin sijaan. Tässä tapauksessa kaivumaata voidaan käyttää enemmän muihin rakennuskohteisiin.

Kuljetus
Normaalin toiminnan aikana voidaan käsitellä yksi kapseli päivässä. Kapseleiden kuljettamistapa kapselointilaitoksesta riippuu siitä, missä loppusijoituslaitos sijaitsee. Kuljetuksiin kuuluvat myös bentoniitin, kaivumaan, täyttöaineiden ja rakennusaineiden sekä ihmisten kuljetus.

Kuljetuksia on eniten rakennusvaiheen loppupuoliskolla, joka kestää noin 3,5 vuotta ja jolloin kuljetetaan 1 000 000 m³ kaivumaata. Liikennemäärät eivät juurikaan kasva laitoksen toiminnan aikana nykytilanteeseen verrattuna.

Kuva 9. Tässä luonnoksessa loppusijoituslaitoksen maanpäälliset tilat on sijoitettu teollisuusalueelle, jossa nykyään sijaitsee Forsmarkin ydinvoimalan asuinalue.

Ympäristövaikutukset

Ympäristövaikutusten arviointi

Ydinvoimalatoimintalain (Nuclear Activities Act) ja ympäristölain (Environmental Code) mukaisten lupahakemusten mukana annetaan ympäristövaikutusten arviointiselostus (EIS). Tässä asiakirjassa kerrotaan kapselointilaitoksen ja loppusijoituslaitoksen sekä niihin liittyvien toimenpiteiden ympäristövaikutuksista. EIS kattaa koko ajanjakson laitosten rakentamisen aloittamisesta maanalaisten tunneleiden täyttämiseen ja sulkemiseen sekä maanpäällisten tilojen siivoamiseen ja entisöintiin.

Käytetyn ydinpolttoaineen kapselointi- ja loppusijoituslaitokset vaikuttavat alueella asuviin ja työskenteleviin ihmisiin. Tämän vuoksi ympäristövaikutusten lisäksi tutkitaan myös laitosten vaikutusta yhteisöön ja ihmisten terveyteen.

Vaikutukset ja seuraukset

Kapselointilaitoksen säteilyvaikutus päästöinä veteen ja ilmaan on hyvin pieni. Se on vain muutama kymmenestuhannesosa siitä, mikä ydinvoimalaitokselle sallitaan. Kapseloidun polttoaineen kuljetuksissa loppusijoituspaikkaan tai kapseleiden loppusijoituksessa ei todennäköisesti ole odotettavissa päästöjä, joilla olisi säteilyvaikutusta.

Suurimmat ympäristövaikutukset ovat oletettavasti muita kuin säteilyvaikutuksia, ja ne aiheutuvat kaivumaan käsittelystä ja kuljettamisesta ja lisäävät paikallista ilman ja veden saastumista.

Laitosten rakentamisen aikana kasvavat liikennemäärät alueelle ja alueella lisäävät päästöjä ilmakehään. Lisäksi räjäytystyöt ja kivien murskaus loppusijoituslaitoksessa lisäävät hiukkaspäästöjä. Lisääntyvä liikenne ja räjäytystyöt kasvattavat myös paikallisia typpioksidi- ja hiilimonoksidipäästöjä.

Kapselointi- ja loppusijoituslaitoksen rakentamisen aikaisten töiden hulevedet sisältävät hiukkasia, öljyä ja epäpuhtauksia. Vesi puhdistetaan, ennen kuin se päästetään Itämereen. Kaivauskasojen suotovesi testataan ja puhdistetaan tarvittaessa.

Tunneleiden, kuilujen ja loppusijoituslaitoksen maanalaisten osien rakentaminen alentaa paikallista pohjavesitasoa (alenema). Loppusijoituksen sulkemisen jälkeen luonnollinen pohjavesitaso palautuu, mutta siihen saattaa kulua useita vuosikymmeniä.

Melu ja tärinä aiheutuvat pääasiassa kivitöistä, kuljetuksista ja tuulettimista. Melutaso lisääntyy muutaman kilometrin säteellä laitoksista sekä kuljetusteillä.

Turvallisuus ja säteilysuojelu

SKB:n ydinvoimalaitosten turvallisuuden takaaminen perustuu lainsäädäntöön ja valvontaviranomaisen vaatimuksiin. SKB tekee useita erilaisia selvityksiä ja raportteja kapselointilaitoksen, Clabin, loppusijoituslaitoksen ja kuljetusjärjestelmien turvallisuudesta ja säteilysuojelusta.

Laitoksen turvallisuusselosteessa kerrotaan, miten ydinvoimalaitoksen turvallisuus- ja säteilysuojeluasiat on hoidettu, jotta ympäristö ja ihmisten terveys eivät vaarannu.

Käytetyn ydinpolttoaineen kuljettaminen on luokiteltu ydinvoimalatoiminnaksi, joten sitä koskevat SKI:n ja SSI:n edellyttämät ydinvoimalatoimintalain (Nuclear Activities Act) mukaiset erityisluvat.

Käytetyn ydinpolttoaineen loppusijoituksessa käytettävää KBS-3-menetelmää on kehitetty 1970-luvun lopulta lähtien. SKB on vuosien aikana tehnyt useita selvityksiä loppusijoituksen pitkäaikaisesta turvallisuudesta.

Rajojen yli ulottuva ympäristövaikutus
Käytetyn ydinpolttoaineen kapselointilaitoksesta ja loppusijoituksesta aiheutuvat pääympäristövaikutukset ovat muita kuin säteilyseurauksia. Ne liittyvät liikennemäärien kasvuun, kaivumaan käsittelystä aiheutuvien kuljetusten vaikutuksiin (melu, valo, tärinä) ja vaikutukseen pohjavesitasolle. Melulla katsotaan olevan kaikkein suurin vaikutusalue. Melutaso lisääntyy muutaman kilometrin säteellä laitoksista sekä kuljetusteillä.

Ainoat mahdolliset toiminnot tai toimenpiteet, joilla voi olla vaikutusta muihin maihin, liittyvät loppusijoituksen radionuklidipäästöihin. SR-Can on turvallisuusselvitys, jossa keskitytään Forsmarkin ja Laxemarin KBS-3-menetelmän pitkäaikaisen turvallisuuden ensiarviointiin.

Mellanlagring, inkapsling och slutförvaring av använt kärnbränsle

Översiktlig struktur av MKB-dokumentet för slutförvarssystemet

Svensk Kärnbränslehantering AB
December 2007

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556175-2014 Säte Stockholm

Administrativa uppgifter

Nyckeluppgifter om sökanden, såsom adress/kontaktuppgifter, organisationsnummer, SNI-kod, juridiskt ombud m.m.

Saken

Denna miljökonsekvensbeskrivning utgör en bilaga till ansökan om tillstånd enligt kärntekniklagen för ett slutförvar för använt kärnbränsle samt till ansökan om tillstånd enligt miljöbalken för ett slutförvar för använt kärnbränsle, en inkapslingsanläggning för använt kärnbränsle samt för Centralt mellanlager för använt kärnbränsle (Clab).

Medverkande

Medarbetare inom MKB-enheten på SKB.

Läsanvisning

I de inledande kapitlen beskrivs SKB:s uppdrag och verksamhet, platserna för sökt och övervägd lokalisering samt nollalternativet, vilket är gemensamt för hela slutförvarssystemet.

För att man ska kunna se vilken miljöpåverkan respektive *anläggning* har, beskrivs sedan slutförvaret och inkapslingsanläggningen tillsammans med Clab i var sitt kapitel. Kapitlen innehåller detaljerade beskrivningar av anläggningarna och deras verksamhet samt en bedömning av dess effekter och konsekvenser.

Slutligen beskrivs de sammanlagda konsekvenser som hela slutförvarssystemet ger upphov till och en samlad bedömning görs.

Icke-teknisk sammanfattning

Innehåll

1 Inledning

En kort introduktion till projektet.

2 Syfte

2.1 Projektet

- Vad vi ansöker om
- Syftet med slutförvarssystemet

2.2 Miljökonsekvensbeskrivning

Beskrivning av MKB-processen enligt 6 kap miljöbalken och syftet med MKB:n.

3 Bakgrund

3.1 SKB:s uppdrag

- SKB:s syfte
- SKB:s forskning (Stripa, Äspö, Kapsellab mm)
- Fud-processen

3.2 Befintligt avfallssystem

Beskrivning av dagens system med kärnkraftverken, Clab (Centralt mellanlager för använt kärnbränsler), SFR (Slutförvar för radioaktivt driftavfall), m/s Sigyn.

3.3 KBS-3 metoden

Historisk beskrivning av hur metoden har arbetats fram

3.4 Lokaliseringsprocessen

En sammanfattning av lokaliseringsprocessen där motiv anges för samtliga val. Beskrivningen stannar vid valet av Forsmark och Oskarshamn för platsundersökningar.

3.5 Platsundersökningarna

Beskrivning av det arbete som gjorts under platsundersökningarna.

3.6 Andra metoder

En kort sammanfattning av de metoder SKB studerat och motivering till varför de avfärdats.

4 Alternativredovisning

En kort sammanfattning av den alternativredovisning som görs i kapitel 9 och 10.

4.1 Sökt lokalisering

Beskrivning av den valda lokaliseringen för respektive anläggning: slutförvaret, inkapslingsanläggningen och Clab. Motiv till lokaliseringsvalet ges.

4.2 Övervägd lokalisering

Beskrivning av den övervägda lokaliseringen för respektive anläggning: slutförvaret och inkapslingsanläggningen. En förklaring ges till varför Clab saknar alternativ lokalisering.

4.3 Sökt metod och utformning

Beskrivning av den sökta metoden, KBS-3, och anläggningarnas utformning.

4.4 Alternativ utformning

Beskrivning av alternativa utformningar .

4.5 Nollalternativ

Nollalternativet är gemensamt för hela systemet. Beskrivningen omfattar:

- miljöpåverkan, effekter och konsekvenser samt skadeförebyggande åtgärder
- hushållning med naturresurser
- risk- och säkerhetsfrågor

5 Övergripande avgränsning

Viktiga övergripande avgränsningar vi har gjort och motiv till detta. Ett exempel är att kapselfabriken inte ingår i ansökningarna.

6 Samråd

En sammanfattning av samrådsredogörelsen, som i sin helhet ligger som bilaga. Hur och med vilka samråd har skett, vad som har framkommit och hur synpunkterna har beaktats.

7 Platsförutsättningar

7.1 Oskarshamn

- Geologiska förutsättningar
- Planförhållanden och infrastruktur
- Riksintressen och skyddade områden
- Boendemiljö och hälsa
- Buller
- Radiologiska kontroller
- Naturmiljö
- Kulturmiljö och landskap
- Friluftsliv och rekreation

7.2 Forsmark

- Geologiska förutsättningar
- Planförhållanden och infrastruktur
- Riksintressen och skyddade områden
- Boendemiljö och hälsa
- Buller
- Radiologiska kontroller
- Naturmiljö
- Kulturmiljö och landskap
- Friluftsliv och rekreation

8 Risk- och säkerhetsanalyser

Här beskrivs de risk- och säkerhetsanalyser som genomförts, inklusive kortfattade metodbeskrivningar (hur, vad och varför). Dessa är analys av slutförvarets långsiktiga säkerhet (SR-Site och dess föregångare), preliminär säkerhetsredovisning av kärntekniska risker under drift av inkapslingsanläggning och Clab respektive slutförvar (PSAR), risker vid transporter av radiologiskt material samt en miljöriskanalys omfattande icke-radiologiska konsekvenser. För långsiktig säkerhet beskrivs de scenarier som analyserats. Resultaten av analyserna beskrivs i kapitel 9 och 10.

9 Slutförvaret för använt kärnbränsle

9.1 Bakgrund

9.2 Avgränsningar

9.2.1 Avgränsning i tid

9.2.1.1 Byggskede

9.2.1.2 Driftskede

9.2.1.3 Rivnings-/Förslutningsskede

9.2.2 Avgränsning i sak

9.2.2.1 Verksamhet

9.2.2.2 Påverkan, effekter och konsekvenser

9.3 Verksamhetsbeskrivning

Beskrivning av själva verksamheten vid slutförvaret i projektets olika skeden.

9.4 Sökt alternativ

Beskrivning av anläggningarna i projektets olika skeden. Transporterna (radiologiska och icke-radiologiska) beskrivs, eftersom dessa är att betrakta som följdverksamheter till anläggningarna vid miljöbalksprövningen.

9.4.1 Geografisk avgränsning

9.4.1.1 Lokaliseringsområde

Lokaliseringsområdet är det område där de olika anläggningarna placeras (ovan respektive under mark) samt de omgivande markområden där det finns risk för direkt fysisk störning på grund av anläggningsarbeten.

9.4.1.2 Påverkansområde

Påverkansområdet definieras som det område där störningar av olika slag (buller, vibrationer, utsläpp till luft och vatten) kan påverka omgivningen. Påverkansområdet är olika stort för olika typer av påverkan. Buller bedöms vara den aspekt som kan påverka på längst avstånd. Vägar för transporter till och från de olika åtgärderna ingår också i påverkansområdet genom att transporterna ger upphov till bullerstörningar och utsläpp till luft.

9.4.2 Anläggningsutformning

9.4.3 Följdföretag

9.4.3.1 Transporter

Kapseltransporter

Övriga transporter (skedesindelat)

9.4.4 Påverkan och skadeförebyggande åtgärder (skedesindelat)

9.4.4.1 Ianspråktagande av mark

9.4.4.2 Påverkan på grundvattennivå

9.4.4.3 Buller och vibrationer

9.4.4.4 Utsläpp av radioaktiva ämnen till luft och vatten

9.4.4.5 Utsläpp av övriga ämnen till luft

9.4.4.6 Utsläpp av övriga ämnen till vatten

9.4.4.7 Ljussken

9.4.5 Effekter och konsekvenser (skedesindelat)

9.4.5.1 Boendemiljö och hälsa

Buller och vibrationer

Utsläpp till luft

Utsläpp av radioaktiva ämnen

Psykosociala effekter

9.4.5.2 Kulturmiljö och landskap

9.4.5.3 Naturmiljö

9.4.5.4 Friluftsliv

9.4.6 Hushållning med naturresurser

9.4.6.1 Avfall

9.4.6.2 Energi

9.4.6.3 Vattenförbrukning

9.4.6.4 Masshantering

9.4.7 Risk och säkerhetsfrågor

Här beskrivs de skadehändelser som kan ske vid slutförvaret som identifierats kunna medföra betydande risker **för platsen** i respektive säkerhetsanalys. Vidtagna skadeförebyggande, avhjälpande och kompensatoriska åtgärder beskrivs. För långsiktig säkerhet beskrivs utvecklingen på platsen samt dosutsläpp i de olika scenarierna.

9.5 Övervägt alternativ

9.5.1 Geografisk avgränsning

9.5.1.1 Lokaliseringsområde

9.5.1.2 Påverkansområde

9.5.2 Anläggningsutformning

9.5.3 Följdföretag

9.5.3.1 Transporter

Kapseltransporter

Övriga transporter (skedesindelat)

9.5.4 Påverkan och skadeförebyggande åtgärder (skedesindelat)

9.5.4.1 Ianspråktagande av mark

9.5.4.2 Påverkan på grundvattennivå

9.5.4.3 Buller och vibrationer

9.5.4.4 Utsläpp av radioaktiva ämnen till luft och vatten

9.5.4.5 Utsläpp av övriga ämnen till luft

9.5.4.6 Utsläpp av övriga ämnen till vatten

9.5.4.7 Ljussken

9.5.5 Effekter och konsekvenser (skedesindelat)

9.5.5.1 Boendemiljö och hälsa

Buller

Utsläpp till luft

Utsläpp av radioaktiva ämnen

Psykosociala effekter

9.5.5.2 Kulturmiljö och landskap

9.5.5.3 Naturmiljö

9.5.5.4 Friluftsliv

9.5.6 Hushållning med naturresurser

9.5.6.1 Avfall

9.5.6.2 Energi

9.5.6.3 Vattenförbrukning

9.5.6.4 Masshantering

9.5.7 Risk och säkerhetsfrågor

9.6 Sammanfattande slutsatser

9.7 Osäkerheter

Beskrivning av osäkerheter förknippade med bland annat de långa tidsperspektiven.

9.8 Uppföljning

Hur miljökonsekvenserna avses följas upp i respektive skede.

9.9 Referenser

10 Inkapslingsanläggning och Clab

10.1 Bakgrund

10.2 Avgränsningar

10.2.1 Avgränsning i tid

10.2.1.1 Byggskede

10.2.1.2 Driftskede

10.2.1.3 Rivningsskede

10.2.2 Avgränsning i sak

10.2.2.1 Verksamhet

10.2.2.2 Påverkan, effekter och konsekvenser

10.3 Clab - verksamhetsbeskrivning

Beskrivning av utformning, verksamhet, transporter med mera i projektets olika skeden.

10.4 Inkapslingsanläggningen - verksamhetsbeskrivning

Beskrivning av utformning, verksamhet, transporter med mera i projektets olika skeden.

10.5 Sökt Alternativ – Oskarshamn

10.5.1 Geografisk avgränsning

10.5.1.1 Lokaliseringsområde

10.5.1.2 Påverkansområde

10.5.2 Anläggningsutformning

En beskrivning av hur inkapslingsanläggningen kommer att utformas.

10.5.3 Följdföretag

10.5.3.1 Transporter

Transporter från kärnkraftverken

Övriga transporter (skedesindelat)

10.5.4 Påverkan och skadeförebyggande åtgärder (skedesindelat)

10.5.4.1 Ianspråktagande av mark

10.5.4.2 Påverkan på grundvattennivå

10.5.4.3 Buller och vibrationer

10.5.4.4 Utsläpp av radioaktiva ämnen till luft och vatten

10.5.4.5 Utsläpp av övriga ämnen till luft

10.5.4.6 Utsläpp av övriga ämnen till vatten

10.5.4.7 Ljussken

10.5.5 Effekter och konsekvenser (skedesindelat)

10.5.5.1 Boendemiljö och hälsa

Buller

Utsläpp till luft

Utsläpp av radioaktiva ämnen

Psykosociala effekter

10.5.5.2 Kulturmiljö och landskap

10.5.5.3 Naturmiljö

10.5.5.4 Friluftsliv

10.5.6 Hushållning med naturresurser

10.5.6.1 Avfall

10.5.6.2 Energi

10.5.6.3 Vattenförbrukning

10.5.6.4 Masshantering

10.5.7 Risk och säkerhetsfrågor

Här beskrivs de skadehändelser vid inkapslingsanläggningen och Clab som identifierats medföra betydande risker **för platsen** i respektive säkerhetsanalys. Vidtagna skadeförebyggande, avhjälpande och kompensatoriska åtgärder beskrivs.

10.6 Övervägt alternativ – Forsmark

10.6.1 Geografisk avgränsning

10.6.1.1 Lokaliseringsområde

10.6.1.2 Påverkansområde

10.6.2 Anläggningsutformning

En beskrivning av hur inkapslingsanläggningen kommer att utformas.

10.6.3 Följdföretag

10.6.3.1 Transporter

Transporter från kärnkraftverken

Övriga transporter (skedesindelat)

10.6.4 Påverkan och skadeförebyggande åtgärder (skedesindelat)

10.6.4.1 Ianspråktagande av mark

10.6.4.2 Påverkan på grundvattennivå

10.6.4.3 Buller och vibrationer

10.6.4.4 Utsläpp av radioaktiva ämnen till luft och vatten

10.6.4.5 Utsläpp av övriga ämnen till luft

10.6.4.6 Utsläpp av övriga ämnen till vatten

10.6.4.7 Ljussken

10.6.5 Effekter och konsekvenser (skedesindelat)

10.6.5.1 Boendemiljö och hälsa

Buller

Utsläpp till luft

Utsläpp av radioaktiva ämnen

Psykosociala effekter

10.6.5.2 Kulturmiljö och landskap

10.6.5.3 Naturmiljö

10.6.5.4 Friluftsliv

10.6.6 Hushållning med naturresurser

10.6.6.1 Avfall

10.6.6.2 Energi

10.6.6.3 Vattenförbrukning

10.6.6.4 Masshantering

10.6.7 Risk och säkerhetsfrågor
Här beskrivs de skadehändelser vid inkapslingsanläggningen och Clab som identifierats medföra betydande risker **för platsen** i respektive säkerhetsanalys. Vidtagna skadeförebyggande, avhjälpande och kompensatoriska åtgärder beskrivs

10.7 Sammanfattande slutsatser

10.8 Osäkerheter

Beskrivning av osäkerheter förknippade med bland annat de långa tidsperspektiven.

10.9 Uppföljning

Hur miljökonsekvenserna avses följas upp under respektive skede.

10.10 Referenser

11 Sammanlagda konsekvenser för hela systemet

Här beskrivs de sammanlagda konsekvenser som hela systemet ger, det vill säga inkapslingsanläggning/Clab – slutförvar – transporter.

12 Samlad bedömning

En samlad bedömning av systemet där viktiga skillnader mellan alternativen framgår. Nollalternativet jämförs med det sökta alternativet. Även andra viktiga slutsatser rörande till exempel slutförvarssystemets konsekvenser över tiden och för olika intressen kommer att sammanfattas här.

13 Osäkerheter

14 Uppföljning

Hur miljökonsekvenserna avses följas upp under byggskede, driftskede, rivning och förslutning samt efter förslutning.

15 Uppfyllelse av miljömål

En avstämning mot gällande nationella, regionala och lokala miljömål.

16 Gränsöverskridande miljöpåverkan

Den huvudsakliga miljöpåverkan som kommer att orsakas av inkapslingsanläggningen och slutförvaret för använt kärnbränsle kommer att bli icke-radiologiska konsekvenser relaterade till ökningen av trafiken, transporter (buller, ljussken, vibrationer) relaterade till hanteringen av bergmassor samt påverkan på grundvattennivån. Buller bedöms bli den aspekt som kommer att resultera i påverkan längst bort. Förhöjda bullernivåer kommer att uppstå inom några kilometer från anläggningarna och längs vägarna.

Det enda som skulle kunna påverka andra länder är om radionuklider sprids från slutförvaret. Detta kommer att beskrivas i säkerhetsanalysen, se kapitel 9.

17 Ordlista

18 Referenser

Interim storage facility, encapsulation plant and final repository for spent nuclear fuel

General structure of the EIS for the final repository system, to be submitted with the permit applications

Svensk Kärnbränslehantering AB

December 2007

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Swedish Nuclear Fuel
and Waste Management Co
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Samråd 0801-1 E

Administrative particulars

Key information about the applicant, such as address/contact information, Corp. ID No., SIC code, legal representative etc.

The EIS

This environmental impact statement (EIS) comprises an appendix to an application for a permit under the Nuclear Activities Act for a final repository for spent nuclear fuel and to an application for permits under the Environmental Code for a final repository for spent nuclear fuel, an encapsulation plant for spent nuclear fuel and the central interim storage facility for spent nuclear fuel (Clab).

Participants

Staff at the EIA Unit at SKB.

Reading instructions

The initial chapters describe SKB's mission and activities, the sites considered and the sites for which permit applications have been submitted, and the consequences if the activity or measure is not implemented, the so called "zero alternative", which is common for the entire final repository system.

In order to show what environmental impact each facility has, two separate chapters then describe the final repository and the encapsulation plant together with Clab. The chapters contain detailed descriptions of the facilities and the activities pursued at them plus an assessment of their effects and consequences.

Finally, the total consequences of the entire final repository system are described, and an overall assessment is made.

Non-technical summary

Contents

1 Introduction

A brief introduction to the project.

2 Purpose

2.1 The project

- What SKB are applying for
- The purpose of the final repository system

2.2 Environmental Impact Assessment/Statement

Description of the EIA process referred to in Chapter 6 of the Environmental Code and the purpose of the EIS.

3 Background

3.1 SKB's mission

- SKB's purpose
- SKB's research (Stripa, Äspö, Canister Lab etc.)
- The RD&D process

3.2 Existing waste system

Description of today's system with the nuclear power plants, Clab (Central interim storage facility for spent nuclear fuel), SFR (Final repository for radioactive operational waste), m/s Sigyn (SKB's specially designed vessel).

3.3 The KBS-3 method

Historical description of how the method was developed.

3.4 The siting process

A summary of the siting process where reasons are given for the choices. The account stops at the choice of Forsmark and Oskarshamn for site investigations.

3.5 The site investigations

Description of the work done during the site investigations in Forsmark and Oskarshamn.

3.6 Other methods

A brief summary of the other methods SKB has studied and the reasons why they have been dismissed.

4 Alternatives report

A brief summary of the alternatives report that is given in Chapters 9 and 10.

4.1 Applied-for sites

Description of the applied-for sites for the different facilities: the final repository, the encapsulation plant and Clab. The reasons for the choice of site are given.

4.2 Considered sites

Description of the considered sites for the final repository and the encapsulation plant. An explanation is given as to why there is no alternative site for the existing facility Clab.

4.3 Applied-for method and design

Description of the applied-for method, KBS-3, and the design of the facilities.

4.4 Alternative design

Description of alternative designs.

4.5 Zero alternative

The zero alternative is common for the entire system. The description includes:

- environmental impact, effects and consequences as well as damage prevention
- conservation of natural resources
- risk and safety issues

5 Scoping

Important general delimitations and the reasons for these. An example is that the canister factory is not included in the applications.

6 Consultations

A summary is given of the consultation report, which is included in its entirety as an appendix. How and with whom consultations have been held, what has emerged and how the viewpoints have been taken into account.

7 Site features

7.1 Oskarshamn

- Geological conditions
- Planning and infrastructure
- National interests and protected areas
- Residential environment and health
- Noise
- Radiological checks
- Natural environment
- Cultural environment and landscape
- Outdoor activities and recreation

7.2 Forsmark

- Geological conditions
- Planning and infrastructure
- National interests and protected areas
- Residential environment and health
- Noise
- Radiological checks
- Natural environment
- Cultural environment and landscape
- Outdoor activities and recreation

8 Risk and safety assessments

Description of the risk and safety assessments that have been conducted, including brief method descriptions (how, what and why). These include assessment of the long-term safety of the final repository (SR-Site and its predecessors), preliminary safety analysis reports (PSARs) on nuclear risks during operation of the encapsulation plant and Clab and of the final repository, risks associated with transportation of radiological material, and an environmental risk analysis covering non-radiological consequences. With regard to long-term safety, the scenarios that have been analyzed are described. The results of the risk and safety assessments are described in Chapters 9 and 10.

9 Final repository for spent nuclear fuel

9.1 Background

9.2 Scoping

9.2.1 Chronological delimitation

9.2.1.1 Construction phase

9.2.1.2 Operating phase

9.2.1.3 Decommissioning/Closure phase

9.2.2 Operational delimitation

9.2.2.1 Activities

9.2.2.2 Impact, effects and consequences

9.3 Description of activities

Description of the activities at the final repository in the different phases of the project.

9.4 Applied-for alternative

Description of the facilities in the different phases of the project. Transportation (radiological and non-radiological) is described, since it is considered a follow-on activity to the facilities in connection with licensing under the Environmental Code.

9.4.1 Geographic delimitation

9.4.1.1 Siting area

The siting area is the area where the different facilities are located (above and below ground) as well as the surrounding land areas where there is a risk of direct physical disturbance due to the civil engineering works.

9.4.1.2 Impact area

The impact area is defined as the area where disturbances of various kinds (noise, vibration, emissions to air and water) can affect the environment. The impact area differs in size for different types of impact. Noise is judged to be the aspect that can have an impact furthest away. Roads for shipments to and from the various facilities are also included in the impact area since the shipments give rise to noise disturbances and atmospheric emissions.

9.4.2 Facility design

9.4.3 Follow-on activities

9.4.3.1 Transportation

Canister shipments

Other transportations and shipments (divided into phases)

9.4.4 Impact and damage prevention (divided into phases)

9.4.4.1 Land claim

9.4.4.2 Impact on groundwater level

9.4.4.3 Noise and vibration

9.4.4.4 Emissions of radionuclides to air and water

9.4.4.5 Emissions of other substances to air

9.4.4.6 Emissions of other substances to water

9.4.4.7 Light

9.4.5 Effects and consequences (divided into phases)

9.4.5.1 Residential environment and health

Noise and vibration

Emissions to air

Emissions of radionuclides

Psychosocial effects

9.4.5.2 Cultural environment and landscape

9.4.5.3 Natural environment

9.4.5.4 Outdoor activities

9.4.6 Conservation of natural resources

9.4.6.1 Waste

9.4.6.2 Energy

9.4.6.3 Water consumption

9.4.6.4 Rock spoil handling

9.4.7 Risk and safety issues

Description of harmful events that could occur at the final repository and that have been identified as entailing considerable risks **for the site** in the relevant site safety assessment. Adopted preventive, remedial and compensatory measures are described. With regard to long-term safety, the evolution of the site and dose releases in the various scenarios are described.

9.5 Considered alternative

9.5.1 Geographic delimitation

9.5.1.1 Siting area

9.5.1.2 Impact area

9.5.2 Facility design

9.5.3 Follow-on activities

9.5.3.1 Transportation

Canister shipments

Other transportations and shipments (divided into phases)

9.5.4 Impact and damage prevention (divided into phases)

9.5.4.1 Land claim

9.5.4.2 Impact on groundwater level

9.5.4.3 Noise and vibration

9.5.4.4 Emissions of radioactive substances to air and water

9.5.4.5 Emissions of other substances to air

9.5.4.6 Emissions of other substances to water

9.5.4.7 Light

9.5.5 Effects and consequences (divided into phases)

9.5.5.1 Residential environment and health

Noise and vibration

Emissions to air

Emissions of radionuclides

Psychosocial effects

9.5.5.2 Cultural environment and landscape

9.5.5.3 Natural environment

9.5.5.4 Outdoor activities

9.5.6 Conservation of natural resources

9.5.6.1 Waste

9.5.6.2 Energy

9.5.6.3 Water consumption

9.5.6.4 Rock spoil handling

9.5.7 Risk and safety issues

9.6 Summarizing conclusions

9.7 Uncertainties

Description of uncertainties associated with, for example, the long time perspectives.

9.8 Monitoring

How the environmental consequences will be monitored in each phase.

9.9 References

10 Encapsulation plant and Clab

10.1 Background

10.2 Scoping

10.2.1 Chronological delimitation

10.2.1.1 Construction phase

10.2.1.2 Operating phase

10.2.1.3 Decommissioning phase

10.2.2 Operational delimitation

10.2.2.1 Activities

10.2.2.2 Impact, effects and consequences

10.3 Clab – description of activities

Description of design, activities, transportation etc. in the different phases of the project.

10.4 The encapsulation plant – description of activities

Description of design, activities, transportation etc. in the different phases of the project.

10.5 Oskarshamn

10.5.1 Geographic delimitation

10.5.1.1 Siting area

10.5.1.2 Impact area

10.5.2 Facility design

A description of how the encapsulation plant will be designed.

10.5.3 Follow-on activities

10.5.3.1 Transportation

Shipments from the nuclear power plants

Other transportations and shipments (divided into phases)

10.5.4 Impact and damage prevention (divided into phases)

10.5.4.1 Land claim

10.5.4.2 Impact on groundwater level

10.5.4.3 Noise and vibration

10.5.4.4 Emissions of radioactive substances to air and water

10.5.4.5 Emissions of other substances to air

10.5.4.6 Emissions of other substances to water

10.5.4.7 Light

10.5.5 Effects and consequences (divided into phases)

10.5.5.1 Residential environment and health

Noise and vibration

Emissions to air

Emissions of radionuclides

Psychosocial effects

10.5.5.2 Cultural environment and landscape

10.5.5.3 Natural environment

10.5.5.4 Outdoor activities

10.5.6 Conservation of natural resources

10.5.6.1 Waste

10.5.6.2 Energy

10.5.6.3 Water consumption

10.5.6.4 Rock spoil handling

10.5.7 Risk and safety issues

Description of harmful events at the encapsulation plant and Clab that have been identified as entailing considerable risks **for the site** in the relevant site safety assessment. Adopted preventive, remedial and compensatory measures are described.

10.6 Considered alternative – Forsmark

10.6.1 Geographic delimitation

10.6.1.1 Siting area

10.6.1.2 Impact area

10.6.2 Facility design

A description of how the encapsulation plant will be designed.

10.6.3 Follow-on activities

10.6.3.1 Transportation

Shipments from the nuclear power plants

Other shipments (divided into phases)

10.6.4 Impact and damage prevention (divided into phases)

10.6.4.1 Land claim

10.6.4.2 Impact on groundwater level

10.6.4.3 Noise and vibration

10.6.4.4 Emissions of radioactive substances to air and water

10.6.4.5 Emissions of other substances to air

10.6.4.6 Emissions of other substances to water

10.6.4.7 Light

10.6.5 Effects and consequences (divided into phases)

10.6.5.1 Residential environment and health

Noise and vibration

Emissions to air

Emissions of radionuclides

Psychosocial effects

10.6.5.2 Cultural environment and landscape

10.6.5.3 Natural environment

10.6.5.4 Outdoor activities

10.6.6 Conservation of natural resources

10.6.6.1 Waste

10.6.6.2 Energy

10.6.6.3 Water consumption

10.6.6.4 Rock spoil handling

10.6.7 Risk and safety issues

Description of harmful events at the encapsulation plant and Clab that have been identified as entailing considerable risks **for the site** in the relevant site safety assessment. Adopted preventive, remedial and compensatory measures are described

10.7 Summarizing conclusions

10.8 Uncertainties

Description of uncertainties associated with, for example, the long time perspectives.

10.9 Monitoring

How the environmental consequences will be monitored in each phase.

10.10 References

11 Combined consequences of the entire system

Here the combined consequences resulting from the entire system (encapsulation plant/Clab – final repository – transportation) are described.

12 Overall assessment

An overall assessment of the system showing important differences between the alternatives. The zero alternative is compared with the applied-for alternative. Other important conclusions concerning, for example, the consequences of the final repository system over time and for different interests will be summarized here.

13 Uncertainties

14 Monitoring

How the environmental consequences will be monitored during the construction phase, the operating phase, decommissioning and closure as well as after closure.

15 Fulfilment of environmental objectives

A cross-check against existing national, regional and local environmental objectives.

16 Transboundary environmental impact

The main environmental impacts due to the Encapsulation plant and the Final repository for spent nuclear fuel will be non-radiological consequences related to increase in traffic, transportations (noise, light, vibrations) due to handling of rock spoil and impact on groundwater table. Noise is judged to be the aspect that can have an impact furthest away. Elevated sound levels will be noticed a few kilometres from the facilities and along the roads.

The only possible activities or measures that might have an impact in other countries are related to release of radionuclides from the final repository. This will be described in safety assessments, see chapter 9.

17 Glossary

18 References

Käytetyn ydinpolttoaineen väliaikainen varastointi,
kapselointi ja loppusijoitus

Loppusijoitusjärjestelmästä laadittavan EIS-arviointiselostuksen yleisrakenne, annetaan yhdessä lupahakemusten kanssa

Svensk Kärnbränslehantering AB

Joulukuu 2007

Samråd 0801-1 E

Hallinnolliset tiedot

Hakijan tiedot, kuten osoite/yhteystiedot, yritystunnus, SIC-koodi, laillinen edustaja jne.

EIS

Ympäristövaikutusten arviointiselostus (EIS) on ydinvoimalatoimintalain (Nuclear Activities Act) mukaisen käytetyn ydinpolttoaineen loppusijoituslaitoksen lupahakemuksen ja ympäristölain (Environmental Code) mukaisen käytetyn ydinpolttoaineen loppusijoituslaitoksen, kapselointilaitoksen ja keskusvälivaraston (Clab) lupahakemusten liite.

Osalliset

SKB:n YVA-yksikön henkilöstö.

Lukuohjeet

Alkuluvuissa kerrotaan SKB:n tavoitteista ja toiminnasta, harkituista sijoituspaikoista ja paikoista, joiden lupahakemukset on jo jätetty, sekä seurauksista, jos toimintaa tai toimenpidettä ei toteuteta. Tämä ns. nollavaihtoehto on yhteinen koko loppusijoitusjärjestelmälle.

Kahdessa erillisessä luvussa kerrotaan loppusijoitus- ja kapselointilaitoksista sekä Clabin välivarastosta, ja näistä luvuista selviää laitosten ympäristövaikutukset. Luvuissa on yksityiskohtaista tietoa laitoksista ja niiden toiminnasta sekä arvio laitosten vaikutuksista ja seurauksista.

Lopuksi kerrotaan koko loppusijoitusjärjestelmän kokonaisseuraukset ja tehdään kokonaisarvio hankkeesta.

Yleistajuinen yhteenveto

Sisällysluettelo

1 Johdanto

Lyhyt johdanto hankkeeseen.

2 Tarkoitus

2.1 Hanke

- Mitä lupia SKB hakee
- Loppusijoitusjärjestelmän tarkoitus

2.2 Ympäristövaikutusten arviointi/arviointiselostus

Ympäristölain (Environmental Code) 6 luvun mukaisen YVA-prosessin kuvaus ja EIS:n tarkoitus

3 Taustaa

3.1 SKB:n tavoite

- SKB:n tarkoitus
- SKB:n tutkimus (Stripa, Äspö, kapselilaboratorio jne.)
- Tutkimus-, kehitys- ja esittelyhankkeet

3.2 Nykyinen jätejärjestelmä

Kuvaus ydinvoimalaitosten nykyisistä järjestelmistä: Clab (käytetyn ydinpolttoaineen keskusvälivarasto), SFR (radioaktiivisen voimalaitosjätteen loppusijoitus), m/s Sigyn (SKB:n erikoisrakenteinen kuljetusalus).

3.3 KBS-3-menetelmä

Kuvaus menetelmän kehittämisestä.

3.4 Paikan valinta

Paikan valintaprosessin yhteenveto, jossa valinnat perustellaan. Selvitys päättyy Forsmarkin ja Oskarshamnin valintaan, joista tehdään maastotutkimukset.

3.5 Maastotutkimukset

Kuvaus maastotutkimusten aikaisista töistä Forsmarkissa ja Oskarshamnissa.

3.6 Muut menetelmät

Lyhyt yhteenveto muista SKB:n tutkimista menetelmistä ja syyt niiden hylkäämiseen.

4 Vaihtoehtoraportti

Lyhyt yhteenveto lukujen 9 ja 10 vaihtoehtoraportista.

4.1 Haetut sijoituspaikat

Kuvaus eri laitosten haetuista sijoituspaikoista: loppusijoitus, kapselointilaitos ja Clab. Sijoituspaikan valinnan perustelut.

4.2 Harkitut sijoituspaikat

Kuvaus loppusijoitus- ja kapselointilaitoksen harkituista sijoituspaikoista. Selitys sille, miksi nykyiselle Clabin laitokselle ei mietitty vaihtoehtoista sijoituspaikkaa.

4.3 Sovellettava menetelmä ja suunnitelma

Kuvaus sovellettavasta menetelmästä (KBS-3) ja laitosten suunnittelusta.

4.4 Vaihtoehtoinen suunnitelma

Vaihtoehtoisten suunnitelmien kuvaus.

4.5 Nollavaihtoehto

Nollavaihtoehto on yhteinen koko järjestelmälle. Luvussa kerrotaan seuraavista asioista:

- ympäristövaikutukset, seuraukset ja vaikutukset sekä vahinkojen ehkäiseminen
- luonnonvarojen suojelu
- riskit ja turvallisuusnäkökohdat.

5 Laajuus

Tärkeät yleiset rajaukset ja niiden syyt. Esimerkkinä se, että kapselitehdas ei kuulu hakemuksiin.

6 Neuvottelut

Yhteenveto neuvotteluraportista, joka on kokonaisuudessaan liitteenä. Millaisia neuvotteluja on ollut ja kenen kanssa niitä on pidetty, mitä aiheita on käsitelty ja miten eri näkökohdat on otettu huomioon.

7 Tietoja sijoituspaikoista

7.1 Oskarshamn

- Geologiset olosuhteet
- Suunnittelu ja infrastruktuuri
- Kansalliset edut ja suojelualueet
- Asuinympäristö ja terveys
- Melu
- Säteilytarkastukset
- Luonnonympäristö
- Kulttuuriympäristö ja maisema
- Ulkoilu- ja virkistysalueet

7.2 Forsmark

- Geologiset olosuhteet
- Suunnittelu ja infrastruktuuri
- Kansalliset edut ja suojelualueet
- Asuinympäristö ja terveys
- Melu
- Säteilytarkastukset
- Luonnonympäristö
- Kulttuuriympäristö ja maisema
- Ulkoilu- ja virkistysalueet

8 Riski- ja turvallisuusselvitykset

Kuvaus tehdyistä riski- ja turvallisuusselvityksistä, mukaan lukien lyhyt menetelmien kuvaus (miten, mitä ja miksi). Selvityksiin kuuluu arvio loppusijoituksen pitkäaikaisesta turvallisuudesta (SR-Site ja muut arviot), alustavat turvallisuusselosteet ydinvahingon vaarasta kapselointilaitoksessa, Clabin varastossa ja loppusijoituslaitoksessa, radioaktiivisten aineiden kuljetukseen liittyvät riskit ja ympäristöriskien arviointi, mukaan lukien myös muut kuin säteilyseuraukset. Niistä pitkäaikaiseen turvallisuuteen liittyvistä suunnitelmista kerrotaan, jotka on analysoitu. Riski- ja turvallisuusselvitysten tulokset kerrotaan luvuissa 9 ja 10.

9 Käytetyn ydinpolttoaineen loppusijoitus

9.1 Taustaa

9.2 Laajuus

9.2.1 Kronologiset rajoitukset

9.2.1.1 Rakennusvaihe

9.2.1.2 Käyttövaihe

9.2.1.3 Käytöstäpoisto/sulkemisvaihe

9.2.2 Käyttörajoitukset

9.2.2.1 Toiminta

9.2.2.2 Vaikutukset ja seuraukset

9.3 Toiminnan kuvaus

Kuvaus loppusijoituslaitoksen toiminnasta hankkeen eri vaiheissa.

9.4 Sovellettavat vaihtoehdot

Laitosten kuvaukset hankkeen eri vaiheissa. Kuljetusta (radioaktiivisten ja muiden kuin radioaktiivisten aineiden) käsitellään, sillä se luetaan laitosten toiminnaksi ympäristölain (Environmental Code) mukaiseen lupaan liittyen.

9.4.1 Maantieteelliset rajoitukset

9.4.1.1 Sijoituspaikka

Sijoituspaikka on se alue, jolla eri laitokset sijaitsevat (maanpinnan ylä- ja alapuolella) ja niitä ympäröivä maa-alue, jossa on rakennusteknisistä töistä johtuva suoran fyysisen häiriön vaara.

9.4.1.2 Vaikutusalue

Vaikutusalueena pidetään sitä aluetta, jossa erilaiset häiriöt (melu, tärinä, ilma- ja vesipäästöt) voivat vaikuttaa luontoon. Vaikutusalueiden koko vaihtelee vaikutuksen laadun mukaan. Melulla katsotaan olevan kaikkein suurin vaikutusalue. Myös kuljetustiet eri laitoksiin kuuluvat vaikutusalueeseen, sillä kuljetukset lisäävät meluhäiriöitä ja päästöjä ilmakehään.

9.4.2 Laitosten suunnittelu

9.4.3 Liitännäistoiminnot

9.4.3.1 Kuljetus

Kapseleiden siirtäminen

Muut kuljetukset ja siirrot (jaettu vaiheisiin)

9.4.4 Vaikutukset ja vahinkojen ehkäiseminen (jaettu vaiheisiin)

9.4.4.1 Maavaatimukset

9.4.4.2 Vaikutus pohjavesitasolla

9.4.4.3 Melu ja tärinä

9.4.4.4 Radionuklidipäästöt ilmaan ja veteen

9.4.4.5 Muut päästöt ilmaan

9.4.4.6 Muut päästöt veteen

9.4.4.7 Valo

9.4.5 Vaikutukset ja seuraukset (jaettu vaiheisiin)

9.4.5.1 Asuinympäristö ja terveys

Melu ja tärinä

Päästöt ilmaan

Radionuklidipäästöt

Psykososiaaliset vaikutukset

9.4.5.2 Kulttuuriympäristö ja maisema

9.4.5.3 Luonnonympäristö

9.4.5.4 Ulkoilualueet

9.4.6 Luonnonvarojen suojelu

9.4.6.1 Jäte

9.4.6.2 Energia

9.4.6.3 Vedenkulutus

9.4.6.4 Kaivumaan käsittely

9.4.7 Riskit ja turvallisuusnäkökohdat

Kuvaus haitallisista tapauksista, joita voi sattua loppusijoituksessa ja joihin on kyseisessä turvallisuusselvityksessä katsottu liittyvän huomattavia riskejä **sijoituspaikalle**. Luvussa kerrotaan, mitä ennalta ehkäiseviä, korjaavia ja korvaavia toimenpiteitä on toteutettu. Pitkäaikaiseen turvallisuuteen liittyen kerrotaan eri suunnitelmien mukainen sijoituspaikan kehitys ja päästömäärät.

9.5 Harkittu vaihtoehto

9.5.1 Maantieteelliset rajoitukset

9.5.1.1 Sijoituspaikka

9.5.1.2 Vaikutusalue

9.5.2 Laitosten suunnittelu

9.5.3 Liitännäistoiminnot

9.5.3.1 Kuljetus

Kapseleiden siirtäminen

Muut kuljetukset ja siirrot (jaettu vaiheisiin)

9.5.4 Vaikutukset ja vahinkojen ehkäiseminen (jaettu vaiheisiin)

9.5.4.1 Maavaatimukset

9.5.4.2 Vaikutus pohjavesitasolla

9.5.4.3 Melu ja tärinä

9.5.4.4 Radioaktiivisten aineiden päästöt ilmaan ja veteen

9.5.4.5 Muut päästöt ilmaan

9.5.4.6 Muut päästöt veteen

9.5.4.7 Valo

9.5.5 Vaikutukset ja seuraukset (jaettu vaiheisiin)

9.5.5.1 Asuinympäristö ja terveys

Melu ja tärinä

Päästöt ilmaan

Radionuklidipäästöt

Psykososiaaliset vaikutukset

9.5.5.2 Kulttuuriympäristö ja maisema

9.5.5.3 Luonnonympäristö

9.5.5.4 Ulkoilualueet

9.5.6 Luonnonvarojen suojelu

9.5.6.1 Jäte

9.5.6.2 Energia

9.5.6.3 Vedenkulutus

9.5.6.4 Kaivumaan käsittely

9.5.7 Riskit ja turvallisuusnäkökohdat

9.6 Loppupäätelmät

9.7 Epävarmuustekijät

Kuvaus epävarmuustekijöistä, jotka liittyvät esimerkiksi pitkäaikaisiin näkökulmiin.

9.8 Seuranta

Miten ympäristövaikutuksia seurataan eri vaiheissa.

9.9 Viitteet

10 Kapselointilaitos ja Clab

10.1 Taustaa

10.2 Laajuus

10.2.1 Kronologiset rajoitukset

10.2.1.1 Rakennusvaihe

10.2.1.2 Käyttövaihe

10.2.1.3 Käytöstäpoistovaihe

10.2.2 Käyttörajoitukset

10.2.2.1 Toiminta

10.2.2.2 Vaikutukset ja seuraukset

10.3 Clab – toiminnan kuvaus

Kuvaus suunnitelmista, toiminnasta, kuljetuksista jne. hankkeen eri vaiheissa.

10.4 Kapselointilaitos – toiminnan kuvaus

Kuvaus suunnitelmista, toiminnasta, kuljetuksista jne. hankkeen eri vaiheissa.

10.5 Oskarshamn

10.5.1 Maantieteelliset rajoitukset

10.5.1.1 Sijoituspaikka

10.5.1.2 Vaikutusalue

10.5.2 Laitosten suunnittelu

Kuvaus kapselointilaitoksen suunnittelusta.

10.5.3 Liitännäistoiminnot

10.5.3.1 Kuljetus

Kuljetukset ydinvoimalaitoksista

Muut kuljetukset ja siirrot (jaettu vaiheisiin)

10.5.4 Vaikutukset ja vahinkojen ehkäiseminen (jaettu vaiheisiin)

10.5.4.1 Maavaatimukset

10.5.4.2 Vaikutus pohjavesitasolla

10.5.4.3 Melu ja tärinä

10.5.4.4 Radioaktiivisten aineiden päästöt ilmaan ja veteen

10.5.4.5 Muut päästöt ilmaan

10.5.4.6 Muut päästöt veteen

10.5.4.7 Valo

10.5.5 Vaikutukset ja seuraukset (jaettu vaiheisiin)

10.5.5.1 Asuinympäristö ja terveys

Melu ja tärinä

Päästöt ilmaan

Radionuklidipäästöt

Psykososiaaliset vaikutukset

10.5.5.2 Kulttuuriympäristö ja maisema

10.5.5.3 Luonnonympäristö

10.5.5.4 Ulkoilualueet

10.5.6 Luonnonvarojen suojelu

10.5.6.1 Jäte

10.5.6.2 Energia

10.5.6.3 Vedenkulutus

10.5.6.4 Kaivumaan käsittely

10.5.7 Riskit ja turvallisuusnäkökohdat

Kuvaus haitallisista tapauksista kapselointilaitoksessa ja Clabissa, joihin on kyseisessä turvallisuusselvityksessä katsottu liittyvän huomattavia riskejä **sijoituspaikalle**. Luvussa kerrotaan, mitä ennalta ehkäiseviä, korjaavia ja korvaavia toimenpiteitä on toteutettu.

10.6 Harkittu vaihtoehto – Forsmark

10.6.1 Maantieteelliset rajoitukset

10.6.1.1 Sijoituspaikka

10.6.1.2 Vaikutusalue

10.6.2 Laitosten suunnittelu

Kuvaus kapselointilaitoksen suunnittelusta.

10.6.3 Liitännäistoiminnot

10.6.3.1 Kuljetus

Kuljetukset ydinvoimalaitoksista

Muut kuljetukset (jaettu vaiheisiin)

10.6.4 Vaikutukset ja vahinkojen ehkäiseminen (jaettu vaiheisiin)

10.6.4.1 Maavaatimukset

10.6.4.2 Vaikutus pohjavesitasolla

10.6.4.3 Melu ja tärinä

10.6.4.4 Radioaktiivisten aineiden päästöt ilmaan ja veteen

10.6.4.5 Muut päästöt ilmaan

10.6.4.6 Muut päästöt veteen

10.6.4.7 Valo

10.6.5 Vaikutukset ja seuraukset (jaettu vaiheisiin)

10.6.5.1 Asuinympäristö ja terveys

Melu ja tärinä

Päästöt ilmaan

Radionuklidipäästöt

Psykososiaaliset vaikutukset

10.6.5.2 Kulttuuriympäristö ja maisema

10.6.5.3 Luonnonympäristö

10.6.5.4 Ulkoilualueet

10.6.6 Luonnonvarojen suojelu

10.6.6.1 Jäte

10.6.6.2 Energia

10.6.6.3 Vedenkulutus

10.6.6.4 Kaivumaan käsittely

10.6.7 Riskit ja turvallisuusnäkökohdat

Kuvaus haitallisista tapauksista kapselointilaitoksessa ja Clabissa, joihin on kyseisessä turvallisuusselvityksessä katsottu liittyvän huomattavia riskejä **sijoituspaikalle**. Luvussa kerrotaan, mitä ennalta ehkäiseviä, korjaavia ja korvaavia toimenpiteitä on toteutettu.

10.7 Loppupäätelmät

10.8 Epävarmuustekijät

Kuvaus epävarmuustekijöistä, jotka liittyvät esimerkiksi pitkäaikaisiin näkökulmiin.

10.9 Seuranta

Miten ympäristövaikutuksia seurataan eri vaiheissa.

10.10 Viitteet

11 Koko järjestelmän yhteisvaikutukset

Luvussa kerrotaan koko järjestelmästä (kapselointilaitos/Clab, loppusijoitus, kuljetus) aiheutuvat yhteisvaikutukset.

12 Kokonaisarvio

Järjestelmän kokonaisarvio, josta vaihtoehtojen tärkeät erot ilmenevät. Nollavaihtoehtoa verrataan sovellettavaan vaihtoehtoon. Luvussa esitetään myös muita tärkeitä päätelmiä muun muassa loppusijoitusjärjestelmän pitkäaikaisista vaikutuksista ja vaikutuksista eri etuihin.

13 Epävarmuustekijät

14 Seuranta

Miten ympäristövaikutuksia seurataan rakennusvaiheessa, käyttövaiheessa, käytöstäpoisto- ja sulkemisvaiheessa sekä sulkemisen jälkeen.

15 Ympäristötavoitteiden täyttäminen

Nykyisten kansallisten, alueellisten ja paikallisten ympäristötavoitteiden täyttymisen tarkistus.

16 Rajojen yli ulottuva ympäristövaikutus

Käytetyn ydinpolttoaineen kapselointilaitoksesta ja loppusijoituksesta aiheutuvat pääympäristövaikutukset ovat muita kuin säteilyseurauksia. Ne liittyvät liikennemäärien kasvuun, kaivumaan käsittelystä aiheutuvien kuljetusten vaikutuksiin (melu, valo, tärinä) ja vaikutukseen pohjavesikerrokselle. Melulla katsotaan olevan kaikkein suurin vaikutusalue. Melutaso lisääntyy muutaman kilometrin säteellä laitoksista sekä kuljetusteillä.

Ainoat mahdolliset toiminnot tai toimenpiteet, joilla voi olla vaikutusta muihin maihin, liittyvät loppusijoituksen radionuklidipäästöihin. Tätä käsitellään turvallisuusselvityksessä, katso luku 9.

17 Sanasto

18 Viitteet

Interim storage facility, encapsulation plant and final repository for spent nuclear fuel

Safety and radiation protection

Svensk Kärnbränslehantering AB

May 2007

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Contents

Reading instructions

This is background material for consultations under Chapter 6 of the Environmental Code held in May/June 2007. The consultations are a part of the preparations for applications for licences/permits under Chapters 9 and 11 of the Environmental Code to operate an interim storage facility for spent nuclear fuel and to build and operate facilities for encapsulation and final disposal of spent nuclear fuel. The consultations are also part of the preparations for an application for a licence under the Nuclear Activities Act for final disposal of spent nuclear fuel.

The material contains a general description of SKB's work with safety and radiation protection.

The material was prepared during the spring of 2007 and reflects the state of knowledge at that time. It is based both on previously done work and ongoing work that has not yet been published.

The background material was presented in connection with the public consultation meetings in Oskarshamn (28 May) and Forsmark (31 May). It was also made available on SKB's website, *www.skb.se*, about three weeks before these meetings. Furthermore it was sent out for written consultations to the county administrative boards in Kalmar and Uppsala counties, other concerned government agencies, the municipalities of Oskarshamn and Östhammar, and the organizations that obtain funding from the Nuclear Waste Fund to participate in the consultations.

1 Introduction

SKB (Swedish Nuclear Fuel and Waste Management Co) has been assigned the task of managing and disposing of the radioactive waste from the Swedish nuclear power plants. We have developed a method for final disposal of the spent nuclear fuel known as the KBS-3 method (KBS stands for Kärnbränslesäkerhet = Nuclear Fuel Safety). The method entails that the spent nuclear fuel is placed in copper canisters with cast iron inserts and then deposited, embedded in bentonite clay, at a depth of about 500 metres in the bedrock. The KBS-3 method requires an encapsulation plant where the spent nuclear fuel is encapsulated, and a hard rock facility (a final repository) where the canisters are deposited.

Today the spent nuclear fuel is temporarily stored in Clab (Central interim storage facility for spent nuclear fuel), which is situated on the Simpevarp Peninsula in Oskarshamn Municipality. SKB's proposal is to locate the encapsulation plant adjacent to Clab. Site investigations are being conducted in the municipalities of Oskarshamn and Östhammar as a basis for the siting of the final repository.

1.1 Spent nuclear fuel

Nuclear fuel is fabricated from natural radioactive uranium mineral. The radioactivity of the fuel increases sharply during the operation of a nuclear reactor. After about five years of use, the fuel is taken out of the reactor and is then at its peak radiotoxicity. Its radioactivity and thereby its toxicity declines with time as the radioactive substances decay. After about 30 years of interim storage in Clab only one or two percent of the radioactivity remains.

The risks associated with spent nuclear fuel can be described in terms of radiotoxicity and accessibility. Radiotoxicity describes the harm ionizing radiation can cause if people are exposed to it. Accessibility describes the degree to which a person can be exposed to radiation in different situations, for example during transport, interim storage or final disposal.

Most radionuclides in spent nuclear fuel decay within a few hundred years. After that the radiotoxicity of the fuel is dominated by substances that will remain for a very long time. After about 100,000 years the radiotoxicity of the spent fuel will have declined to a level that is equivalent to that of the natural uranium mineral from which it was originally fabricated.

1.2 Applications and licensing review

The encapsulation plant, Clab and the final repository require permits/licences under the Environmental Code and the Nuclear Activities Act. In November 2006, SKB submitted an application under the Nuclear Activities Act for a permit to build and own an encapsulation plant for spent nuclear fuel and a licence to operate it integrated with Clab.

Since the encapsulation plant will be integrated with Clab, Clab's existing permits under the Nuclear Activities Act and the Environmental Code are affected. At the end of 2009, SKB plans to apply for permits under the Environmental Code for the encapsulation plant, Clab and the final repository. At the same time, SKB will apply for a permit under the Nuclear Activities Act to build the final repository and a licence to operate it, see Figure 1-1. Due to this procedure, all background material will have been presented before any decision is taken. The Government will have an opportunity to decide at one and the same time on both a permit under the Nuclear Activities Act and permissibility under the Environmental Code.

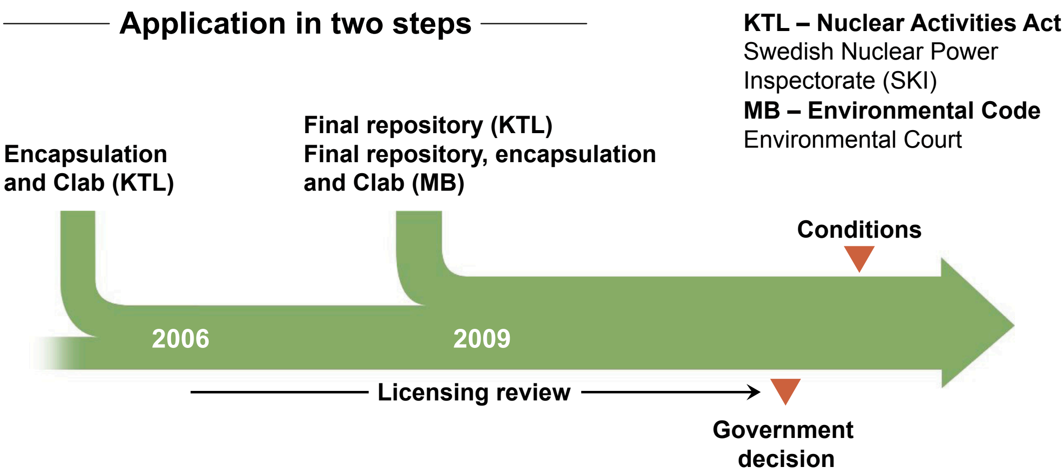

***Figure 1-1**. Schematic plan of the licensing process.*

1.3 Consultations

An environmental impact statement (EIS), as described in Chapter 6 of the Environmental Code, must be appended to the applications under the Environmental Code and the Nuclear Activities Act. Besides compiling the EIS, the EIA (environmental impact assessment) work includes both studies and consultations.

According to the provisions of the Environmental Code (Chap. 6, Sec. 4), the consultations shall be concerned with the siting, scope, design and environmental impact of the activity and the content and design of the environmental impact statement. Another important purpose is to take advantage of the local expertise possessed by individuals and organizations. SKB's goal with the consultations is that everyone who wants to get involved is given an opportunity to do so. This applies to both private citizens and organizations as well as local and national authorities.

The consultation process leading up to the applications for permits for the final repository and the encapsulation plant was begun during 2002 and 2003 in the municipalities of both Oskarshamn and Östhammar. Early consultations have been completed. In accordance with a decision by the County Administrative Board in Kalmar County and the County Administrative Board in Uppsala County, SKB also commenced extended consultations. The consultations will continue until the applications for the encapsulation plant, Clab and the final repository are submitted.

Changes were made in the Environmental Code in 2005. The terms "early" and "extended" consultations were then removed. Now only the concept "consultations" is used.

Disposal of the spent nuclear fuel is a large project that generates a great deal of material to deal with in the consultations. Studies, site investigations, design work etc have been under way for many years and will continue for several more years to come. It is not possible to consult about everything involved in the project on a few isolated occasions. SKB has therefore tried to arrange consultations on different themes as the relevant studies have been completed. The theme for this consultation is safety and radiation protection. Questions and discussions at a consultation meeting are not limited to this theme, but focus on the participants' questions and viewpoints. All matters pertaining to interim storage, encapsulation and final disposal of spent nuclear fuel can be brought up.

From now on we plan to hold 1–2 public consultation meetings per year in Oskarshamn and in Forsmark up until the time the applications are submitted. When more results pertaining to safety and radiation protection are available, we will hold an additional consultation with this theme. The current consultation plan is available on SKB's website, *www.skb.se*.

2 General requirements and points of departure

The general requirements and points of departure for the management and disposal of spent nuclear fuel are found in Swedish legislation and international agreements.

The purpose of the Environmental Code (SFS 1998:808) is to assure current and future generations a healthy and good environment.

According to the Nuclear Activities Act (SFS 1984:3) with associated regulations, the holder of a licence for nuclear activities shall make sure that any resulting spent nuclear fuel is disposed of in a safe manner. Post-closure safety shall be based on a system of passive barriers, and the final repository shall not require monitoring or maintenance.

According to the Radiation Protection Act (SFS 1988:220) with associated regulations, radioactive waste shall be handled so that an acceptable level of protection is ensured for human health and the environment.

In addition to Swedish legislation there are international agreements and conventions with which Sweden has undertaken to comply, for example:

The UN nuclear watchdog agency IAEA's (International Atomic Energy Agency) nuclear waste convention says that appropriate steps shall be taken to avoid imposing undue burdens on future

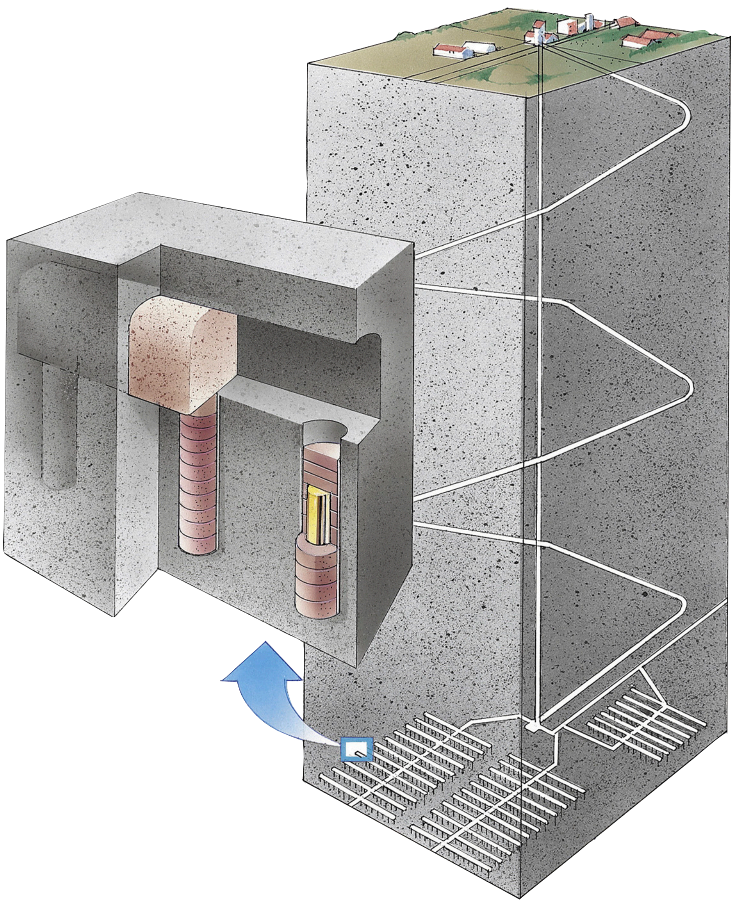

Figure 2-1. *Final repository according to the KBS-3 method.*

generations. This means that the waste problem should essentially be solved by the generation that utilizes the electricity generated by the nuclear power plants. Furthermore, it says that waste should be disposed of in the State in which it was generated.

Sweden signed the Non-Proliferation Treaty (NPT) in 1968, which means we have undertaken to use nuclear energy solely for peaceful purposes and have consented to submit Swedish nuclear material to IAEA safeguards. According to the NPT, the system for disposal of spent nuclear fuel shall be designed to prevent illicit tampering with nuclear materials or nuclear waste.

Primarily based on these requirements and points of departure, SKB has defined the purpose of the work for the disposal of the spent nuclear fuel:

SKB's purpose is to build, operate and close a final repository with a focus on safety, radiation protection and environmental considerations. The final repository is being designed to prevent illicit tampering with nuclear fuel both before and after closure. Long-term safety will be based on a system of passive barriers.

The final repository is intended for spent nuclear fuel from the Swedish nuclear reactors and will be created within Sweden' boundaries with the voluntary participation of the concerned municipalities.

The final repository will be established by those generations that have derived benefit from the Swedish nuclear reactors and designed so that it will remain safe after closure without maintenance or monitoring.

3 Safety work with different time perspectives and purposes

3.1 General about concepts and reports

The safety work for SKB's nuclear facilities is based on legislation and regulatory requirements. SKB's highest body for safety matters is the safety committee, which is chaired by SKB's president. The safety committee deals with safety matters of a fundamental and strategic nature. SKB also has a special department – Nuclear Safety – that develops and oversees safety matters. Day-to-day responsibility for the safety of the facilities is included in operation.

SKB performs several different types of assessments and reports regarding safety and radiation protection for the encapsulation plant, Clab, the final repository and the transportation system. They deal with different time scales and have different purposes.

Preliminary safety analysis reports

A facility's safety analysis report describes how safety and radiation protection in a nuclear facility are arranged to protect human health and the environment. The safety analysis report is prepared in the following steps:

1. Preliminary safety analysis report.
2. Renewed safety analysis report prior to trial operation.
3. Supplementary safety analysis report prior to routine operation.
4. Constantly updated safety analysis report.

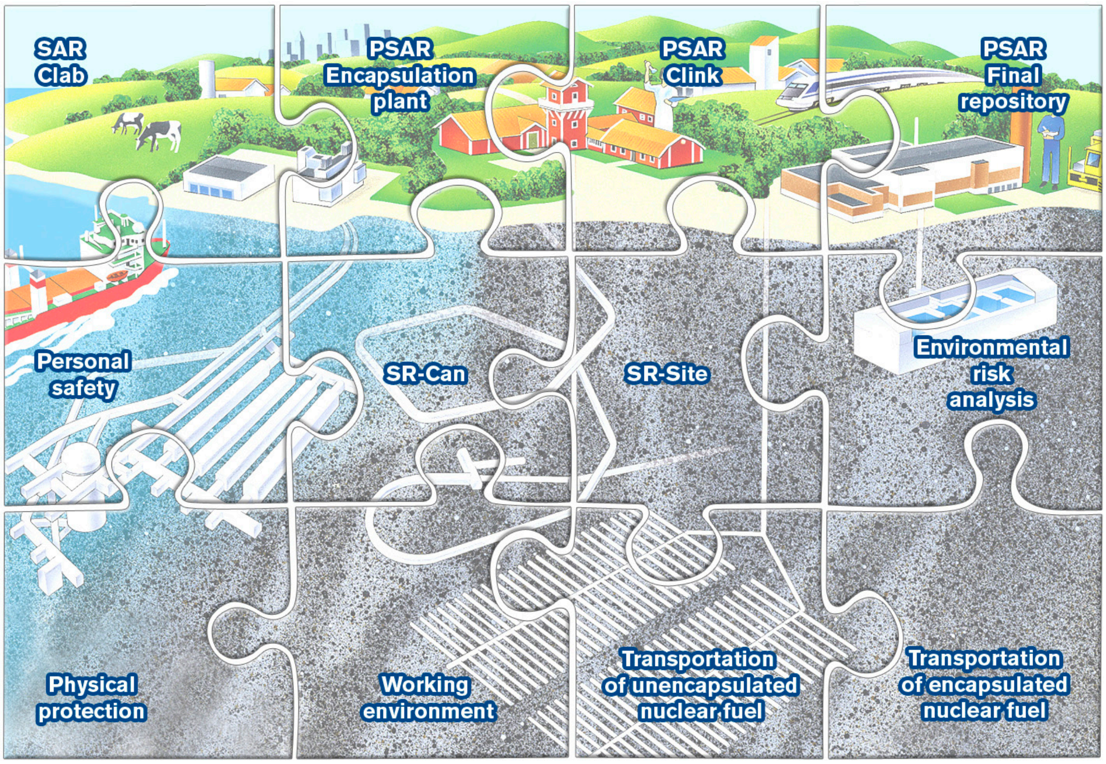

***Figure 3-1**. Schematic illustration of concepts and reports which SKB uses in its work with risk and safety matters.*

The safety analysis reports are prepared according to steps 1–4 and undergo review, which is done in two steps. The first step is performed by the departments within SKB that are in charge of the particular issue at hand. The second step is performed by the Department of Nuclear Safety, which is independent in relation to the above departments. The Department of Nuclear Safety reports directly to SKB's top management. This procedure is regulated by the Swedish Nuclear Power Inspectorate's (SKI) regulation SKIFS 2004:1, which deals with safety in nuclear facilities. SKB's review is supplemented by review and approval by SKI and the Swedish Radiation Protection Authority (SSI).

The purpose of the *preliminary safety analysis report* is to give an account of safety and radiation protection during normal operation and to evaluate the risks of disturbances and mishaps in and around a facility and their consequences. The report is supposed to show that the facility meets the requirements of the Swedish authorities. It must be submitted along with applications under the Nuclear Activities Act. In the autumn of 2006 SKB submitted a preliminary safety analysis report for the encapsulation plant, called "PSAR encapsulation plant". In 2008 it will be supplemented by a joint report for the encapsulation plant and Clab, "PSAR Clink" (Clab/encapsulation plant).

When the application under the Nuclear Activities Act for the final repository is submitted, a preliminary safety analysis report for the final repository will be appended. Besides an account of the safety of the final repository during the operating period (operational safety), it will also include an account of the post-closure safety of the final repository (long-term safety). SKB has chosen to submit separate safety analysis reports for operational safety and post-closure safety. The account of operational safety is called "PSAR final repository". The preliminary safety analysis report for the long-term (post-closure) safety of the repository is submitted pursuant to the requirements in SKIFS 2002:1 and SSI FS 1998:1. It is called "SR-Site".

The renewed safety analysis report describes the pre-operational state of the facility and is submitted to receive a permit for trial operation. For natural reasons it is more detailed than the preliminary report. Changes that have occurred since the PSAR are described along with the reasons for them.

Subsequently, before the facility is allowed to be put into routine operation, the safety analysis report must be augmented. *The supplementary safety analysis report,* SAR, is a living document that describes the actual facility and is updated as changes occur.

Transportation of spent nuclear fuel

Since transportation of spent nuclear fuel is classified as a nuclear activity, special permits are required from SKI and SSI according to the Nuclear Activities Act. There are also other regulations that govern the transportation of radioactive material, mainly the Transport of Dangerous Goods Act (SFS 2006:263) and a number of national and international regulations. SKI's and SSI's supervision of nuclear shipments also includes certification of the containers to be used. Other applicable regulations include, for example, the Swedish Rescue Services Agency's regulations on safety advisers for transport of dangerous goods (SRVFS 2006:9).

Some of the combined safety analysis report for the existing transportation system is included in SKB's most recent safety report for the transportation system /SKB 2005/. The report contains a description of the transportation system in its entirety with requirements, functional description, description of technical components and description of completed safety assessments. It is not formally an SAR since the transportation system is not a facility. There are no special safety reports for transport casks.

As supporting material for the application for the encapsulation plant, SKB has prepared a report that describes an envisioned transportation system for encapsulated fuel with requirements, technical data for a fuel transport cask, functional description of the transportation system and safety aspects /Broman et al. 2005/. We will prepare a new report for the application for a permit to build the final repository. The siting of the final repository, as well as the transport logistics within the repository, will have been decided by then.

Physical protection for facilities

Physical protection is the part of the system for protective security aimed at preventing theft of nuclear material and nuclear waste in various ways, but also at protecting against sabotage and attack that could lead to radiological consequences. The governing legislation for SKB's work with physical protection is the Protective Security Act (SFS 1996:627), the Protective Security Ordinance (SFS 1996:633) and SKI's regulation on physical protection (SKIFS 2005:1).

SKI's regulation contains provisions for background checks (for example search of public records, interviews, references), study visits, handling of information on security measures and IT security. The provisions are based on a design threat scenario of a violent and well-equipped attacker. The design threat scenario should not be confused with the actual threat scenario, which varies over time and is in principle only valid on the date it is described.

The greater part of the report dealing with physical protection is classified, since the information in the report could facilitate theft or sabotage.

Environmental risk analysis

In an environmental risk analysis SKB has determined the risks of non-radiological consequences for the construction phase, the operating phase and decommissioning of the encapsulation plant, Clab and the final repository, as well as for closure of the repository. The analysis comprises a basis for an assessment of the consequences for the natural environment, the cultural environment and health in the EIS. It also serves as a basis for an assessment of possible risk reduction in the form of accident-preventive and damage-mitigating measures in the design of the facilities.

Working environment

The framework for work environment management is laid down in the Work Environment Act (SFS 1997:1160). The purpose of the Act is to prevent ill health and accidents at work and to otherwise ensure a good working environment. The Swedish Work Environment Authority issues general regulations and recommendations defining what requirements are made on the working environment. The construction and operation of the encapsulation plant and the final repository are governed primarily by the provisions regarding Systematic Work Environment Management (AFS 2001:1), the provisions for Building and Civil Engineering Work (AFS 1999:3) and the provisions for Rock Work (AFS 2003:2).

All working environment aspects are included in the design of the facilities. Aspects that tie in with the areas of responsibility of the Swedish Rescue Services Agency, for example fire protection, are also included in the design process. These matters, as well as working environment matters, lie outside the EIA work and the consultations and are not included in the applications.

3.2 KBS-3 and long-term safety

Development of the KBS-3 method for final disposal of spent nuclear fuel has been going on since the late 1970s. The scientific and technical basis for the method has been successively developed and reported to the regulatory authorities and the Government every third year in the RD&D programmes. Over the course of the years SKB has carried out several analyses of the long-term safety of the final repository.

KBS-3

The results of the KBS-3 study /SKBF/KBS 1983/ served as a basis for the applications for permits to fuel the Forsmark 3 and Oskarshamn 3 nuclear power reactors. After a comprehensive review process the Government found that "the method in its entirety has been found essentially acceptable with regard to safety and radiation protection" and approved the fuelling permit applications for the two reactors in June 1984.

SKB 91

The safety assessment SKB 91 /SKB 1992/ differs from the KBS-3 study in several ways. The knowledge base was greater and the computers had greater computational power. Furthermore, there were new models that made it possible to take into account the variability in the permeability of the rock and a site-adapted repository geometry. The conclusion in SKB 91 is that a repository built deep down in the Swedish crystalline bedrock with durable engineered barriers meets the safety requirements stipulated by the regulatory authorities with good margin.

SR 95

The main purpose of SR 95 /SKB 1995/ was not to carry out a "real" safety assessment, but to prepare a template for how assessments of long-term safety should be carried out and reported. The methodology and the proposed template in SR 95 were then applied in SR 97.

SR 97

Prior to the start of the site investigations in the work of siting the final repository, the Government and the regulatory authorities requested an assessment of the repository's long-term safety. The requested safety assessment has the working name SR 97 and was published in 1999 /SKB 1999/. The main purposes of the assessment were:

- to determine whether spent nuclear fuel can be safely disposed of in Swedish bedrock over a very long period of time,
- to demonstrate the methodology for the safety assessment.

The methodology that was applied in SR 97 was to first describe the properties of the repository when it has just been closed. Then we analyzed how the system changes with time as a result of both internal processes in the repository and external forces. The future evolution of the repository system was analyzed in five scenarios. The first was a base scenario where the repository is built according to specifications and where present-day conditions in the surroundings, including climate, persist. The four other scenarios showed how the evolution of the repository differs from that in the base scenario if the repository contains a few initially defective canisters, in the event of climate change, in the event of earthquakes, and in the event of future inadvertent human intrusion. The evolution of the repository was broken down into thermal, hydraulic, mechanical and chemical sub-evolutions. The ultimate purpose of the analyses was to examine the ability of the repository to isolate the waste in the canisters and to delay a possible release of radionuclides if canisters are damaged. The time perspective for the analyses was (in accordance with the regulations) up to a million years.

The results show that there are good prospects for disposing of spent nuclear fuel in the Swedish bedrock. SR 97 comprised an important basis for formulating and quantifying requirements and preferences regarding the rock in which the final repository is built based on the perspective of long-term safety. Experience from SR 97 was used to formulate an integrated programme for investigation and evaluation of sites /SKB 2000/.

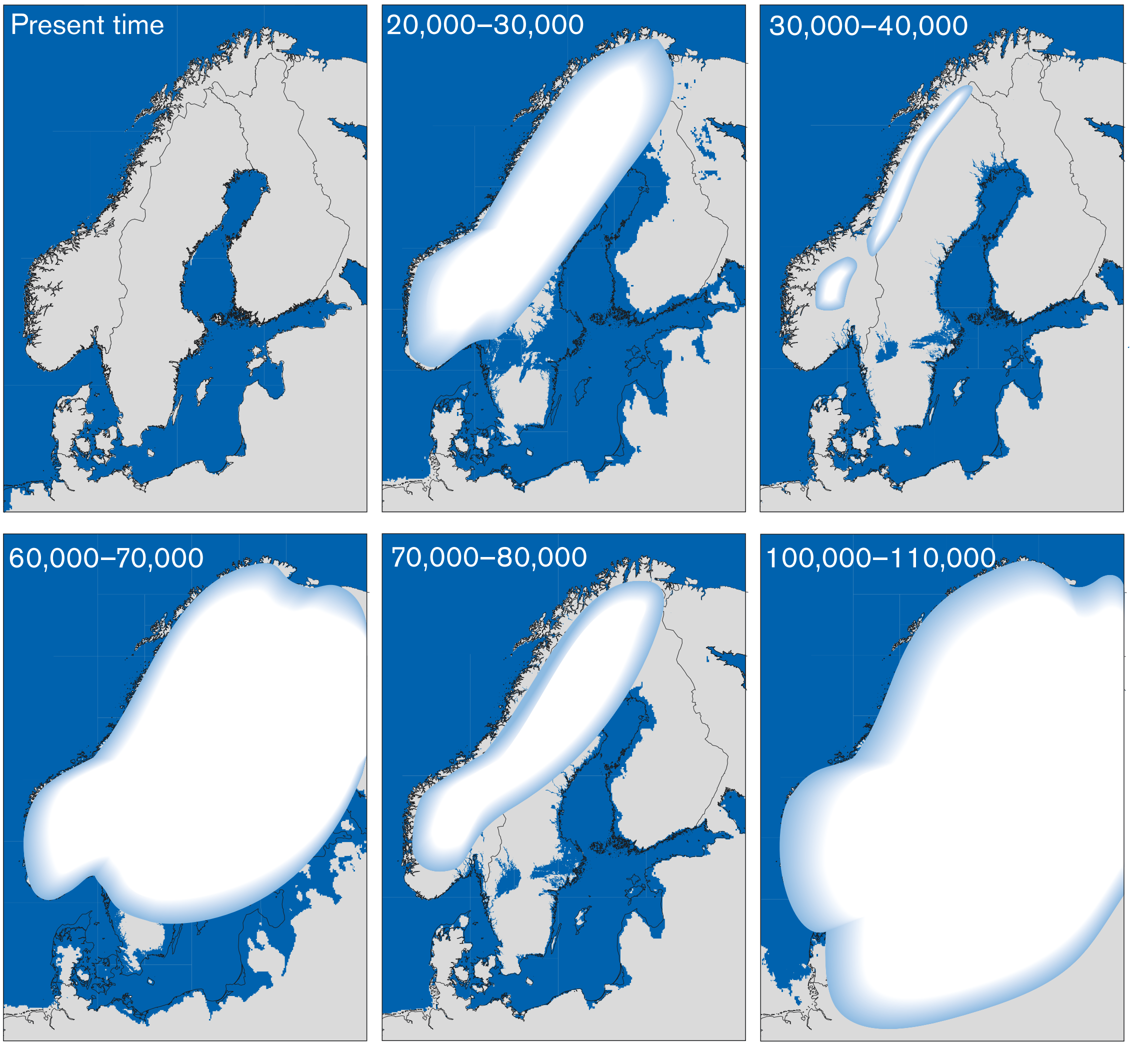

***Figure 3-2**. Assumed extent of ice sheet and changes in coastline during future ice ages.*

4 Safety analysis reports for the operating period

4.1 SAR for Clab

Clab is a facility that is in routine operation. Safety and radiation protection at Clab are described in the safety analysis report, SAR. Clab's first SAR was produced in 1983–85 and has been updated several times since then /SAR Clab/. Major revisions have been made on several occasions in the light of new experience and to meet modern reporting requirements. Such a revision is currently being undertaken.

Actual releases of radioactive substances from the operation of Clab to air and water as well as radiation doses to personnel are given in section 4.2 and are compared to estimates of the emissions from the encapsulation plant. A description of SKB's safety management procedures for the operation of Clab is provided here.

Clab is built on the principle that all safety systems are passive. This means that the systems do not have any moving components and do not require an external power supply to work. The storage canisters in which the spent nuclear fuel is stored can be mentioned as an example. They ensure that the fuel is always kept subcritical, in other words it cannot start a nuclear reaction on its own, and that it is protected from mechanical impact. Clab has many systems – design, safety barriers and safety organization – that interact to provide a robust defence-in-depth, so that the safety features with which the facility is equipped should never need to enter into play.

Management of the safety work is subject to a special safety management. Under this management model, all safety-related decisions are re-examined by a higher level in the organization to broaden the decision base and obtain as broad an illumination of the safety issues as possible. The shift leader is responsible for ensuring that the facility is operated according to the Operational Limits and Conditions, OLC. The OLC is a controlling operational document that contains a condensate of SAR. Each 24 hours of operation are re-examined daily at an operations meeting. Here the shift leader gives an account of the operating events of the past 24 hours and presents a plan for the activities of the next 24 hours. Clab's plant manager then judges the facility's operational readiness, i.e. whether the facility is working as intended.

Abnormal events are dealt with in a forum called the event evaluation meeting. Here the impact of the event on nuclear safety is evaluated. The event evaluation meeting judges the safety-related significance of the event and whether the event has caused the facility to deviate from the OLC. The event is reported to SKI if it has led to a deviation from the OLC. Then the event is reported as a reportable occurrence (RO) within 30 days. The event evaluation meeting decides on measures to be taken so that the event will not be repeated.

Decisions made at the operations meeting and the event evaluation meeting are re-examined each month at the operations management meeting, which is led by the head of SKB's operations department. Decisions are made at this meeting regarding safety at all facilities operated by SKB.

4.2 PSAR for the encapsulation plant

SKB submitted a preliminary safety analysis report for the encapsulation plant /SKB 2006c/ to SKI in the autumn of 2006 in conjunction with the submission of an application under the Nuclear Activities Act. In this report we analyzed the radiological impact on the ambient environment associated with normal operation, disturbances and mishaps, in accordance with SKI's regulations. The calculations are based on conservative assumptions. This means that the actual activity levels are expected to be much lower than those calculated in the event of an accident.

Figure 4-1. *Illustration of the encapsulation plant adjacent to Clab.*

Normal operation

The radiation in the encapsulation plant mainly comes from the spent nuclear fuel. However, it can be noted that the strongest radiation source in the facility is the X-ray machine for non-destructive testing. Release of radioactivity in the encapsulation plant can take place to water, as long as the spent nuclear fuel is being handled in the plant's pools, or to air in the plant's handling cells. All handling of the nuclear fuel takes place in isolated and radiation-shielded areas with controlled ventilation.

Different areas are classified based on the risk of contamination and the radiation level. This classification determines how access is limited to different areas. Once the fuel has been encapsulated it is no longer a source of airborne activity, but radiation shielding is nevertheless required during its further handling.

The maximum quantity of spent nuclear fuel that will be handled in the encapsulation plant at any given time is about 70 tonnes. By comparison it can be mentioned that just over 4,000 tonnes is stored in Clab today. Before the nuclear fuel is taken into the encapsulation plant, its radioactivity has declined after about 30 years of interim storage.

Small quantities of activity are emitted to the water in the handling pool when the nuclear fuel is standing in the pool in the encapsulation plant. The encapsulation plant will be connected to Clab's purification system. When necessary, surplus water will be released together with the cooling water from Clab into Hamnefjärden. Activity levels are checked after each release. Further purification takes place as needed, and water is not released to Hamnefjärden until it meets limit values for release levels /SKB 2006b/.

The releases to water from the encapsulation plant have been estimated at 157 MBq per year, which is equivalent to an annual dose to the critical group of 4.81×10^{-7} mSv. The estimate is based on experience of releases from Clab during the past five years and on a conservative assumption that the release from the encapsulation plant is of the same size as that from Clab.

Airborne releases take place via the encapsulation plant's ventilation stack. An estimate of the airborne release is based on experience from the operation of Clab. In view of the fact that fuel handling and maintenance are on a smaller scale in the encapsulation plant, the releases have been assumed to be half of the releases from Clab. Based on this assumption the annual releases have been estimated to be 12 MBq, which is equivalent to an annual dose to the critical group of 1.4×10^{-6} mSv.

A study of possible measures to reduce activity releases to water and air has been conducted /ALARA 2006/. The study resulted in a number of possible measures to reduce activity releases to water. If all measures can be adopted without impairing safety in the plant, it is estimated that releases can be reduced by 95–99%. In the case with the integrated facility (Clab and the encapsulation plant), releases could be reduced to between 6 and 10 MBq per year.

A possible large point source for atmospheric emissions in the encapsulation plant is the dry handling of spent nuclear fuel in the handling cell. Assuming a separation efficiency of 99.999%, as proposed in the study, the assumed release from the handling cell is 0.1 MBq. This is equivalent to an annual dose to the critical group of 9.3×10^{-9} mSv.

The personnel in the encapsulation plant will be exposed to radiation in connection with normal operating duties and maintenance work. The collective dose, expressed in manSv, is the average dose to individuals in a group multiplied by the number of individuals in the group. The activities in the encapsulation plant are estimated to give rise to a collective dose of 22 mmanSv per year. The collective dose in Clab in 2004 was 14 mmanSv /SSI 2005/. According to SSI's regulation (SSI FS 1998:4), the dose limit for single years is 50 mSv per individual, and for a five-year interval 100 mSv per individual. The estimated collective dose to the personnel in the encapsulation plant is thus on a level with the dose limit per individual, regarded as a mean value during a five-year interval. This is well below the limit. The collective dose to Clab's personnel may increase as a consequence of the increased waste handling when the encapsulation plant is in operation.

By comparison it can be mentioned that the average annual radiation dose to people in Sweden is approximately 4 mSv per person. Nearly half is from radon in the indoor air.

Disturbances

Disturbances are events that can occur at some time during the operating period of the encapsulation plant. Examples of disturbances that are analyzed in PSAR Clab are loss of power supply, component malfunction in the process and handling systems (for example loss of ventilation and loss of cooling in pools), operator error, water leakage and internal flooding, activity release, computer failure and limited fire.

The disturbances may require the process to be stopped and the fuel to be returned to Clab. But they do not lead to fuel damage or radiological consequences for the surrounding environment /SKB 2006b/.

Mishaps

Mishaps are unlikely events which are not expected to occur, but which must be analyzed to demonstrate the ability of the plant to handle them with acceptable consequences for the personnel and surroundings. Mishaps analyzed in PSAR Clab include major fire, operator error that can damage the fuel and handling mishaps (for example dropped transfer canister or fuel assembly) /SKB 2006b/.

In order to estimate the maximum impact of a handling mishap in the encapsulation plant, a purely hypothetical case can be assumed where all fuel that is being handled or kept in the plant is damaged, except for the fuel that is encapsulated. This type of mishap will be included in PSAR Clink.

4.3 PSAR for Clab and the encapsulation plant

The encapsulation plant is planned to be integrated with Clab. Some systems will be interconnected to supply both plant parts. This means that the safety analysis report, PSAR Clink, should apply to both plants.

PSAR Clink should show what requirements apply to all items and systems included in the plant. It also describes how the plant is built and will work when the encapsulation plant has been connected to Clab. The report will be based on an updated SAR for Clab and PSAR for the encapsulation plant. PSAR Clink is supposed to be finished and submitted to SKI in 2008.

4.4 PSAR for the final repository

The preliminary safety analysis report for the final repository includes two parts: one that describes the safety of the repository during the facility's operating period (operational safety) and one that describes the facility's post-closure safety (long-term safety). The report on long-term safety is called SR-Site, see section 5.

The preliminary safety analysis report will be submitted in 2009 in conjuction with the application under the Nuclear Activities Act. The radiological conditions associated with normal operation, disturbances and mishaps are analyzed in the PSAR for the operating period. Approximate assessments have already been done, however.

Normal operation

The design of the final repository is based on the assumption that the copper canisters that enclose the fuel are absolutely leaktight and that the fuel has decayed for many years before it is handled. No radionuclides can escape from the canisters, to either air or water, during normal operation of the final repository. The only releases of radioactive substances during operation will be the radon that is present naturally in the rock and is ventilated out to maintain a good working environment, see section 9.

Ionizing radiation will occur in the final repository and comes from the spent nuclear fuel that is contained in copper canisters. All handling of the copper canisters takes place with radiation shielding. The personnel in the final repository will be exposed to some radiation in connection with normal operating duties and maintenance work. The collective dose will be studied during the period up to when an application is submitted in 2009, but is estimated to be low.

Disturbances

Disturbances are events that can occur on rare occasions during the final repository's operating period. Disturbances can in some cases necessitate an interruption in the deposition process and return of fuel to the encapsulation plant. Examples of disturbances analyzed in PSAR final repository are loss of power supply, operator error, failure of handling equipment and limited fire.

No disturbances have so far been identified that lead to canister damage with radiological consequences for the surrounding environment.

Mishaps

Mishaps that are analyzed include large fire and handling mishaps. Handling mishaps include dropped copper canister and collision during underground transport.

No mishaps during the operation of the facility that could lead to a release of activity from the canisters have as yet been identified. This does not mean that there is no risk of environmental impact due to release of activity from the final repository during the operating phase of the facility.

5 Long-term safety

SKB is conducting an ongoing assessment of long-term safety for a final repository for spent nuclear fuel. The most recent safety assessment, SR-Can (Can = canister), was submitted to SKI in early November 2006 /SKB 2006a/. It is an initial evaluation of how the repository sites in Forsmark and Laxemar function together with the copper canisters that will be sealed in the encapsulation plant. Preliminary data from the Forsmark and Laxemar sites are used in the assessment. The assessment shows that the canister functions as it should in the final repository and the repository has the potential to satisfy the regulatory requirements on safety regardless of whether it is built in Forsmark or Oskarshamn.

SR-Can is a preparatory step for the SR-Site safety assessment, which is planned to be published in 2009. SR-Site is the part of the preliminary safety analysis report for the final repository that deals with long-term safety. SR-Site will be based on the total body of data gathered during the site investigations and the design of the final repository.

Within the framework of the Nuclear Fuel Project, a study is being conducted to show how SKB will ensure that the initial state assumed in SR-Site will be achieved during construction and operation of the final repository. This study includes an account of how the barriers are being handled within the entire KBS-3 system and by its suppliers in relation to stipulated requirements. This entails documentation of the entire handling chain, quality assurance, acceptance criteria, requirements and design premises for canister, buffer, backfill, rock works and final closure. A report on the results of this study will be submitted in conjunction with the applications in 2009.

6 Transportation of spent nuclear fuel

SKB owns and operates a transportation system for shipments of spent nuclear fuel from the nuclear power plants to Clab in Simpevarp and of low- and intermediate-level operational waste to SFR in Forsmark. Sea shipments are performed by SKB's specially designed vessel m/s Sigyn. Overland shipments are performed by slow-moving terminal vehicles. The spent nuclear fuel and operational waste is enclosed in transport casks during transport.

Operation of the transportation system includes design, procurement, operation, maintenance and renewal of transport casks, ships and terminal vehicles. It also includes permits and procedures.

Unencapsulated spent nuclear fuel is transported from the nuclear power plants to Clab. Encapsulated fuel will be transported from the encapsulation plant to the final repository. If the encapsulation plant is not sited adjacent to Clab, unencapsulated fuel will have to be transported from Clab to the encapsulation plant.

Transport casks

The transport cask that is used today for shipments between the nuclear power plants and Clab meets the requirements for "type B packages" according to IAEA rules. This means that extensive calculations as well as physical tests on a prototype cask are performed in order to guarantee that the cask can prevent contact between the contents of the cask and the environment. This also applies in the event of severe accidents.

Figure 6-1. *Terminal vehicle with transport cask for spent nuclear fuel.*

The requirements on a type B package have been applied to shipments of spent nuclear fuel for many years all over the world. The strength requirements included in calculations and tests are chosen to ensure that the cask is capable of withstanding a wide variety of conceivable and inconceivable stresses. As far as is known, such a cask has never been involved in an accident resulting in a release of radioactivity. SKB has many years of experience of using such casks, and no incidents have ever occurred that have affected their function.

The transport cask that is planned to be used for the shipments between the encapsulation plant and the final repository (regardless of siting) will also meet the requirements for type B packages.

6.1 Transportation of unencapsulated fuel

Environmental safety in connection with shipments of unencapsulated fuel from the nuclear power plants has been analyzed for normal operation, design-basis accidents and hypothetical accidents.

Normal operation

For normal operation it has mainly been a question of determining the radiological premises for designing radiation shields. The function and reliability of the system has been verified in actual operation (about 20 years so far).

The radiological conditions, as well as the stresses and disturbances that have occurred, show that environmental and safety requirements can be met in connection with both normal operation and disturbances and stresses to which the system is subjected.

Figure 6-2. *Lashing of casks for spent nuclear fuel on m/s Sigyn.*

Design-basis accidents

Regarding accidents, an inventory of the events, courses of events and conditions that could lead to a radiological accident was performed in conjunction with the procurement of the transportation system. Most conceivable ship accidents do not result in any damage to the cargo and the ship remains afloat. The studies were concentrated on such serious mishaps that the damage to the ship could affect the casks. The consequences of the cargo being dropped from the ship or the ship sinking as a result of a collision, as well as the ship being damaged or burning after a collision, were analyzed.

The cask is expected to remain intact in all design-basis accident situations, so that accidents do not have any radiological consequences. The ship meets the rules on buoyancy with ample margin. A radiological accident would not occur even if the ship were to sink.

Hypothetical accidents

The assessment of environmental safety for the transportation system /SKB 2005/ includes an environmental impact scenario in the event of a radiological accident. Such an accident requires a barrier breach, i.e. the transport cask must be damaged so that radioactive substances can escape. This type of damage to the cask lies beyond the design criteria, but must be assumed in order to show radiological consequences. Events of this type are therefore assumed to be possible, and are designated hypothetical accidents. The hypothetical accidents that have been analyzed are mechanical damage to a cask, fire of long duration, and sinking of the cask to the bottom of the sea.

The assessment shows that the consequences for human health and the environment are negligible, despite very conservative assumptions with regard to releases of radioactivity.

6.2 Transportation of encapsulated fuel

The point of departure for transport of encapsulated fuel is that the canisters are absolutely leaktight and that the fuel is encapsulated and has decayed for about 30 years. These transport casks are also designed to withstand very severe stresses. This means that no radioactive release can occur as a consequence of conceivable accidents during transport.

The calculations that have been carried out /Ekendahl and Pettersson 1998/ are therefore based on purely hypothetical assumptions, in this case that neither the transport cask, the canister nor the fuel cladding are completely leaktight. Even in these scenarios, which are very unlikely to occur, the dose impact is extremely small – far below dangerous levels. The conclusion of the assessment is that the consequences for human health and the environment as regards releases of radioactivity are negligible, even in the event of improbable accidents.

7 Protective security

Based on the legal requirements, SKB has designed a protective security system consisting primarily of three parts: physical protection, personal security and a scanning of the world around.

Physical protection of nuclear facilities includes fencing, alarm, entrance control, camera surveillance etc and has two overall purposes. One is to contribute to general security by preventing deliberate acts from leading to radiological accidents, while the other is to prevent illicit tampering with nuclear material and nuclear waste.

SKI's regulations apply to all nuclear facilities that have permits under Section 5 of the Nuclear Activities Act, including Clab, the encapsulation plant and the final repository. For security reasons it is not possible to describe in detail the measures that are adopted to protect the facilities against hostile actions and threats. One purpose of the measures is to make the time it takes to gain entrance to the facility as long as possible so that the police can deploy their resources.

Personal security includes, for example, screening of employees and visitors. SKB carries out background checks on its own personnel and contractors. This background check also includes a check by Säpo (the Swedish Security Service) under the Protective Security Ordinance (SFS 1996:633).

The scanning of the world around includes studying what is happening in the surrounding region, in Sweden and in the world. The scanning includes regular contacts with the police, Security Service, SKI and other nuclear licensees in Sweden, such as the nuclear power plants, Studsvik and the Westinghouse fuel factory.

7.1 Physical protection for Clab and the encapsulation plant

Clab and the encapsulation plant will have a common physical protection system. A special plan has been drawn up for the construction phase. Preliminary physical protection plans have been drawn up for the operating phase and were included as classified material in the application under the Nuclear Activities Act for the encapsulation plant in November 2006.

7.2 Physical protection for the final repository

A preliminary plan for physical protection during the construction and operating phases will be drawn up for the applications in 2009. This material will also be classified.

7.3 Physical protection for the transportation system

The physical protection requirement only applies to shipments of spent fuel, but is in principle also applied to shipments of other radioactive waste.

The physical protection in the transportation system is designed to:

- prevent theft and removal of transport casks,
- prevent intentional sabotage of transport casks that could lead to activity releases.

The system consists of a combination of engineering and other measures that both physically protect the spent fuel and permit rapid detection and alarm should anything abnormal occur. The content of these measures is also classified.

8 Environmental risk analysis

An initial environmental risk analysis regarding non-radiological consequences was carried out in 2006 /Andersson et al. 2006/. As in previous studies, groundwater lowering in conjunction with the construction of the final repository was judged to constitute a risk. A groundwater lowering may affect wells and animal and plant life. A hydrogeological study is currently being conducted, which will provide a more detailed picture of the groundwater conditions in affected areas and what the environmental consequences of a groundwater lowering might be, as well as loss prevention measures.

According to the environmental risk analysis, a large portion of other identified risks involve spills of oil or diesel fuel, mainly on land. Generally, the risks mainly occur during the construction phase and do not differ from the risks associated with any large construction project. These risks can be minimized with a good organization and established procedures, and spills can be cleaned up as needed. Something that has a relatively high probability of occurring and cannot be easily cleaned up is damaged trucks or road tankers that leak oil. The magnitude of the damage this causes depends on where it occurs (near sources of water, sensitive fauna etc) and possibly also when.

An update of the environmental risk analysis will be performed prior to the applications in 2009. Then the design work will have proceeded further and the layout and location of the facilities will have been more precisely determined. Additional risk scenarios, for example fire, will be analyzed in the update.

9 Working environment

All studies, all planning and documentation of work environment management take place within the framework of designing the encapsulation plant and the final repository. By "systematic work environment management" in the regulations is meant the employer's efforts to investigate, execute and follow up the activity in such a way that ill health and accidents at work are prevented and a satisfactory working environment is achieved. A written working environment policy and written procedures describing how the work environment is managed shall be provided.

The regulations for the construction and civil engineering work state that a working environment plan shall be prepared. The underground working environment is characterized by noise, dust, gases (e.g. radon), damp, darkness and confined spaces. According to the provisions for rock work, the need for ventilation and the design of the ventilation system shall be planned and documented before the work is begun. There shall also be a written plan of action regarding what to do in the event of an accident. The plan of action will comprise a part of the working environment plan.

Responsibility for management of the work environment on different construction sites rests with the owner, in this case SKB. Coordination of the work is usually entrusted to one of the major contractors.

The design work is also governed by laws and regulations that lie within the area of responsibility of the Swedish Rescue Services Agency. These kinds of matters, as well as working environment matters, are not included in the applications, but preliminary versions of all documentation will exist when the applications are submitted in 2009.

10 References

ALARA, 2006. Utredning av tekniker och metoder för reduktion av radioaktiva utsläpp från centralt mellanlager för använt kärnbränsle (Clab) och planerad inkapslingsanläggning för använt kärnbränsle, Simpevarp, Oskarshamns kommun. ALARA engineering report 06-0008R, Revision 1.

Andersson J, Herly L, Pettersson L, 2006. Miljöriskanalys för inkapslingsanläggning och slutförvar. SKB P-06-108, Svensk Kärnbränslehantering AB.

Broman U, Dybeck P, Ekendahl A-M, 2005. Transport av inkapslat bränsle. SKB R-05-65, Svensk Kärnbränslehantering AB.

Ekendahl A-M, Pettersson S, 1998. Säkerheten vid transport av inkapslat bränsle. SKB R-98-14, Svensk Kärnbränslehantering AB.

SAR for Clab. Clab Säkerhetsrapport. OKG report 8/A1. (Internal report)

SKB, 1992. SKB 91. Final disposal of spent nuclear fuel. Importance of the bedrock for safety. Svensk Kärnbränslehantering AB.

SKB, 1995. SR 95 – Template for safety reports with descriptive example. Svensk Kärnbränslehantering AB.

SKB, 1999. SR 97, Main Report Volumes I and II. Svensk Kärnbränslehantering AB.

SKB, 2000. Integrated account of method, site selection and programme prior to the site investigation phase. SKB TR-01-03, Svensk Kärnbränslehantering AB.

SKB, 2005. Säkerhetsrapport för transportsystemet. D-05-02, Svensk Kärnbränslehantering AB.

SKB, 2006a. Long-term safety for KBS-3 repositories at Forsmark and Laxemar – a first evaluation. Main report of the SR-Can project. SKB TR-06-09, Svensk Kärnbränslehantering AB.

SKB, 2006b. Ansökan om tillstånd enligt kärntekniklagen. Inkapslingsanläggning och centralt mellanlager för använt kärnbränsle, vid Simpevarp i Oskarshamns kommun. Miljökonsekvens-beskrivning (MKB). Svensk Kärnbränslehantering AB. October 2006.

SKB, 2006c. Ansökan om tillstånd enligt kärntekniklagen. Inkapslingsanläggning och centralt mellanlager för använt kärnbränsle, vid Simpevarp i Oskarshamns kommun. Bilaga F. Preliminär säkerhetsredovisning. Svensk Kärnbränslehantering AB. November 2006.

SKBF/KBS, 1983. Final storage of spent nuclear fuel – KBS-3. Parts I–IV. Svensk Kärnbränsleförsörjning AB.

SSI, 2005. Personalstrålskydd inom kärnkraftsindustrin under 2004. Swedish Radiation Protection Authority, SSI report 2005:12.

The references that are not available on SKB's website, *www.skb.se*, can be obtained on request.

Technical Report

TR-06-09

Long-term safety for KBS-3 repositories at Forsmark and Laxemar – a first evaluation

Main Report of the SR-Can project

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October 2006

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Long-term safety for KBS-3 repositories at Forsmark and Laxemar – a first evaluation

Main Report of the SR-Can project

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October 2006

Preface

This document is the main report of the SR-Can project, an assessment of long-term safety for a KBS-3 repository. The project is a preparatory step for an assessment intended to support a licence application for a final repository in Sweden.

The undersigned has edited the report and has been responsible for the methodology development in consultation with mainly Johan Andersson, JA Streamflow AB and Kristina Skagius, Kemakta Konsult AB.

Johan Andersson has also acted as a co-ordinator of the site investigation, the repository engineering and the safety assessment projects, and he and Kristina Skagius have written most of the descriptions of the Laxemar and the Forsmark sites in chapter 4 of this report. Kristina Skagius is responsible for the development of the FEP database and Karin Pers, Kemakta Konsult AB for the systematic description of the initial state of the engineered barriers.

The following persons, SKB employees unless otherwise noted, have had the main responsibilities for specific subject areas in the assessment: Kastriot Spahiu (fuel); Lars Werme (fuel and canister); Patrik Sellin (buffer and backfill); Jan-Olof Selroos (geosphere flow and transport); Johan Andersson, JA Streamflow AB and Raymond Munier (geomechanical issues); Ignasi Puigdomenech (geochemistry); Lena Morén (issues related to future human actions); Ulrik Kautsky (biosphere), Jens-Ove Näslund (climate issues) and Fredrik Vahlund and the undersigned (integrated radionuclide transport modelling).

Jürg Schneider, Piet Zuidema and Lawrence Johnson, Nagra, kindly provided comments on an early version of this document.

The report has been reviewed by SKB's international Site Investigation Expert Review Group (SIERG): Per-Eric Ahlström, SKB (chair); Jordi Bruno Enviros, Spain; John Hudson, Rock Engineering Consultants, UK; Ivars Neretnieks Royal Institute of Technology, Sweden; Roland Pusch, Geodevelopment AB; Gunnar Gustafson, Chalmers University of Technology, Sweden; Lars Söderberg, SKB and Mike Thorne, Mike Thorne and Associates Ltd, UK. It has also been reviewed by Olle Olsson, Rolf Christiansson, Christer Svemar and Peter Wikberg, SKB.

Stockholm, October 2006

Allan Hedin

Project leader SR-Can

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Summary

Introduction

This document is the main report from the safety assessment project SR-Can. The SR-Can project is a preparatory stage for the SR-Site assessment, the report that will be used in support of SKB's application for a final repository. The purposes of the safety assessment SR-Can are the following:

1. To make a first assessment of the safety of potential KBS-3 repositories at Forsmark and Laxemar to dispose of canisters as specified in the application for the encapsulation plant.
2. To provide feedback to design development, to SKB's R&D programme, to further site investigations and to future safety assessment projects.
3. To foster a dialogue with the authorities that oversee SKB's activities, i.e. the Swedish Nuclear Power Inspectorate, SKI, and the Swedish Radiation Protection Authority, SSI, regarding interpretation of applicable regulations, as a preparation for the SR-Site project.

The assessment relates to the KBS-3 disposal concept in which copper canisters with a cast iron insert containing spent nuclear fuel are surrounded by bentonite clay and deposited at approximately 500 m depth in saturated, granitic rock, see Figure 1. Preliminary data from the Forsmark and Laxemar sites, presently being investigated by SKB as candidates for a KBS-3 repository are used in the assessment.

An important aim of this report is to demonstrate the proper handling of requirements placed on the safety assessment in applicable regulations. Therefore, regulations issued by the Swedish Nuclear Power Inspectorate (SKIFS 2002:1) and the Swedish Radiation Protection Institute (SSI FS 1998:1) are reproduced in an Appendix where references are given to sections in the main text where the handling of the different requirements is discussed. The principal acceptance criterion requires that "the annual risk of harmful effects after closure does not exceed 10^{-6} for a representative individual in the group exposed to the greatest risk". "Harmful effects" refer to cancer and hereditary effects. The risk limit corresponds to an effective dose limit of about $1.4 \cdot 10^{-5}$ Sv/yr. This, in turn, corresponds to around one percent of the effective dose due to natural background radiation in Sweden.

The timeframe for the assessment is one million years after repository closure, in accordance with regulatory requirements. The above risk limit is applicable as a quantitative regulatory limit during approximately the first one hundred thousand years, and thereafter as a basis for discussing the protective capability of the repository, according to SSI.

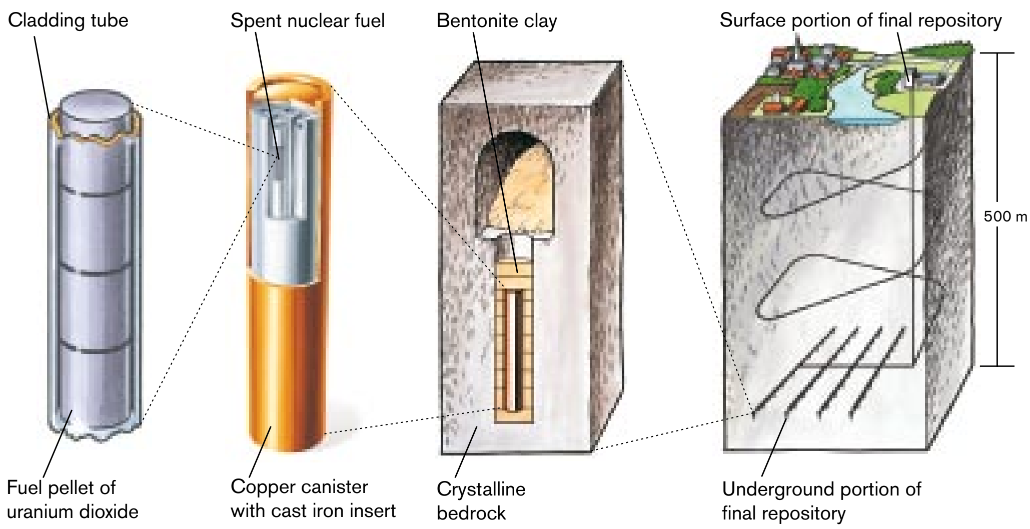


***Figure 1.** The KBS-3 concept for disposal of spent nuclear fuel.*

Methodology

The repository system, broadly defined as the deposited spent nuclear fuel, the engineered barriers surrounding it, the host rock and the biosphere in the proximity of the repository, will evolve over time. Future states of the system will depend on:

- the initial state of the system,
- a number of radiation-related, thermal, hydraulic, mechanical, chemical and biological processes acting internally in the repository system over time and,
- external influences acting on the system.

A methodology in ten steps has been developed for SR-Can, as summarised in Figure 2. The steps are carried out partly concurrently and partly consecutively.

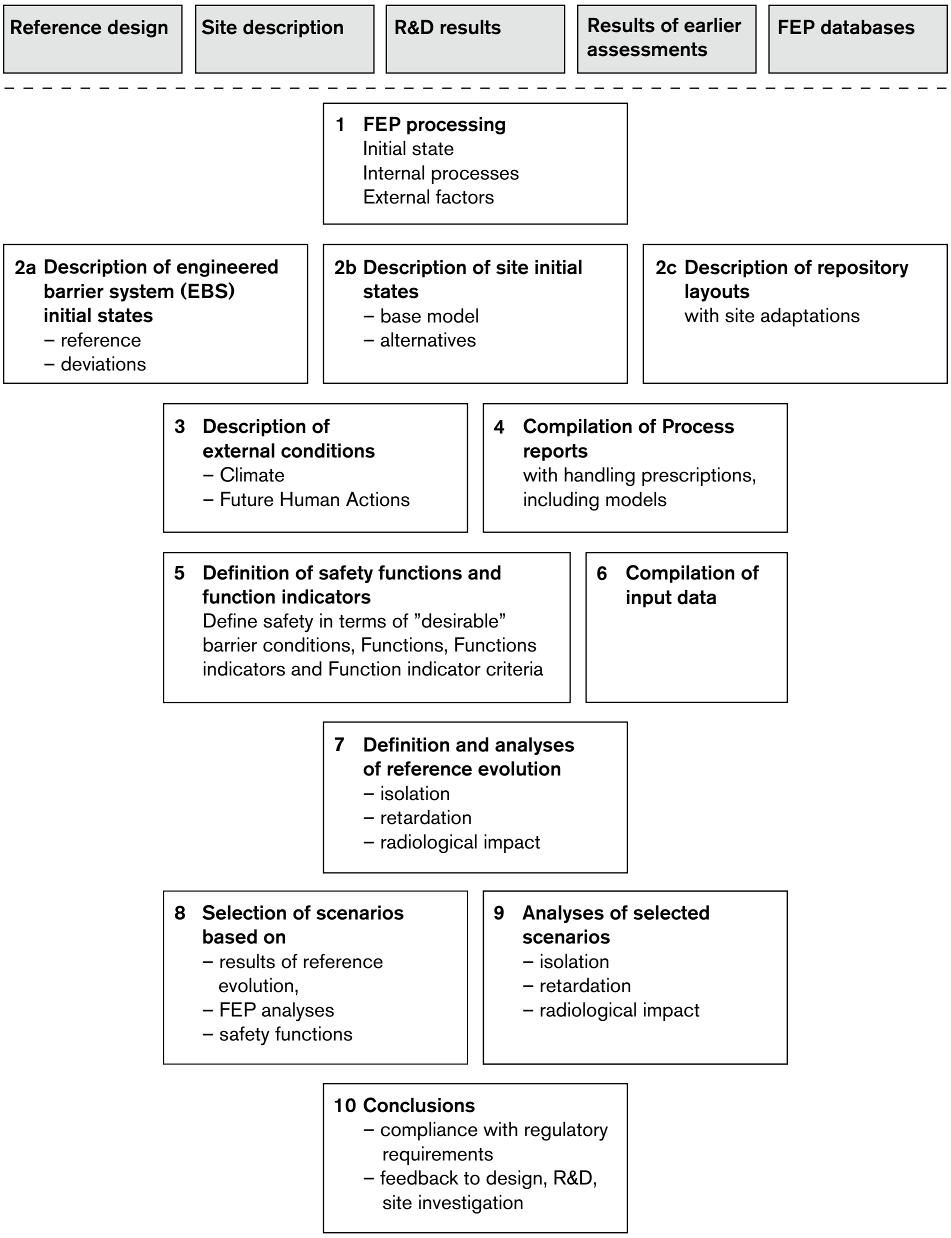


Figure 2. *Outline of the ten main steps of the SR-Can safety assessment. The boxes at the top above the dashed line are inputs to the assessment.*

The ten steps are described in more detail below.

1. Identification of factors to consider (FEP processing)

   This step consists of identifying all the factors that need to be included in the analysis. Experience from earlier safety assessments and KBS-3 specific and international databases of relevant features, events and processes (FEPs) influencing long-term safety are utilised. An SKB FEP database is developed where the great majority of FEPs are classified as being either initial state FEPs, internal processes or external FEPs. Remaining FEPs are either related to assessment methodology in general or determined to be irrelevant for the KBS-3 concept. Based on the results of the FEP processing, an SR-Can FEP catalogue, containing FEPs to be handled in SR-Can, has been established. This step of FEP processing is further described in Chapter 3 and fully documented in the SR-Can **FEP report**[1].

2. Description of the initial state

   The initial state of the system is described, based on the design specifications of the KBS-3 repository, a descriptive model of the repository site and a site-specific layout of the repository. The initial state of the fuel and the engineered components is that immediately after deposition as described in the **Initial state report**. The initial state of the geosphere and the biosphere is that of the natural system prior to excavation, as described in the site descriptive models of the Forsmark /SKB 2005c/ and Laxemar /SKB 2006b/ sites. The repository layouts adapted to the sites are provided in underground design reports for each site /Brantberger et al. 2006/ and /Janson et al. 2006/. See further Chapter 4.

3. Description of external conditions

   Factors related to external conditions are handled in the three categories "climate related issues", "large-scale geological processes and effects" and "future human actions". The handling of these factors is described in the **Climate report,** the **Geosphere process report**, and the **FHA report**, respectively. See further Chapter 5.

4. Description of processes

   The identification of relevant processes is based on earlier assessments and FEP screening. All identified processes within the system boundary relevant to the long-term evolution of the system are described in dedicated **Process reports**. Short-term geosphere processes/alterations due to repository excavation are also described in these Process reports and are taken into account in the assessment. For each process, its general characteristics, the time frame in which it is important, the other processes to which it is coupled and how the process is handled in the safety assessment are documented. See further Chapter 6.

5. Definition of safety functions, safety function indicators and safety function indicator criteria

   This step consists of an account of the safety functions of the system and of how they can be evaluated by means of a set of safety function indicators that are, in principle, measurable or calculable properties of the system. Criteria for the safety function indicators are provided. The process reports are important references for this step. A FEP chart is developed, showing how FEPs are related to the safety function indicators. The execution and results of this step are described in Chapter 7.

6. Compilation of input data

   Data to be used in the quantification of repository evolution and in dose calculations are selected using a structured procedure. The process of selection and the data values adopted are reported in a dedicated **Data report**. Also, a template for discussion of input data uncertainties has been developed and applied. See further Chapter 8.

7. Definition and analysis of reference evolution

   A reference evolution, providing a description of a plausible evolution of the repository system, is defined and analysed. The isolating potential of the system over time is analysed in a first step, yielding a description of the general system evolution and an evaluation of the safety function indicators. If the evolution indicates breaching of isolation, the retarding potential of the repository and its environs is analysed and dose consequences are calculated for the long-term conditions identified in the first step. Also some canister failure modes not resulting from the reference evolu-

[1] The FEP report is one of several principal references in this Main report. See section 2.2.1 for a complete list and nomenclature for referencing.

tion are analysed in order to further elucidate the retarding properties of the system. Each process is handled in accordance with the plans outlined in the process reports. See further Chapter 9 for the analysis of the general evolution and the isolating potential and Chapter 10 for the analysis of the retarding potential.

8. Selection of scenarios

   A set of scenarios for the assessment is selected. A comprehensive main scenario is defined in accordance with SKI's regulations SKIFS 2002:1. The main scenario is closely related to the reference evolution analysed in step 7. The selection of additional scenarios is focused on the safety functions of the repository and the safety function indicators defined in step 4 form an important basis for the selection. For each safety function, an assessment is made as to whether any reasonable situation where it is not maintained can be identified. If this is the case, the corresponding scenario is included in the risk evaluation for the repository with the overall risk determined by summation over such scenarios. The set of selected scenarios also includes e.g. scenarios explicitly mentioned in applicable regulations, such as human intrusion scenarios, and scenarios and variants to explore the roles of various components in the repository. See further Chapter 11 for the scenario selection methodology and the application of the selection method.

9. Analysis of selected scenarios

   The main scenario is analysed essentially by referring to the reference evolution in step 7. An important result is a calculated risk contribution from the main scenario. The additional scenarios are analysed by focussing on the factors potentially leading to situations in which the safety function in question is not maintained. In most cases, these analyses are carried out by comparison with the evolution for the main scenario, meaning that they only encompass aspects of repository evolution for which the scenario in question differs from the main scenario. For these scenarios, as for the main scenario, a risk contribution is estimated. See further Chapter 12.

10. Conclusions

    This step includes integration of the results from the various scenario analyses, development of conclusions regarding safety in relation to regulatory criteria and feedback concerning design, continued site investigations and SKB's RD&D programme. See further Chapter 13.

The sites and the repository layouts

From site data to SR-Can

The information transfer from field investigation to the safety assessment application involves several steps. *Field data* are obtained from various investigation activities, such as air-borne and surface-based geophysics, borehole drilling and borehole testing. The data are quality controlled and then entered into the SKB site characterisation database, Sicada. The field data are interpreted and evaluated into an overall inter-disciplinary *Site Descriptive Model* (SDM), being a synthesis of geology, rock mechanics, thermal properties, hydrogeology, hydrogeochemistry, bedrock transport properties and surface system properties. The SDM is reported in an SDM report. Site data used in SR-Can are assessed in the **Data report**, using the SDM versions 1.2 as input. The data report also describes how non-site specific information were taken into account, adds judgements, based on how the data will be used in SR-Can, on how to handle the uncertainties identified in the SDM and reports the final selections of model input data.

Forsmark

The Forsmark site is located in northern Uppland within the municipality of Östhammar, about 170 km north of Stockholm. The landscape in Forsmark is a relatively flat bedrock plain that dips gently towards the east. The whole area is located below the highest shoreline that occurred during the last deglaciation. Today's landscape is strongly influenced by the ongoing vertical shore-level uplift of approximately 6 mm per year.

The bedrock in the Forsmark region has been affected by both ductile and brittle deformation. The ductile deformation has resulted in large-scale ductile high-strain zones, but the candidate area is situated within a tectonic lens enclosed between ductile high-strain zones. The bedrock inside the lens is relatively homogeneous, and is dominated by a metagranite with high content of quartz, whereas the lithology and deformation is more complex outside the lens. No potential for metallic and industrial mineral deposits has been recognised within the candidate area. Due to its rather high quartz content, the bedrock is characterised by high thermal conductivity and high mechanical strength compared to typical rock conditions in Sweden.

Three major sets of deformation zones with distinctive orientations have been recognized. In addition to vertical and steeply dipping zones, there are also gently south-east- and south-dipping zones. These gently dipping zones are more frequent in the south-eastern part of the candidate volume and have higher hydraulic transmissivity than vertical and steeply dipping deformation zones at the site. They seem to play an important role in determining the properties of the Forsmark site, such as the distribution of stress, fracturing and the transmissivity distribution of the fractures. The frequency of open and partly open fractures is very low below approximately 300 m depth compared to what is observed in the upper part of the bedrock in the north-western part of the candidate volume, which is the target volume for a potential repository at the site. In addition, the rock stresses are high compared to typical values of the Swedish bedrock, with a potential correlation to the low fracture frequency in this part of the bedrock. The more fractured upper part of the bedrock overlying the target volume is highly transmissive in the horizontal plane and in good hydraulic contact over long distances, whereas at depth the rock appears to have very low permeability with few transmissive fractures. Meteoric water is present in the uppermost approximately 200 m of the bedrock. At depths between 200 and 800 m, the salinity remains fairly constant (5,000–6,000 mg/L) and the water composition indicates remnants of Littorina Sea water. At depths between 800 and 1,000 m, the salinity increases to higher values.

Laxemar

The Laxemar site is part of the Simpevarp candidate area located in the municipality of Oskarshamn, about 300 km south of Stockholm. The topography is relatively flat. The whole area is located below the highest shoreline associated with the last deglaciation. There is still vertical shore-level uplift of approximately 1 mm per year.

The northern and central parts of the area is dominated by Ävrö granite, whereas in the southern part of the area there are rock domains consisting mainly of quartz monzodiorite and diorite to gabbro forming an arc-shaped body dipping to the north with the concave side to the north. No potential for metallic and industrial mineral deposits has been recognised within the area. Many of the rock types of the Laxemar subarea have low and spatially varying quartz contents. This results in relatively low and varying thermal conductivity, compared to typical values of Swedish bedrock. The mean uniaxial compressive strength is comparatively low in most of the rock types and it also shows a quite large spread. However, these results are based on data from a few samples and are possibly biased by their proximity to a larger deformation zone.

The principal orientations of deformation zones are north-south and east-west. It is judged that most of the local major, steeply dipping zones have been identified at the surface and that gently dipping regional zones do not exist within the local model domain. There remain, however, uncertainties as to the details. There is a high variability in the fracturing and the fracture network description is uncertain. Both measurement data and stress modelling results suggest that the Laxemar subarea can be divided into two different stress domains (I and II), where Stress Domain II has lower stress. The limited data available for the Laxemar 1.2 SDM at the time of the data freeze for this report suggested that the rock volume could be divided into hydraulic domains with different and depth-dependent hydraulic properties. New data available after the data freeze, strongly support these previous indications that there is a depth dependence of hydraulic conductivity and that the rock domains in southern Laxemar have lower conductivities than those in northern Laxemar.

The complex groundwater evolution and patterns at the Laxemar subarea are a result both of the past evolution of groundwater flow and modifications of the groundwater composition caused by microbial processes and water/rock interactions. In the Laxemar subarea, fresh (meteoric) water is found down to 800 m depths, whereas the interface is much shallower at the Simpevarp subarea, which is closer to the sea. Brackish water is found at intermediate depths (500–950 m) and deeper (900–1,200 m) the water becomes saline (6,000–20,000 mg/L Cl, 25–30 g/L TDS). Highly saline water (> 20,000 mg/L Cl, max TDS ~ 70 g/L) has only been found in one borehole at depths larger than 1,200 m.

Although the Laxemar 1.2 SDM is based on a significant amount of data, only a few of these are representative of the potential repository volume(s). This is especially evident for the fracture, thermal and hydraulic data. Data acquired after the data freeze as well as data that will be acquired in the future will allow a more elaborate set of analyses as for Forsmark to be performed also for Laxemar. At this time, it has been decided within the SR-Can team to only carry out a limited set of analyses of the Laxemar site.

Repository layouts

Preliminary repository layouts, based on the site descriptions, have been developed for the two sites. The layouts relate to a repository for 6,000 canisters. At Forsmark, the reference layout, assessed in SR-Can, is developed for the –400 m level. At Laxemar, the reference layout is developed for the –500 m level.

In order to avoid detrimental impacts from potential future earthquakes, the design applies a respect distance for deformation zones with traces longer than 3 km. For zones with traces shorter than 3 km, a margin for construction, less than 100 m, is applied. A minimum canister separation distance is determined based on the thermal properties. A degree-of-utilisation is estimated by considering mechanical stability, the probability of deposition holes intersecting fractures or deformation zones with radius $R > 75$ m, and the inflow of water to tunnels and deposition holes using criteria defined in preset design premises. The degree-of-utilisation affects the size of the repository in the layout, i.e. the repository is made large enough to find space for 6,000 accepted canister positions. At Forsmark, the degree-of-utilisation is 89% in the layout and at Laxemar the design is based on a degree-of-utilisation of 80%.

The canister position selection criteria that are applied in the design are preliminary. SR-Can has, therefore, explored the importance of such criteria. The full perimeter intersection criterion (FPC) states that if a fracture is observed over the entire perimeter of the deposition tunnel no deposition hole should be located such that it would be intersected by the assumed extension of that fracture. The evaluation of this criterion has indicated a high efficiency in reducing the number of deposition holes that are intersected by large fractures and at the expense of only a moderate increase in total deposition tunnel length. It is, therefore, assumed in SR-Can that the FPC rule has been implemented in the layouts at the two sites. It is likely that practical criteria concerning flow conditions would relate to results of hydraulic tests, observations of seepage in deposition tunnels or in deposition holes. However, the practicalities or effectiveness of such hydraulic criteria have not yet been assessed by SKB, and SR-Can only makes some initial exploration on the potential importance of flow-related acceptance criteria.

Safety

The development of the KBS-3 repository concept has been guided by a number of *safety principles*. The long-term performance of the repository can be expressed by studying a set of *safety functions* that should preferably be upheld during the one million year time period covered by the assessment. The safety principles and the implementation of safety functions in SR-Can are summarised below.

Safety principles

Since work on the Swedish final repository project commenced at the end of the 1970s, SKB has established a number of principles for the design of a final repository. The principles can be said to constitute the safety philosophy behind the KBS-3 concept. They are summarised below.

- By placing the repository at depth in a long-term stable geological environment, the waste is isolated from the human and near-surface environment. This means that the repository is strongly affected neither by societal changes nor by the direct effects of long-term climate change on the ground surface.
- By locating the repository at a site where the host rock can be assumed to be of no economic interest to future generations, the risk of human intrusion is reduced.
- The spent fuel is surrounded by several engineered and natural safety barriers.
- The primary safety function of the barriers is to isolate the fuel.

- Should isolation be breached, the secondary safety function of the barriers is to retard a potential release from the repository.
- Engineered barriers shall be made of naturally occurring materials that are stable in the long term in the repository environment. The long-term properties of the materials shall be verifiable.
- The repository shall be designed and constructed so that temperatures that could have significant detrimental effects on the long-term properties of the barriers are avoided.
- The barriers should be passive, i.e. they should function without human intervention and without artificial supply of matter or energy.

Together with many other considerations, like the geological setting in Sweden and the requirement that the repository must be feasible to construct from a technical point of view, these principles have led to the development of the KBS-3 system for spent nuclear fuel.

Safety functions

The key safety related features of the KBS-3 disposal system can be summarised in the safety functions isolation and retardation.

A detailed and quantitative understanding and evaluation of repository safety requires a full description of how the main safety functions of isolation and retardation are achieved by the components of the repository. Based on the understanding of the properties of the components and the long-term evolution of the system, a number of subordinate safety functions to isolation and retardation can be identified. The following definitions are used:

- A safety function is a role through which a repository component contributes to safety.
- A safety function indicator is a measurable or calculable property of a repository component that indicates the extent to which a safety function is fulfilled.
- A safety function indicator criterion is a quantitative limit such that if the safety function indicator to which it relates fulfils the criterion, the corresponding safety function is maintained.

An overview of the safety functions, their indicators and the indicator criteria is given in Figure 3.

Safety functions aid in the evaluation of safety, but the fulfilment of all safety function indicator criteria is neither necessary nor sufficient to argue safety. The different safety function indicator criteria are furthermore determined with varying margins to acceptable performance.

Safety functions are related to, but not the same as, design criteria. Whereas the latter relate to the initial state of the repository and primarily to its engineered components, the former should be fulfilled throughout the assessment period and relate, in addition to the engineered components, to the natural system.

Reference evolution of the repository

A reference evolution of KBS-3 repositories at the Forsmark and Laxemar sites over the entire one million year assessment period is studied to gain an understanding of the overall evolution of the system as a basis for scenario selection and scenario analyses. The aim is to describe a reasonable evolution of the repository system over time.

Two variants of the reference evolution are analysed:

- A base variant where the external conditions during the first 120,000 year glacial cycle are assumed to be similar to those experienced during the last cycle, the Weichselian. Thereafter, seven repetitions of that cycle are assumed to cover the entire one million year assessment period.
- A greenhouse variant in which the future climate and, hence, external conditions are assumed to be substantially influenced by antropogenic greenhouse gas emissions.

The analysis is carried out in four time frames and in each frame the safety functions mentioned above are evaluated.

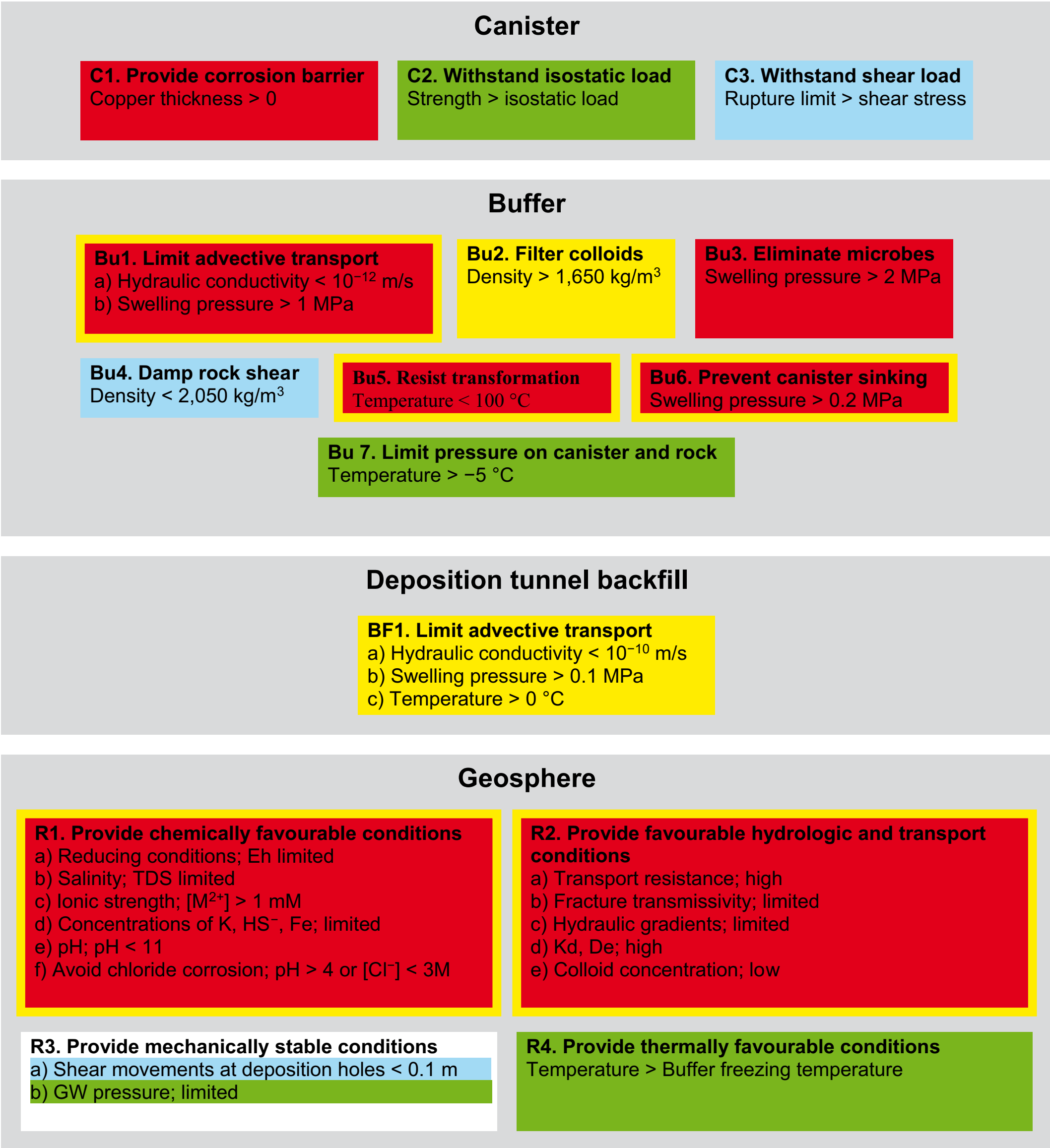


Figure 3. *Safety functions (bold), safety function indicators and safety function indicator criteria. When quantitative criteria cannot be given, terms like "high", "low" and "limited" are used to indicate favourable values of the safety function indicators. The colour coding shows how the functions contribute to the canister safety functions C1 (red), C2 (green), C3 (blue) or to retardation (yellow). Many functions contribute to both C1 and retardation (red box with yellow board).*

The excavation/operation phase

The analyses for the excavation and operation phases of the repository, expected to last several decades, mainly focus on disturbances of the mechanical, hydrological and chemical conditions induced by the excavation/operational activities. Issues of potential importance to long term safety include:

- The creation of an excavation damaged zone (EDZ) around deposition holes and in particular deposition tunnels, impairing the retention properties of the rock, relating to the safety functions R2a and R2b in Figure 3.
- The potential for the buffer to experience piping, i.e. the formation of hydraulically conductive channels, immediately after deposition, due to the high groundwater pressure gradients in the open repository. This, in turn, may lead to erosion of the deposited buffer, caused by water flowing in the pipes. This relates to the safety function Bu1 in Figure 3.

The initial temperate period

This period is expected to last several thousand years. The host rock and back-filled tunnels are expected to be re-saturated and the subsequent evolution in the geosphere is characterised by a return to the natural, undisturbed situation prior to excavation. The analysis of this period includes comprehensive thermal, hydrogeological, mechanical and chemical modelling.

An important safety relevant issue with long-term consequences is the occurrence of spalling of the rock around the deposition holes, induced by additional stresses from the thermal load of the deposited waste. This relates to the safety functions R2a and R2b in Figure 3.

The evolution during the initial temperate period does not imply that any other safety functions are jeopardised.

The first glacial cycle

The occurrence of permafrost and glacial conditions, exemplified by a model reconstruction of the last glacial cycle, called the Weichselian and comprising the Weichselian glacial and the Holocene interglacial, implies major alterations on the ground surface and also of some of the bedrock conditions of importance for repository safety. These include:

- The development of permafrost.
- Altered mechanical loads on the bedrock from an overlying ice sheet, leading to altered rock stresses and potentially the occurrence of large earthquakes.
- Increased hydrostatic pressures at repository depth for glacial conditions.
- The occurrence of dilute groundwaters during glacial conditions potentially causing erosion of buffer and backfill through colloid-formation that, in turn, would lead to enhanced canister corrosion.
- The possible penetration of oxygen to repository depth for short periods of increased groundwater flow during glacial conditions.
- Factors affecting retardation in the geosphere, such as temporarily increased groundwater flows.

The results of the analyses imply the following.

- Large earthquakes, of magnitude 6 or larger, in the vicinity of the repository are highly unlikely but cannot be completely ruled out. The results of the probabilistic calculations imply that the mean number of canister failures during the initial glacial cycle due to such events is 0.014 and 0.0077 for the Forsmark and Laxemar sites, respectively. This relates to safety functions C3 and R3a in Figure 3.
- Dilute groundwaters may occur for extended periods of time when glacial conditions prevail. This may lead to loss of buffer mass in some deposition holes, to the extent that advective conditions are created. This leads to enhanced canister corrosion, but no canisters are assessed to fail during the initial glacial cycle. This relates mainly to the safety functions C1, Bu1 and R1c in Figure 3.

Other aspects of the evolution during the first glacial cycle are assessed not to threaten any of the safety functions of the repository.

The time after the first glacial cycle up to one million years

The continued evolution of the repository system is analysed by assuming another seven repetitions of the 120,000 year Weichselian glacial cycle.

The same phenomena as for the initial glacial cycle could impair safety for the repeated glacial cycles:

- The likelihood of large earthquakes is assessed to increase with time. The mean number of canister failures for the entire one million year assessment period is calculated to 0.12 for Forsmark and to 0.065 for Laxemar.
- The extent of loss of buffer mass due to erosion is expected to increase with time. The resulting enhanced canister corrosion may lead to failures of a few canisters during the one million year assessment period. The result is sensitive to a number of factors analysed in the reference evolution.

The results of the analysis do not implicate threats to any additional safety functions.

The greenhouse variant

In the greenhouse variant, it is assumed that a temperate climate prevails for 50,000 years before the relatively mild onset of the base variant of the next glacial cycle, as opposed to a few thousand years of initial temperate conditions without an increased greenhouse effect. Throughout the report it is implicitly understood that the greenhouse variant describes a situation with an increased greenhouse effect.

As seen above, the processes that are potentially the most detrimental to repository safety are related to glacial conditions. Therefore, a prolonged period of temperate climate is essentially beneficial for safety.

Radiological consequences

Radionuclide transport and dose calculations are carried out for four canister failure modes. Two of these, failure due to corrosion and due to shear movements, were identified in the reference evolution. Two additional failure modes are analysed to further illustrate retardation, the secondary safety function of the repository.

A comprehensive set of calculation cases are carried out to analyse retardation and to elucidate the impact of a number of uncertain factors identified in the reference evolution. In the biosphere, radionuclide transport and dose consequences are estimated using a novel approach based on site specific biosphere data and taking the temporal development of the landscape into account.

The results imply that the canister failures potentially resulting from *the reference evolution* yield consequences that are well below the regulatory risk limit.

Scenarios

The further assessment of repository safety is broken down into a number of scenarios. A comprehensive main scenario represents a reasonable evolution of the repository system. The evolution of this scenario is closely linked to the reference evolution. A set of additional scenarios are defined in order to cover uncertainties not addressed in the reference evolution, e.g. more extreme climate conditions than those obtained from the reconstruction of the Weichselian glacial cycle in the reference evolution.

The safety functions are used to obtain a comprehensive set of additional scenarios, focussing on issues of relevance to repository safety. When defining a scenario, a violation of a safety function is *postulated* and all conceivable routes to such a violation are then scrutinised. The aim is to answer the question: Is there any reasonable way in which this scenario could occur? If this is found to be the case, the consequences of the scenario in question are included in a risk summation for the repository. If not, the scenario is considered as “residual”, and consequences may be analysed for illustrative purposes.

A scenario addressing canister failure due to isostatic over-pressure exemplifies the approach. In this scenario, mishaps in the manufacturing of the load bearing canister insert, higher than reference buffer swelling pressures and very large ice sheets yielding high groundwater pressures are considered.

In addition to the so derived scenarios, scenarios required by regulations or otherwise identified as relevant for the assessment are also sought, resulting in a selection of several scenarios related to future human actions. These are residual scenarios, i.e. they are not included in the risk assessment for the repository. Table 1 gives an overview of the selected scenarios.

The selected scenarios are analysed, often as extensions of the analyses of the reference evolution. Two failure modes of the canister were found to contribute to risk:

- Failure due to copper corrosion when advective conditions prevail in the deposition hole as a result of buffer erosion. The buffer erosion is caused by colloid formation due to glacial melt waters of low ionic strength. This failure occurs in the reference evolution and hence in the main scenario. In the canister corrosion scenario, which is analysed to cover uncertainties not addressed in the reference evolution, larger consequences than for the reference evolution are predicted.
- Failure due to rock shear movements caused by large earthquakes. This failure mode has a low probability, but cannot be entirely ruled out.

Table 1. Result of scenario selection. Green cells denote conditions for the base variant of the main scenario, red cells denote deviations from these conditions. EBS stands for engineered barrier system, i.e. the canister, the buffer and the deposition tunnel.

Main scenario				
Name	**Initial state EBS**	**Initial state Site**	**Process handling**	**Handling of external conditions**
Base variant	Reference ± tolerances	Site descriptive model version 1.2 (with variants/ uncertainties)	According to Process Reports	Reference climate (repetitions of Weichselian glacial cycle) No future human actions (FHA)
Greenhouse variant	Reference ± tolerances	Site descriptive model version 1.2 (with variants/ uncertainties)	According to Process Reports	Extended warm period No future human actions (FHA)
Additional scenarios based on potential loss of safety functions (“less probable” or “residual” based on outcome of analysis)				
Name	**Initial state EBS**	**Initial state Site**	**Process handling**	**Handling of external conditions**
Buffer advection	Scrutinise uncertainties of relevant initial state factors, internal processes and external conditions possibly leading to violation of safety function indicator under consideration. Analysis of main scenario used as starting point.			
Buffer freezing	See above			
Buffer transformation	See above			
	Consider each of above three buffer states + intact buffer when analysing below three canister scenarios.			
Canister failure due to isostatic load	Scrutinise uncertainties of relevant initial state factors, internal processes and external conditions possibly leading to violation of safety function indicator under consideration. Analysis of main scenario used as starting point.			
Canister failure due to shear movement	See above			
Canister failure due to corrosion	See above			
Scenarios related to future human actions				
Name	**Initial state EBS**	**Initial state Site**	**Process handling**	**Handling of external conditions**
Boring intrusion	As base variant of main scenario	As base variant of main scenario	As base variant of main scenario, except processes affected by boring	Reference climate + boring
Additional intrusion cases, e.g. nearby rock facility	As base variant of main scenario	As base variant of main scenario	As base variant of main scenario, except processes affected by intrusion	Reference climate + intrusion activity
Unsealed repository (not analysed in SR-Can)	As base variant of main scenario, but insufficient sealing	As base variant of main scenario	As base variant of main scenario, modified according to initial state	Reference climate

Main results and conclusions

The most important findings in the SR-Can project are summarised in subsections A, B and C below. A more detailed discussion on compliance with the regulatory risk limit is given in subsection D and additional results and conclusions are summarised in subsection E.

A. Compliance with the regulatory risk criterion

No canisters are assessed to fail during the initial temperate period, expected to last several thousand years

No canister failures are expected for either of the sites during the initial temperate period after deposition, estimated to last several thousand years. Furthermore, the evaluations of the canister sealing procedure undertaken so far, have led to the conclusion that all canisters will be tight at deposition.

A repository at Forsmark is assessed to comply with the regulatory risk criterion

The preliminary analyses carried out in SR-Can suggest that a KBS-3 repository at Forsmark will comply with the regulatory risk criterion issued by SSI.

Uncertainties in the hydrogeological interpretation and understanding of the Forsmark site are, however, considerable and, when propagated to various parts of the analyses, lead to a wide range of conclusions regarding e.g. buffer colloid release and water flow properties. A reduction of these uncertainties would allow more definite conclusions in future assessments. Even the most pessimistic interpretation of the Forsmark site is, however, assessed to comply with the regulatory risk criterion.

A repository at Laxemar is preliminarily assessed to comply with the regulatory risk criterion – but more representative data is required

The Laxemar site descriptive model version 1.2 is not sufficiently representative of the potential repository volume to allow definite conclusions regarding compliance. In particular, the hydraulic interpretation of the site is based on data partly obtained outside the candidate volume for the repository. Furthermore, recently obtained data indicate more favourable hydraulic properties than those on which the site model used in SR-Can is based.

However, it is noted that with the data used for Laxemar, the site is assessed to comply with the risk criterion and that use of more recent data would likely strengthen this conclusion.

B. Issues related to glacial conditions

In general, the most severe impact on the repository will occur during future glacial conditions. A number of conclusions regarding effects of such conditions can be drawn.

Freezing of an intact buffer is assessed as ruled out – even for very pessimistically chosen climate conditions

Freezing of an intact buffer is assessed as ruled out for both sites, even for the most pessimistic climate conditions considered. For a water-filled cavity in an eroded buffer, freezing is not entirely ruled out for the most pessimistically chosen climate development at Forsmark, but calculations demonstrate that the mechanical pressure on the canister is acceptable in such cases.

Canister failure due to isostatic load is assessed as ruled out – even for very pessimistically chosen climate conditions

Canister failure due to isostatic load is assessed as ruled out for both sites, also for the most severe future glacial conditions considered.

Oxygen penetration is preliminarily assessed as ruled out – even for very pessimistically chosen conditions

Oxygen penetration to repository depth for enhanced groundwater flows under an ice sheet, jeopardising the favourable reducing chemical conditions, is assessed as ruled out, based on the analyses carried out in SR-Can. This result is in agreement with conclusions from several earlier assessments. The modelling example is, however, stylised and simplified, meaning that additional analyses are warranted to increase confidence in the results. Such studies will be undertaken in SR-Site.

The risk contribution from earthquakes is assessed as small

Canister failures due to post-glacial earthquakes cannot be completely ruled out. The risk contribution from this failure mode is, however, small. The probabilistic analyses made imply that, on average, it would take considerably more than one million years for even one such canister failure to occur.

Loss of buffer may occur from exposure to glacial melt waters but the extent is uncertain – further studies are required

Substantial loss of buffer through buffer erosion/colloid release may occur as a result of intrusion of low ionic strength glacial melt waters in a 100,000 year perspective. The knowledge of the processes involved is uncertain and further research is being undertaken as a matter of priority. A status report will be given in SKB's RD&D programme 07 to be published in 2007.

Substantial loss of buffer may lead to canister failures in very long time perspectives

Loss of buffer mass, to the extent that advective conditions prevail in the buffer, which cannot be ruled out in a 100,000 year perspective, will lead to enhanced canister corrosion rates. In a one million year perspective, this may lead to failures of some tens of canisters for the pessimistic hydraulic interpretation of the Forsmark site, with cautious assumptions regarding sulphide concentrations and cautious assumptions regarding deposition hole acceptance rules.

A prolonged period of warm climate (increased greenhouse effect) before the next glacial period is assessed as primarily beneficial for repository safety

Since the processes that are potentially the most detrimental to repository safety are related to glacial conditions, a prolonged period of temperate climate is deemed as beneficial for safety. This concerns in particular the two main contributions to the calculated risk in SR-Can, namely i) potential buffer erosion with subsequent enhanced canister corrosion as a result of intrusion of glacial melt waters and ii) the occurrence of large earthquakes during deglaciation. Further evaluations of the geochemical evolution for a prolonged warm period are required in order to better substantiate the conclusion that the geochemical conditions would remain beneficial.

C. Other issues related to barrier performance and design

Crucial to avoid deposition positions intersected by large or highly water conductive fractures – further studies are required

The main risk contributors in SR-Can are related to the occurrence of large and/or highly transmissive fractures intersecting deposition holes. This applies to the buffer colloid release process and the impact of major earthquakes in the vicinity of the repository. These two phenomena are related to canister failures due to canister corrosion and to secondary rock shear movements, respectively. As also the retention in a large, highly transmissive fracture is small, such failures are in general associated with high consequences. Such fractures will be avoided when identified. The likelihood of occurrence of such fractures and the probability of unsuitable deposition holes remaining unidentified are, in many respects, uncertain and the results of the analysis are sensitive to these uncertainties. It is important to establish well-founded acceptance criteria for deposition holes as a basis for future assessments. This needs to be studied both by simulation of the effects of applying potential criteria and by exploring the practicability of applying the criteria.

The heat from the canister may fracture the rock in the deposition hole wall, which may enhance the in- and outward transport of dissolved substances – further studies are required

Thermally induced spalling around deposition holes may have a considerable impact on mass exchange between the flowing groundwater and the buffer as long as diffusion is the dominant transport mechanism in the buffer. If advective conditions prevail in the buffer, the effects of spalling are much less pronounced because it adds little to the already increased flow rate. There are uncertainties regarding the extent and the consequences of spalling and further studies are ongoing.

The importance of the backfilled deposition tunnels as a transport path for radionuclides is limited

The importance of the backfilled deposition tunnel as a transport path for radionuclides is limited in comparison with fractures intersecting a deposition hole. Also, deterioration of the deposition tunnel backfill material has limited consequences in terms of radionuclide releases from the near field.

The importance of the excavation damaged zone in the rock around the deposition tunnels as a transport path for radionuclides is limited

The importance of the excavation damaged zone (EDZ) around deposition tunnels is limited in comparison to other transport routes for radionuclides, even for very pessimistic assumptions about the EDZ in relation to the reference excavation method.

Cautious excavation methods are still recommended for the deposition tunnels, because competing transport routes may be assessed as less important with additional data and because the conclusion regarding the EDZ is based on simplified, stylised modelling.

D. Calculated individual risks

The calculated individual risks for repositories at Forsmark and Laxemar are presented in Figure 4. Note that temperate conditions are assumed for the biosphere, whereas it is expected that the sites will be submerged or covered by ice during a considerable part of the one million year assessment time, yielding negligible risks for these periods. Also, several pessimistic assumptions have been made in order to not underestimate the risk.

Compliance for the initial glacial cycle

For the initial glacial cycle, two risk contributions are identified: That from earthquakes and that from canister failures due to corrosion if the buffer has been eroded by glacial melt waters.

The probability of canister failures due to earthquakes for this period is very small and this probability is included in the risk estimate.

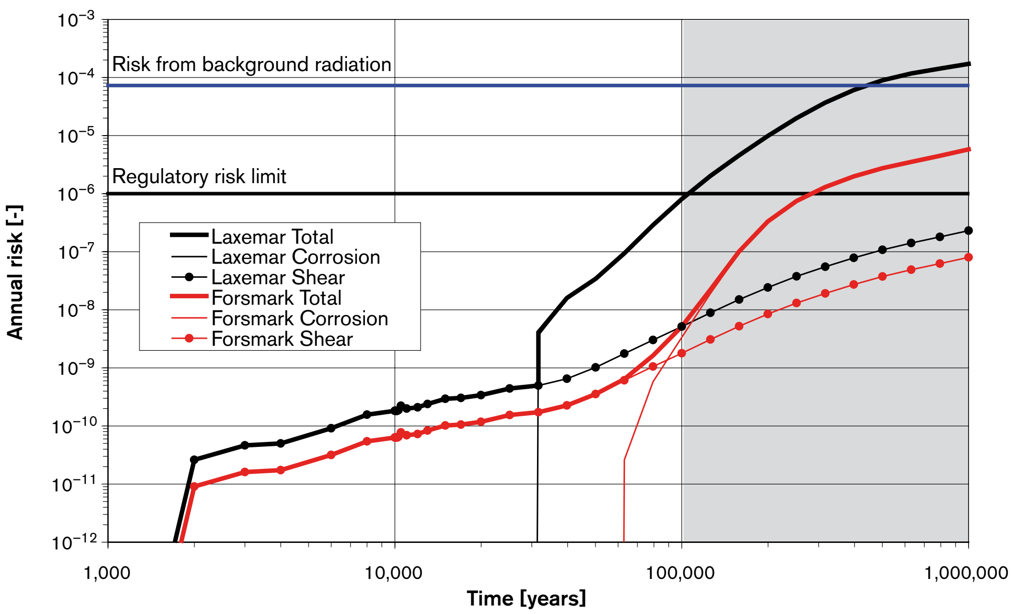


***Figure 4.** Risk summation for the two sites. Temperate conditions are assumed for the biosphere, whereas it is expected that the sites will be submerged or covered by ice during a considerable part of the one million year assessment period, yielding negligible doses. Several other uncertainties are handled pessimistically.*

As concerns failures due to corrosion, a few canisters are calculated to fail during the initial glacial cycle at both sites. The total calculated risk up to 100,000 years is at most, i.e. after 100,000 years, close to the regulatory risk limit at Laxemar and about two orders of magnitude below at Forsmark. The risk is pessimistically based on that calculated for the canister corrosion scenario, where several uncertainties are handled pessimistically, due to insufficient understanding of groundwater flow and composition for glacial conditions and of the response of the buffer to glacial groundwaters. The risk calculated for Forsmark is based on a pessimistic interpretation of the current hydraulic situation. As also pointed out previously, the representativity of the Laxemar hydrogeological model is questionable. More recent site data from the candidate repository area indicate that the hydrogeological conditions are more favourable than those adopted in the model used in SR-Can. This would reduce the risk contribution from canister failures due to corrosion.

It is, thus, concluded that the calculated risks for the two sites comply with the regulatory requirements during the initial glacial cycle after closure.

Repository performance for the time beyond the initial glacial cycle

The same canister failure modes as for the initial glacial cycle contribute to individual risk during the period after the initial glacial cycle up to one million years after closure.

For Forsmark, the calculated risk contribution from earthquakes is more than one order of magnitude below the regulatory limit throughout the assessment period, whereas the contribution from corrosion failures is above the regulatory limit at the end of the one million year period.

For Laxemar, the contribution from earthquakes is similar to that for Forsmark, whereas that from corrosion failures exceeds the risk limit by about two orders of magnitude at the end of the assessment period.

As stated in SSI's general guidance, "*a strict quantitative comparison of calculated risk in relation to the criterion for individual risk in the regulations is not meaningful*" for this time period. Rather, the results are used as a basis for discussing how pessimistically handled uncertainties can be reduced and how the protective capability of the repository can be improved as suggested by the general guidance.

It is important to note that the calculated risks, although exceeding the risk limit applicable for the initial 100,000 years, are considerably less than those due to the background radiation throughout the assessment period for Forsmark. For Laxemar, they are well below the background radiation for several hundred thousand years and become comparable to the background radiation only at the end of the one million year assessment period. Furthermore, as for the initial glacial cycle, a number of issues have been treated pessimistically and further knowledge may lead to a substantial reduction of these risk estimates in future assessments.

It is, thus, concluded that calculated risks for the time beyond the initial glacial cycle fulfil the regulatory requirements for this time period.

E. Additional results and conclusions

A number of additional results have been obtained on which conclusions are drawn from the SR-Can assessment:

- A first evaluation of effects on the environment from release of radionuclides has been made. Most radionuclides fall below screening limits, meaning that no additional analyses are required. A few nuclides in the most pessimistic calculation cases exceed the screening limits at the end of the assessment period, requiring more detailed assessments.
- Two alternative safety indicators have been used as a complement to the risk indicator; release constraints issued by the Finnish regulator STUK and contents of naturally occurring radionuclides in the environment at the repository sites.
- A first account is made of the aspects of Best Available Technique, BAT, that can be addressed based on the results of the safety assessment.
- A number of bounding cases, assuming fictitious complete loss of one or several barrier functions have been analysed. The results indicate that the calculated doses are below the natural background radiation also for very severe losses of safety functions. For example, an initial total loss of the

canister and buffer in all deposition holes yields, for a repository at the Forsmark site, doses that are comparable to those caused by the background radiation. The bounding analyses demonstrate the multi-barrier character of the KBS-3 system.

- A set of design basis cases have been derived. These are to be used as one of several inputs to substantiate the design basis for the repository which includes the establishment of requirements on barrier properties.
- Detailed feedback is provided to canister design and fabrication, to repository design, to further site investigations and site modelling, to SKB's RD&D programme and to the next safety assessment, SR-Site.

Contents of this report

Following the introductory Chapter 1, this report outlines the methodology for the SR-Can assessment in Chapter 2, and presents in Chapter 3 the handling of features, events and processes, FEPs, of importance for long-term safety. Chapters 4, 5 and 6 present the initial state of the system for both of the sites, and the plans and methods for handling external influences and internal processes, respectively. Safety functions and safety function indicators are discussed in Chapter 7. The collection of input data for the assessment is described in Chapter 8. The material presented in the first eight chapters is utilised in the analysis of the reference evolution in Chapter 9, focussing on isolation, and Chapter 10, addressing radionuclide transport and dose assessments. Scenarios for the further evaluation of safety are selected in Chapter 11 and the selected scenarios are analysed in Chapter 12. Finally, conclusions and feedback are provided in Chapter 13. References are provided in Chapter 14. Appendix A is an account of how applicable regulations are addressed in the assessment. Miscellaneous calculation models are presented in Appendix B and material relating to reviews of previous assessments in Appendix C. A glossary of abbreviations and specialised terms used in SR-Can is found in Appendix D.

Sammanfattning

Inledning

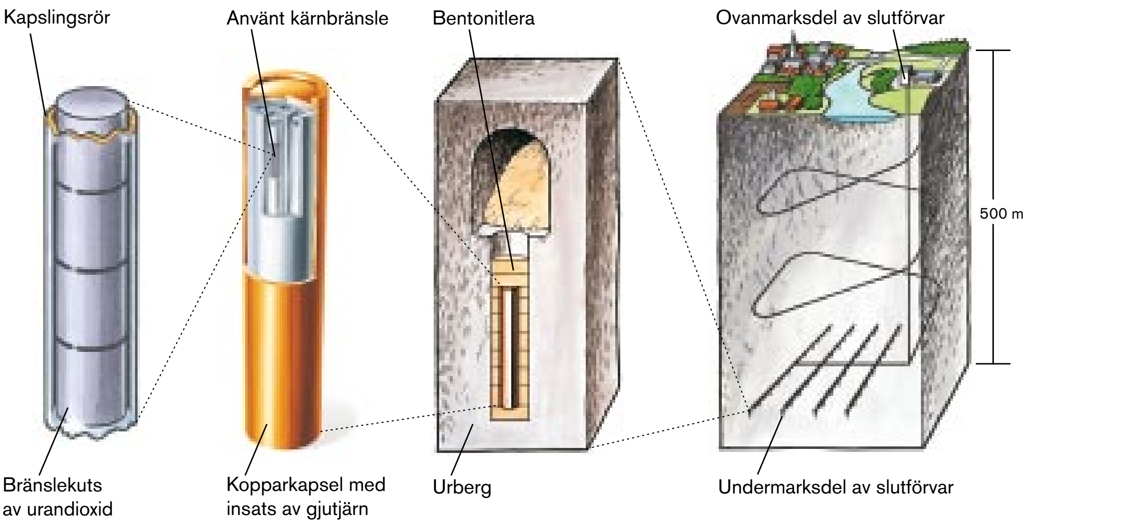
Detta dokument är huvudrapporten från säkerhetsanalysen SR-Can. SR-Can-projektet är ett förberedande steg inför SR-Site-analysen, som ska ligga till grund för SKB:s ansökan om att bygga ett slutförvar. Säkerhetsanalysen SR-Can har följande syften:

1. Att preliminärt bedöma säkerheten för KBS-3-förvar vid Forsmark och Laxemar med kapslar enligt ansökan för Inkapslingsanläggningen.
2. Att ge återkoppling till kapselutveckling, till anläggningsutformning för slutförvaret, till fortsatta platsundersökningar, till SKB:s program för forskning kring frågor av betydelse för långsiktig säkerhet samt till kommande säkerhetsanalyser samt
3. Att bereda SKI och SSI tillfälle att granska SKB:s preliminära säkerhetsredovisning inför tillämpningen i ansökan om att uppföra ett slutförvar för använt kärnbränsle.

Analysen gäller slutförvarsmetoden KBS-3, där kopparkapslar med en gjutjärnsinsats innehållande använt kärnbränsle deponeras på cirka 500 m djup i granitiskt berg och omges av bentonitlera, se figur 1. I analysen används preliminära data från platserna Forsmark och Laxemar, som SKB för närvarande undersöker som kandidatplatser för ett KBS-3-förvar.

Ett viktigt syfte med denna rapport är att visa hur kraven på säkerhetsanalys i gällande föreskrifter hanteras. Därför återges de föreskrifter som har utfärdats av Kärnkraftsinspektionen (SKIFS 2002:1) och Strålskyddsinstitutet (SSI FS 1998:1) i en bilaga där referenser ges till de kapitel i huvudtexten där hanteringen av olika krav demonstreras. Det huvudsakliga acceptanskriteriet kräver att ”den årliga risken för skadeverkningar efter förslutning blir högst 10^{-6} för en representativ individ i den grupp som utsätts för den största risken”. Med ”skadeverkningar” avses cancer och ärftliga skador. Riskgränsen motsvarar en effektiv dosgräns på cirka $1{,}4 \cdot 10^{-5}$ Sv/år, dvs cirka en procent av den naturliga bakgrundsstrålningen i Sverige.

Tidsperspektivet för analysen är en miljon år efter förslutning av förvaret, i enlighet med myndighetskrav. Ovannämnda riskgräns gäller enligt SSI som en kvantitativ gräns under de första cirka etthundratusen åren, och därefter som ett underlag för diskussion om slutförvarets skyddsförmåga.



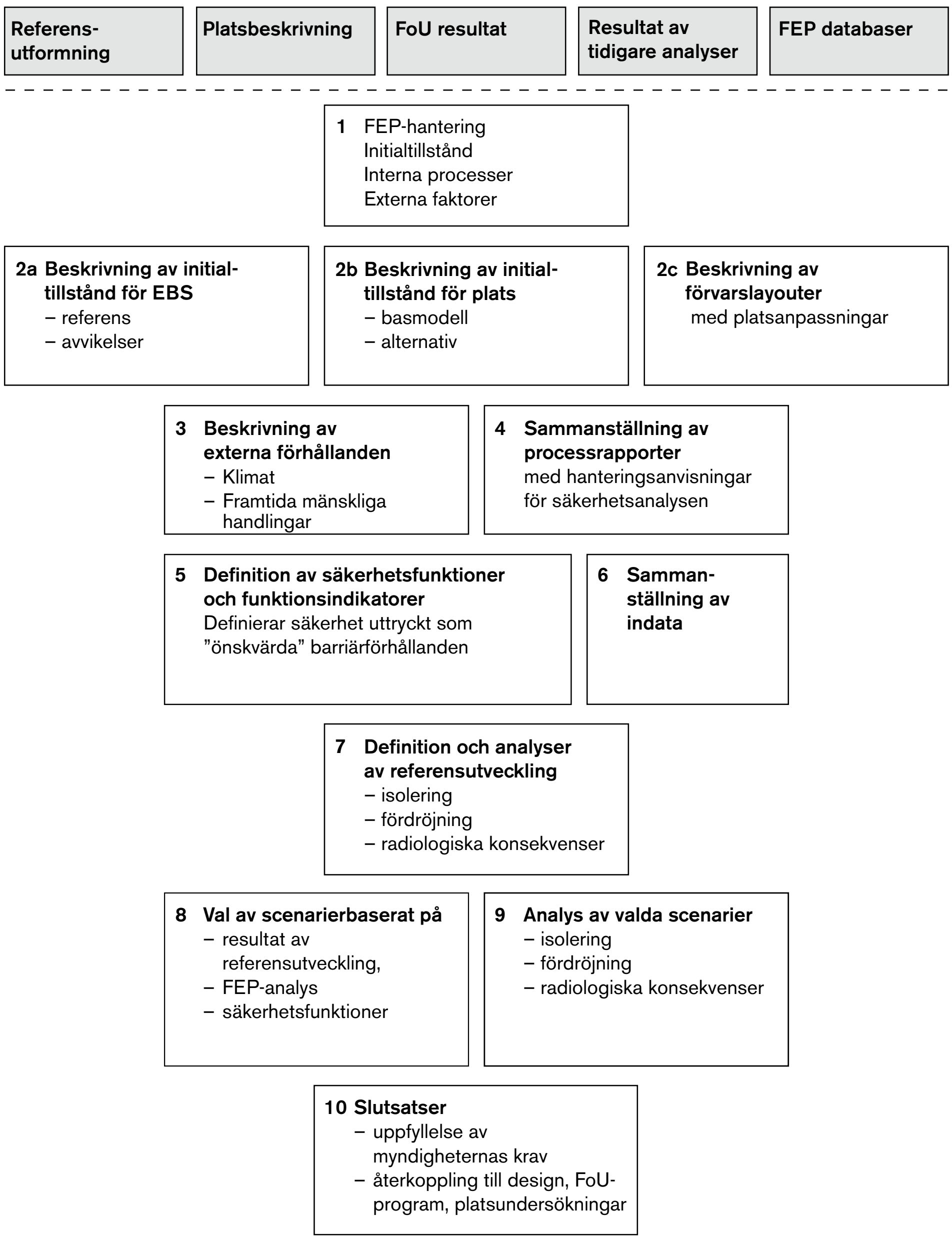
Figur 1. *KBS-3-metoden för slutförvaring av använt kärnbränsle.*

Metodik

Förvarssystemet, brett definierat som det deponerade använda kärnbränslet, de tillverkade barriärerna kring det, förvarsberget och biosfären i anslutning till slutförvaret, kommer att utvecklas över tiden. Systemets framtida tillstånd kommer att bero på:

- systemets initialtillstånd,
- ett antal termiska, hydrauliska, mekaniska och kemiska processer som verkar internt i förvarssystemet över tiden,
- extern påverkan på systemet.

En metodik i tio steg har utvecklats för SR-Can. Den sammanfattas i figur 2. Dessa steg utförs delvis parallellt, delvis konsekutivt.



Figur 2. *Översikt av de tio huvudstegen i säkerhetsanalysen SR-Can. Rutorna ovanför den streckade linjen visar indata till analysen.*

De tio stegen beskrivs närmare nedan.

1. Identifiering av faktorer att beakta (FEP-hantering)

   Detta steg består av att identifiera alla faktorer som ska ingå i analysen. Erfarenhet från tidigare säkerhetsanalyser används, tillsammans med KBS-3-specifika och internationella databaser över relevanta egenskaper, händelser och processer (eng. features, events and processes, FEP) som påverkar den långsiktiga säkerheten. En FEP-databas har utvecklats för SR-Can. I denna klassificeras de allra flesta FEP som relaterade till initialtillståndet, till interna processer eller till externa faktorer. Återstående FEP är antingen relaterade till analysmetodiken i allmänhet, eller bedömda som irrelevanta för KBS-3-metoden. Utgående från resultaten av FEP-hanteringen har en FEP-katalog för SR-Can upprättats, med FEP som ska behandlas i SR-Can. Detta steg i FEP-hanteringen beskrivs ytterligare i kapitel 3 och dokumenteras fullständigt i **FEP-rapporten**[1] i SR-Can.

2. Beskrivning av initialtillståndet

   Systemets initialtillstånd beskrivs utgående från specifikationerna för KBS-3-förvaret, en beskrivande modell av platsen för slutförvaret och en platsspecifik layout av förvaret. Initialtillståndet för bränslet och de tillverkade komponenterna avser förhållandena omedelbart efter deponering, så som beskrivs i **Initialtillståndsrapporten**. Initialtillståndet för geosfären och biosfären avser de naturliga förhållandena innan brytningsarbetet inleds, enligt de platsbeskrivande modellerna för platserna Forsmark /SKB 2005c/ och Laxemar /SKB 2006b/. Förvarslayouter, anpassade till platserna, ges i /Brantberger et al. 2006/ och /Janson et al. 2006/ för Forsmark respektive Laxemar. Se vidare kapitel 4.

3. Beskrivning av externa förhållanden

   Faktorer relaterade till externa förhållanden delas in i de tre kategorierna ”klimatrelaterade frågor”, ”storskaliga geologiska processer och effekter” samt ”framtida mänskliga handlingar”. Hanteringen av dessa faktorer beskrivs i **Klimatrapporten, Geosfärprocessrapporten**, respektive **FHA-rapporten**. Se vidare kapitel 5.

4. Beskrivning av processer

   Identifieringen av relevanta processer bygger på tidigare analyser och FEP-hantering. Alla identifierade processorer inom systemgränsen som är relevanta för den långsiktiga utvecklingen av systemet beskrivs i särskilda **processrapporter**. Kortsiktiga geosfärprocesser/ändringar på grund av brytning beskrivs också i dessa processrapporter och beaktas i analysen. För varje process dokumenteras dess generella egenskaper, under vilken tidsperiod den har betydelse, vilka andra processer den är kopplad till och hur processen ska hanteras i säkerhetsanalysen. Se vidare kapitel 6.

5. Definition av säkerhetsfunktioner, säkerhetsfunktionsindikatorer och kriterier för säkerhetsfunktionsindikatorer

   Detta steg består av en redogörelse för systemets säkerhetsfunktioner och av hur dessa kan utvärderas med hjälp av en uppsättning säkerhetsfunktionsindikatorer som i princip utgörs av mätbara eller beräkningsbara egenskaper hos systemet. Kriterier ges för säkerhetsfunktionsindikatorerna. Processrapporterna är viktiga referensdokument för detta steg. Ett FEP-diagram tas fram som visar hur FEP förhåller sig till säkerhetsfunktionsindikatorer. Genomförande och resultat av detta steg beskrivs i kapitel 7.

6. Sammanställning av indata

   En strukturerad procedur används för att välja data till kvantifieringen av slutförvarets utveckling och i dosberäkningar. Urvalsprocessen och valda datavärden beskrivs i en särskild **Datarapport**. En flexibel mall för diskussion av osäkerheter i indata har utvecklats och tillämpats. Se även kapitel 8.

7. Definition och analys av referensutveckling

   En referensutveckling, som beskriver en tänkbar utveckling av förvarssystemet, definieras och analyseras. Systemets isoleringsförmåga över tiden analyseras i ett första steg. Denna analys beskriver den allmänna utvecklingen av systemet och en utvärdering av säkerhetsfunktionsindikatorerna görs. Om utvecklingen leder till att isoleringen bryts analyseras den fördröjande potentialen hos slutförvaret och dess omgivning och doskonsekvenser beräknas för de långsiktiga

[1] **FEP-rapporten** är en av flera **huvudreferenser** till SR-Can. Avsnitt 2.2.1 innehåller en fullständig lista över huvudreferenserna och förklarar nomenklaturen som används för dessa rapporter.

förhållandena som identifieras i det första steget. Vissa typer av kapselbrott som inte inträffar i referensutvecklingen analyseras för att ytterligare klargöra systemets fördröjningsegenskaper. Varje process hanteras i enlighet med de planer som beskrivs i processrapporterna. Se även kapitel 9 för en analys av den allmänna utvecklingen och isoleringsförmågan, samt kapitel 10 för en analys av fördröjningsförmågan.

8. Val av scenarier

   En uppsättning scenarier väljs för analys. Ett omfattande huvudscenario definieras i enlighet med SKI:s föreskrifter SKIFS 2002:1. Huvudscenariot liknar referensutvecklingen som analyserades i steg 7. Valet av ytterligare scenarier bygger på säkerhetsfunktionerna i förvaret. Säkerhetsfunktions indikatorerna som definierades i steg 4 är en viktig utgångspunkt för valet. För varje säkerhetsfunktion analyseras om det rimligen skulle kunna uppstå en situation där funktionen inte upprätthålls. Om så är fallet får motsvarande scenario ingår i riskvärderingen för slutförvaret. Den totala risken fastställs genom summering över sådana scenarier. I uppsättningen valda scenarier ingår även t ex scenarier som nämns explicit i tillämpliga föreskrifter, som mänskligt intrång, liksom scenarier och varianter som har till syfte att undersöka konstruktionsmässiga frågor och olika komponenters roller i förvaret. Se vidare kapitel 11 för en beskrivning av metodiken för scenarioval och tillämpning av urvalsmetoden.

9. Analys av valda scenarier

   Huvudscenariot analyseras i första hand genom hänvisning till referensutvecklingen i steg 7. Ett viktigt resultat är ett beräknat riskbidrag från huvudscenariot. Ytterligare scenarier analyseras genom att man fokuserar på faktorer som potentiellt kan leda till situationer där säkerhetsfunktionen i fråga inte upprätthålls. I de flesta fall utförs dessa analyser genom jämförelse med utvecklingen för huvudscenariot. Analyserna innefattar alltså endast de aspekter på förvarets utveckling där scenariot i fråga avviker från huvudscenariot. För dessa scenarier, liksom för huvudscenariot, uppskattas ett riskbidrag. Se vidare kapitel 12.

10. Slutsatser

    Detta steg innefattar sammanställning av resultat från de olika scenarioanalyserna, slutsatser med avseende på säkerhet i relation till myndighetskriterier och återkoppling med avseende på förvarsutformning, fortsatta platsundersökningar och SKB:s FUD-program. Se vidare kapitel 13.

Platserna och förvarslayouterna

Från platsdata till SR-Can

Informationsöverföringen från fältundersökning till tillämpning i säkerhetsanalysen omfattar flera steg. *Fältdata* hämtas från olika undersökningsverksamheter, som flygspanings- och markbaserad geofysik, provborrningar och borrhålsundersökningar. Data kvalitetskontrolleras och matas in i SKB:s platsdatabas, Sicada. Fältdata tolkas och utvärderas i en integrerad och tvärvetenskaplig *platsbeskrivningsmodell* (SDM – Site Descriptive Model) som utgör en syntes av geologi, bergmekanik, termiska egenskaper, hydrogeologi, hydrogeokemi, transportegenskaper i berget och egenskaper hos ytsystemet. Modellerna dokumenteras i SDM-rapporter. Platsdata som används i SR-Can värderas i en **datarapport** med SDM version 1.2 som indata. Datarapporten beskriver även hur icke platsspecifik information har beaktats. I den rapporten och gör bedömningar baserade på hur data kommer att användas i SR-Can och hur osäkerheterna som identifieras i SDM hanteras. Det slutliga valet av indata till modellen rapporteras.

Forsmark

Kandidatplatsen Forsmark ligger i norra Uppland, i Östhammars kommun. Landskapet kring Forsmark utgörs av en relativt plan urbergsplatå som sluttar svagt mot öster. Hela området ligger under högsta kustlinjen från den senaste avsmältningen av inlandsis. Dagens landskap är starkt påverkat av den vertikala landhöjningen på cirka 6 mm per år.

Urberget kring Forsmark har påverkats av både duktil och spröd deformation. Den duktila deformationen har medfört stora duktila områden med hög spänning, men kandidatområdet befinner sig inom en tektonisk lins mellan duktila zoner med hög spänning. Urberget inom linsen är förhållandevis homogent och domineras av metagranit med hög halt av kvarts. Litologin och deformationen är mera komplex utanför linsen. Ingen potential för fyndigheter av metaller eller industrimineraler har konstaterats i kandidatområdet. På grund av sin relativt höga kvartshalt karakteriseras berget av hög termisk konduktivitet och hög mekanisk hållfasthet i jämförelse med typiska bergsförhållanden i Sverige.

Tre större uppsättningar deformationszoner med tydliga orienteringar har konstaterats. Förutom vertikala och brant lutande zoner finns zoner som lutar svagt åt sydost och syd. Dessa svagt lutande zoner förekommer mera i den sydöstra delen av kandidatområdet och de har högre hydraulisk transmissivitet än de vertikala och brant lutande deformationszonerna vid platsen. De förefaller spela en viktig roll för att fastställa egenskaperna för platsen vad gäller spänningsfördelning, sprickbildning och transmissivitetsfördelningen hos sprickor. Frekvensen av öppna och partiellt öppna sprickor är mycket låg under cirka 300 m djup, jämfört med vad som observerats i den övre delen av urberget i den nordvästra delen av kandidatvolymen. Det senare området är målvolym för ett potentiellt förvar vid platsen. Dessutom är spänningarna i berget stora i jämförelse med typiska värden för svensk berggrund, möjligen kopplat till den låga förekomsten av sprickor i denna del av berggrunden. Den övre del av berggrunden med större förekomst av sprickor, som ligger ovanför målvolymen, uppvisar hög transmissivitet i horisontalplanet och ger god hydraulisk kontakt över långa avstånd, medan den djupare berggrunden förefaller ha mycket låg permeabilitet med få transmissiva sprickor. Det finns meteoriskt vatten i det översta cirka 200 m tjocka skiktet av berggrunden. På djup mellan 200 och 800 m är salthalten tämligen konstant (5 000–6 000 mg/l) och vattensammansättningen uppvisar spår från Littorinahavets vatten. På djup mellan 800 och 1 000 m ökar salthalten.

Laxemar

Platsen Laxemar är en del av kandidatområdet Simpevarp i Oskarshamns kommun. Topografin är relativt flack. Hela området ligger under den högsta kustlinjen från den senaste avsmältningen av inlandsis. Det pågår fortfarande en vertikal landhöjning på cirka 1 mm per år.

Områdets norra och centrala delar domineras av Ävrögranit, medan det i den södra delen finns bergsområden som huvudsakligen består av kvartsmonzodiorit och diorit till gabbro. Denna formation bildar en båge som lutar mot norr och vars konkava sida är riktad mot norr. Ingen potential för fyndigheter av metaller eller industrimineraler har konstaterats i området. Många av bergstyperna i delområdet Laxemar har låg och rumsligt varierande kvartshalt. Detta ger upphov till låg och varierande termisk konduktivitet, i jämförelse med typiska värden för svensk berggrund. Medelvärdet för enaxlig kompressionshållfasthet är relativt lågt i de flesta typerna av berggrund, och spridningen är relativt stor. Emellertid baseras dessa resultat på data från ett fåtal prov och de kan vara påverkade av närheten till en större deformationszon.

Deformationszonerna löper i huvudsak i nord-sydlig och öst-västlig riktning. Bedömningen är att de flesta lokala större och brant lutande zonerna har identifierats och att det inte förekommer några svagt lutande regionala zoner inom det lokala modellområdet. Emellertid kvarstår osäkerheter på detaljnivå. Sprickbildningen är mycket variabel och beskrivningen av spricknätverket är osäker. Både mätdata och resultat från spänningsmodellering visar att delområdet Laxemar kan delas in i två olika spänningsområden (I och II), där spänningsområde II uppvisar lägre spänning. Den begränsade tillgången på data för Laxemar vid tiden då data frystes för denna rapport antyder att bergsvolymen skulle kunna delas in i hydrauliska områden med olika och djupberoende hydrauliska egenskaper. Nya data som har kommit fram efter att data frystes ger starkt stöd för ovannämnda indikationer om att den hydrauliska konduktiviteten är beroende av djupet och att bergsområdena i södra Laxemar har lägre konduktiviteter än de i norra Laxemar.

Grundvattnets komplexa utveckling och mönster vid delområdet Laxemar beror både på tidigare utveckling av grundvattenflöde och förändringar av grundvattensammansättningen orsakad av mikrobiella processer och interaktion mellan vatten och berg. I delområdet Laxemar finns sött (meteoriskt) vatten ner till ett djup av 800 m, medan gränsen är mycket grundare i delområdet Simpevarp som ligger närmare havet. Bräckt vatten förekommer på mellanliggande djup (500–950 m). På större djup (900–1 200 m) blir vattnet salt (6 000–20 000 mg/l Cl, 25–30 g/l TDS). Vatten med hög salthalt (> 20 000 mg/l Cl, max TDS ~ 70 g/l) har bara hittats på djup större än 1 200 m.

Även om version 1.2 av den platsbeskrivande modellen för Laxemar bygger på en stor mängd data är bara ett fåtal mätningar representativa för den/de potentiella förvarsvolymen/-volymerna. Detta är särskilt tydligt då det gäller data om sprickor samt termiska och hydrauliska data. Data som samlats in efter att data frysts, liksom data som ska samlas in framgent kommer att tillåta en utförligare uppsättning analyser (liknande den för Forsmark) även för Laxemar. Inom SR-Can har en mer begränsad uppsättning analyser för platsen Laxemar genomförts.

Förvarslayouter

Preliminära förvarslayouter, baserade på platsbeskrivningarna, har tagits fram för de båda platserna. Layouterna avser ett slutförvar för 6 000 kapslar. Vid Forsmark har referenslayouten, som analyseras i SR-Can, tagits fram för nivån –400 m. Vid Laxemar har referenslayouten tagits fram för nivån –500 m.

För att undvika skadlig inverkan från potentiella framtida jordskalv tillämpas ett säkerhetsavstånd till deformationszoner med längd överstigande 3 km. För zoner kortare än 3 km tillämpas ett säkerhetsavstånd som understiger 100 m. Ett minsta tillåtet avstånd mellan kapslarna fastställs utgående från termiska egenskaper. En nyttjandegrad uppskattas genom att man beaktar den mekaniska stabiliteten, sannolikheten för att ett deponeringshål kommer att skära sprickor eller deformationszoner med radie R > 75 m, och inflöde av vatten till tunnlar och deponeringshål. Här utnyttjar man kriterier som definieras i fastställda konstruktionsförutsättningar. Nyttjandegraden påverkar förvarets storlek i layouten. Förvaret ska alltså göras stort nog för 6 000 acceptabla kapselpositioner. Vid Forsmark är nyttjandegraden 89 % i layouten och vid Laxemar baseras konstruktionen på nyttjandegraden 80 %.

De kriterier för val av kapselplacering som tillämpas i konstruktionen är preliminära. SR-Can har därför undersökt betydelsen av sådana kriterier. Det så kallade FPC-kriteriet (FPC – full perimeter intersection criterion) anger att om en spricka observeras runt en deponeringstunnels hela omkrets får inget deponeringshål placeras så att det skulle skära den antagna förlängningen av sprickan. Utvärdering av detta kriterium har påvisat dess goda förmåga att minska antalet deponeringshål som skärs av stora sprickor, till priset av obetydligt ökad total längd hos deponeringstunnlarna. Man antar därför i SR-Can att FPC-regeln har använts i layouterna för de båda platserna. Det är sannolikt att praktiska kriterier med avseende på flödesförhållanden skulle komma att relatera till resultaten av hydrauliska test – observationer av inflöden till deponeringstunnlar eller deponeringshål. Emellertid har inte de praktiska aspekterna eller effektiviteten hos sådana kriterier ännu analyserats av SKB, och SR-Can gör endast en första analys av den potentiella betydelsen hos flödesrelaterade acceptanskriterier.

Säkerhet

Utvecklingen av KBS-3-konceptet har styrts av ett antal *säkerhetsprinciper*. Den långsiktiga funktionen hos förvaret kan uttryckas genom att studera en uppsättning *säkerhetsfunktioner* som helst ska upprätthållas under den period på en miljon år som täcks av analysen. Säkerhetsprinciperna och användningen av säkerhetsfunktioner i SR-Can sammanfattas nedan.

Säkerhetsprinciper

Sedan arbetet med det svenska slutförvarsprojektet inleddes i slutet av 1970-talet har SKB etablerat en rad principer för utformningen av ett slutförvar. Dessa principer kan sägas utgöra säkerhetsfilosofin bakom KBS-3-metoden. De sammanfattas nedan.

- Genom att placera slutförvaret på stort djup i en långsiktigt stabil geologisk miljö, kommer avfallet att isoleras från människor och ytnära miljö. Det betyder att förvaret inte påverkas i högre grad av vare sig samhälleliga förändringar eller av direkta effekter av långsiktiga klimatförändring på jordens yta.
- Genom att placera slutförvaret på en plats där förvarsberget kan antas ha litet ekonomiskt intresse för framtida generationer minskar risken för mänskligt intrång.
- Det använda kärnbränslet omges av flera tillverkade och naturliga säkerhetsbarriärer.
- Barriärernas primära säkerhetsfunktion är att isolera bränslet.
- Om isoleringen skulle brytas är barriärernas sekundära säkerhetsfunktion att fördröja ett eventuellt utsläpp från förvaret.
- Tillverkade barriärer ska bestå av naturligt förekommande material som är långsiktigt stabila i förvarsmiljön. De långsiktiga materialegenskaperna ska kunna verifieras.
- Förvaret ska utformas så att höga temperaturer som kan ha betydande skadlig effekt på barriärernas egenskaper på lång sikt undviks.
- Barriärerna ska vara passiva, dvs de ska fungera utan mänskliga ingrepp och utan aktiv tillförsel av material eller energi.

Tillsammans med många andra aspekter, som ramarna som ges av Sveriges geologiska miljö och kravet att förvaret måste vara tekniskt möjligt att bygga, har dessa principer lett fram till KBS-3-systemet för slutförvaring av använt kärnbränsle.

Säkerhetsfunktioner

De viktigaste säkerhetsrelaterade egenskaperna för KBS-3-förvaret kan sammanfattas i säkerhetsfunktionerna isolering och fördröjning.

För en detaljerad och kvantitativ förståelse och utvärdering av förvarets säkerhet krävs en fullständig beskrivning av hur de huvudsakliga säkerhetsfunktionerna isolering och fördröjning uppnås av komponenterna i förvaret. Utgående från förståelsen av komponenternas egenskaper och den långsiktiga utvecklingen av systemet kan ett antal säkerhetsfunktioner identifieras som är underordnade isolering och fördröjning. Följande definitioner används:

- En säkerhetsfunktion är den roll som en förvarskomponent har för att bidra till säkerheten.
- En säkerhetsfunktionsindikator är en mätbar eller beräkningsbar egenskap hos en komponent i ett förvar som anger i vilken utsträckning en säkerhetsfunktion är uppfylld.
- Ett kriterium för en säkerhetsfunktionsindikator är en kvantitativ gräns. Om funktionsindikatorn uppfyller kriteriet är motsvarande säkerhetsfunktion uppfylld.

En översikt över säkerhetsfunktioner, deras indikatorer och kriterier ges i figur 3.

Säkerhetsfunktioner bidrar till säkerhetsbedömningen, men uppfyllelse av alla kriterier för säkerhetsfunktionsindikatorer är varken nödvändigt eller tillräckligt för att fastställa att förvaret är säkert. De olika kriterierna för säkerhetsfunktionsindikatorer anges dessutom med olika acceptansmarginaler.

Säkerhetsfunktioner är relaterade till, men inte identiska med, konstruktionkriterier. Medan konstruktionskriterier hänför sig till förvarets initialtillstånd och i första hand till dess tillverkade komponenter, ska säkerhetsfunktioner vara uppfyllda under hela analysperioden och hänför sig till såväl tillverkade komponenter som det naturliga systemet.

Förvarets referensutveckling

En referensutveckling för ett KBS-3-förvar vid platserna Forsmark och Laxemar, som täcker hela analysperioden på en miljon år, studeras för att förstå systemutvecklingen i stort och för att ge underlag för scenarieval och scenarieanalyser. Målet är att beskriva en rimlig utveckling av förvarssystemet över tid.

Två varianter av referensutveckling analyseras:

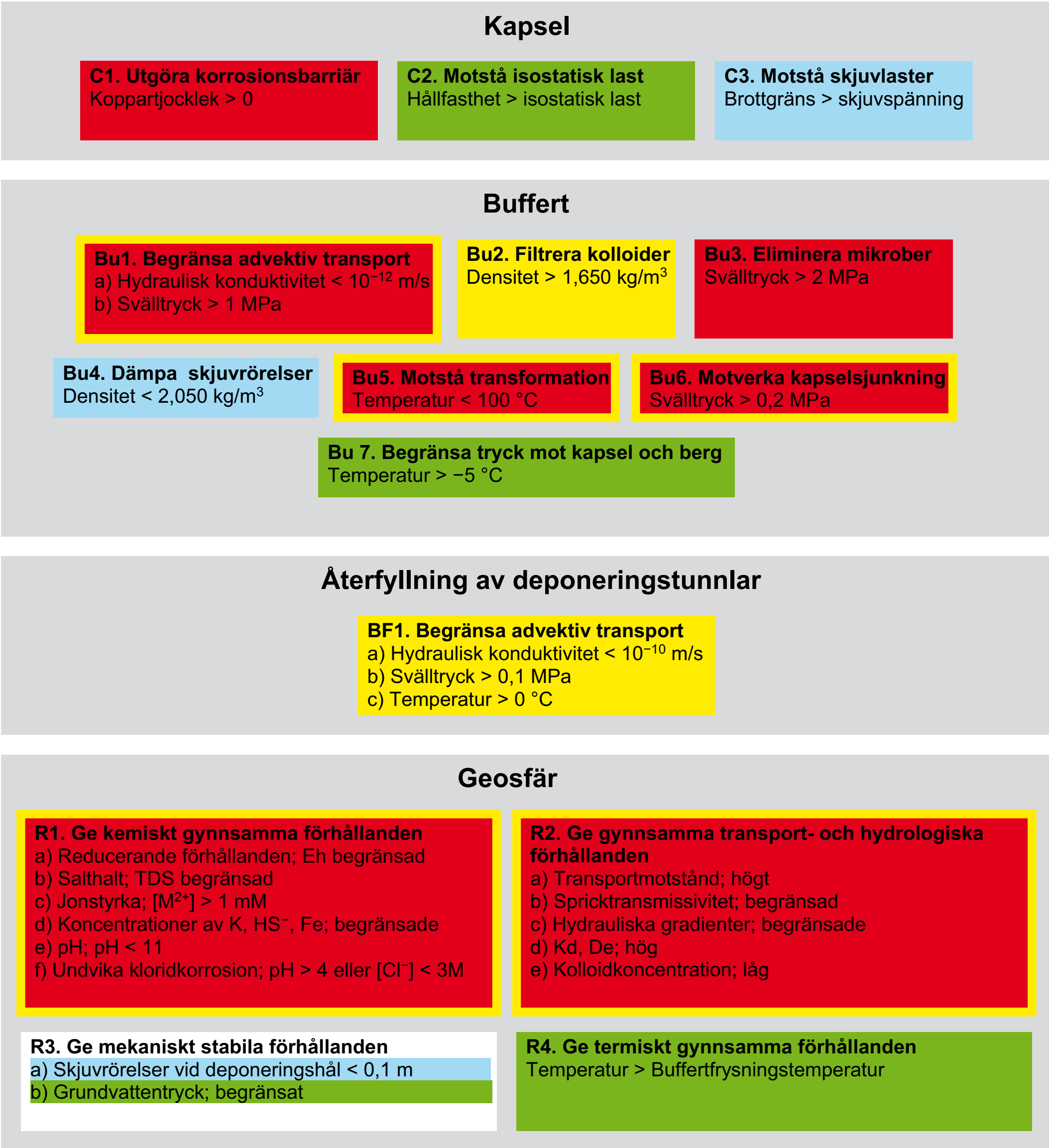
- En basvariant där de externa förhållandena under den första glaciationscykeln på 120 000 år antas likna dem som rådde under den senaste glaciationscykeln, weichselistiden. Därefter antas sju upprepningar av samma glaciationscykel täcka hela analysperioden på en miljon år.
- En växthusvariant där det framtida klimatet och följaktligen de externa förhållandena antas starkt påverkade av antropogena utsläpp av växthusgaser.

Analysen genomförs i fyra tidsepoker. Inom varje epok utvärderas ovannämnda säkerhetsfunktioner.

Byggnads- och driftsfasen

Analyserna av förvarets byggnads- och driftsfaser, som förväntas pågå under flera decennier, inriktar sig främst på störningar av mekaniska, hydrologiska och kemiska förhållanden på grund av byggnad och drift av förvaret. Bland frågor av potentiell betydelse för den långsiktiga säkerheten kan nämnas:

- Bildningen av en sprängskadad zon (EDZ – excavation damaged zone) kring deponeringshål och framför allt kring deponeringstunnlar, som försämrar bergets retentionsegenskaper relaterade till säkerhetsfunktionerna R2a och R2b i figur 3.
- Kanalbildning i bufferten, dvs bildning av hydrauliskt ledande kanaler omedelbart efter deponering på grund av de höga grundvattentryckgradienterna i det öppna förvaret. Kanalbildningen kan i sin tur medföra erosion av den deponerade bufferten, när vatten strömmar genom kanalerna. Detta är kopplat till säkerhetsfunktionen Bu1 i figur 3.



Figur 3. *Säkerhetsfunktioner (fetstil), säkerhetsfunktionsindikatorer och kriterier för säkerhetsfunktionsindikatorer. Om kvantitativa kriterier inte kan ges används i stället termer som "hög", "låg" och "begränsad" för att ange gynnsamma värden för funktionsindikatorerna. Färgkodningen visar hur funktionerna bidrar till kapselns säkerhetsfunktioner C1 (röd), C2 (grön), C3 (blå) eller till fördröjning (gul). Många funktioner bidrar till både C1 och fördröjning (röd ruta med gul kant).*

Den första tempererade perioden

Denna period förväntas vara i flera tusen år. Förvarsberget och de återfyllda tunnlarna förväntas bli vattenmättade och den efterföljande utvecklingen av geosfären karakteriseras av återgång till det naturliga, ostörda tillståndet före brytning. Analysen av denna period innefattar termisk, hydrogeologisk, mekanisk och kemisk modellering.

En viktig säkerhetsrelaterad fråga med långsiktiga konsekvenser är sprickbildning, s k termisk spjälkning, av berget kring deponeringshålen, orsakad av spänningar från värmeutvecklingen i det deponerade avfallet. Detta är kopplat till säkerhetsfunktionerna R2a och R2b i figur 3.

Inga andra säkerhetsfunktioner bedöms hotade av utvecklingen under den första tempererade perioden.

Den första glaciationscykeln

Förekomst av permafrost och glaciala förhållanden studeras med hjälp av en modellrekonstruktion av den senaste glaciationscykeln, weichselistiden. Den innefattar weichselistiden och den interglaciala perioden Holocen och påvisar stora förändringar på ytan och även av vissa geosfärsförhållanden som har betydelse för förvarets säkerhet. Som exempel kan nämnas:

- Tillväxt av permafrost.
- Förändrad mekanisk belastning på berget på grund av ett överliggande istäcke som förändrar spänningsfördelningen i berget och eventuellt skapar större jordskalv.
- Ökade hydrostatiska tryck på förvarsnivå under glaciala förhållanden.
- Förekomsten av jonfattigt grundvatten under glaciala förhållanden kan potentiellt orsaka erosion av buffert och återfyllning genom kolloidbildning. Detta skulle i sin tur öka kapselkorrosionen.
- Möjlig nedträngning av syre till förvarsdjup under kortare perioder av ökat grundvattenflöde under glaciala förhållanden.
- Faktorer som påverkar fördröjning i geosfären, som temporärt ökade grundvattenflöden.

Analysresultaten visar följande.

- Större jordskalv, med magnitud 6 eller större, i närheten av förvaret är mycket osannolika men kan inte uteslutas helt. Resultaten av probabilistiska beräkningar anger att medelantalet kapselbrott under den första glaciationscykeln, som följd av sådana händelser, är 0,014 för Forsmark och 0,0077 för Laxemar. Detta är kopplat till säkerhetsfunktionerna C3 och R3a i figur 3.
- Jonfattiga grundvatten kan förekomma under långa perioder när glaciala förhållanden råder. Detta kan leda till förlust av buffertmassa i några deponeringshål, så mycket att advektiva förhållanden uppstår. Advektiva förhållanden leder till ökad kapselkorrosion, men inga kapslarbrott förväntas under den första glaciationscykeln. Detta är kopplat till säkerhetsfunktionerna C1, Bu1 och R1c i figur 3.

Andra aspekter på utvecklingen under den första glaciationscykeln bedöms inte hota några av förvarets säkerhetsfunktioner.

Tiden efter den första glaciationscykeln, fram till en miljon år

Den vidare utvecklingen av förvarssystemet analyseras genom att man antar ytterligare sju upprepningar av den 120 000 år långa weichselistiden.

Samma fenomen som för den första glaciationscykeln skulle kunna inverka menligt på säkerheten under framtida glaciationscykler:

- Sannolikheten för större jordskalv bedöms öka med tiden. Medelantalet kapselbrott för hela analysperioden på en miljon år beräknas till 0,12 för Forsmark och till 0,065 för Laxemar.
- Omfattningen av buffertförlust på grund av erosion förväntas öka med tiden. Detta leder till ökad kapselkorrosion, vilket kan medföra haveri av ett fåtal kapslar under analysperioden på en miljon år. Resultatet påverkas av många faktorer som analyseras i referensutvecklingen.

Analysresultaten pekar inte på att några ytterligare säkerhetsfunktioner hotas.

Växthusvarianten

I växthusvarianten antas ett tempererat klimat råda under 50 000 år före den relativt milda övergången till basvarianten av nästa glaciationscykel, i stället för bara några tusen år av initiala tempererade förhållanden om ingen ökad växthuseffekt inträffar. I hela rapporten gäller implicit att växthusvarianten beskriver en situation med *ökad* växthuseffekt.

Som framgår ovan är de mest negativa processerna för förvarets säkerhet relaterade till glaciala förhållanden. Därför är en förlängd period av tempererat klimat i princip gynnsam för säkerheten.

Radiologiska konsekvenser

Radionuklidtransport och dosberäkningar utförs för fyra typer av kapselbrott. Två av dessa, orsakade av korrosion och respektive skjuvrörelser, identifierades i referensutvecklingen. Ytterligare två hypotetiska skadetyper analyseras för att illustrera fördröjning, förvarets sekundära säkerhetsfunktion.

En stor uppsättning beräkningar görs för att analysera fördröjning och för att klargöra konsekvenserna av många osäkerheter som identifieras i referensutvecklingen. I biosfären uppskattas radionuklidtransport och doskonsekvenser med en ny metod som är baserad på platsspecifika biosfärdata och som tar hänsyn till landskapets utveckling över tid.

Resultaten anger att potentiella kapselbrott som följd av *referensutvecklingen* medför konsekvenser som ligger väl under myndigheternas riskgränser.

Scenarier

Den vidare analysen av förvarets säkerhet bryts ner i ett antal scenarier. Ett omfattande huvudscenario representerar en rimlig utveckling av förvarssystemet. Utvecklingen av detta scenario är nära kopplat till referensutvecklingen. En uppsättning ytterligare scenarier definieras för att täcka osäkerheter som inte beaktas i referensutvecklingen, t ex mera extrema klimatförhållanden än de som resulterar av en upprepning av weichselistiden i referensutvecklingen.

Säkerhetsfunktionerna används för att få en omfattande uppsättning scenarier. Fokus ligger på viktiga frågor för förvarssäkerheten. När man definierar ett scenario *postuleras* att en säkerhetsfunktion bryts, varefter alla tänkbara vägar till ett sådant brott granskas. Målet är att svara på frågan: Finns det någon rimlig möjlighet att detta scenario skulle kunna inträffa? Om så visar sig vara fallet tas konsekvenserna av scenariot i fråga med i en risksummering för förvaret. I annat fall betraktas scenariot som ett ”restscenario”, och konsekvenser kan analyseras som illustration.

Ett scenario med kapselbrott på grund av isostatiskt övertryck får exemplifiera angreppssättet. I detta scenario beaktas missöden vid tillverkningen av de lastbärande kapselinsatserna, svälltryck som överstiger referensvärdena för bufferten och mycket kraftiga istäcken som ger högre grundvattentryck.

Förutom scenarierna som tagits fram på detta sätt söks scenarier som krävs av myndighetsföreskrifter eller som av andra skäl bedöms som relevanta. Detta ledde till att ett antal scenarier relaterade till framtida mänskliga handlingar valdes. Dessa är restscenarier, dvs de ingår inte i förvarets riskanalys. Tabell 1 ger en översikt över valda scenarier.

Valda scenarier analyseras, ofta som en utökad analys av referensutvecklingen. Två typer av kapselskador konstaterades bidra till risken:

- Skada på grund av kopparkorrosion när advektiva förhållanden råder i deponeringshålet på grund av att bufferten eroderat. Bufferterosionen orsakas av kolloidbildning på grund av glacialt smältvatten med låg jonstyrka. Denna skada uppträder i referensutvecklingen och följaktligen i huvudscenariot. I kapselkorrosionscenariot, som analyseras för att täcka osäkerheter som inte beaktas i referensutvecklingen, förutses större konsekvenser än för referensutvecklingen.
- Haveri på grund av skjuvrörelser i berget, orsakade av större jordskalv. Denna typ av kapselskada har låg sannolikhet, men kan inte uteslutas helt.

Tabell 1. Resultat av scenarievalet. Gröna rutor anger förhållanden för basvarianten av huvudscenariot, röda anger avvikelser från dessa förhållanden. EBS (Engineered Barrier System) betecknar de tillverkade barriärerna, dvs kapseln, bufferten och deponeringstunneln.

Huvudscenario				
Namn	**Initialtillstånd EBS**	**Initialtillstånd plats**	**Processhantering**	**Hantering av externa förhållanden**
Basvariant	Referens ± toleranser	Platsbeskrivande modell version 1.2 (med varianter/osäkerheter)	Enligt processrapporter	Referensklimat (upprepningar av weichselistiden) Inga framtida mänskliga handlingar (FHA)
Växthusvarianten	Referens ± toleranser	Platsbeskrivningsmodell version 1.2 (med varianter/osäkerheter)	Enligt processrapporter	Förlängd tempererad period Inga framtida mänskliga handlingar (FHA)
Ytterligare scenarier baserade på potentiell förlust av säkerhetsfunktioner (”mindre sannolika” eller ”restscenarier” beroende på analysresultatet)				
Namn	**Initialtillstånd EBS**	**Initialtillstånd plats**	**Processhantering**	**Hantering av externa förhållanden**
Advektion i bufferten	Utvärdera osäkerheter för relevanta initialtillståndsfaktorer, inre processer och externa förhållanden som skulle kunna leda till förlust av den aktuella säkerhetsfunktionen. Analysen av huvudscenariot utgör utgångspunkt.			
Buffertfrysning	Se ovan			
Buffertomvandling	Se ovan			
	Beakta vart och ett av de tre bufferttillstånden ovan + intakt buffert, för analys av de tre kapselscenarierna nedan.			
Kapselbrott på grund av isostatisk last	Utvärdera osäkerheter för relevanta initialtillståndsfaktorer, inre processer och externa förhållanden som skulle kunna leda till förlust av den aktuella säkerhetsfunktionen. Analysen av huvudscenariot utgör utgångspunkt.			
Kapselbrott på grund av skjuvrörelse	Se ovan			
Kapselbrott på grund av korrosion	Se ovan			
Scenarier relaterade till framtida mänskliga handlingar				
Namn	**Initialtillstånd EBS**	**Initialtillstånd plats**	**Processhantering**	**Hantering av externa förhållanden**
Intrång genom borrning	Som basvarianten av huvudscenariot	Som basvarianten av huvudscenariot	Som basvarianten av huvudscenariot, utom processer som påverkas av borrning	Referensklimat + borrning
Ytterligare intrångsfall, t ex näraliggande brytningsplats	Som basvarianten av huvudscenariot	Som basvarianten av huvudscenariot	Som basvarianten av huvudscenariot, utom processer som påverkas av intrång	Referensklimat + intrång
Ej förslutet förvar (analyseras inte i SR-Can)	Som basvarianten av huvudscenariot, men ofullständig förslutning	Som basvariant av huvudscenariot	Som basvarianten av huvudscenariot, modifierad beroende på initialtillstånd	Referensklimat

Huvudsakliga resultat och slutsatser

De viktigaste resultaten från SR-Can-projektet sammanfattas i avsnitten A, B och C nedan. En mera detaljerad diskussion om uppfyllelse av SSI:s riskkriterium ges i avsnitt D, medan ytterligare resultat och slutsatser sammanfattas i avsnitt E.

A. Uppfyllelse av riskkriteriet

Inga kapselbrott bedöms inträffa under den första perioden av tempererat klimat, som förväntas sträcka sig flera tusen år framåt

Inga kapselbrott förväntas vid någon av platserna under den initiala tempererade perioden efter deponering, som bedöms fortgå i flera tusen år. Dessutom har hittills utförda utvärderingar av defekter i kapselförslutningen lett till slutsatsen att alla kapslar kommer att vara täta vid deponeringen.

Ett förvar vid Forsmark bedöms uppfylla riskkriteriet

Den preliminära analysen i SR-Can anger att ett KBS-3-förvar vid Forsmark kommer att uppfylla SSI:s riskkriterium.

Osäkerheterna är dock betydande i den hydrogeologiska tolkningen och förståelsen för Forsmark. När dessa osäkerheter propageras till olika delar av analysen leder det till ett brett spann av möjligheter kring t ex utsläpp av buffertkolloider och vattenflödets egenskaper. En minskning av dessa osäkerheter skulle tillåta säkrare slutsatser i framtida analyser. Även den mest pessimistiska tolkningen av Forsmark bedöms dock uppfylla SSI:s riskkriterium.

Ett förvar vid Laxemar bedöms preliminärt uppfylla riskkriteriet – men mer representativa data krävs

Den platsbeskrivande modellen version 1.2 för Laxemar är inte tillräckligt representativ för den potentiella förvarsvolymen för att möjliggöra definitiva slutsatser om kravuppfyllelse. Framför allt baseras den hydrauliska tolkningen av platsen på data som delvis samlats in utanför kandidatvolymen för förvaret. Dessutom visar nyligen insamlade data på mera gynnsamma hydrauliska egenskaper än dem som platsmodellen i SR-Can bygger på.

Man kan dock konstatera att med de data som används för Laxemar bedöms platsen uppfylla riskkriteriet. Denna slutsats skulle troligen stärkas med användning av senare insamlade data.

B. Frågor relaterade till framtida istider

Generellt är det framtida istider som kommer att ha störst inverkan på förvaret. Ett antal slutsatser kan dras om inverkan av sådana förhållanden.

Frysning av en intakt buffert bedöms uteslutet – också för mycket pessimistiskt valda klimatförhållanden

Frysning av en intakt buffert bedöms uteslutet för båda platserna, även för mycket pessimistiskt valda klimatförhållanden. Vid den mest pessimistiska klimatutvecklingen vid Forsmark går det inte att helt utesluta frysning av en vattenfylld hålighet i en eroderad buffert. Beräkningarna visar dock att även i sådana fall förblir det mekaniska trycket på kapseln inom tillåtna gränser.

Kapselbrott på grund av isostatisk last bedöms uteslutet – också för mycket pessimistiskt valda klimatförhållanden

Kapselbrott på grund av isostatisk belastning bedöms uteslutet för båda platserna, även för de svåraste framtida glaciala förhållandena som beaktats.

Syrenedträngning bedöms preliminärt som uteslutet – också för mycket pessimistiskt valda förhållanden

Syrenedträngning till förvarsdjup ökar grundvattenflödet under en inlandsis och kan förändra den gynnsamma reducerande kemiska miljön. Denna utveckling bedöms dock som utesluten utgående från de analyser som genomförts inom SR-Can. Detta resultat överensstämmer med slutsatserna från flera tidigare analyser. Modelleringsexemplet är dock stiliserat och förenklat. Det krävs därför ytterligare analyser för att öka trovärdigheten för resultaten. Sådana studier kommer att genomföras inom ramen för SR-Site.

Riskbidraget från jordskalv bedöms som litet

Kapselbrott på grund av post-glaciala jordskalv kan inte uteslutas helt. Denna eventualitet ger dock ett litet riskbidrag. De probabilistiska analyserna anger att det i genomsnitt skulle dröja betydligt mer än en miljon år innan ens ett enda sådant kapselbrott inträffar.

Buffertmaterial kan förloras då bufferten utsätts för glaciala smältvatten, men omfattningen är osäker – ytterligare studier krävs

Det kan uppstå en betydande förlust av buffert genom kolloidbildning som följd av att glaciala smältvatten med låg jonstyrka tränger in – sett över ett tidsperspektiv på 100 000 år. Kunskapen om de aktuella processerna är begränsad och ytterligare forskning inom området prioriteras. En statusrapport ges i SKB:s FUD-program 07 som publiceras 2007.

Omfattande förlust av buffert kan leda till kapselbrott på mycket lång sikt

Förlust av buffertmassa, i sådan utsträckning att advektiva förhållanden börjar råda i bufferten, kan inte uteslutas på 100 000 års sikt. Detta skulle leda till ökad kapselkorrosionshastighet. Sett över en miljon år kan det bli frågan om några tiotal kapselbrott med den pessimistiska hydrauliska tolkningen av Forsmark, försiktiga antaganden om sulfidkoncentrationer och försiktiga antaganden om acceptanskriterier för deponeringshål.

En förlängd period av varmt klimat (ökad växthuseffekt) innan nästa istid bedöms i huvudsak som positivt för förvarets säkerhet

Eftersom de processer som potentiellt skulle vara mest skadliga för förvarets säkerhet är relaterade till glaciala förhållanden skulle en förlängd period med tempererat klimat vara positivt för säkerheten. Detta gäller i synnerhet de båda huvudsakliga bidragen till den beräknade risken i SR-Can, nämligen i) potentiell bufferterosion med därav följande ökad kapselkorrosion på grund av att glaciala smältvatten tränger in, och ii) större jordskalv under avsmältning av en inlandsis. Ytterligare utvärderingar behövs om den geokemiska utvecklingen vid en förlängd tempererad period. Detta skulle ge ökad tyngd åt slutsatsen att de geokemiska förhållandena skulle förbli gynnsamma.

C. Andra frågor relaterade till barriärkonstruktion och -funktion

Viktigt att undvika deponeringshål som skärs av stora eller starkt vattenförande sprickor – ytterligare studier krävs

De största riskbidragen i SR-Can gäller förekomst av stora och/eller höggradigt transmissiva sprickor som skär deponeringshålen. Detta gäller frigörelse av buffertkolloider och inverkan av större jordskalv i närheten av förvaret. Dessa två fenomen är relaterade till kapselbrott på grund av kapselkorrosion respektive till sekundära skjuvrörelser i berget. Eftersom retentionen är liten i en stor och höggradigt transmissiv spricka ges sådana kapselbrott generellt stora konsekvenser. Sådana sprickor ska undvikas i den mån de hittas. Sannolikheten för sådana sprickor och sannolikheten för att olämpliga deponeringshål förblir oupptäckta är i många avseenden svåra att kvantifiera. Resultatet av analysen är känsligt för dessa osäkerheter. Det är viktigt att fastställa välmotiverade acceptanskriterier för deponeringshål som grund för framtida analyser. Detta måste studeras både genom att man simulerar effekten av att tillämpa potentiella kriterier, och genom att man undersöker om det är praktiskt möjligt att tillämpa kriterierna.

Värmen från kapseln kan orsaka sprickor i deponeringshålets vägg, vilket kan ge ökad in- och uttransport av lösta ämnen – ytterligare studier krävs

Termiskt inducerad spjälkning kring deponeringshål kan ha stor inverkan på materialutbytet mellan strömmande grundvatten och buffert, så länge diffusion är den dominerande transportmekanismen i bufferten. Om advektiva förhållanden råder i bufferten blir inverkan av spjälkningen mycket mindre tydlig eftersom spjälkningen då ger ett litet bidrag till det redan ökade flödet. Det råder osäkerhet kring omfattning och konsekvenser av spjälkning och ytterligare studier pågår.

Återfyllda deponeringstunnlar har begränsad betydelse som transportväg för radionuklider

Betydelsen av den återfyllda deponeringstunneln som transportväg för radionuklider är begränsad i jämförelse med sprickor som skär deponeringshålet. Även försämring av återfyllningsmaterialet i deponeringstunnlarna har begränsade konsekvenser vad gäller radionuklidutsläpp från närzonen.

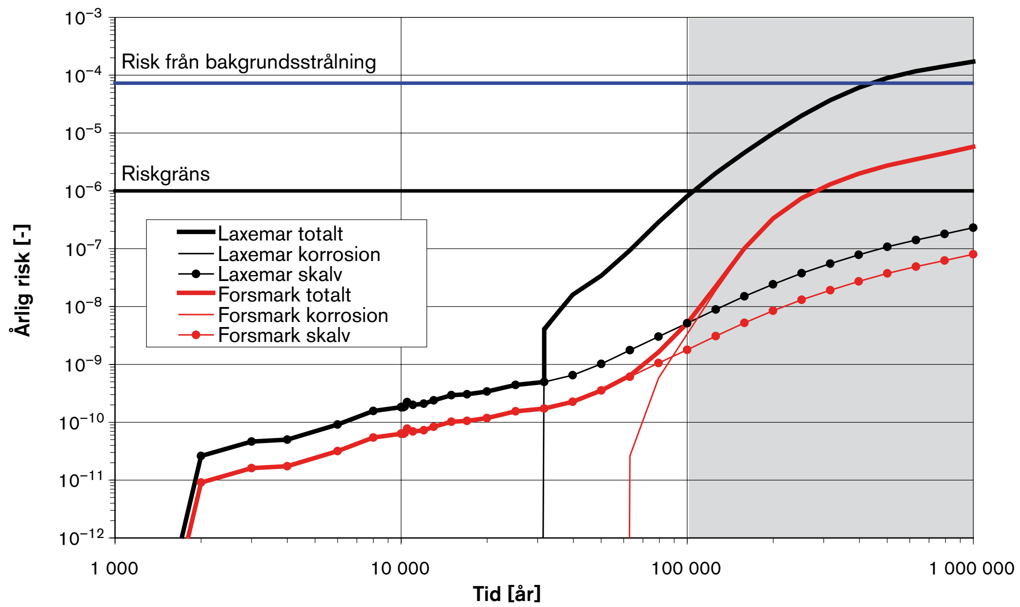
Sprängskador i berget kring deponeringstunneln har begränsad betydelse som transportväg för radionuklider

Betydelsen av den sprängskadade zonen (EDZ – excavation damaged zone) kring deponeringstunnlarna är begränsad i jämförelse med övriga transportvägar för radionuklider, även vid mycket pessimistiska antaganden om EDZ i förhållande till referensmetoden för bergbrytning.

Försiktiga brytningsmetoder rekommenderas ändå för deponeringstunnlar, eftersom konkurrerande transportvägar kan bedömas som mindre viktiga med stöd av ytterligare data, och eftersom slutsatserna om EDZ bygger på förenklad stiliserad modellering.

D. Beräknade individrisker

Beräknade individrisker för förvar vid Forsmark och Laxemar visas i figur 4. Observera att tempererade förhållanden postuleras för biosfären, medan det är sannolikt att platserna kommer att ligga under vatten eller vara täckta med is under en stor del av analysperioden på en miljon år. Därmed blir riskerna försumbara för dessa perioder. Dessutom görs flera pessimistiska antaganden, för att risken inte ska underskattas.



Figur 4. *Risksummering för de två platserna. Tempererade förhållanden postuleras för biosfären, medan det är sannolikt att platserna kommer att ligga under vatten eller vara täckta med is under en stor del av analysperioden på en miljon år vilket skulle ge försumbara doser. Flera andra osäkerheter bedöms pessimistiskt.*

Kravuppfyllelse för den första glaciationscykeln

För den första glaciationscykeln har två riskbidrag identifierats; från jordskalv och från kapselbrott på grund av korrosion om bufferten har eroderats av glaciala smältvatten.

Sannolikheten för kapselbrott på grund av jordskalv under perioden är ytterst liten och den sannolikheten ingår i riskuppskattningen.

Vad beträffar kapselbrott på grund av korrosion beräknas ett fåtal kapslar haverera under den första glaciationscykeln vid båda platserna. Maxvärdet för den totala beräknade risken upp till 100 000 år, dvs värdet vid 100 000 år, ligger nära myndigheterna riskgräns vid Laxemar och cirka två storleksordningar lägre vid Forsmark. Risken är pessimistiskt baserad på den som beräknats för kapselkorrosionscenariot, där flera av osäkerheterna hanteras pessimistiskt på grund av otillräcklig förståelse för grundvattenflöde och grundvattensammansättning under glaciala förhållanden, och för buffertens reaktion på kontakt med glaciala grundvatten. Risken som beräknats för Forsmark bygger på en pessimistisk tolkning av den rådande hydrauliska situationen. Som nämnts tidigare kan det ifrågasättas om den hydrogeologiska modellen för Laxemar är tillräckligt representativ. Senare platsdata från kandidatområdena för förvar visar att de hydrogeologiska förhållandena är mera gynnsamma än de som används i modellen som utgör grund för SR-Can. Detta skulle minska riskbidraget från kapselbrott på grund av korrosion.

Man kan alltså dra slutsatsen att de beräknade riskerna för de båda platserna uppfyller myndigheternas krav avseende den första glaciationscykeln efter förslutning.

Förvarets funktion för tiden efter den första glaciationscykeln

Samma typer av kapselbrott som för den första glaciationscykeln bidrar till individrisk under perioden efter den första glaciala cykeln, upp till en miljon år efter förslutning.

För Forsmark ligger det beräknade riskbidraget från jordskalv mer än en storleksordning under myndigheternas gräns under hela analysperioden, medan däremot bidraget från korrosionsskador ligger över riskgränsen vid en miljon år.

För Laxemar är riskbidraget från jordskalv likt det för Forsmark, men bidraget från korrosionshaverier ligger omkring två storleksordningar över riskgränsen vid analysperiodens slut.

SSI:s anger i sina allmänna råd för denna tidsperiod följande: ”En strikt kvantitativ jämförelse av beräknad risk mot föreskrifternas kriterium för individrisk [är] inte meningsfull.” Resultaten används som underlag för att diskutera hur pessimistiskt hanterade osäkerheter kan minskas och hur skyddsförmågan för förvaret kan förbättras, så som anges i de allmänna råden.

Det är viktigt att observera att den beräknade risken visserligen överstiger riskgränsen som gäller för den första perioden på 100 000 år, men ändå är betydligt lägre än riskerna som är kopplade till den naturliga bakgrundsstrålningen under analysperioden för Forsmark. För Laxemar ligger riskerna betydligt under dem för bakgrundsstrålningen under flera hundra tusen år och blir jämförbar med riskerna kopplade till bakgrundsstrålningen först vid slutet av analysperioden på en miljon år. Dessutom har, på samma sätt som för den första glaciationscykeln, många frågor behandlats pessimistiskt och ytterligare kunskap kan medföra en betydande minskning av dessa riskuppskattningar i framtida analyser.

Man kan alltså dra slutsatsen att de beräknade riskerna för tiden efter den första glaciationscykeln uppfyller myndigheternas krav för denna period.

E. Ytterligare resultat och slutsatser

Många ytterligare resultat har framkommit som gör det möjligt att dra slutsatser från SR-Can-analysen:

- En första utvärdering har gjorts av inverkan på miljön från utsläpp av radionuklider. De flesta radionuklider ligger under en sovringsgräns, vilket betyder att inga ytterligare analyser behövs. I de mest pessimistiska beräkningsfallen kan ett fåtal nuklider komma att överstiga gränsen vid analysperiodens slut. Detta kräver en mer detaljerade analyser.
- Två alternativa säkerhetsindikatorer har används som komplement till riskindikatorn: Utsläppsbegränsningar från den finska tillsynsmyndigheten STUK och sammansättningen av naturligt förekommande radionuklider i miljön kring förvaret.

- En första diskussion ges kring de aspekter av begreppet Bästa Tillgängliga Teknik (BAT – Best Available Technique) som kan belysas med hjälp av resultaten från säkerhetsanalysen.
- Många gränssättande fall har analyserats, där total förlust av en eller flera barriärfunktioner förutsätts. Resultaten visar att beräknade doser understiger den naturliga bakgrundsstrålningen, även vid mycket omfattande förluster av säkerhetsfunktioner. Till exempel ger en tidig, total förlust av kapsel och buffert i samtliga deponeringshål vid Forsmark doser som är jämförbara med dem för den naturliga bakgrundsstrålningen. De gränssättande analyserna visar tydligt multibarriär-egenskaperna hos KBS-3-systemet.
- En uppsättning konstruktionsstyrande fall har sammanställts. Dessa ska användas som ett av flera underlag till konstruktionsförutsättningar för förvaret, såsom fastställande av krav på barriäregenskaper.
- Detaljerad återkoppling ges till fortsatt arbete med kapselkonstruktion och -tillverkning, till fortsatt arbete med förvarsutformning, till ytterligare platsundersökningar och platsmodellering, till SKB:s FUD-program och till nästa säkerhetsanalys, SR-Site.

Innehållet i denna rapport

Efter det inledande kapitlet 1 ger denna rapport ger en översikt över metodiken för SR-Can-analysen i kapitel 2, och presenterar i kapitel 3 den hantering av egenskaper, händelser och processer – FEP – som har betydelse för den långsiktiga säkerheten. Kapitel 4 redovisar systemets initialtillstånd för de båda platserna. Kapitlen 5 och 6 redovisar planer och metoder för hantering av extern påverkan respektive av interna processer. Säkerhetsfunktioner och säkerhetsfunktionsindikatorer diskuteras i kapitel 7. Sammanställningen av indata för analysen beskrivs i kapitel 8. Materialet som presenteras i de första åtta kapitlen används i analysen av referensutvecklingen i kapitel 9, med tonvikt på isolering, och i kapitel 10 som behandlar radionuklidtransport och dosanalyser. Scenarier för ytterligare utvärdering av säkerheten väljs i kapitel 11 och valda scenarier analyseras i kapitel 12. Slutligen presenteras slutsatser och återkoppling i kapitel 13. Referenser ges i kapitel 14. Bilaga A redogör för hur tillämpliga föreskrifter hanteras i analysen. Diverse beräkningsmodeller presenteras i bilaga B och material från granskningar av tidigare analyser i bilaga C. En ordlista med förkortningar och specialtermer i SR-Can finns i bilaga D.

1 Introduction

1.1 SKB's programme for spent nuclear fuel

Radioactive waste from nuclear power plants in Sweden is managed by the Swedish Nuclear Fuel and Waste Management Co, SKB. Within SKB's programme for the management of spent nuclear fuel, an interim storage facility and a transportation system are today (October 2006) in operation. Several decades of research and development has led SKB to put forward the KBS-3 method for the final stage of spent nuclear fuel management. In this method, copper canisters with a cast iron insert containing spent nuclear fuel are surrounded by bentonite clay and deposited at approximately 500 m depth in saturated, granitic rock, see Figure 1-1. Around 9,000 tonnes of spent nuclear fuel is forecasted to arise from the Swedish nuclear power programme, corresponding to roughly 4,500 canisters in a KBS-3 repository.

Two principal remaining tasks in the programme are to locate, build and operate i) the final repository and ii) an encapsulation plant in which the spent fuel will be emplaced in canisters to be deposited in the final repository.

SKB is currently pursuing site investigations for a final repository in the municipalities of Östhammar (Forsmark area) and Oskarshamn (subareas Simpevarp and Laxemar), Figure 1-2. The investigations are conducted in two stages, an initial phase followed by a complete site investigation phase, if the expected site suitability is confirmed. The aim is to build a final repository at one of these candidate sites, provided that the bedrock and other relevant conditions are found suitable. An application for a final repository will be made at the end of 2009 according to current plans. The initial stage has now (October 2006) been completed and SKB has decided to pursue the investigations at the Forsmark site and at the Laxemar subarea at the Oskarshamn site. The Simpevarp subarea has been set aside, since it has been judged to be, albeit suitable from the point of view of long-term safety, less flexible in terms of available space for deposition than the Laxemar subarea.

The favoured alternative for the location of the encapsulation plant is at Oskarshamn, in conjunction with the existing interim storage facility. An application for an encapsulation plant will be made in November 2006.

1.1.1 Reporting of long-term safety during the current programme stage

The overall aim of the reporting of long-term safety during the current programme stage is to produce a safety report supporting the application in 2009 for a final repository. That safety report, here called the SR-Site report since SR-Site is the name of the project of which it is a product, will be based on data from the completed site investigations.

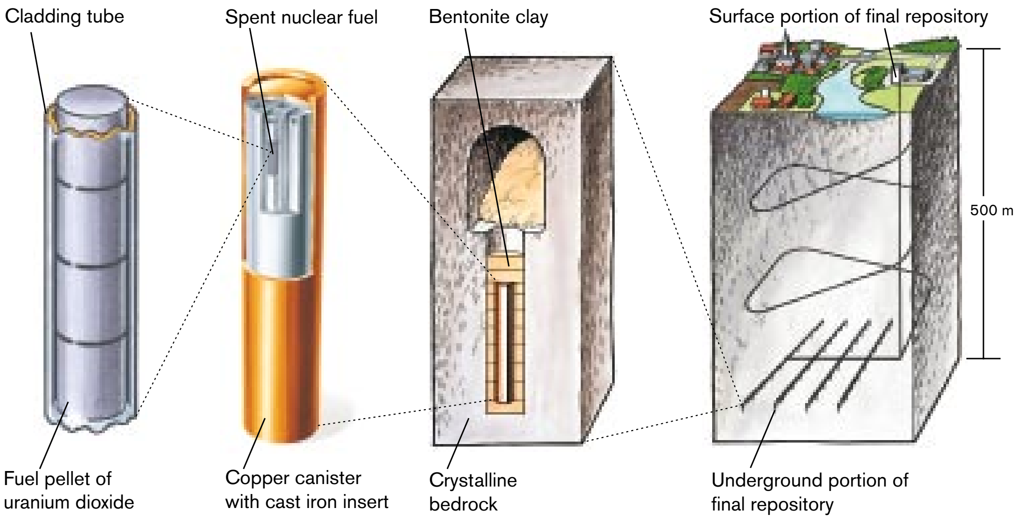


Figure 1-1. *The KBS-3 concept for disposal of spent nuclear fuel.*

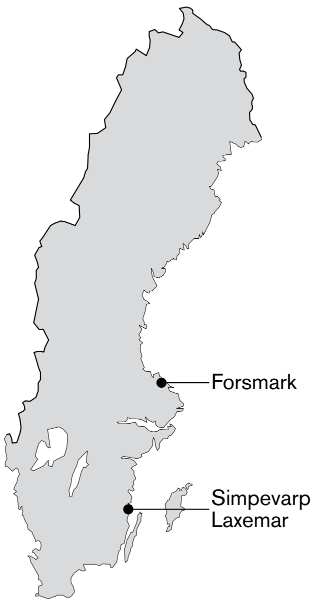


Figure 1-2. *The locations of the candidate sites.*

The present report is a preparation for the SR-Site report. The project that has produced this report is, for historical reasons, called the SR-Can[2] project and this term occurs often in the report and in its main references. The main purposes of the report are to obtain a first assessment of long-term safety of a repository at the Forsmark and Laxemar sites, based on data from the initial site investigation stage, and to foster a dialogue with responsible authorities regarding interpretations of the applicable regulations and the acceptability of the approach adopted for safety assessment.

Also, preliminary safety evaluations, PSEs, of each site have been made as sub-tasks within the SR-Can project. The main purposes of those evaluations were to determine whether earlier judgements of the suitability of the candidate areas for a final repository with respect to long-term safety remained valid in the light of borehole and other data obtained at the sites, and to provide feed-back to continued site investigations and site-specific repository design. PSEs of the Simpevarp, Forsmark and Laxemar sites are presented in /SKB 2005a/, /SKB 2005b/ and /SKB 2006a/, respectively. The overall conclusions from these evaluations are that the sites are indeed suitable for a final repository. Several issues requiring further analysis were identified and these have been taken into account in the SR-Can project. The analyses presented here are more comprehensive and detailed than the preliminary evaluations in the PSEs. This report thus supersedes the PSEs which will, therefore, in general not be further cited below.

A variant with horizontal emplacement of the waste canisters, KBS-3H, is also being studied in a joint research project between SKB and Posiva, the Finnish waste management organisation. By the middle of 2007, a safety assessment of the KBS-3H variant, using the Finnish site Olkiluoto as the reference location, will be presented by Posiva. Both the SR-Can and the SR-Site projects relate only to the vertical emplacement mode shown in Figure 1-1.

1.2 Purpose of the SR-Can safety assessment project

As mentioned, the SR-Can project is a preparatory stage for the SR-Site assessment, the report which will be used in support of SKB's application for a final repository. The purposes of the safety assessment SR-Can are the following:

1. To make a first assessment of the safety of potential KBS-3 repositories at Forsmark and Laxemar to dispose of canisters as specified in the application for the encapsulation plant.

[2] The SR in the acronym SR-Can stands for Safety Report and Can is short for canister. This title of the project was chosen since it was originally intended to support the application to build an encapsulation plant. A report on long-term safety is, however, no longer required for that application. For practical reasons, this altered purpose of the SR-Can project has not been reflected in a change of the name of the project, since it is since long well established.

2. To provide feedback to design development, to SKB's R&D programme, to further site investigations and to future safety assessment projects.
3. To foster a dialogue with the authorities that oversee SKB's activities, i.e. the Swedish Nuclear Power Inspectorate, SKI, and the Swedish Radiation Protection Authority, SSI, regarding interpretation of applicable regulations, as a preparation for the SR-Site project.

As SKB's waste management programme continues, the encapsulation technique will be further developed and selection of materials for buffer and backfill and procedures for manufacturing and deposition of engineered barriers will be further specified. Also, the sites will become progressively better characterised and excavation techniques specified in more detail. Safety assessments at various stages of the programme will draw on the information available at that particular stage. Information on all the components is needed at every stage, since safety depends on all these elements. The focus of a particular assessment will, however, be determined not only by the information available but also by the purpose of the assessment, i.e. the decision or decisions that it is intended to support.

The objective of the SR-Can report is to investigate whether the KBS-3 method has the potential of fulfilling regulatory safety criteria, given the host rock conditions at the sites in so far as they can be specified after the initial site investigation phase. The intention of the SR-Can report is not to fully establish the suitability of the studied sites – this will be done in SR-Site. The intention is also not to finally establish the technical system for disposal – but rather to investigate the safety of the system as it is specified at this stage, and to give feedback for further developments to that specification.

1.3 Feedback from review of the interim report

An interim version of this report, focussing on methodology, was published in September 2004 /SKB 2004a/. It has since been reviewed by SKI and SSI, aided by an evaluation /SKI/SSI 2005a/ by an international review team. Some of the main conclusions from these reviews are summarised in the following quotations from the authorities' joint review report /SKI/SSI 2005b/:

- The authorities believe, as does the international panel of experts, that SKB's method of safety assessment is well structured and logically built up and that it has conditions to provide a good starting point for future safety analyses.
- The authorities believe, as does the international panel of experts, that there are deficiencies in SKB's method for the identification and choice of scenarios.
- The authorities believe that the biosphere models that have been announced are promising but cannot give any deeper assessment since most of the models have not been fully developed.
- The authorities feel that there are discrepancies in the quality assurance of the interim report and that this has in some respects made it more difficult to assess SKB's methods of safety assessment.
- The authorities feel, as does the international panel of experts, that it is not clear how SKB will apply the requirements on optimisation and use of the best available technology, and what role the safety assessment has for this.

These conclusions have been considered in the preparation of this report. This is in accordance with the QA procedures for SR-Can, that require that findings in regulatory reviews of previous assessments are considered. Apart from being taken into account throughout the text, the review findings are directly addressed in Appendix C.

1.4 Regulations

The form and content of a safety assessment, and above all the criteria for judging the safety of the repository, are defined in regulations issued by SKI and SSI. The regulations are based on various pertinent components of framework legislation, the most important being the Nuclear Activities Act and the Radiation Protection Act. Guidance on radiation protection matters is provided by a number of international bodies, and national legislation is often, as in the case of Sweden, influenced by international rules and recommendations.

Regarding long-term safety of nuclear waste repositories, there are two more detailed regulations of particular relevance, issued by SSI and SKI, respectively:

- "The Swedish Radiation Protection Institute's Regulations concerning the Protection of Human Health and the Environment in connection with the Final Management of Spent Nuclear Fuel or Nuclear Waste" (SSI FS 1998:1).
- "The Swedish Nuclear Power Inspectorate's regulations concerning safety in final disposal of nuclear waste" (SKIFS 2002:1).

These two documents are reproduced in their entirety in Appendix A to this report. The way in which this SR-Can report addresses the requirements is indicated by references to relevant sections of this report, as inserts in the regulatory texts in the Appendix.

1.4.1 Regulations for final disposal of spent nuclear fuel, SSI FS 1998:1

The parts of SSI FS 1998:1 most relevant to an assessment of long-term safety imply the following:

- Protection of human health shall be demonstrated by compliance with a risk criterion that states that "the annual risk of harmful effects after closure does not exceed 10^{-6} for a representative individual in the group exposed to the greatest risk". "Harmful effects" refer to cancer and hereditary effects. The risk limit corresponds, according to SSI, to an effective dose limit of about $1.4 \cdot 10^{-5}$ Sv/yr. This, in turn, corresponds to around one percent of the natural background radiation in Sweden.
- Regarding environmental protection, biological effects of ionising radiation due to releases of radioactive materials from the repository in living environments and ecosystems of relevance shall be described, based on available knowledge.
- The consequences of intrusion into a repository shall be reported and the protective capability of the repository after intrusion shall be described.
- SSI requires a more detailed assessment for the first 1,000 years following repository closure than for later times.

SSI has also issued General guidance concerning the application of SSI FS 1998:1. There, more detailed information regarding the above aspects is given. Also the General guidance are reproduced in Appendix A.

In the General guidance, it is indicated that the time scale of a safety assessment for a final repository for spent nuclear fuel should be one million years after closure, see further section 2.4. A detailed risk analysis is required for the first thousand years after closure. Also, for the period up to approximately one hundred thousand years, the reporting is required to be based on a quantitative risk analysis.

For the period beyond one hundred thousand years, SSI's general guidance states that a strict quantitative comparison of calculated risk in relation to the criterion for individual risk in the regulations is not meaningful. Rather, it should be demonstrated that releases from both engineered and geological barriers are limited and delayed as far as reasonably possible using calculated risk as one of several indicators.

It is, therefore, concluded that compliance with the 10^{-6} risk criterion is required to be demonstrated for the first one hundred thousand years after closure.

1.4.2 The Swedish Nuclear Power Inspectorate's regulations concerning safety in final disposal of nuclear waste, SKIFS 2002:1

The parts of SKIFS 2002:1 most relevant to an assessment of long-term safety imply the following requirements.

- A safety assessment shall take into account features, events and processes (FEPs) that can lead to the dispersion of radioactive substances after closure.
- A safety assessment shall cover as long a period as barrier functions are required, but at least ten thousand years.

- Reporting of
  - analysis methods for system description and evolution,
  - analysis methods for the selection of scenarios (including a main scenario that takes into account the most probable changes in the repository and its environment),
  - the applicability of models, parameter values and other conditions used in the analyses,
  - handling of uncertainties and sensitivity analyses.
- Regarding analysis of post-closure conditions, SKI requires descriptions of the evolution of the biosphere, geosphere and repository for selected scenarios; and evaluation of the environmental impact of the repository for selected scenarios, including the main scenario, with respect to defects in engineered barriers and other identified uncertainties.

SKI has also issued General Recommendations concerning the application of SKIFS 2002:1. There, more detailed information regarding e.g. classification of scenarios and uncertainties is given. Excerpts from the Recommendations, relevant to an assessment of long-term safety, are also given in Appendix A, along with a statement of how this SR-Can report addresses the requirements.

1.5 Organisation of the SR-Can project

The SR-Can project started in 2002. Throughout the project, a number of specialists at SKB as well as external consultants have formed a core group of the project. The group consists of several generalists in the field of safety assessments of nuclear waste repositories and a number of experts in key areas of importance for the assessment. The individuals presently forming the SR-Can team and their roles are listed in the preface to this report. A large number of external experts have also contributed, mainly by producing specialised analyses and documentation of the scientific basis for the assessment. The roles, experience and other characteristics of both the SR-Can team and of the external experts are given in the SR-Can expert database, see further section 2.6.

1.6 Related projects

The safety assessment project is closely linked to ongoing site investigation and engineering activities at SKB, see Figure 1-3.

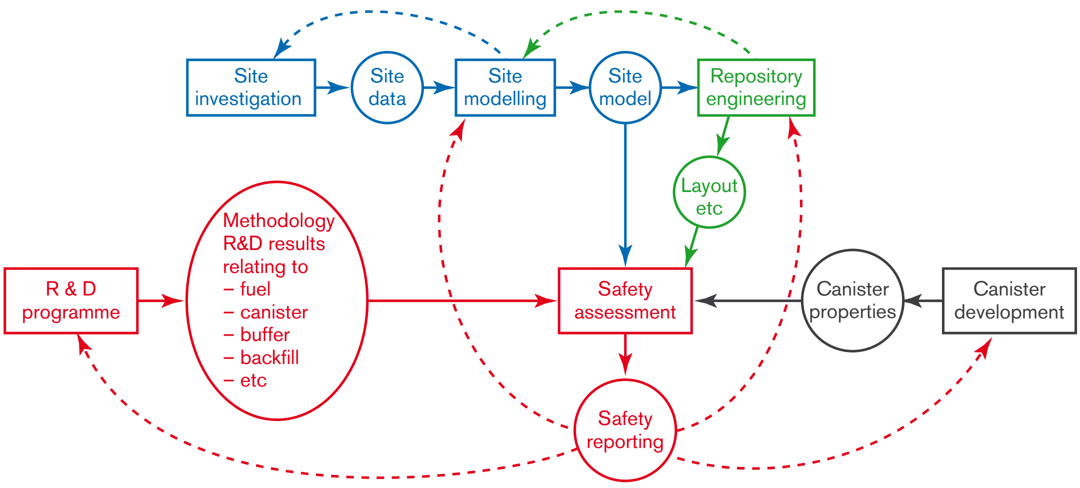


Figure 1-3. *Relations to other projects. Activities are shown as rectangles and products as ellipses. As indicated by the dashed lines, the safety report provides feedback to repository engineering concerning e.g. layout issues and choice of backfill materials and to site investigations, via the site model, concerning further site investigation needs. The latter type of feedback is also given by the site modelling group independent of the safety assessment. Feedback is also given from the safety assessment to SKB's R&D programme.*

1.6.1 Site investigations and site modelling

A considerable part of the basis for the safety assessments SR-Can and SR-Site is provided from SKB's ongoing site investigations in the municipalities of Oskarshamn and Östhammar.

Field data from the site investigations are analysed, within the site investigation project, by a site analysis team that produces a sequence of site descriptive models of the geosphere and the biosphere. The team consists of several groups specialising in different disciplines. The site descriptive model is a synthesis of observations of the current state of the site and of the understanding of past and ongoing e.g. hydraulic and geochemical, processes driven by phenomena such as land uplift and climate change. Model simulations of the historical evolution of the site are an important part of the synthesis work carried out by the site analysis group. The resulting geosphere 3D model of current conditions provides thermal, hydraulic, mechanical, chemical and transport properties of the rock, within a geometrical and geological framework describing major structures at the site. The biosphere part of the model includes a description of the ecosystems at the site and is developed to be coherent with the geosphere model. The site descriptive model is accompanied by a comprehensive description of the inter-disciplinary analysis and interpretation work underpinning it.

The site descriptive model provides descriptions of the present geosphere and biosphere conditions for the safety assessment. A more detailed account is given in chapter 4.

The model describes the situation prior to rock excavation for the final repository. Analyses of how the excavation activities will affect the undisturbed, natural state of the rock are also needed and parts of this work are undertaken by a repository engineering group, using the site description and in cooperation with the site model experts, in conjunction with their determination of a suitable repository layout in the site model. The results of these analyses are part of the input to SR-Can and are described in relevant parts of this report.

Apart from providing descriptions of the geosphere and the biosphere, the site descriptive model gives an understanding of past and ongoing processes at the site. This information is useful for the description and modelling of the future development of the site and repository, the results of which have to be compatible with the understanding of the site history.

The safety assessment uses the hydrogeological simulation models set up by the site analysis group. Whereas these are essentially used to simulate the site history by the site analysis group, the future evolution is in focus in the safety assessment.

The results of the safety assessment provide feedback to both further site investigations and design work. Regarding the site model, an overall assessment of the confidence in the site descriptive model is made within the safety assessment, informed by insights from the site analysis group.

1.6.2 Repository engineering

Repository engineering develops a reference repository concept that is practically achievable while providing the required safety functions. The reference concept includes basic dimensions of the facilities as well as reference technical solutions for buffer and backfill. Using the reference concept and based on the site description, repository engineering then develops site-adapted layouts of the final repository. Feedback is given to the continued site modelling work. The concepts and the site adapted repository layouts are further discussed in chapter 4.

Depending on the stage of the programme, there will be various design options that need to be considered in a safety assessment, in order to provide feedback from the point of view of long-term safety to the further development/selection of options. Such options concern e.g. materials for buffer and deposition tunnel backfill in SR-Can, see further chapter 4.

1.6.3 Canister development

As a result of a comprehensive encapsulation project, a licence for an Encapsulation plant will be filed in November 2006. Within that project, techniques for canister production and sealing are developed and documented. The project provides input to SR-Can in terms of canister properties, summarised in chapter 4.

2 Methodology

2.1 Introduction

This chapter outlines the methodology that has been used for SR-Can. The methodology builds on that presented in the SR-Can Interim report /SKB 2004a/ which, in turn, was a development of the methodology used in SKB's most recent comprehensive safety assessment, the SR 97 study /SKB 1999a/. The methodology development has also been influenced and inspired by several recent safety assessment studies in e.g. Switzerland /Nagra 2002/, Finland /Vieno and Nordman 1999/, Belgium /ONDRAF/NIRAS 2001/, Japan /JNC 2000/, the U.S. /BSC 2002/, Canada /Gierszewski et al. 2004/ and France /Andra 2005/ and by international cooperation in the area organised by the OECD Nuclear Energy Agency /NEA 1997a, 1999, 2001, 2004ab/.

The main purpose of a safety assessment of a final repository is to investigate whether the repository can be considered radiologically safe over time. In principle, this is established by comparing estimated releases of repository derived radionuclides and associated radiation doses with regulatory criteria (see section 1.4 and Appendix A). For a KBS-3 repository, the primary safety function is to completely isolate the waste throughout the period for which an assessment is required, see further below. An important purpose of this safety assessment is, therefore, also to demonstrate near-complete isolation of the wastes under a wide range of circumstances and for a very long time.

Appropriate scientific and technical support for all statements made and data selected is essential to give confidence in the calculated results. Demonstrating understanding of the disposal system and its evolution is thus a crucial component in any safety assessment.

The repository system, broadly defined as the deposited spent nuclear fuel, the engineered barriers surrounding it, the host rock and the biosphere in the proximity of the repository, will evolve over time. Future states of the system will depend on:

- its initial state,
- a number of radiation related, thermal, hydraulic, mechanical, chemical and biological processes acting internally in the repository system over time,
- external influences acting on the system.

Internal processes are e.g. the decay of radioactive material, leading to the release of heat and the subsequent warming of the fuel, the engineered barriers and the host rock. Groundwater movements and chemical processes affecting the engineered barriers and the composition of groundwater are other examples. External influences include effects of future climate and climate-related processes, such as glaciations and land uplift. Another example is the build-up of mechanical energy due to plate tectonic movements. Also, future human actions may influence the repository.

The initial state, the internal processes and the external influences and the way they together determine repository evolution, can never be fully described or understood. There are thus uncertainties of various types associated with all aspects of the repository evolution and hence with the evaluation of safety. A central theme in any safety assessment methodology must therefore be the management of all relevant types of uncertainty. This management amounts to classifying and describing uncertainties, as well as handling them in a consistent manner in the quantification of the repository evolution and of the radiological consequences to which it leads. It also implies comparing the results of the assessment with regulatory criteria in such a way that appropriate allowance is made for the uncertainties associated with the assessment.

The primary safety function of the KBS-3 system described in Figure 1-1 is to completely isolate the spent nuclear fuel within the copper/iron canisters over the entire assessment period. Should a canister be damaged, the secondary safety function is to ensure that any releases from the canister are retarded and dispersed sufficiently to ensure that the resultant radionuclide concentrations are reduced to levels that do not cause unacceptable consequences. The two issues of isolation and retardation are, therefore, principal considerations throughout the assessment.

The next section gives a brief overview of the assessment methodology. The subsequent sections in this chapter elaborate on various general aspects of the methodology. Several important parts of the methodology, like the selection of scenarios, are difficult to fully explain without demonstrating how the methodology is applied. Much of the methodology is, therefore, further developed and applied in the subsequent chapters.

2.2 Methodology in ten steps

The safety assessment SR-Can consists of a number of main steps, which are carried out partly concurrently and partly consecutively. From a project management point of view, many of the steps can be seen as sub-projects in a larger integrated safety assessment project. Figure 2-1 is a graphical illustration of the steps.

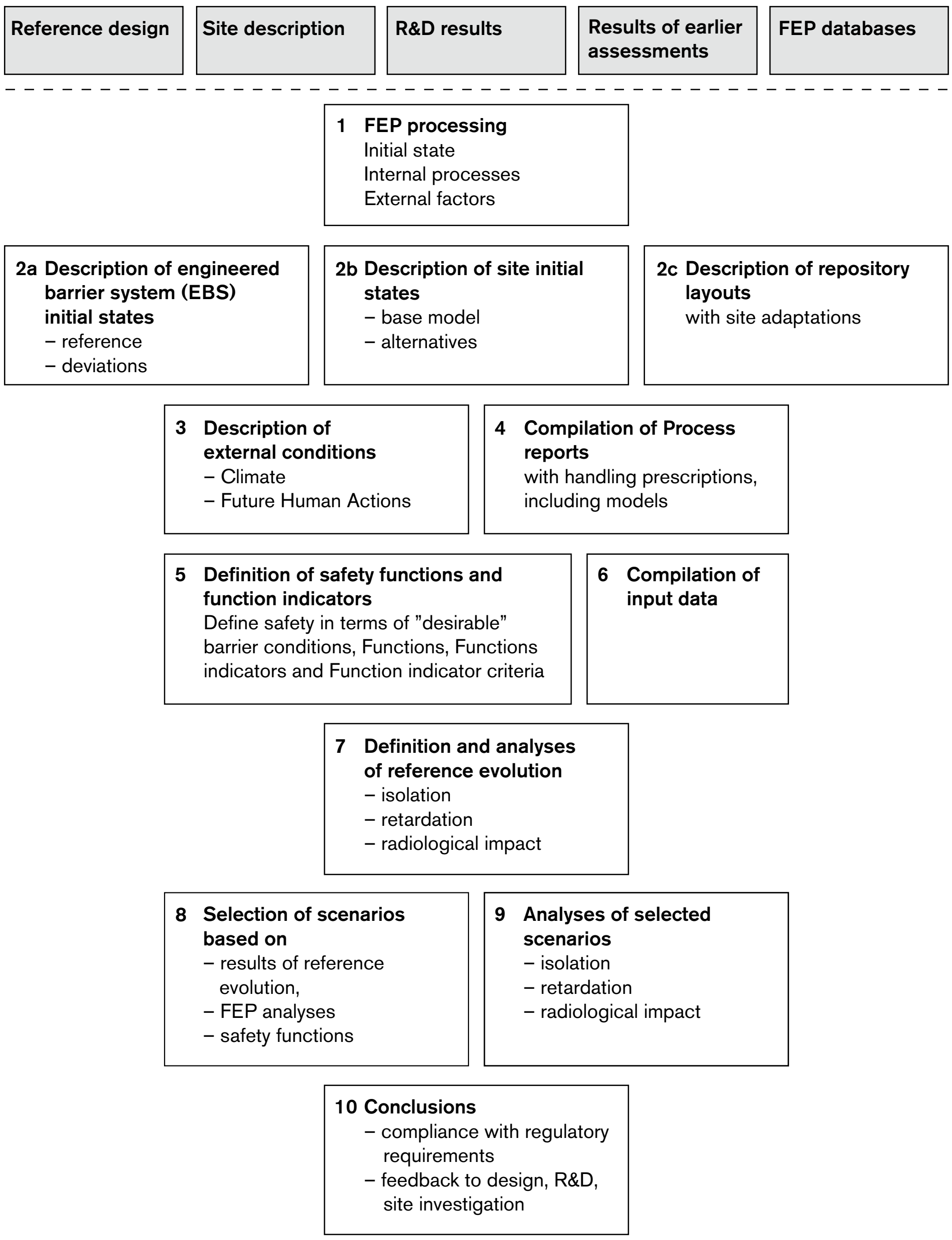


Figure 2-1. *An outline of the ten main steps of the SR-Can safety assessment. The boxes at the top above the dashed line are inputs to the assessment. The products of each step are described in detail in the main text.*

The main steps of the assessment are the following:

1. Identification of factors to consider (FEP processing)

   This step consists of identifying all the factors that need to be included in the analysis. Experience from earlier safety assessments and KBS-3 specific and international databases of relevant features, events and processes (FEPs) influencing long-term safety are utilised. An SKB FEP database is developed where the great majority of FEPs are classified as being either initial state FEPs, internal processes or external FEPs. Remaining FEPs are either related to assessment methodology in general or determined to be irrelevant for the KBS-3 concept. Based on the results of the FEP processing, an SR-Can FEP catalogue, containing FEPs to be handled in SR-Can, has been established. This step of FEP processing is further described in chapter 3 and fully documented in the SR-Can **FEP report**[3].

2. Description of the initial state

   The initial state of the system is described, based on the design specifications of the KBS-3 repository, a descriptive model of the repository site and a site-specific layout of the repository. The initial state of the fuel and the engineered components is that immediately after deposition as described in the **Initial state report**. The initial state of the geosphere and the biosphere is that of the natural system prior to excavation, as described in the site descriptive models of the Forsmark /SKB 2005c/ and Laxemar /SKB 2006b/ sites. The repository layouts adapted to the sites are provided in underground design reports for each site /Brantberger et al. 2006/ and /Janson et al. 2006/. See further chapter 4.

3. Description of external conditions

   Factors related to external conditions are handled in the three categories "climate related issues", "large-scale geological processes and effects" and "future human actions". The handling of these factors is described in the **Climate report,** the **Geosphere process report**, and the **FHA report**, respectively. See further chapter 5.

4. Description of processes

   The identification of relevant processes is based on earlier assessments and FEP screening. All identified processes within the system boundary relevant to the long-term evolution of the system are described in dedicated **Process reports**. Short-term geosphere processes/alterations due to repository excavation are also described in these Process reports and are taken into account in the assessment. For each process, its general characteristics, the time frame in which it is important, the other processes to which it is coupled and how the process is handled in the safety assessment are documented. See further chapter 6.

5. Definition of safety functions, safety function indicators and safety function indicator criteria

   This step consists of an account of the safety functions of the system and of how they can be evaluated by means of a set of safety function indicators that are, in principle, measurable or calculable properties of the system. Criteria for the safety function indicators are provided. The process reports are important references for this step. A FEP chart is developed, showing how FEPs are related to the safety function indicators. The execution and results of this step are described in chapter 7.

6. Compilation of input data

   Data to be used in the quantification of repository evolution and in dose calculations are selected using a structured procedure. The process of selection and the data values adopted are reported in a dedicated **Data report**. Also, a template for discussion of input data uncertainties has been developed and applied. See further chapter 8.

7. Definition and analysis of reference evolution

   A reference evolution, providing a description of a plausible evolution of the repository system, is defined and analysed. The isolating potential of the system over time is analysed in a first step, yielding a description of the general system evolution and an evaluation of the safety function indicators. If the evolution indicates breaching of isolation, the retarding potential of the repository

[3] The FEP report is one of several principal references in this Main report. See section 2.2.1 for a complete list and nomenclature for referencing.

and its environs is analysed and dose consequences are calculated for the long-term conditions identified in the first step. Also some canister failure modes not resulting from the reference evolution are analysed in order to further elucidate the retarding properties of the system. Each process is handled in accordance with the plans outlined in the process reports. See further chapter 9 for the analysis of the general evolution and the isolating potential and chapter 10 for the analysis of the retarding potential.

8. Selection of scenarios

   A set of scenarios for the assessment is selected. A comprehensive main scenario is defined in accordance with SKI's regulations SKIFS 2002:1. The main scenario is closely related to the reference evolution analysed in step 7. The selection of additional scenarios is focused on the safety functions of the repository and the safety function indicators defined in step 4 form an important basis for the selection. For each safety function, an assessment is made as to whether any reasonable situation where it is not maintained can be identified. If this is the case, the corresponding scenario is included in the risk evaluation for the repository with the overall risk determined by summation over such scenarios. The set of selected scenarios also includes e.g. scenarios explicitly mentioned in applicable regulations, such as human intrusion scenarios, and scenarios and variants to explore the roles of various components in the repository. See further chapter 11 for the scenario selection methodology and the application of the selection method.

9. Analysis of selected scenarios

   The main scenario is analysed essentially by referring to the reference evolution in step 7. An important result is a calculated risk contribution from the main scenario. The additional scenarios are analysed by focussing on the factors potentially leading to situations in which the safety function in question is not maintained. In most cases, these analyses are carried out by comparison with the evolution for the main scenario, meaning that they only encompass aspects of repository evolution for which the scenario in question differs from the main scenario. For these scenarios, as for the main scenario, a risk contribution is estimated. See further chapter 12.

10. Conclusions

   This step includes integration of the results from the various scenario analyses, development of conclusions regarding safety in relation to regulatory criteria and feedback concerning design, continued site investigations and SKB's R&D programme. See further chapter 13.

2.2.1 Report hierarchy in the SR-Can project

As indicated in the previous section, several of the steps carried out in the SR-Can assessment result in specific reports that are of central importance for the conclusions and analyses in this Main report. Table 2-1 lists these *main references* and defines the abbreviations by which they are identified in the text hereinafter. The report with the full title "Initial state report for the safety assessment SR-Can" is e.g. referred to as the **Initial state report**. There is also a large number of *additional references*, treating more narrow issues, and that support either the main report or one of the main references. The report hierarchy is illustrated in Figure 2-2.

Furthermore, as mentioned in section 1.6, two of the most fundamental input documents to the SR-Can project are the site descriptive models of the Forsmark /SKB 2005c/ and Laxemar /SKB 2006b/ sites. Also, the site-adapted repository layouts /Brantberger et al. 2006/ and /Janson et al. 2006/, provide necessary input to the project.

Table 2-1. Main references in the SR-Can project. All these reports are available at www.skb.se.

Full title	Abbreviation used when referenced in this Main report	Text in reference list (chapter 14)
FEP report for the safety assessment SR-Can	**FEP report**	**FEP report, 2006.** FEP report for the safety assessment SR-Can, SKB TR-06-20. Svensk Kärnbränslehantering AB.
Initial state report for the safety assessment SR-Can	**Initial state report**	**Initial state report, 2006.** Initial state report for the safety assessment SR-Can, SKB TR-06-21. Svensk Kärnbränslehantering AB.
Fuel and canister process report for the safety assessment SR-Can	**Fuel and canister process report**	**Fuel and canister process report, 2006.** Fuel and canister process report for the safety assessment SR-Can, SKB TR-06-22. Svensk Kärnbränslehantering AB.
Buffer and backfill process report for the safety assessment SR-Can	**Buffer and backfill process report**	**Buffer and backfill process report, 2006.** Buffer and backfill process report for the safety assessment SR-Can, SKB TR-06-18. Svensk Kärnbränslehantering AB.
Geosphere process report for the safety assessment SR-Can	**Geosphere process report**	**Geosphere process report, 2006.** Geosphere process report for the safety assessment SR-Can, SKB TR-06-19. Svensk Kärnbränslehantering AB.
Climate and climate related issues for the safety assessment SR-Can	**Climate report**	**Climate report, 2006.** Climate and climate related issues for the safety assessment SR-Can, SKB TR-06-23. Svensk Kärnbränslehantering AB.
Model summary report for the safety assessment SR-Can	**Model summary report**	**Model summary report, 2006.** Model summary report for the safety assessment SR-Can, SKB TR-06-26. Svensk Kärnbränslehantering AB.
Data report for the safety assessment SR-Can	**Data report**	**Data report, 2006.** Data report for the safety assessment SR-Can, SKB TR-06-25. Svensk Kärnbränslehantering AB.
Handling of future human actions in the safety assessment SR-Can	**FHA report**	**FHA report, 2006.** Handling of future human actions in the safety assessment SR-Can, SKB TR-06-24. Svensk Kärnbränslehantering AB.

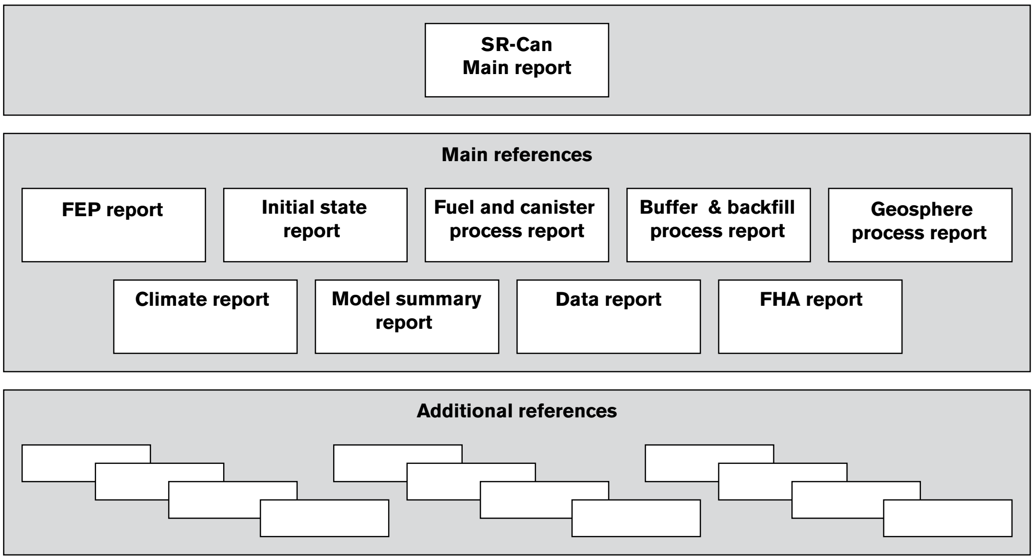


Figure 2-2. *The hierarchy of the reports produced within the SR-Can project. The main references support the main report. The additional references may either support the main report directly or one of the main references.*

2.3 System boundary

The repository system encompasses the spent nuclear fuel, the canisters, the buffer, the backfilled deposition tunnel and other repository cavities, the geosphere and the biosphere in the proximity of the repository, see Figure 1-1. In the development of the SR-Can FEP database (see below), the system boundary was defined in more detail. The following key aspects are taken from that definition.

- In general, a strict boundary definition is neither possible nor necessary, and the same boundaries will not necessarily be relevant to all parts of the safety assessment. The following definitions were the basis for the FEP sorting – and thus have affected the system description.
- Roughly, the portion of the biosphere studied in site investigations, i.e. an area of the order of 100–300 km^2 above the repository, is regarded as part of the system, whereas the biosphere on a larger scale is regarded as external. The analysis of the biosphere extends downward to the surface of the rocks in this assessment. Depending on the analysis context this definition may be somewhat modified.
- Roughly the corresponding portion of the geosphere down to a depth of about 1,000 m is regarded as part of the system. Depending on the analysis context, this definition may also be modified. For example, the local groundwater model, which is the scale most relevant to safety, has a smaller projected surface area than 100 km^2, whereas e.g. larger areas than 300 km^2 and greater depths than 1,000 m may be required for regional groundwater modelling. Boundary conditions for the local groundwater model are provided from such a larger regional model.
- Future human behaviour on a local scale is internal to the system, but not issues related to the characteristics and behaviour of future society at large.

2.4 Timescales

A time scale for the safety assessment needs to be established since this provides a general limit on the scope of the assessment and also cut-off times for e.g. radionuclide transport calculations. The issue is addressed in applicable regulations as cited below.

2.4.1 Regulatory requirements and guidance

The SKI regulations SKI FS 2002:1 state that the safety assessment should cover the period during which the barrier functions are needed, though to at least 10,000 years after closure. The recommendations accompanying the SKI regulation suggest that the timescale of an assessment should be related to the hazard posed by the inventory in comparison with naturally occurring radionuclides. In the recommendations it is also noted that "*...it should also be possible to take into consideration the difficulties of conducting meaningful analyses for extremely long time-periods, beyond one million years...*".

SSI's regulations state that "*For the first thousand years following repository closure, the assessment of the repository's protective capability shall be based on quantitative analyses of the impact on human health and the environment.*" "*For the period after the first thousand years following repository closure, the assessment of the repository's protective capability shall be based on various possible sequences for the development of the repository's properties, its environment and the biosphere.*"

SSI's general guidance states the following regarding a repository for spent nuclear fuel: "*...the risk analysis should at least include approximately one hundred thousand years or the period for a glaciation cycle to illustrate reasonably predictable external strains on the repository. The risk analysis should thereafter be extended in time as long as it provides important information about the possibility of improving the protective capability of the repository, although at the longest for a time period of up to one million years*".

For the time beyond approximately one hundred thousand years, SSI's guidance furthermore state: "*A strict quantitative comparison of calculated risk in relation to the criterion for individual risk in the regulations is not meaningful. The assessment of the protective capability of the repository should instead be based on reasoning on the calculated risk together with several supplementary indicators of the protective capability of the repository such as barrier functions, radionuclide fluxes and concentrations in the environment.*"

2.4.2 Timescale covered by the safety assessment

Apart form the obvious necessity of fulfilling regulatory requirements, arguments relating to the radiotoxicity of the spent nuclear fuel can also be considered when a timescale for a safety assessment is determined.

After approximately 100,000 years, the radiotoxicity of the spent nuclear fuel is comparable with that of the natural uranium ore once used to produce the fuel /Hedin 1997/. Also the sum of toxicity of all fractions in the nuclear fuel cycle is comparable to that of the utilised uranium ore after 100,000 years, see Figure 2-3. The latter comparison is equivalent to comparing the radiotoxicity of the amount of natural U-235 and U-238 consumed in the reactor, to the radiotoxicity of the amounts of the new products created in the reactor (fission products and actinides) remaining after 100,000 years.

Another criterion that may be considered to justify a timescale for a safety assessment is that the period analysed should go beyond the point in time at which peak doses from the repository occur. In SKB's most recent safety assessment for the KBS-3 system, SR 97, the peak dose occurred within one million years in most of the calculation cases. One million years was also the assessment period used in SR 97. However, there are also examples where the peak dose occurs at the end of the assessment period due to in-growth of the naturally occurring nuclide Ra-226 from disposed U-238. Since the KBS-3 concept is aiming at complete isolation of the waste for time periods very far into the future through encapsulation, the peak dose criterion is not considered an appropriate criterion for defining the assessment timescale.

In SR-Can, the timescale for the assessment will be one million years. This timescale is in accordance with the suggestions in SKI's recommendations and in SSI's general guidance cited above. It is furthermore longer than that needed to reduce the radiotoxicity of the inventory to a level comparable with that of the corresponding amount of natural uranium ore. It is also noted that the key radionuclides remaining in the waste beyond one million years are also those, such as U-238, associated with natural uranium ore.

As expressed in the guidance to SSI's regulations, the quantitative risk criterion is applicable as a quantitative regulatory limit during approximately the first one hundred thousand years, and thereafter as a basis for discussing the protective capability of the repository. The risk calculations in SR-Can will, therefore, be extended to one million years, and the results used in accordance with SSI's general advice in the compliance discussion in chapter 13.

However, a brief general discussion of the evolution beyond one million years is also given.

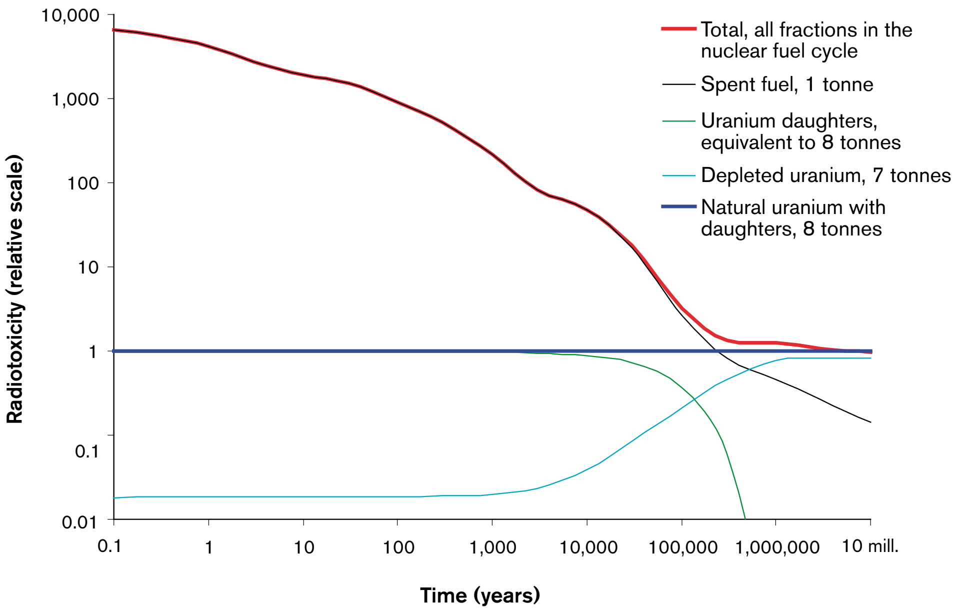


Figure 2-3. *Radiotoxicity on ingestion of uranium ore (blue line), and of the sum of all fractions that arise when the same quantity of uranium mineral is used in the nuclear fuel cycle (red line). The time refers to the time after reactor operation. The different fractions comprise the spent fuel (38 MWd thermal energy/kg U of type SVEA 64 BWR), the depleted uranium and the uranium daughters that are separated in the uranium mill. From /Hedin 1997/.*

2.4.3 Timescales relevant for repository evolution

There are a number of timescales relevant to repository evolution as summarised below.

- A fundamental timescale is that relevant for the decrease of the radiotoxicity of the waste as shown in Figure 2-3. At the time of deposition, the radiotoxicity has decreased by roughly a factor of ten compared with the situation one month after reactor operation, and then continues to decrease by about a factor of ten for every ten-fold increase in time. As mentioned above, the radiotoxicity of the spent nuclear fuel is comparable with that of the natural uranium ore once used to produce the fuel after about 100,000 years.
- The timescale of long-term geological processes, occurring over millions of years, including tectonic movements of continental plates and associated, more or less static, ridge push caused by these movements.
- Climate change occurs on timescales of a few tens of years up to more than one million years. One main timescale relate to the length of glacial cycles, which for the past approximately 700,000 years evolved in 100,000 year cycles. In Sweden each cycle include several episodes of permafrost and glacial conditions. The mechanical, hydraulic and groundwater chemical conditions in the host rock vary in consequence of the climatic evolution, in particular as a result of glacial overriding. It is considered likely that these cycles will in the future be perturbed by human-induced climate changes, but the amount and persistence of such perturbations remains a subject of considerable debate.
- There are a number of timescales on which biological evolution occurs; e.g. man has evolved considerably during the past several hundred thousand years.
- The natural development of ecosystems in general could lead to considerable changes in a 1,000 year perspective. This is e.g. the case for coastal ecosystems in Sweden, that are strongly affected by land-uplift.
- Most aspects of society have changed substantially over the past 100 years and significant changes may occur abruptly or over only a few years. Historical records of humanity cover a few thousand years.
- The thermal evolution of a KBS-3 repository due to the residual power of the fuel results in peak temperatures in the near field after of the order of ten years, and elevated temperatures in the host rock for a few thousand years.
- The resaturation of the buffer, the backfill and the host rock typically requires tens to hundreds of years for Swedish conditions.
- The chemical conditions in the host rock after excavation and operation of a final repository are expected to have largely returned to natural conditions in a 100 or 1,000 year perspective. The chemical conditions in the buffer will change to some degree during the period of elevated temperatures. Canister corrosion under typical repository conditions requires millions of years to cause canister failures.

Timescales is a recurring issue in this report, e.g. in the context of process descriptions, section 6.3, and when analysing repository evolution, chapter 9. The issue of timescales in safety assessments has recently been addressed in an NEA Workshop /NEA 2004a/ in which SKB participated.

2.5 Safety

2.5.1 Safety principles for the KBS-3 repository

Since work on the Swedish final repository project commenced at the end of the 1970s, SKB has established a number of principles for the design of a final repository. The principles can be said to constitute the safety philosophy behind the KBS-3 concept. They are summarised below.

- By placing the repository at depth in a long-term stable geological environment, the waste is isolated from the human and near-surface environment. This means that the repository is strongly affected neither by societal changes nor by the direct effects of long-term climate change on the ground surface.
- By locating the repository at a site where the host rock can be assumed to be of no economic interest to future generations, the risk of human intrusion is reduced.

- The spent fuel is surrounded by several engineered and natural safety barriers.
- The primary safety function of the barriers is to isolate the waste.
- Should isolation be breached, the secondary safety function of the barriers is to retard a potential release from the repository.
- Engineered barriers shall be made of naturally occurring materials that are stable in the long term in the repository environment. The long-term properties of the materials shall be verifiable.
- The repository shall be designed and constructed so that temperatures that could have significant detrimental effects on the long-term properties of the barriers are avoided.
- The barriers should be passive, i.e. they should function without human intervention and without artificial supply of matter or energy.

Together with many other considerations, like the geological setting in Sweden and the requirement that the repository must be feasible to construct from a technical point of view, these principles have led to the development of the KBS-3 system for spent nuclear fuel.

2.5.2 Safety functions and measures of safety

The key safety related features of the KBS-3 disposal system can be summarised in the safety functions isolation and retardation.

The fuel is placed in corrosion-resistant copper canisters with a cast iron insert providing mechanical strength. The copper canisters are surrounded by bentonite clay in deposition holes at a depth of approximately 500 m in the host rock (see Figure 1-1). The bentonite clay protects the canisters from minor rock movements and limits the inflow of the low concentrations of corrosive agents in the groundwater. The host rock provides a long-term chemically, mechanically, thermally and hydrogeologically stable environment for the canisters and the bentonite clay. The canisters, therefore, constitute an isolating barrier with a very long life-time in the environment provided by the buffer and the host rock.

The fuel, the canister, the buffer and the host rock contribute to retarding any potential release of radionuclides should a canister be damaged. The fuel matrix is in itself very stable in the reducing environment at repository depth. Many of the most hazardous radionuclides have a very low solubility in groundwater and thereby have a limited accessibility for outward transport. Both the cast iron insert and the copper canister limit the inflow of water even if damaged. The buffer limits the inflow of water to a damaged canister. It also limits the release of radionuclides by limiting water flow and through sorption. The groundwater moves slowly in the fracture system of the rock nearest to the canisters and many radionuclides have a strong propensity for diffusion into, and sorption in, the host rock matrix.

The fundamental criterion regarding safety is expressed in SSI's regulation SSI FS 1998:1 where it is stated that the aim is to ensure that "the annual risk of harmful effects after closure does not exceed 10^{-6} for a representative individual in the group exposed to the greatest risk". The risk criterion corresponds to effective doses that are roughly one per cent of those due to naturally occurring background radiation.

Results of risk calculations in the safety assessment are compared with this criterion in order to assess compliance. However, the risk results depend in a complex fashion on a large number of factors. In a safety assessment, it is necessary to not only assess compliance with an overall criterion, but also to demonstrate how safety is related to key properties of the barriers and how these properties vary over time. An obvious property is the integrity of the copper canisters. This in turn depends on a number of factors like the buffer properties and the chemical environment of the repository.

In chapter 7, a number of safety function indicators for the barriers are presented and discussed. Criteria are provided for properties like buffer temperature and buffer and backfill density, hydraulic conductivity and swelling pressure. Demonstrating compliance with these criteria provides arguments that the barriers will function as intended as the repository system evolves. Conversely, should a safety function indicator criterion be breached, this signals that safety in one way or the other is potentially jeopardised and that the consequences need to be further considered. However, it does not automatically imply that overall system performance is unacceptable.

Chapter 7 also provides a discussion of alternative "top level" indicators to the risk criterion. The alternative criteria are more directly related to releases from the geosphere and do not require detailed assumptions about biosphere conditions or human habits.

2.6 Expert judgements

Information based on expert judgements of various nature permeates safety assessments. Expert judgements can include anything from a scientist's interpretation of a result of a straightforward experiment to an expert's judgement on the impact of human-induced greenhouse effects on the future climatic evolution or to an assessment of the likelihood of a the occurrence of a particular process/phenomenon that could have an impact on repository evolution. A judgement could consist of anything from a well-justified quantitative or qualitative statement in a report, to an exhaustive and formal questioning of a carefully selected panel of experts using an approved elicitation protocol.

Furthermore, there are issues on which different experts have differing views. In cases where a consensus view or statement cannot be achieved, it is necessary to take the differing views into account in the assessment. This can be done e.g. through the formulation of several calculation cases or by choosing the most pessimistic approach, if such an approach can be shown to exist.

Most of the information based on expert judgements in SR-Can is provided either in the form of reports written by one or several experts or as decisions made by generalists in e.g. the screening of FEPs, the selection of scenarios or the formulation of calculation cases. Formal questioning of a panel of experts has not been employed in SR-Can.

2.6.1 Documentation of expert judgements

For the traceability of the assessment, it is important to clearly state where expert judgements are made and by whom. For this purpose, a database with descriptions of all important experts providing, in one way or another, expert judgements for SR-Can has been developed. A template is used, requiring information on e.g.

- level of education,
- experience in the field,
- scientific publications of relevance to the particular area of expertise,
- role in SR-Can.

References to the appropriate experts represented in the database are then made where the judgements are used in the assessment. In order not to burden the text with numerous references of this nature, these are, for this main report, provided in the preface. For e.g. the process reports, one responsible expert is identified for each process. For the underlying reports, the experts are readily identified as the author(s) of the report in question.

Also, the present and other reports have been subject to scrutiny within SKB and by external reviewers, as documented in the review protocols. These experts are also included in the database.

The database has been established and all contributing experts have been entered. Comprehensive data regarding every expert have, however, not been compiled within the SR-Can project. This is partly due to lack of time, but also for practical reasons, since all entries will have to be updated in the SR-Site project. The incomplete status of the database is seen as acceptable considering the role of SR-Can as a preparatory step towards the fully quality assured SR-Site assessment. The expert database will not be published, but will be made available to reviewing authorities on request.

2.6.2 Selecting experts

In general no formal rules for the selection of experts have been applied. The generalists in the core team of the assessment provide a large fraction of the expert judgements and these individuals have, as is documented in the database, been working with the safety of the KBS-3 system for a number of years and are, therefore, among the most experienced individuals available on the various aspects of the analysis of the system. This does, however, also imply a risk of bias, stressing the importance of external reviews of the material developed within the project, see further section 2.8.

Regarding experts for the documentation of process understanding, for the selection of models or of input data for the quantitative aspects of the assessment, the ambition has been to contract leading experts in the field. The merits of these experts are documented in the database, but there has been no formalised selection procedure. The documentation in the database of the merits of the selected experts is considered to provide a sufficient justification for their involvement.

2.7 Overall information/uncertainty management

A safety assessment handles a vast amount of information of qualitative and quantitative nature, including the uncertainties associated with that information. This section gives an overview of issues related to information and uncertainty management in SR-Can. Since this issue permeates the entire analysis, the overview is, in part, a summary of the different steps of the methodology described in section 2.2, but with emphasis on information/uncertainty management. In all management of uncertainty, it is important to consider the significance of the uncertain issue relative to the purposes of the safety assessment.

As a background, section 2.7.1 gives a brief description of the different types of uncertainty that have to be managed in the safety assessment.

2.7.1 Classification of uncertainties

There is no unique way in which to classify uncertainties in a safety assessment. The classification adopted below is, however, compatible with international practice /NEA 1991, 1997a/ in this type of analysis. SKB has previously discussed the classification and nature of uncertainties in detail, see e.g. /SKB 1996, section 3.4/ and /Andersson 1999, section 2.1/. Here, only a brief outline is given, setting the context for the presentation of the management plan.

The safety assessment is built on the analysis of how a system with an initial state evolves as a result of actions on the system by a number of internal processes and external influences/events. From this description, a number of issues regarding uncertainties can be identified, as listed below.

- How well is the initial state known, qualitatively and quantitatively, i.e. are all important aspects of the initial state identified and how well can they be quantitatively described?
- Have all relevant internal processes been identified in the relevant time frames? How well are they understood mechanistically?
- Have all relevant external events and phenomena been identified? How well can they be quantified?
- How can a representative account of the system evolution be given, taking into account all the types of uncertain factors mentioned above? How well can the internal processes be represented mathematically to give a realistic account of the system evolution? How well are all the input data necessary for the quantification of the system evolution known?

In defining a structure for a rigorous approach to the above issues, it is customary /NEA 1997a/ to describe uncertainty in the categories system/scenario uncertainty, conceptual uncertainty and data uncertainty. A general conclusion from international collaboration efforts in the area of assessment methodology is that there is no unique or correct way to describe or classify uncertainty. Rather, in any safety assessment, it is important to make clear definitions of the use of different terms in this area, in the light of the results from international efforts such as the compilation of lessons learnt from ten performance assessment studies /NEA 1997a/.

In SR-Can, the following broad definitions are used.

System uncertainty concerns comprehensiveness issues, i.e. the question of whether all aspects important for the safety evaluation have been identified and whether the analysis is capturing the identified aspects in a qualitatively correct way, e.g. through the selection of an appropriate set of scenarios. In short, have all factors, FEPs, been identified and included in a satisfactory manner?

Conceptual uncertainty essentially relates to the understanding of the nature of processes involved in repository evolution. This concerns not only the mechanistic understanding of a process or set of coupled processes, but also how well they are represented, and what is not represented, in a possibly considerably simplified mathematical model of repository evolution.

Data uncertainty concerns all quantitative input data used in the assessment. There are a number of aspects to take into account in the management of data uncertainty. These include correlations between data, the distinction between uncertainty due to lack of knowledge (epistemic uncertainty) and due to natural variability (aleatoric uncertainty) and situations where conceptual uncertainty is treated through a widened range of input data. The input data required by a particular model is in part a consequence of the conceptualisation of the modelled process, meaning that conceptual uncertainty and data uncertainty are to some extent intertwined. Also, there are several conceivable strategies for deriving input data. One possibility is to strive for pessimistic data in order to obtain an upper bound on consequences in compliance calculations, another option is the full implementation of a probabilistic assessment requiring input data in the form of probability distributions. These aspects are further discussed in chapter 8 and in the **Data report**.

The plan presented in section 2.7.3 below demonstrates how all the discussed types of uncertainty are managed in the safety assessment.

2.7.2 Need for stylised examples

The inner parts of the system, which provide the safety functions isolation and retardation, are treated most fully in the management of uncertainty, whereas the biosphere and the external conditions are handled in a more stylised manner, i.e. through simplified representations where the important aspects of these sub-systems are captured, often in a pessimistic fashion. These latter parts do not incorporate principal safety related features of the system and they are too complex to be modelled in detail in the safety assessment.

The local biosphere is by definition a part of the system, i.e. it lies within the system boundaries and biosphere uncertainties should thus be managed in the same way as for other internal parts. However, in the biosphere, the list of processes determining the system development is long and the system in which they occur is highly inhomogeneous, including a number of different ecosystems each with a large number of components. Furthermore, the time scale on which the biosphere changes is in general considerably shorter than for other parts of the system, and the interactions with humans are stronger and associated with partly irreducible, large uncertainties. Although some aspects of the development of the biosphere at a particular location can be reasonably forecasted in maybe a 1,000 year perspective, a large part of the description, particularly of human behaviour has to be through stylised examples, see further section 10.2.

Also in relation to the effects of external conditions, uncertainty management largely has to be through stylised examples devised to cover the range of possible future evolutions, e.g. regarding climate change. A detailed treatment of all the processes involved in climatic development is outside the scope of the safety assessment. Climate research is furthermore a rapidly evolving field of science, where uncertainties are fundamental and in part irreducible. The approach is instead to follow the development of the field, and derive a number of stylised possible example evolutions that together give a reasonable coverage of what could be expected in the future. In particular, extreme conditions that could have a negative effect on repository safety are captured in these examples. These conditions include

- maximum glacial overburden and the resulting hydraulic/mechanical pressures and hydraulic/mechanical loads on the bedrock,
- intrusion of waters of extreme composition, such as oxygenated glacial melt water of low ionic strength,
- extreme surface boundary conditions for groundwater flow possibly leading to high groundwater fluxes at repository level or groundwater movements that could cause intrusion of deeply lying saline groundwaters,
- conditions leading to extreme permafrost depths.

2.7.3 Uncertainty management

The purpose of the safety assessment affects the management of uncertainties. In this context, the purpose of the assessment is essentially two-fold:

- to assess compliance with Swedish regulations,
- to give feedback to design, research and development and further site investigations.

The first purpose can, if there are sufficient safety margins, be largely accomplished by a pessimistic handling of many uncertainties. The second, however, requires more sophisticated management in order to determine quantitatively which uncertain factors and open design issues affect safety most.

In the following, the broad features of the management of uncertainties in SR-Can are outlined. QA aspects of the handling are further discussed in section 2.8.

System uncertainty

System uncertainty is generally handled through the proper management of FEPs in the FEP database according to the routines described in the **FEP report** and summarised in chapter 3.

The database structure and FEP management routines have been set up to assure that the following information is obtained.

- A sufficient set of initial conditions. This is obtained by including all initial state FEPs in the database. These are, however, often formulated in general terms and have to be expressed in a way that is specific to the KBS-3 system. This is done through the systematic documentation of a reference initial state in accordance with the description in the **Initial state report** and by using that reference initial state as a starting point for alternative initial states.
- A sufficient set of internal, coupled processes. This is obtained by including in the assessment all relevant process FEPs in the database. It is important to note that the database already from the start includes the result of several earlier exercises aiming at process identification for the KBS-3 concept. This is further described in section 6.1.1. Influences between processes are handled, in the **Process reports**, by systematically going through a set of defined physical variables that could mediate influences and by the systematic treatment of boundary conditions for each process. These procedures are further described in section 6.3. Hence, in addition to including FEPs describing influences and couplings, the procedures for process documentation are set up in a way that enforces a systematic search for such influences.
- A sufficient set of external influences. This is obtained by including in the assessment all relevant external FEPs and by structuring the documentation of these in the **Climate report** in a format similar to that used for the internal processes, see further chapter 5.

Scenario selection

Another aspect of system uncertainty concerns the selection of a sufficient set of scenarios, through which all relevant FEPs are considered in an appropriate way in the analysis. The selection of scenarios is a task of subjective nature, meaning that it is difficult to propose a method that would guarantee the correct handling of all details of scenario selection. However, several measures have been taken to build confidence in the selected set of scenarios:

- A structured and logical approach to the scenario selection, see further chapter 11.
- The use of safety function indicators in order to focus the selection on safety relevant issues, see chapter 7.
- The use of bounding calculation cases to explore the robustness of the system to the effects of alternative ways of selecting scenarios, including unrealistic scenarios that can put an upper bound on possible consequences.
- QA measures to ensure that all FEPs have been properly handled in the assessment.
- The use of external reviews.

Conceptual uncertainty

The handling of conceptual uncertainty for internal processes is essentially described in the **Process reports**. For each process, the knowledge base, including remaining uncertainties, is described and, based on that information, a handling of the process in the safety assessment is established. (Uncertainty regarding influences between processes can be seen as either system uncertainty or conceptual uncertainty, it is described as system uncertainty above.)

Through the use of a defined format for all process descriptions, see section 6.3, it is assured that the processes and their associated conceptual uncertainties are described in a consistent manner. External reviews of central parts of the process documentation have also been performed.

Conceptual uncertainty for external influences is handled in a more stylised manner, essentially through the definition of a sufficient set of scenarios and by using state-of-the-art models for the quantification of external influences, e.g. ice models for the modelling of glacial cycles. Another method is the use of bounding cases that ensure that the consequences are overestimated.

Data uncertainty

Data uncertainties are handled according to the routines described in chapter 8 and further in the **Data report**.

Quality assurance is obtained through the use of a template for data uncertainty documentation, through clearly defined roles for participating experts and generalists and by the use of external reviews prior to finally establishing input data for the assessment.

Modelling

An essential part of the assessment concerns the quantification of both repository evolution and dose and risk consequences through mathematical modelling. Apart from requiring appropriately defined models that represent relevant conceptualisations of the processes to be modelled and quality assured input data, this step requires:

- good model documentation, including results of code verification and results of benchmarking against other models,
- procedures to detect and protect against human error in the execution of the models.

A dedicated **Model summary report**, compiled according to a pre-established template describes models used in the assessment and provides references to more detailed descriptions of the models, including quality assurance aspects. The mapping of processes to models, see chapter 6, provides an overview of the models used. A guiding principle is that models and data should be documented in sufficient detail to allow calculations to be reproduced and audited.

Human errors can be minimised e.g. by formal procedures for checking that input data are correct and by the use of alternative, often simplified, models for crucial aspects of quantification. An example of the latter is given in calculations of radionuclide transport and dose in chapter 10.

Integrated handling of uncertainties

The overall management of uncertainties is closely related to the selection of a sufficient set of scenarios and to the way all types of uncertainties are handled in the subsequent analysis of these. The handling of uncertainties is therefore revisited and further developed in section 11.5, following a description of the method for scenario selection.

Another general issue relating to the integrated handling of uncertainties is the use of deterministic or probabilistic approaches. Most of the calculations in SR-Can are deterministic. Probabilistic calculations are used essentially as a means of handling data uncertainty and spatial variability in modelling radionuclide transport and dose.

2.8 Quality assurance

SKB applies a management system that fulfils the requirements of ISO 9001:2000 and that has been certified by DNV Certification AB, Sweden. In accordance with SKB's procedures for project management, described in the management system, a quality assurance plan for the SR-Can project has been developed and partially implemented.

It is noted that, due to time constraints, the QA plan has not been fully implemented in SR-Can. Within SR-Can, what has been done is to establish all routines, to implement most of them and to undertake review of all routines and specific examples of their implementation. The SR-Site assessment, for which a full QA plan must be implemented throughout, will require some revision of the QA routines presented here, to fit the context in which that project will be carried out.

The QA of the repository engineering layout work is described in the Deep Repository Underground Design Premises document /SKB 2004b/, UDP/D1. It defines the project organisation, roles and responsibilities including interfaces with site modelling and safety assessment as well as interfaces between client-design coordinator, design coordinator – designer and design coordinator – reviewer. UDP/D1 contains QA instructions aiming at "doing the right things", "doing things the right way" and for checking and review of the design results.

The QA of the site descriptive modelling work is conducted in accordance with a QA-plan developed for site characterisation and site modelling work. For each model version, project plans are prepared defining, among other things, the project organisation, roles and responsibilities and the steering documents that are applicable for the work. Examples of important steering documents for site modelling are instruction for handling of quality assured field data collected in the SKB database Sicada and the SKB Geographic Information System (GIS), and instructions for handling of quality assured, discipline-specific site models that are stored in the SKB model database Simone.

The following text is based on the introductory sections of the SR-Can QA plan.

2.8.1 General

In broad terms, a QA plan for a long-term safety assessment of a spent nuclear fuel repository aids in assuring that all relevant factors for long-term safety have been appropriately included and handled in the safety assessment. Although no QA system will rigorously prove that this is the case, a purpose-designed QA plan and QA system will assist the implementer in carrying out the safety assessment in a structured and comprehensive manner and aid a reviewer in judging the quality and comprehensiveness of the assessment.

A principal purpose of a safety assessment of a final repository is to investigate whether the repository can be considered radiologically safe over time. In principle, this is established by comparing estimated releases and associated radiation doses with regulatory criteria.

A large number of factors affecting long-term safety need to be handled in the assessment in a quality assured manner. These factors, or features, events and processes, FEPs, are collected in a database that is also used as a QA instrument. The FEP database and underlying reports demonstrate how specific FEPs are included in the assessment or why they have been excluded.

The handling of many of the FEPs occurs in modelling of the repository evolution. This requires a scientific evaluation of the understanding of the processes involved in the modelling, the formulation of mathematical models that simulate the process or system of coupled processes based on the understanding of the phenomena, the translation of the mathematical model into a computer code, derivation of input data and execution of the code. All these aspects need to be documented and quality assured.

Central parts of the QA plan thus relate to the FEP database and to the quantitative treatment of repository evolution. The parts of the Swedish Nuclear Power Inspectorate's regulation SKIFS 2004:1 that relate to independent review are applicable to a safety assessment for a formal licence application for a final repository. Since SR-Can will not be used for a licence application, these aspects are not addressed in the QA plan.

In establishing the SR-Can plan, the ISO 10005 standard "Quality management – guidelines for quality plans" has been use as an overall guide.

2.8.2 Objectives of the QA plan

The objective of the QA plan is to ensure that all relevant factors for long-term safety have been appropriately included and handled in the safety assessment SR-Can. In particular, it has been designed to aid in demonstrating:

- that adequate project management procedures, procedures for documentation, etc have been followed in the project,
- that all factors relevant for long-term safety occurring in earlier version of SKB databases and in the international NEA FEP database have been considered in the assessment,
- that the exclusion of any of these factors is well justified by identifiable experts,
- that the approaches adopted to handling of included factors are well justified by identifiable experts,
- how quantitative aspects of the assessment are handled by mathematical models and how the models (computer codes) have been quality assured,
- how appropriate data for quantitative aspects of the assessment have been derived and used in the assessment in a quality-assured manner,
- how the safety assessment reports have been properly reviewed and approved for correct and complete content.

2.8.3 SR-Can steering documents

A number of steering documents for the SR-Can project are established in the QA plan. These documents are listed in Table 2-2 and are available in an SR-Can project archive. For instance, the QA plan is item 4 in Table 2-2.

As mentioned, the QA-plan and its associated routines will be updated for the SR-Site assessment and adapted to the QA routines applicable in the larger project of which SR-Site will be a sub-project.

2.9 Approach to risk calculations

2.9.1 Regulatory requirements and guidance

The quantitative acceptance criterion in Sweden for long-term safety of a nuclear waste repository is a limit on annual risk. SSI FS 1998:1 states the following: "A repository for spent nuclear fuel or nuclear waste shall be designed so that the annual risk of harmful effects after closure does not exceed 10^{-6} for a representative individual in the group exposed to the greatest risk." The conversion between effective dose and risk is to be carried out using ICRP's probability coefficient for cancer and hereditary effects of 0.073 per Sievert. An annual risk limit of 10^{-6} thus corresponds to an effective dose limit of about $1.4 \cdot 10^{-5}$ Sv/yr.

SSI's general guidance state the following: "The individual risk should be calculated as an annual average on the basis of an estimate of the lifetime risk for all relevant exposure pathways for every individual."

As already mentioned in section 2.4, according to the guidance to SSI's regulations, the quantitative risk criterion is applicable as a quantitative regulatory limit during approximately the first one hundred thousand years, and thereafter as a basis for discussing the protective capability of the repository.

It is furthermore important to note that scenarios relating to future human actions should not be included in the risk calculation according to SSI's general guidance.

2.9.2 Application in SR-Can

This section describes some basic aspects of how SSI's risk criterion has been implemented in SR-Can. Most of the material below has been presented and discussed at an NEA Workshop on the role of risk in safety assessments /NEA 2005/ and at an international conference on probabilistic safety assessment and management /Hedin 2004a/.

Table 2-2. Steering documents for the SR-Can project.

Item	Object	Language
1.	Project decision	Swedish
2.	Project plan	Swedish
3.	Project risk analysis	Swedish
4.	Quality assurance plan	English
5.	Time plan	English
6.	Reports of project QA audits	Swedish
7.	List of regulatory review reports on previous safety assessments to be considered in SR-Can	English
8.	Expert database	English
9.	Review plan for SR-Can reports	English
10.	Template for review comments	English
11.	Instructions for handling the FEP database	English
12.	Instructions for developing SR-Can process descriptions	English
13.	Template for model documentation	English
14.	Procedures for quality assurance of input data	English

Scenario disaggregation

In principle, the product of dose consequences and likelihoods of all possible future evolutions of the repository should be weighed together and presented as a time-dependent risk. The spectrum of possible evolutions is, however, very wide and cannot be captured in a detailed sense. This is also recognised in SSI's regulations and associated general guidance.

The usual approach taken in safety assessments, and also in SR-Can, is to work with scenarios and variants that are designed to capture the broad features of a number of representative possible future evolutions. Together, these are intended to give a reasonable coverage of possible future exposure situations. Conditional risks are calculated for each scenario and variant and these are then weighed together using the probability for each scenario/variant. Furthermore, each variant, represented by a specific calculation case, may be evaluated probabilistically in order to determine the mean exposure given the data uncertainties for the particular variant.

The approach of calculating risk as a weighted sum over a number of scenarios constrains the way in which scenarios are selected and defined. It must be possible to logically explain the determination of probabilities. In short, the scenarios should be mutually exclusive, and the set of scenarios comprehensive in the sense that all relevant future evolutions are covered.

A "normal evolution" scenario with a high probability of occurrence must e.g. contain initially defective canisters and other barrier insufficiencies, if such are likely when the entire ensemble of canisters and deposition holes in the repository is considered. Furthermore, in evaluating less likely scenarios treating disruptive events during the course of repository evolution, the consequences of these need to be superimposed on those of the normal evolution scenario. This does not mean that the calculation case for the latter must include also the normal evolution, but it must be possible to superimpose the two in order to correctly represent the disruptive scenario in the final risk calculation.

Since SSI's general guidance states that the risk criterion concerns a repository undisturbed by man, scenarios involving direct intrusion into the repository are excluded from the risk summation. Also human actions that disturb the immediate environment of the repository, e.g. the local groundwater flow field, are considered in the treatment of future human actions in section 12.10, but excluded from the risk summation.

Overestimation of risk

The formulation of scenarios, variants and calculation cases, and the subsequent weighing together of these to give a total risk aims at an over prediction of risk. SSI's regulation requires that the annual risk should be less than 10^{-6}. There are a number of uncertainties that cannot be managed quantitatively in any other rigorous manner from the point of view of demonstrating compliance than by pessimistic assumptions. An example is the handling of uncertain immobilisation phenomena in the geosphere. The present knowledge base, in combination with the modelling capacity for consequence calculations, does not allow credit to be taken for such processes in estimating the safety of a repository and they have to be pessimistically neglected.

Another situation in which risk has to be overestimated concerns scenario probabilities. Regarding e.g. future climate, both repetitions of past 100,000 year glacial cycles and an alternative where this development is considerably perturbed by a greenhouse effect can be envisaged. Although the two are mutually exclusive, both must be regarded as likely. In the risk summation, the logical position is adopted that the summed consequence of a set of mutually exclusive scenarios can, at any point in time, never exceed the maximum of the individual scenario consequences. For scenarios and variants where defensible probabilities are difficult to derive, a scenario or variant giving high consequences can pessimistically be assigned unit probability and other scenarios and variants yielding lower dose impacts can be "subsumed" under the one with the more severe consequences.

Although the primary aim with risk calculations is to demonstrate compliance, there is also the clear ambition of clarifying the sensitivities of the calculation results. For this aim, the calculation cases should, in principle, be as realistic as possible in capturing uncertainty. One quantitative tool for this is the use of probabilistic evaluations of calculation cases followed by sensitivity analyses of the results.

It is concluded that pessimistic simplifications should be avoided where a sound scientific basis exists for a quantitative treatment and further that the pessimistically neglected features of the system should be included in a discussion of sensitivities.

Size of the exposed group

The size of the group to which the above risk limit is to be applied must be defined in order to evaluate compliance with the risk criterion. No detailed definition is given in SSI FS 1998:1. In its general guidance SSI however states the following: "*One way of defining the most exposed group is to include the individuals that receive a risk in the interval from the highest risk down to a tenth of this risk. If a larger number of individuals can be considered to be included in such a group, the arithmetic average of individual risks in the group can be used for demonstrating compliance with the criterion for individual risk in the regulations. One example of such exposure situation is a release of radioactive substances into a large lake that can be used as a source of drinking water and for fishing.*"

SSI's general guidance also consider the case of small groups: "*If the exposed group only consists of a few individuals, the criterion of the regulations for individual risk can be considered as being complied with if the highest calculated individual risk does not exceed 10^{-5} per year. An example of a situation of this kind might be if consumption of drinking water from a drilled well is the dominant exposure path. In such a calculation example, the choice of individuals with the highest risk load should be justified by information about the spread in calculated individual risks with respect to assumed living habits and places of stay.*"

The detailed application of these two options in SR-Can is further developed in connection with the consequence calculations in chapter 10.

Time frames

Risk calculations will be carried out for a one million year time frame in SR-Can. In accordance with SSI's general guidance, strict compliance with the risk limit will be evaluated in a 100,000 time frame. For longer times, the results of the risk calculation will be used to discuss the protective capability of the repository and how this capability can be improved, also in accordance with SSI's general guidance.

Time dependent risk or peak over entire assessment period?

In SKB's most recent safety assessment, SR 97, an upper bound on the peak of the time dependent risk was calculated in the following way for a particular probabilistic calculation case: In each realisation, the peak annual effective dose[4] over the one million year assessment period was determined. The mean value of the so determined distribution of peak doses was then compared with the effective dose criterion. While this is a correct way of putting an upper bound on risk, it is more informative and also in agreement with the regulations SSI FS 1998:1 and SKIFS 2002:1 to calculate the mean annual effective dose at each point in time and require that this quantity never exceeds the effective dose corresponding to the risk criterion of 10^{-6}. The two methods are sometimes referred to as "the mean of the peaks" and "the peak of the mean". The "peak of the mean" interpretation is meaningful in the sense that all exposure pathways to hypothetical individuals living in the future are considered whereas the "mean of the peaks" concept is more difficult to interpret. In SR-Can, risk as a function of time is presented by weighing together the time-dependent mean annual effective doses from each scenario to obtain a time-dependent risk. An example of the two types of results is given in Figure 2-4.

Risk dilution

The term "risk dilution" is sometimes used to denote a situation where a higher degree of uncertainty in input parameters, i.e. a broader input distribution, leads to a lower mean value of an output quantity e.g. mean dose or risk /NEA 1997b/. A seemingly paradoxical situation arises where less knowledge implies a safer repository if the mean value to a highly exposed individual at a certain point in time is used as the safety indicator. Less knowledge will spread the dose over more individuals and over longer times. The total exposure to all individuals over all times could be the same or larger, whereas more precise knowledge will "concentrate" the risk to fewer individuals and shorter periods of time. This can e.g. be the case when there is uncertainty concerning the time of an event that would lead to canister rupture. The dose consequence for a given time could then depend strongly on the assumed time at which the rupture occurred. Averaging over alternative situations in which canister rupture and thus peak dose occurs at different points in time would reduce the resulting mean value at any point in time and more so the larger the span of possible rupture times.

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[4] The annual effective dose is the sum of the annual effective dose from external exposure and the annual committed effective dose from internal exposure.

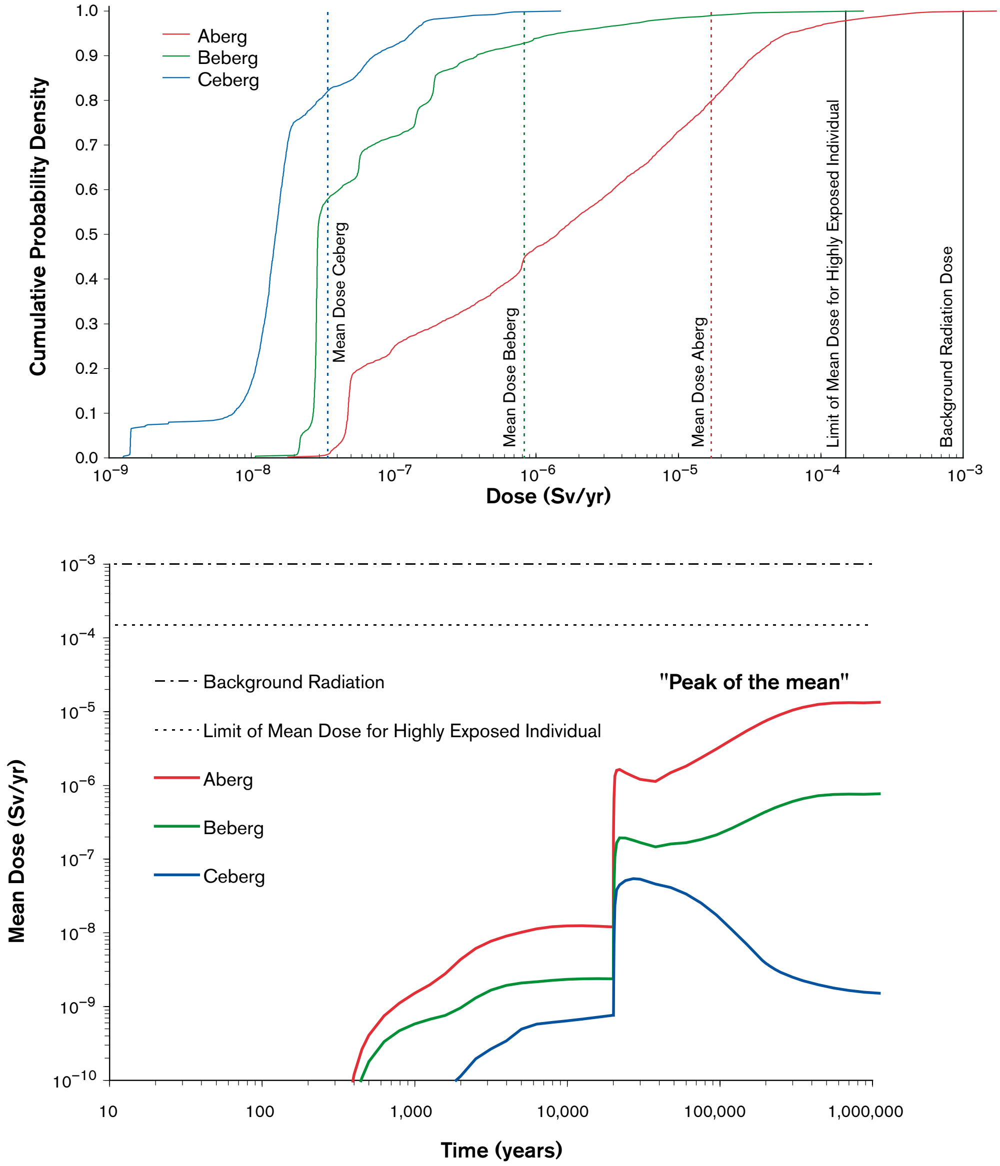


Figure 2-4. *Probabilistically determined peak dose distribution for the three sites analysed in SR 97 (upper) and probabilistically determined mean doses as a function of time for the sites (lower). Both figures are derived from the results of the same probabilistic calculation.*

This effect is inherent in the concept of risk as defined in SSI's regulation and is thus an inevitable consequence of a risk criterion which is to be applied as a function of time and where the quantity to be determined is the mean value considering all relevant uncertainties. Therefore, SSI's general guidance also requires that the issue of risk dilution is addressed when the consequences of releases from the repository are assessed.

A related phenomenon concerns biosphere development during the expected long periods of permafrost or glacial conditions. To illustrate, it is assumed that appreciable doses to man could occur only during temperate periods, and that these periods, as suggested by historical evidence relevant to Sweden, in the long run will prevail in total during about ten percent of the time, but that the temporal location of these temperate intervals cannot be predicted beyond, say 10,000 years into the future. In principle, this situation could be handled by simulating a number of future situations where the onsets of the temperate periods are allowed to vary randomly beyond 10,000 years. Averaging over all these results would, at each point in time beyond 10,000 years, yield a dose consequence a factor of ten smaller than that obtained during a temperate climate period. This simplistic example demonstrates another type of risk dilution, again caused by an uncertainty in the point in time of the occurrence of a phenomenon, which could in principle be compatible with the Swedish risk criterion. The effect will however be avoided in the safety assessment e.g. by assuming the same temporal sequence of climate types in each simulation or by assuming today's biosphere.

For SR-Can several conclusions are drawn from the above, as set out below.

- A broader input data distribution is not necessarily pessimistic, not even if it is broadened towards the high consequence end. Thus, care must be taken in assigning input data distributions so that input data distributions that might influence the calculation end-point in this way are not unduly broadened.
- Disaggregated calculations and disaggregated discussions of the results of more integrated calculations are necessary from the point of view of capturing risk dilution and such calculations and discussions are, therefore, included in SR-Can. A simple but effective means of avoiding risk dilution when its cause has been identified is to illustrate the effect by replacing probabilistic input data of e.g. canister rupture times with a fixed time. This is the main approach taken in SR-Can.
- Another option for capturing risk dilution effects is to complement a "peak of the mean" calculation with a "mean of the peaks" calculation, as described in the previous section.

2.9.3 Alternative safety indicators

The dose/risk safety indicator provides a measure of radiological impact on future humans due to the existence of the repository. Several aspects of biosphere development are highly uncertain, even over a relatively short time perspective. The evaluation of safety depends on a number of assumptions made in order to handle these uncertainties. It is, therefore, of interest to complement the dose/risk indicator with alternative indicators that do not require detailed assumptions about the biosphere or concerning human habits.

The recommendations accompanying SKIFS 2002:1 mention that, for distant futures, the dose indicator can be complemented with other safety indicators, e.g. concentrations in groundwaters or near-surface waters of radionuclides from the repository or the calculated fluxes of radionuclides to the biosphere.

A problem with alternative indicators is that there is, in general, no obvious criterion with which the calculated quantities can be compared. In some cases, calculation results can be compared with natural concentrations or fluxes at the site or elsewhere. However, such criteria do not provide points of reference for man-made radionuclides. The problem can be partly overcome by comparing naturally occurring sum concentrations/fluxes of α- and β-emitters to the corresponding repository related quantities, or by comparing overall toxicities by scaling by dose per unit intake values.

EU SPIN Project

An EU project /EU 2002/ concludes that two alternative indicators could preferably be used to complement the dose indicator. These are:

- Radiotoxicity concentration in biosphere water: preference for medium time frames, i.e. several thousand to several tens of thousands of years.
- Radiotoxicity flux from the geosphere: preference for late time frames.

The project also reports on reference values that could tentatively be used for comparisons to calculated concentrations and fluxes of radionuclides from the repository.

Finnish activity release constraints

The Finnish Radiation and Nuclear Safety Authority STUK has issued activity release constraints to the environment /STUK 2001/.

These nuclide specific constraints are defined for long-lived radionuclides only. The effects of their short-lived progeny have been taken into consideration in the constraints defined for the long-lived parents. The nuclide-specific release rate constraints are

- 0.03 GBq/y for the long-lived α-emitting isotopes of Ra, Th, Pa, Pu, Am, Cm,
- 0.1 GBq/y for Se-79, I-129, and Np-237,
- 0.3 GBq/y for C-14, Cl-36, Cs-135, and the long-lived isotopes of U,
- 1 GBq/y for Nb-94 and Sn-126,
- 3 GBq/y for Tc-99,

- 10 GBq/y for Zr-93,
- 30 GBq/y for Ni-59,
- 100 GBq/y for Pd-107 and Sm-151.

The constraints apply to activity releases that arise from the expected evolution scenarios and that may enter the environment after several thousands of years, whereas dose rate constraints are applied in the shorter term. In applying the above constraints, the activity releases can be averaged over 1,000 years at the most. The sum of the ratios between the nuclide-specific activity releases and the respective constraints shall be less than one. It should be noted that the Finnish regulator has derived these constraints partly based on a set of reference biospheres considered possible in the future at the planned disposal site, Olkiluoto at the coast of the Baltic Sea, and partly on natural fluxes of radionuclides established for similar environments. The reference values of the Finnish regulatory guide are thus not directly applicable for other disposal concepts and sites /EU 2002/. However, both the disposal concept and the sites considered in Sweden are similar to those for which the Finnish activity release constraints have been developed.

Other studies

An SKI/SSI study /Miller et al. 2002/ compiled from the published literature a substantial database of elemental abundances in natural materials and, using these data, calculated a range of elemental and activity fluxes arising due to different processes at different spatial scales. The authors conclude that these fluxes should be comparable to results from safety assessment calculations.

IAEA has published a study entitled "Safety Indicators in Different Time Frames for the Safety Assessment of Underground Radioactive Waste Repositories" /IAEA 1994/ and is currently conducting a research programme on natural concentrations and fluxes.

Implications for SR-Can

As one alternative indicator, the Finnish activity constraints are used in SR-Can. These constraints are strictly applicable only in the Finnish regulatory context, but still deemed useful as an alternative indicator for SR-Can. Also, measured concentrations of naturally occurring radionuclides in ecosystems at one of the candidate sites will be used as an alternative indicator. See further section 10.5.6.

3 FEP processing

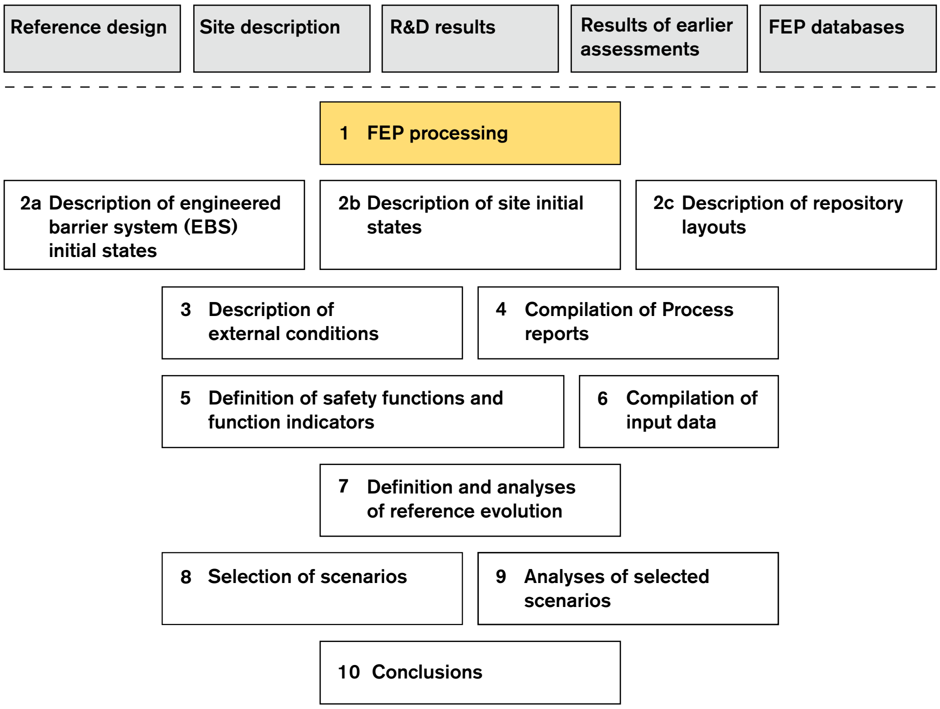


Figure 3-1. *The SR-Can methodology in ten steps (section 2.2), with the present step highlighted.*

3.1 Introduction

Much of the methodology described in the previous section is related to the handling of FEPs through the different steps of the safety assessment. This section describes in more detail how FEPs are handled throughout the assessment and the various tools used to ensure systematic and comprehensive handling.

A main aim in the FEP handling was to establish a catalogue of FEPs that needed to be addressed in the SR-Can assessment.

3.2 SKB FEP database

An important and formal tool for ensuring that all relevant factors have been considered in the safety assessment is provided by available databases of features, events and processes (FEPs) relevant to long-term safety of nuclear waste repositories. An SKB FEP database has been developed for SR-Can, as described in the **FEP report**. This FEP database builds on the outcome of the FEP work conducted in SKB's most recent major safety assessment, the SR 97 assessment, as reported in the SR 97 Process report /SKB 1999b/ and the supporting documentation of the Interaction matrices developed for a deep repository of the KBS-3 type /Pers et al. 1999/.

In the SR 97 Process report, comprehensive sets of long-term processes relevant to repository safety for each of the system components, i.e. fuel, canister, buffer/backfill and geosphere, were identified. For each component, a set of variables needed to describe the evolution of the state of the component over time was also established. As a first step in the development of the SKB FEP database, these identified processes and variables were collected in an SR 97 FEP database, forming an important starting point for the SR-Can FEP handling.

The SR 97 database was then systematically compared with other national databases included in the NEA international FEP database, to ensure that all relevant factors were taken into account. In the SKB FEP database, all items have been classified as one of the following:

- Processes within the system boundaries relevant to long-term safety and the system component specific variables required to describe the state of the component at a specified point in time.
- Factors affecting the initial state of the repository, either directly related to a specific aspect or to the initial state in general.
- External factors relevant to long-term safety, e.g. evolution of climate and climate related issues, and human intrusion.

Most FEPs in the NEA database could be mapped to one of these categories. All other FEPs were characterised as general methodology issues or determined to be irrelevant for the KBS-3 system.

The SKB FEP database thus encompasses the SR 97 processes and variables, all FEPs in the NEA database and in the national databases linked to the NEA database, including the classification and characteristics of these FEPs. A more detailed description of the SR-Can version of the SKB FEP database is given in the **FEP report**.

3.3 SR-Can FEP catalogue

Based on the FEP processing described above, an SR-Can FEP catalogue, containing all FEPs that needed to be handled in SR-Can, was established. It is thus fundamentally a subset of FEPs in the SKB FEP database, but considerable restructuring, differentiation and lumping of FEPs was required in order to obtain a catalogue suitable for the SR-Can assessment.

The categories of FEPs in the catalogue are the following:

- Initial state FEPs.
- Processes in fuel, canister, buffer, backfill and geosphere.
- Variables in fuel, canister, buffer, backfill and geosphere.
- Biosphere FEPs.
- External FEPs.
- Methodology issues.

The FEP catalogue also contains preliminary FEPs for system components that are not treated in detail in SR-Can. These components are tunnel plugs, backfill materials for cavities other than the deposition tunnels, the bottom plates in the deposition holes and borehole seals. These components are treated with simplified assumptions in SR-Can and the handling will be developed to a more comprehensive level in SR-Site.

Furthermore, there is a possibility to enter in the FEP catalogue any issue that is, for whatever reason, identified as relevant for the SR-Can analysis. Such entries could e.g. be issues identified in the preliminary safety evaluations of the sites, see section 1.1.1. Such examples for the Forsmark site include the potential impact of nearby nuclear power plants and the power cable to Finland and the effect of a deep mine excavation near, but outside of, the tectonic lens at Forsmark. These issues are sorted as other FEPs into one of the above categories.

In the following, each category is briefly described.

Initial state FEPs

This category describes deviations from the intended initial state as a consequence of undetected mishaps, sabotage, repository left open, etc. These are propagated to the selection of scenarios described in chapter 11. (The intended initial state with tolerances, the reference initial state, is one of the bases for a main scenario. This is described in the **Initial state report** and summarised in chapter 4. In the FEP catalogue, each variable record, see below, contains also a link to the description of the reference initial state for that variable.)

Processes

These FEPs are long-term processes relevant to repository safety for each of the system components fuel, canister, buffer, backfill and geosphere. A few internal processes for the engineered barriers or the geosphere were added to those identified in the SR 97 assessment, as a result of the auditing against the NEA database. All internal processes are comprehensively documented in a number of process reports, see further chapter 6. The handling of all processes are summarised in process tables, given in chapter 6. There are typically around 20 processes for each system component.

Variables

These FEPs are the variables needed to describe the evolution of the state of the fuel, canister, buffer, backfill and geosphere over time. They are thus essentially tables with definitions. The identification of variables has been done by the experts responsible for the documentation of the processes relevant for long-term safety. The sets of variables were established in conjunction with the documentation of the processes, since it had to be ensured that the variable sets were suited to describing all conceivable alterations of the barrier properties as a result of the long-term processes. There are typically around 10 variables for each system component. In the FEP catalogue, each variable contains a link to the description of the reference initial state for that variable.

The handling of influences between process and variables is described in section 3.4.

Biosphere FEPs

Biosphere processes were not included in the SR 97 Process report and there is, therefore, not the same basis for updating these descriptions as for the engineered barriers and the geosphere. All biosphere FEPs, most of which are processes, have, therefore, been collected in a single category. The further handling of these is described in a Biosphere Process report, see further section 6.1.2.

External FEPs

External FEPs in the NEA database were subdivided into the categories:

- Climate related issues.
- Large-scale geological processes and effects.
- Future human actions.
- Other.

It was checked that all relevant external FEPs were included in the plans for managing these issues in SR-Can. Climate related and large-scale geological FEPs were compared against the plans for modelling these phenomena and the characterisation of future human actions was compared with that in SR 97, which forms the basis for the approach in SR-Can. These checks are recorded in the FEP database and in table format in the **FEP report**. In the category “other”, only meteorite impact was identified and addressed, see further section 5.1.

Methodology issues

A number of relevant issues relating to the factual basis for the assessment and to the methodology of the assessment were identified in the NEA FEP database. Most of these are of a very general nature, but were for the sake of comprehensiveness also propagated to the SR-Can FEP catalogue.

3.4 Couplings

FEPs are coupled in several ways and on several levels. Couplings between processes and variables occur within a system component and the system components influence each other in several ways. The following is a description of different types of couplings and tools used to document and visualise them.

Influence tables

Within a system component, each process is influenced by one or several of the variables describing the state of the component and the process, in turn, influences one or several of the variables. These couplings within a system component are described by influence tables, one for each process in the process report. A distinction is made between influences that exist in principle but are sufficiently insignificant to be neglected in the safety assessment and those that require a detailed treatment. The handling of the latter category is explicitly mentioned when the handling of the process in question is established in the process reports. See section 6.3 for an example of an influence table. The influence tables are fed back to the FEP catalogue from the process reports.

Process diagrams

Based on the sets of variables and processes and the influences between them, a process diagram can be constructed for each system component. This is done in the FEP database. The diagram essentially takes the form of a table with the processes as lines and the variables as columns. The table matrix consists of arrows describing the influences between processes and variables.

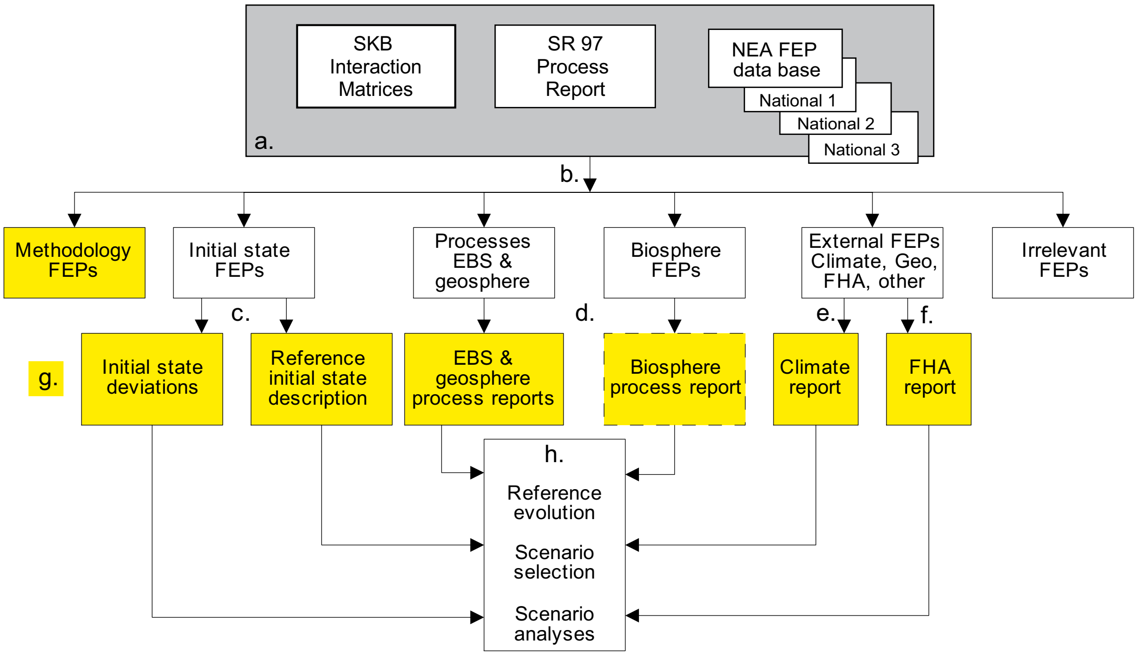
AMF, model summary report

When evaluating repository evolution, a number of coupled or interacting models are utilised. This set of models and the dependencies/interactions between them are described by two assessment model flow charts. One concerns the excavation/operation and initial temperate period and one represents permafrost and glacial conditions. These are further described in section 6.5. A **Model summary report** describes the models represented in the AMFs.

FEP chart

On a higher level, it is desirable to have an instrument providing an overview of how critical initial state factors, variables, processes and external factors influence the safety functions of the repository. To serve this purpose, a FEP chart has been developed. This is further described in section 7.6, following a discussion on repository safety and the definition of a number of safety function indicators.

The handling of FEPs in SR-Can is summarised in Figure 3-2.



a. The starting points for the SR-Can FEP handling are FEPs in i) the SKB interaction matrices, ii) the SR 97 processes as documented in the SR 97 Process Report and iii) the NEA international FEP database with a number of national data bases linked to it.

b. FEPs were sorted into three main categories: i) initial state, ii) process and iii) external FEPs. FEPs were also categorised as irrelevant or as being related to methodology at a general level.

c. Initial state FEPs were either i) included in the initial state description in SR-Can, i.e. the reference description of the KBS-3 repository, the site description or the site-specific layout of the repository or ii) categorised as initial state deviations to be further handled in scenario selection.

d. Process FEPs were used to update the SR 97 set of internal processes for the EBS and the geosphere. The resulting SR-Can set of processes are documented in the SR-Can Process reports. A first version of a Biosphere Process report is being produced.

e. The handling of external FEPs related to long-term climate changes is documented in the SR-Can Climate report. The few external, large-scale geosphere FEPs are addressed in the geosphere process report.

f. The handling of external FEPs related to future human actions (FHA) is developed in the SR-Can FHA report. The only "other" external FEP, meteorite impact, was dismissed as being extremely unlikely.

g. The FEPs handled in the yellow boxes constitute the SR-Can FEP catalogue.

h. The reference initial state, all long-term processes and a reference external evolution is used to define a reference evolution for the repository system. This evolution is an important basis for a comprehensive main scenario. A set of additional scenarios address e.g. deviations from the reference initial state and from the reference external evolution as well as situations related to FHA.

Figure 3-2. *The handling of FEPs in SR-Can.*

4 Initial state of the repository

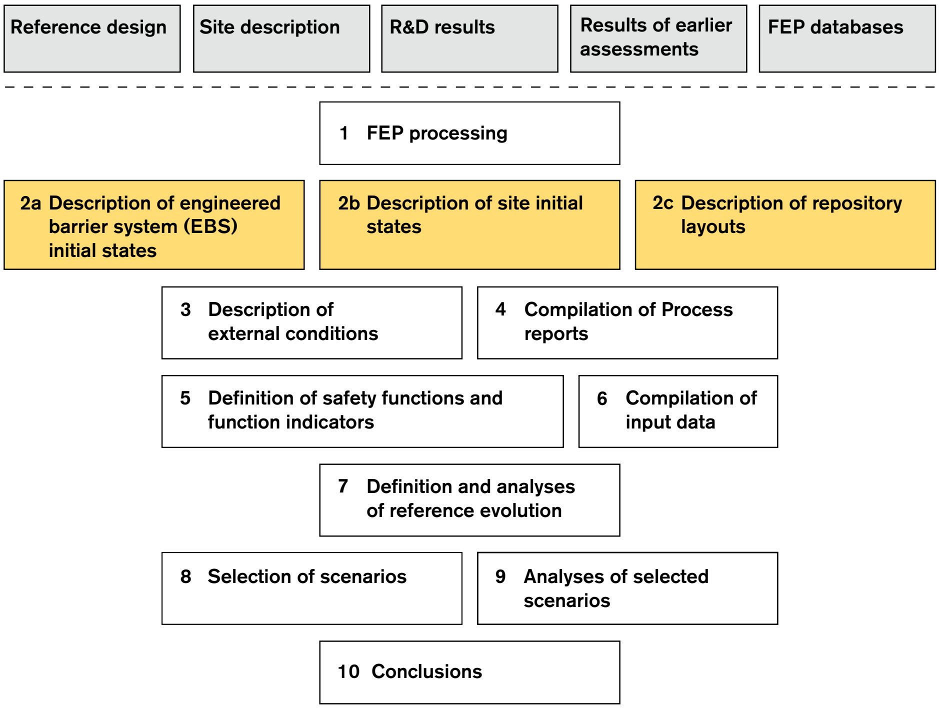


Figure 4-1. *The SR-Can methodology in ten steps (section 2.2), with the present step highlighted.*

4.1 Introduction

As mentioned in section 2.2, a comprehensive description of the initial state of the repository system is one of the main bases for the safety assessment.

There is no obvious definition of the time of the initial state. For the geosphere and the biosphere, the state at the time of beginning of excavation of the repository is a natural starting point, since knowledge of this relatively undisturbed state is available through the site descriptive models that are derived from site investigation data. An alternative would be to consider, for each deposition hole, the state of the surrounding host rock at the time of deposition. Irrespective of which alternative is chosen, the short-term evolution of the host rock from the undisturbed state to that after excavation has to be considered in a safety assessment that is based on observations made prior to excavation. For the biosphere, the problem is less pronounced, since it will be less affected by the excavation of the repository.

For the engineered barrier system, the time of deposition is a natural starting point when a specific part of the system is concerned, e.g. an individual deposition hole with its canister and buffer. However, if the entire ensemble of deposition holes is considered, there is no unique time of deposition. Neither is the time of repository closure a suitable choice for the engineered barrier system, since different parts of the repository will, at that time, have reached different stages of e.g. thermal and hydraulic evolution depending on the time of deposition and on spatial variability of rock conditions within the repository. The most reasonable approach is, therefore, judged to be to define the time of the initial state as that of deposition for each deposition hole with its canister, buffer and backfill, and then to describe the common evolution that all deposition holes will go through, taking the spatial variability into account. For some aspects of the evolution, e.g. the thermal development, the sequential deposition sequence has to be considered.

Based on these considerations, the initial state in SR-Can is defined as the state at the time of deposition for the engineered barrier system and the natural, undisturbed state at the time of beginning of excavation of the repository for the geosphere and the biosphere. The evolution of the natural system is, therefore, at least in some aspects, followed from the time of beginning of excavation in the safety assessment. Short-term geosphere processes/alterations due to repository excavation are, therefore, documented in the **Geosphere process report**, see chapter 6.

The initial state of the engineered parts of the repository system is largely obtained from the design specifications of the repository, including allowed tolerances or deviations. Also the manufacturing, excavation and control methods have had to be described in order to adequately discuss and handle hypothetical initial states outside the allowed limits in the design specifications. The initial state of the engineered parts of the repository system for SR-Can is compiled in a dedicated **Initial state report**.

The initial state of the geosphere and the biosphere is, as mentioned, determined by site investigations. Field data from the site investigations are analysed, within the site investigation project, to produce a site descriptive model of the geosphere and the biosphere for the Forsmark and Laxemar sites, as reported in /SKB 2005c/ and /SKB 2006b/, respectively.

This chapter contains a brief description of the initial state with uncertainties, summarising information on the engineered barriers from the **Initial state report**, the site descriptive models, site-specific repository layouts /Brantberger et al. 2006/ and /Janson et al. 2006/ and the results of the FEP analyses reported in the **FEP report**. The level of detail in this chapter is meant to be sufficient for understanding the remaining parts of the safety report without reading the above reference documents.

4.1.1 Overview of system

The repository system is based on the KBS-3 method, in which copper canisters with a cast iron insert containing spent nuclear fuel are surrounded by bentonite clay and deposited at approximately 500 m depth in saturated, granitic rock, see Figure 4-2.

The facility design with rock caverns, tunnels, deposition positions etc is based on the design originally presented in the KBS-3 report /SKBF/KBS 1983/ which has since been developed and described in more detail. The deposition tunnels are linked by tunnels for transport and communication and shafts for ventilation. One ramp and five shafts connect the surface facility to the underground repository. The ramp is used for heavy and bulky transports and the shafts are for utility systems and for transport of excavated rock, backfill and staff. The different parts of the final repository are sketched in Figure 4-3.

Around 9,000 tonnes of spent nuclear fuel are forecast to arise from the Swedish nuclear power programme /SKB 2003/, corresponding to roughly 4,500 canisters in the repository. These figures are based on an assumed reactor operational time of 40 years. To allow for uncertainties in the future Swedish nuclear power programme, the SR-Can assessment is based on a repository with 6,000 canisters, corresponding to around 12,000 tonnes of fuel.

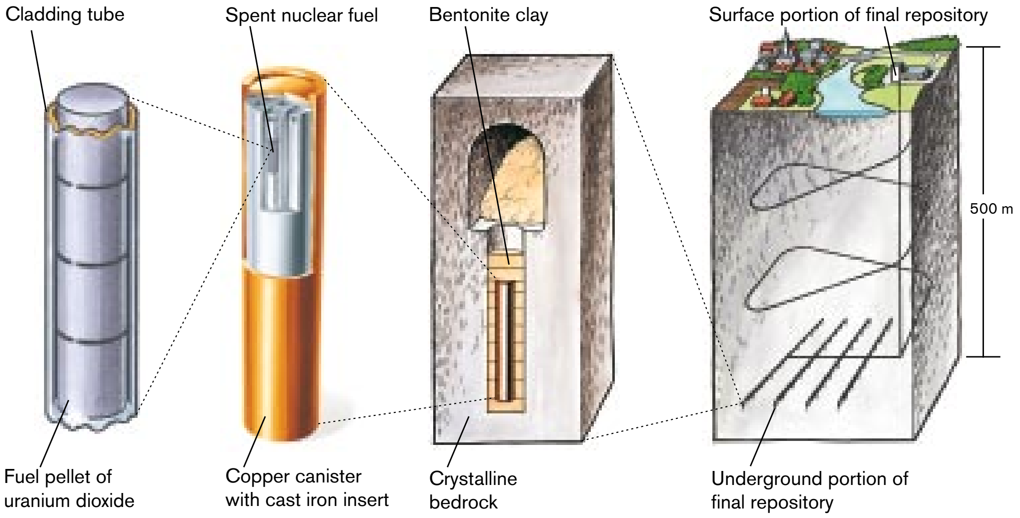


Figure 4-2. The KBS-3 concept for storage of spent nuclear fuel.

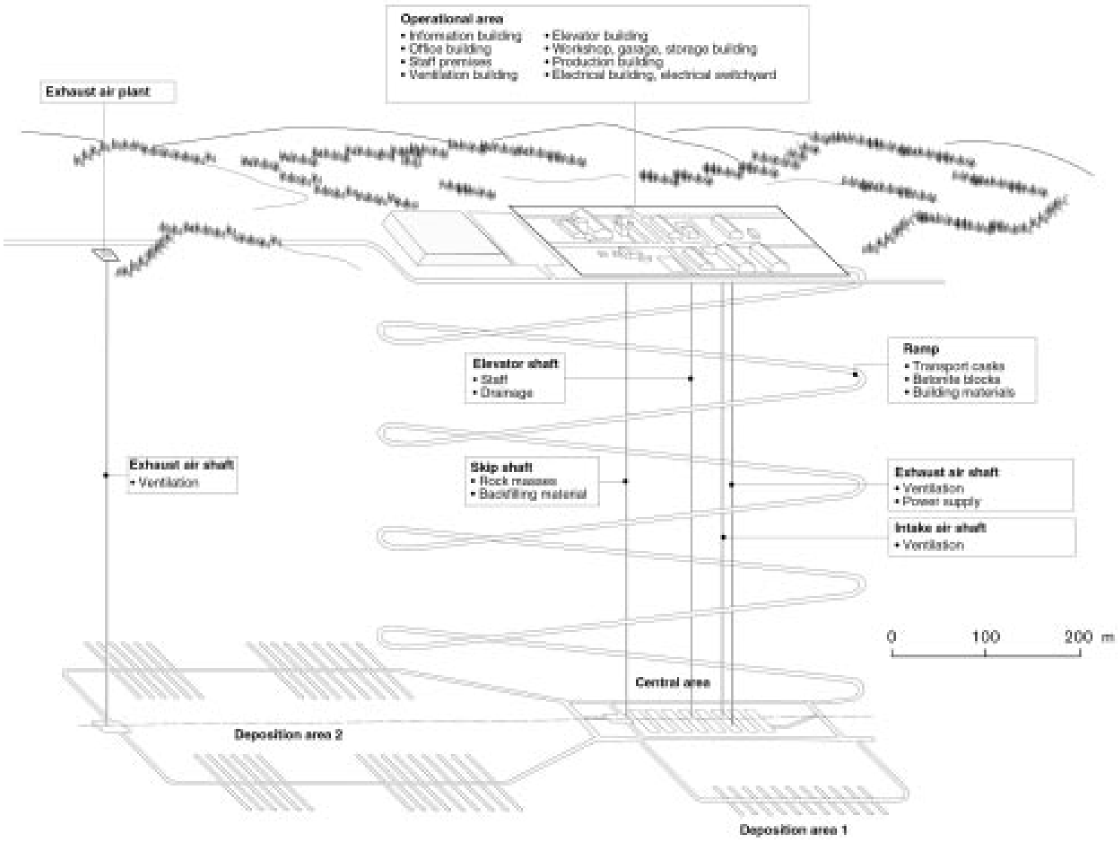


Figure 4-3. Generic example of repository layout.

For the purposes of the safety assessment, the system has been sub-divided into a number of components or sub-systems. These are:

- The fuel, (also including cavities in the canister since strong interactions between the two occur if the canister is ruptured).
- The cast iron insert and the copper canister.
- The buffer in the deposition hole.
- The bottom plate in the deposition hole.
- The deposition tunnel with its backfill material.
- Other repository cavities with their backfill materials, e.g. transport tunnels, shafts and central underground area.
- Repository plugs.
- Investigation boreholes with their sealing material.
- The host rock.
- The biosphere.

This particular sub-division is dictated by the desire to define components that are as homogeneous as possible without introducing an unmanageable multitude of components. Homogeneity facilitates both characterisation of a component and the structuring and handling of processes relevant to its long-term evolution. Also, the importance of a particular feature for safety has influenced the resolution into components. In principle, components close to the source term and those that play an important role for safety are treated in more detail than peripheral components. The components are described in more detail in section 4.2.

4.1.2 Initial state FEPs

The reference initial state of the EBS in SR-Can describes the intended state of the engineered barriers at deposition as described in the **Initial state report** and summarised in section 4.2. The **Initial state report** includes also descriptions of the procedures for manufacturing, operation and control etc for each component.

As mentioned in chapter 3, initial state FEPs in the SR-Can FEP catalogue are either related to the reference initial state or to deviations from the intended reference initial state. The former of these are handled in the category variables in the SR-Can FEP catalogue. In these variable records, a link is given to the description in the **Initial state report** of the reference initial state for that variable.

The initial state FEPs in the SR-Can FEP catalogue that are related to deviations from the intended reference initial state of the canister, the buffer and the backfill of the deposition tunnels, or to more general deviations, are compiled in Table 4-1. One such FEP of more general character is related to severe mishaps like fire, explosions, sabotage and severe flooding. Such events are excluded from the scenario selection. The reasons for this are i) the probabilities for such events are low and ii) if they occur, this will be known prior to repository sealing so that mitigation measures and assessment of possible effects on long-term safety can be based on the specific real event.

Another FEP in the SR-Can FEP catalogue refers the effects of phased operation. This affects mainly the geosphere and the subsequent development of the entire repository. The hydrological state of the bedrock is perturbed as soon as repository excavation starts (a smaller perturbation even occurs earlier during site investigations). Different parts of the repository, completed at different times, will be exposed to different hydrological conditions, affecting e.g. the saturation of the buffer and backfill. Possible upconing of saline water could also vary between different parts of the repository due to phased operation. Other factors to consider are the effects of blasting and underground traffic on completed parts of the repository. All these issues are part of the expected evolution of the repository, but are not automatically captured in the system of processes describing the repository evolution over time or by the initial state descriptions. As they need to be adequately included in the discussion of the repository evolution, they are propagated to the analysis of the reference evolution in section 9.2.6.

Other FEPs in the FEP catalogue concern the effects of an unsealed or abandoned or monitored repository. These issues are also propagated to the scenario selection in chapter 11, but are not further analysed in SR-Can.

FEPs relating to effects detrimental for long-term safety caused by monitoring are excluded from further analysis since this type of monitoring will not be accepted.

Several FEPs concern design deviations due to undetected mishaps during manufacturing, transportation, deposition and repository operations etc. These issues are addressed in the scenario selection and the scenario analyses described in chapters 11 and 12, respectively. Only these FEPs defined for the canister, buffer and the backfill of the deposition tunnels are included in Table 4-1. In addition to these FEPs, the FEP catalogue contains corresponding initial state FEPs for the system components not specifically addressed in SR-Can, i.e. the concrete bottom plate in the deposition holes, plugs in repository tunnels, backfill in other repository cavities and borehole seals. The consequences of deviations in initial state of these system components should, however, be covered by simple bounding calculations undertaken, see section 10.10.

4.2 Reference initial state for fuel and engineered barriers

The reference initial state of the engineered barriers is defined as the design specifications with tolerances including allowance for deviations according to the manufacturing and control procedures.

The tolerances should in principle be possible to derive or verify from the manufacturing and control procedures employed in the engineering activities. At the current stage of the final repository programme, such procedures have reached varying degrees of maturity. This means that the tolerances are more or less well specified for different aspects of the initial state of the engineered barrier system (EBS). For example, regarding the crucial issue of the quality of the canister seals, SR-Can is based on the tolerances determined from test statistics on a prototype sealing system including non-destructive testing. In other cases, the given tolerances are, at this stage, aims for the design of the production

Table 4-1. Initial state FEPs in the SR-Can FEP catalogue and how they are handled in SR-Can.

Initial state FEP		Handling in SR-Can	FEP chart item (see section 7.6)	Comment
ISGen1	Major mishaps/ accidents/sabotage	Excluded. The probabilities for such events are low. If they occur, this will be known prior to repository sealing so mitigation measures and assessments of possible effects on long-term safety can be based on the specific real event.		
ISGen2	Effects of phased operation	Qualitatively assessed based on rock mechanics and transient hydrogeological simulations for an open repository.		See section 9.2.6
ISGen3	Incomplete closure	Propagated to scenario selection. (No direct consequence assessments in SR-Can, but covered by bounding calculations of fictitious barrier losses reported in section 10.10.)		See section 11.3.
ISGen4	Monitoring activities	Excluded. Monitoring activities that could disturb the repository safety functions will not be accepted.		
ISC1	Mishaps – canister	Propagated to the selection of scenarios based on safety function indicators related to canister integrity.	Copper thickness Mechanical strength Rupture limit	See sections 11.4 (scenario selection) and 12.7 to 12.9 (scenario analyses).
ISC2	Design deviations – canister	Propagated to the selection of scenarios based on safety function indicators related to canister integrity.	Copper thickness Mechanical strength Rupture limit	See sections 11.4 (scenario selection) and 12.7 to 12.9 (scenario analyses).
ISBu1	Mishaps – buffer	Propagated to the selection of scenarios based on safety function indicators related to buffer performance.	Density Geometry	See sections 11.4 (scenario selection) and 12.3 to 12.5 (scenario analyses).
ISBu2	Design deviations – buffer	Propagated to the selection of scenarios based on safety function indicators related to buffer performance.	Density Geometry	See sections 11.4 (scenario selection) and 12.3 to 12.5 (scenario analyses).
ISBfT1	Mishaps – backfill in deposition tunnels	Propagated to the selection of scenarios based on safety function indicators.	Density Geometry	See sections 11.4 (scenario selection) and 12.3 (scenario analyses). Transport properties of defective backfill addressed in section 10.5.7.
ISBfT2	Design deviations – backfill in deposition tunnels	Propagated to the selection of scenarios based on safety function indicators.	Density Geometry	See sections 11.4 (scenario selection) and 12.3 (scenario analyses). Transport properties of defective backfill addressed in section 10.5.7.

system in question. For example, this is the case for the buffer density. Here, a qualitative description of a tentative manufacturing and control system exists along with preliminary test results, but the data do not allow derivation of a quantified tolerance.

The approach of managing the uncertainties represented by the tolerances, including the possibility of initial state values outside the tolerances, and the use of safety assessment results in the further design work, is developed in conjunction with the selection of scenarios in chapter 12.

It should also be noted that many parts of the system are as yet not finally designed – there can be many changes in the future. The design and technical solutions presented here are representative of the current stage of development.

Essential parts of the engineered barrier system are shown in Figure 4-4.

4.2.1 Initial state aspects critical to safety

From earlier safety assessments, and from the general understanding of the repository system, a number of initial state aspects of the engineered barrier system critical to safety have been identified. The analyses conducted in SR-Can will inform an update of this set of critical initial state aspects. From earlier safety assessments, the critical aspects include:

- The residual power of the spent fuel in each canister, affecting the short-term thermal evolution of the repository and in particular the peak temperatures in the near field.
- The copper canister tightness, in particular the quality of the sealing welds.
- The strength of the cast iron insert, affected by the quality of the casting process.
- The amount and composition of buffer dry mass emplaced in each deposition hole, affecting the final density of the buffer after water saturation.
- The amount and composition of backfill dry mass emplaced in each deposition tunnel, affecting the final density of the backfill after water saturation.

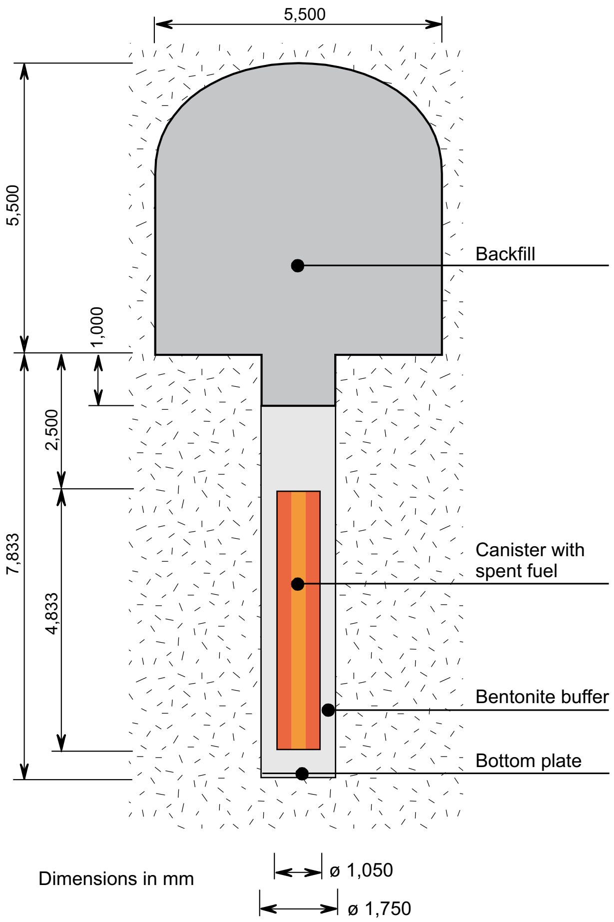


Figure 4-4. *Deposition hole with bentonite buffer and canister. Two backfill candidate materials are considered in SR-Can: Friedland clay and a mixture of bentonite and crushed rock.*

4.2.2 Format for EBS initial state descriptions

Each component in the EBS initial state is described by a specified set of physical variables, selected to allow an adequate description of the long-term evolution of the component in question in the safety assessment. Examples of important variables for describing the buffer are buffer geometry, temperature, swelling pressure, water content, smectite content and impurity content. A structured description of components characterised by variables is fully utilised in the EBS initial state report, whereas a more free format is used here, focusing on the most important aspects of the initial state.

4.2.3 Fuel/cavity in canister

The total quantity of fuel obtained from the Swedish nuclear reactors will depend on operating time, energy output and fuel burn-up. At the end of 2005, approximately 6,300 tonnes of spent fuel had been generated /SKB 2006j/. With an operating lifetime of 40 years for all reactors, except for Barsebäck 1 and 2 which were taken out of operation during 1999 and 2005, respectively, the total quantity of spent fuel has been estimated as 9,300 tonnes /SKB 2006j/.

Several types of fuel are to be deposited in the repository. For the option with 40 years of reactor operation, the quantity of BWR fuel is estimated at 7,200 tonnes and the quantity of PWR fuel at 2,300 tonnes /SKB 2003/. The fuel burn-up may vary from 15 up to 60 MWd/kgU thermal output /SKB 2001/. In addition, 23 tonnes of MOX fuel and 20 tonnes of fuel from the reactor in Ågesta will be deposited. The MOX fuel has an average burnup of 31 MWd/kgHM and a higher Pu content than UOX fuel due to its relatively low burnup (about 2.7%). The Ågesta fuel is heavy water reactor fuel. At present there are 222 such fuel elements in Clab. The majority of those (about 70%) contain natural uranium; the remainder are enriched to 1.35% (one element contains 2.2% U-235). The burnup ranges from 0 to 10 MWd/kgU.

The canisters in SR-Can are assumed to have an initial thermal output of 1,700 W. The inventory of radionuclides is calculated from the assumption of a BWR fuel with a burn-up of 38 MWd/kgU. The sensitivity of radionuclide inventory on burn-up for a given thermal output is rather small, see further the **Data report**, section 3.1.

The existing MOX fuel and the MOX fuel that may/will be used in BWRs in the future is not included in the SR-Can assessment. These fuels will be considered in SR-Site.

Nuclear fuel consists of cylindrical pellets of uranium dioxide. The pellets are stacked in approximately 4-metre-long cladding tubes of Zircaloy, a durable zirconium alloy. The tubes are bundled together into fuel assemblies. Geometric aspects of the fuel cladding tubes of importance in the safety assessment are, as a rule, handled sufficiently pessimistically in analyses of radionuclide transport that differences between different fuel types are irrelevant. The material composition of the assemblies is well known and the uncertainties are small, largely since the quality requirements in the fabrication of fuel assemblies are very strict.

Radionuclides are formed during reactor operation by nuclear fission of uranium-235 and plutonium-239 in particular, and by neutron capture by nuclei in the metal parts of the fuel elements. Most of the radionuclides are embedded in the fuel matrix of uranium dioxide. A few fission products are relatively mobile in the fuel and may migrate to the surface of the fuel pellets during operation. The inventory of radionuclides in the fuel at the time of deposition can be calculated with relatively high accuracy. The uncertainty is typically a few tens of percent and is mostly related to the fuel's burn-up and initial enrichment. Uncertainties related to the inventories of higher actinides and some activation products may be higher. The relative differences in radionuclide inventory with respect to burn-up are small. BWR fuel and PWR fuel differ only to a limited degree regarding radionuclide content. Table 4-2 shows the inventory of radionuclides for one tonne of BWR fuel with a burnup of 38 MWd/kg. This and inventories for additional fuel types and burn-up is given in the **Data report**, section 3.1.

The canister insert is sealed at atmospheric pressure in an atmosphere of at least 90% noble gas and the maximum permissible quantity of water in a canister is 600 grams. This value is equivalent to the void in one fuel rod in each one of the 12 fuel elements in a BWR canister.

Table 4-2. Inventory for BWR fuel with a burn-up of 38 MWd/kg U 40 years after operation.

Activation products		Actinides		Fission products	
	Activity (Bq/t U)		Activity (Bq/t U)		Activity (Bq/tU)
H-3	$1.11 \cdot 10^{12}$	Th-234	$1.17 \cdot 10^{10}$	H-3	$2.07 \cdot 10^{12}$
C-14	$5.00 \cdot 10^{10}$	Pa-233	$1.50 \cdot 10^{10}$	Se-79	$2.82 \cdot 10^{9}$
Ca-41	$6.94 \cdot 10^{6}$	Pa-234m	$1.17 \cdot 10^{10}$	Kr-85	$2.73 \cdot 10^{13}$
Cl-36	$5.46 \cdot 10^{8}$	U-234	$4.64 \cdot 10^{10}$	Sr-90	$1.20 \cdot 10^{15}$
Fe-55	$9.29 \cdot 10^{9}$	U-236	$1.04 \cdot 10^{10}$	Y-90	$1.20 \cdot 10^{15}$
Co-60	$8.92 \cdot 10^{11}$	U-237	$1.85 \cdot 10^{10}$	Zr-93	$5.03 \cdot 10^{10}$
Ni-59	$8.79 \cdot 10^{10}$	U-238	$1.17 \cdot 10^{10}$	Nb-93m	$4.21 \cdot 10^{10}$
Ni-63	$9.29 \cdot 10^{12}$	Np-237	$1.50 \cdot 10^{10}$	Tc-99	$5.72 \cdot 10^{11}$
Sr-90	$2.55 \cdot 10^{7}$	Np-239	$1.17 \cdot 10^{12}$	Ru-106	$2.66 \cdot 10^{4}$
Y-90	$2.55 \cdot 10^{7}$	Pu-238	$9.45 \cdot 10^{13}$	Rh-106	$2.66 \cdot 10^{4}$
Zr-93	$5.62 \cdot 10^{9}$	Pu-239	$9.50 \cdot 10^{12}$	Pd-107	$4.86 \cdot 10^{4}$
Nb-93m	$2.33 \cdot 10^{10}$	Pu-240	$1.18 \cdot 10^{13}$	Cd-113m	$1.69 \cdot 10^{11}$
Nb-94	$2.88 \cdot 10^{9}$	Pu-241	$7.72 \cdot 10^{14}$	Sn-121	$4.39 \cdot 10^{10}$
Mo-93	$4.42 \cdot 10^{7}$	Pu-242	$1.01 \cdot 10^{11}$	Sn-121m	$5.65 \cdot 10^{10}$
Ag-108	$4.34 \cdot 10^{7}$	Am-241	$1.51 \cdot 10^{14}$	Sb-125	$1.11 \cdot 10^{10}$
Ag-108m	$4.98 \cdot 10^{8}$	Am-242m	$4.53 \cdot 10^{11}$	Te-125m	$2.70 \cdot 10^{9}$
Cd-113m	$3.43 \cdot 10^{10}$	Am-242	$4.51 \cdot 10^{11}$	Sn-126	$2.25 \cdot 10^{10}$
Sn-121	$1.35 \cdot 10^{10}$	Am-243	$1.17 \cdot 10^{12}$	Sb-126m	$2.25 \cdot 10^{10}$
Sn-121m	$1.74 \cdot 10^{10}$	Cm-242	$3.73 \cdot 10^{11}$	I-129	$1.32 \cdot 10^{6}$
Sb-125	$1.21 \cdot 10^{9}$	Cm-243	$4.44 \cdot 10^{11}$	Cs-134	$9.10 \cdot 10^{9}$
Te-125m	$2.96 \cdot 10^{8}$	Cm-244	$2.84 \cdot 10^{13}$	Cs-135	$2.05 \cdot 10^{10}$
Eu-154	$3.17 \cdot 10^{11}$	Cm-245	$9.37 \cdot 10^{9}$	Cs-137	$1.79 \cdot 10^{15}$
Eu-155	$1.33 \cdot 10^{10}$	Cm-246	$2.89 \cdot 10^{9}$	Ba-137m	$1.69 \cdot 10^{15}$
Ho-166m	$7.47 \cdot 10^{7}$			Pm-146	$9.84 \cdot 10^{8}$
				Pm-147	$1.54 \cdot 10^{11}$
				Sm-151	$9.36 \cdot 10^{12}$
				Eu-152	$3.28 \cdot 10^{10}$
				Eu-154	$1.81 \cdot 10^{13}$
				Eu-155	$7.62 \cdot 10^{11}$

4.2.4 Cast iron insert and copper canister

The canister consists of an inner container, the insert of cast iron and an outer shell of copper, see Figure 4-5. The cast iron insert provides mechanical stability and the copper shell protects against corrosion in the repository environment. The copper shell is 50 mm thick and the cylindrical canister has a length of approximately 4.8 m and a diameter of 1.05 m. The copper shell is made of pure oxygen-free copper. The insert is cast from spheroidal graphite cast iron and has channels where the fuel assemblies are placed. The uncertainties in material composition are small for the canister materials.

The insert is presently available in two versions: one for 12 BWR assemblies and one for 4 PWR assemblies. A canister holds about two tonnes of spent fuel. Canisters with BWR and PWR assemblies weigh 25 and 27 tonnes, respectively. The decay heat in the spent fuel disposed in one canister is limited to 1,700 W, to fulfil temperature requirements for the bentonite buffer.

Four possible methods for fabrication of the copper tube have been tested by SKB: roll forming of copper plate to tube halves which are welded together, seamless tubes formed by extrusion, pierce and draw processing, and forging. All these methods produce a copper cylinder that must be machined internally and externally as well as on the end surfaces to get the desired dimensions. The reference canister is foreseen to be fabricated with a seamless tube. Lids and bottoms of copper are machined to the desired dimensions from hot forged blanks. The mass production of the canister parts, i.e. the insert, copper tube, lid, and bottom, may very well be done by different companies applying different methods that all fulfil the set requirements.

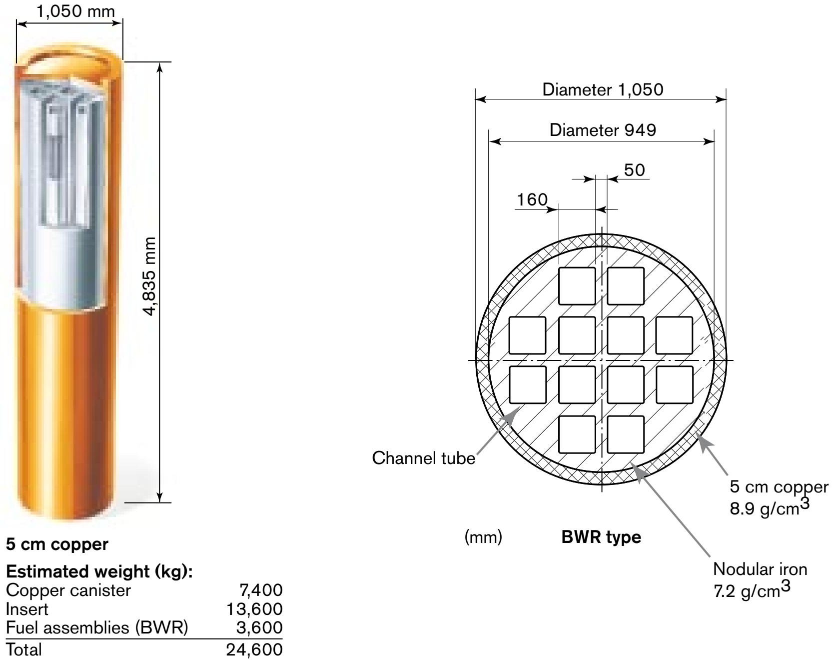


Figure 4-5. *The canister with its cast iron insert and copper shell. Exploded view on the left hand side and cross section on the right hand side.*

Welding of the lid and bottom of the copper canister is done by friction-stir welding (FSW) in the reference case, since this is the preferred alternative according to recent decisions /SKB 2006c/. As an alternative, electron-beam welding (EBW) could be used, but this option is not considered in SR-Can. Radiographic and ultrasonic techniques for non-destructive testing (NDT) of the canisters and welds are being developed and have been subject to an initial evaluation /SKB 2006d/.

The fuel will be placed in the canister in the encapsulation plant. The insert will be closed with a lid, which is fastened with a bolt. The lid of the copper shell is then attached by welding, and the integrity of the weld is verified by NDT.

Minimum initial copper thickness

Defects under normal operation have been observed in a test series of 20 canister lids. Maximum defect sizes are of the order of a few millimetres with the largest being 4.5 mm, see further the **Data report**, section 4.2.

Based on results of statistical analyses of the test series, it is cautiously assumed that all canisters *sealed under normal operation* will have a minimum copper coverage of 40 mm.

Normal operation is defined as conditions where the observable parameters of the sealing process are within a defined “process window”. The probability of detecting these defects is not taken into account. This omission is, however, of minor importance since i) the probability of detection for these defect sizes is fairly low and ii) these defects are acceptable, meaning that a possible detection would not lead to any corrective measures.

If the sealing process parameters at any time lie outside the process window, the statistics of defect sizes referred to above cannot be taken as representative.

A first evaluation of the reliability of the sealing process itself, of its surveillance functions and of the NDT suggests that the likelihood of disturbed operations leading to copper thicknesses below 40 mm is very low. A first crude estimate is that at most one percent of the canisters leaving the encapsulation plant would have such defects. These events will lead to a distribution of copper thicknesses that is difficult to determine. A first, pessimistic assumption is that all such canisters have a minimum copper coverage of 35 mm, i.e. the acceptance criterion of the sealing system. This, however, clearly underestimates the performance of the NDT system.

Thus, 99% of the canisters are assumed to have a thickness between 40 and 50 mm and one percent between 35 and 40 mm in the reference initial state in SR-Can, see further the **Data report**. These thicknesses refer only to the seals of the canisters whereas the major part of the copper shell is assumed to have a thickness of 50 mm in SR-Can.

This is considered to be a pessimistic basis based on the results available today. The derived input is likely to change as the sealing process and the analysis of its performance is further developed, and as also the methods for deriving these input data for safety assessment purposes are enhanced.

The distribution is used for both the top and the bottom seals, since these are to be welded and inspected using the same methods.

4.2.5 Buffer

In the deposition holes, the copper canister is surrounded by a buffer of clay. The buffer is deposited as bentonite blocks below and above the canister and rings surrounding the canister. Each bentonite unit is about 500 mm high and has a diameter of 1,690 mm. The thickness of the rings is 315 mm. One block is placed below the canister, nine rings surround the canister and four blocks are placed above the canister. The blocks placed immediately below and above the canister must be processed so as to fit the canister geometry properly.

Two different types of bentonite have been considered as reference buffer material for the purpose of SR-Can. One is a natural Na-bentonite of Wyoming type (MX-80) supplied by the American Colloid Company and the other is a natural Ca-bentonite (Deponit CA-N) from Milos supplied by Silver and Baryte. The bentonite consists mainly of the smectite mineral montmorillonite with the characteristic property that it swells in contact with water. Data for the two buffer materials are summarised in Table 4-3. SKB has not made a final selection of a buffer material. The two materials analysed in SR-Can are merely examples of possible options.

The bentonite, bought in bulk form and transported by ship, is subject to quality control both before loading in the ship and at reception. Quality control is undertaken also during the manufacture of the blocks and rings; one important check is the water content before pressing so that this can be adjusted.

The important overall aim in the manufacture of bentonite blocks and rings and the subsequent deposition process is to achieve a specific final density in the water–saturated buffer. The density requirement for the saturated buffer is 1,950–2,050 kg/m^3. The bulk density is dependent on the annular gaps between the canister and buffer and between buffer and rock, left in order to facilitate deposition.

Table 4-3. Bentonite composition of MX-80 and Deponit CA-N. The uncertainties are mainly related to the precision of the analysis method used.

Component	MX-80 (wt-%)	Deponit CA-N (wt-%)	Uncertainty (± wt-%)
Calcite + Siderite	0–1	10	1
Quartz	3	1	0.5
Cristobalite	2	1	0.5
Pyrite	0.07	0.5	0.05
Mica	4	0	1
Gypsum	0.7	1.8 (anhydrite)	0.2
Albite	3	0	1
Dolomite	0	3	1
Montmorillonite	87	81	3
Na-	72%	24%	5
Ca-	18%	46%	5
Mg-	8%	29%	5
K-	2%	2%	1
Anorthoclase	0	2	1
CEC (meq/100 g)	75	70	2
Organic carbon	0.2	0.2	–

The annular gap between the canister side and the buffer is nominally 5 mm wide and that along the circumferential boundary between the buffer and the rock is 30 mm. The gaps are left empty or filled with pellets. Filling the void with bentonite pellets could limit, but probably not eliminate the effects of thermal spalling. A pellets filled outer void will limit the possibility for fallout of rock pieces in the wall.

Buffer emplacement in a tunnel may take place several months after the drilling of the deposition holes. The deposition holes are assumed to be filled with water in the meantime, which is why draining is the first step in the preparation of the holes. Deposition starts with the hole at the far end of the tunnel. The buffer is put into position by a specially designed buffer filling vehicle. The bentonite lining is thereafter checked. The emplacement of the copper canister is done with a specially designed deposition machine which also places a top bentonite block immediately after the canister is emplaced. The emplacement of the canister will be documented by appropriate safeguards measures in its final position. The final handling procedures and the final design of the buffer filling vehicle and the deposition machine are not yet decided, but do not affect the description of the work procedures. Small geometric tolerances in the deposition holes mean a very small risk for faulty emplacement of the buffer and canister.

The initial density of the buffer in the deposition hole will be dependent on the amount of bentonite placed in each deposition hole. Based on experience from the installation of the Prototype Repository in the Äspö Hard Rock Laboratory, /Johannesson and Birgersson 2006/ have made a statistical analysis of the variation between the highest and lowest expected buffer densities, both on a level of individual blocks/rings and on full deposition holes. Based on this, the 5999/6000 confidence interval for the saturated density in the deposition holes in the Prototype Repository would be 2,017–2,045 kg/m^3. (It should be noted that the target density for the Prototype Repository was higher than the 2,000 kg/m^3 assumed for SR-Can.) This can be interpreted in terms of one deposition hole having a density outside the given interval. Based on this, the conclusion is that the variation of buffer densities is likely to be kept within the tolerances for every deposition hole, if the normal routines of emplacement are followed.

The bentonite must be protected from water or high humidity until the tunnel is backfilled. The reason is that the buffer may start swelling before the deposition of the canister and/or before the tunnel backfilling can apply its counterforce on the buffer. One possible method is to insert a drain tube in the deposition hole and to protect the whole buffer with a plastic bag that is kept sealed until the backfilling of the tunnel starts. The plastic bag and drain tube would be removed after use. This methodology has been successfully used in several field test, e.g. the Prototype Repository at Äspö HRL /Pusch and Andersson 2004/. In SR-Can it is assumed that the removal of these items will be successful in all cases, or that effective remedial action will be taken in the event of failure.

4.2.6 Bottom plate in deposition holes

The bottom of the deposition hole is levelled off with a cast concrete base plate. The base plate serves as a stiff support and the pile of bentonite blocks thereby has a vertical centre line defined, so that the canister can enter gently and the gap between blocks and rock surface is even enough to allow the block lifting tools and the other parts to pass freely.

The thickness of the cast base plate will be adapted to the roughness of the rock and will be about 5 cm at the thinnest part and 10 cm as a maximum. The base plate is to be cast of concrete with low pH cement. The development of suitable cement is in progress, and a final recipe is presently not available. A copper plate, a few millimetres thick, will be placed on the concrete surface to protect the bentonite from being wetted by ground water penetrating the concrete plate. A peripheral gap is to be left between the concrete base plate and the rock wall where ground water can be collected and pumped up from the hole as long as the deposition tunnel is open.

4.2.7 Backfill of deposition tunnels

The extent of this sub-system component is defined in geometrical terms as the deposition tunnel and the upper one metre of the deposition holes. All materials within the tunnel are included i.e. the backfill material itself, grout in grout holes and the relatively limited amounts of structural and stray materials left in the tunnels. Exploratory boreholes and the plug at the end of the deposition tunnel are distinct sub-systems. Grout in rock fractures is associated with the geosphere.

The final decision on excavation technique for the deposition tunnels has not been taken and two possible techniques, drill and blast or mechanical excavation (tunnel boring machine, TBM), are still possible options. However, only the drill and blast option is analysed in SR-Can. The excavation technique will have implications on the dimensions, the shape of the deposition tunnels and the extent of the excavation damaged zone in the host rock. The cross section in a drill and blast deposition tunnel is a square with an arched roof, whereas the cross section in a mechanically excavated tunnel is circular.

Two backfill concepts are analysed in SR-Can:

- Precompacted blocks of a natural swelling clay (not necessarily a bentonite). Friedland clay is used as an example of such a material in SR-Can. The whole tunnel is filled with pre-compacted blocks. The gaps between the rock and the blocks are filled with pellets of the same material. The estimated volumes and proposed densities are given in Table 4-4.
- Precompacted blocks made of a mixture of bentonite of buffer quality and crushed rock with a weight ratio of 30/70. The gaps between the rock and the blocks are filled with bentonite pellets. The maximum grain size for the ballast material (the crushed rock) is assumed to be 5 mm. The volumes and densities for the mixture are given in Table 4-5.

Friedland Clay is a natural clay, mainly consisting of mixed layer smectite/illite. The full composition is given in Table 4-6, and the mean chemical composition, expressed as oxides as analysed by ICP/AES, of the two bentonites is: 61% SiO_2, 17.3% Al_2O_3, 6.4% Fe_2O_3, 1.9% MgO, 0.4% CaO, 1.1% Na_2O, 3.1% K_2O, 0.9% TiO_2, 0.6% total carbon, 0.5% total sulphur, and 7.6% loss on ignition.

The bentonite component in the 30/70 mixture is assumed to have the same composition as the buffer bentonite, see Table 4-3. The crushed rock is taken from the residues from the excavation of the repository.

The upper metre of the deposition holes will be filled with bentonite blocks with buffer quality in the first concept and with the mixture in the second concept. The mixing concept will have a final clay fraction density of around 1,600 kg/m^3 when water saturated, see further the **Initial state report**.

The manufacturing of the backfill material will take place in a production facility close to the final repository. Quality control of the composition of the material will take place at three stages: the clay and the rock aggregates will be sampled and analysed before mixing, the composition will be controlled after mixing, and samples will also be taken after emplacement in the tunnel to ensure that the homogeneity of the mixture is good.

The average density over the cross section of a deposition tunnel will vary mainly due to the variation in tunnel geometry. It is assumed that the tunnels can be excavated so that the difference in tunnel radius is at most 0.30 m over one blasting round, which typically extends the tunnel by 4 to 7 m.

Table 4-4. Volumes and densities for Friedland Clay.

Material	Estimated fraction of tunnel area (%)	Dry density (kg/m^3)
Block	78	2,000
Pellets	20	1,100
Void	2	0

Table 4-5. Volumes and densities for 30/70 blocks and pellets.

Material	Estimated fraction of tunnel area (%)	Dry density (kg/m^3)	Effective dry clay density (kg/m^3)
Block	78	2,190	1,559
Pellets	20	1,100	1,100
Void	2	0	0
Average	100	1,928	1,335

Table 4-6. Mineralogical composition of Friedland Clay.

Component	Friedland	Note
Feldspars (wt-%)	3 ± 1	
Gypsum (wt-%)	0.8	From chemical analysis
Illite (wt-%)	4 ± 2	
Kaolinite (wt-%)	10 ± 5	
Mica (muscovite wt-%)	9 ± 5	
Mixed layer clay* (wt-%)	44 ± 5	* 33% non-expandable, 67% expandable layers
C organic (wt-%)	0.6	From chemical analysis
Pyrite (wt-%)	0.62	From chemical analysis
Quartz (wt-%)	28 ± 3	
CEC (meq/100 g)	22 ± 2	

Based on current assumptions for the block backfilling method, it is estimated that this would result in 70% to 86% of the tunnel cross-section being filled with blocks. It is assumed that 2% of the cross-section initially is void and the remaining volume is filled with pellets. This would result in a variation in average dry density for the tunnel cross section of 1,700 kg/m^3 to 1,850 kg/m^3 for Friedland clay and 1,840 kg/m^3 to 2,020 kg/m^3 for the example 30/70 material. The variation in backfill density between different blasting rounds will be much smaller.

The aim is to limit the amount of construction and stray materials left in the deposition tunnels. Rock supports, mainly rock bolts and reinforcement nets will be left in the tunnels, as they are essential to workers' safety, whereas the other installations and structures, e.g. roadbeds, will be removed before closure of the deposition tunnels. In addition, the tunnels will be cleaned with highly pressurised water.

4.2.8 Buffer and deposition tunnel material properties

The swelling pressure and the hydraulic conductivity of the buffer and backfill will depend on density, montmorillonite content, adsorbed ionic species and the ionic strength of the surrounding groundwater. The ionic strength of the groundwater is of particular importance for the swelling pressure and hydraulic conductivity of the buffer.

These dependencies have recently been determined in a series of experiments for the two buffer candidate materials MX-80 and Deponit CA-N.

In SR-Can, the buffer has a saturated reference density of 2,000 kg/m^3. The allowed variation of density for the saturated buffer in the deposition hole is ± 50 kg/m^3, but the expected variation is less, based on experience from the Prototype Repository in the Äspö Hard Rock Laboratory (section 4.3.5).

Buffer density is usually expressed as the density of the dry material (ρd). The criterion for the buffer density in the deposition hole is expressed as saturated density (ρsat). The density at saturation can be expressed as:

$$\rho sat = \rho d + (1 - \frac{\rho d}{\rho s})\rho w$$

where ρs is the mineral density and ρw the density of water (ρs = 2,750 kg/m^3 *and* ρw = 1,000 kg/m^3 /Karnland et al. 2006/). The dry density of the SR-Can reference material is 1,570 kg/m^3.

Figure 4-6 shows the swelling pressure for the MX-80 and Deponit CA-N materials exposed to NaCl and $CaCl_2$ solutions, respectively. The swelling pressure for the reference density will be 7.5–8 MPa for both materials. With account taken for the allowed variations in density, the swelling pressure may vary between 4.5 and 13 MPa.

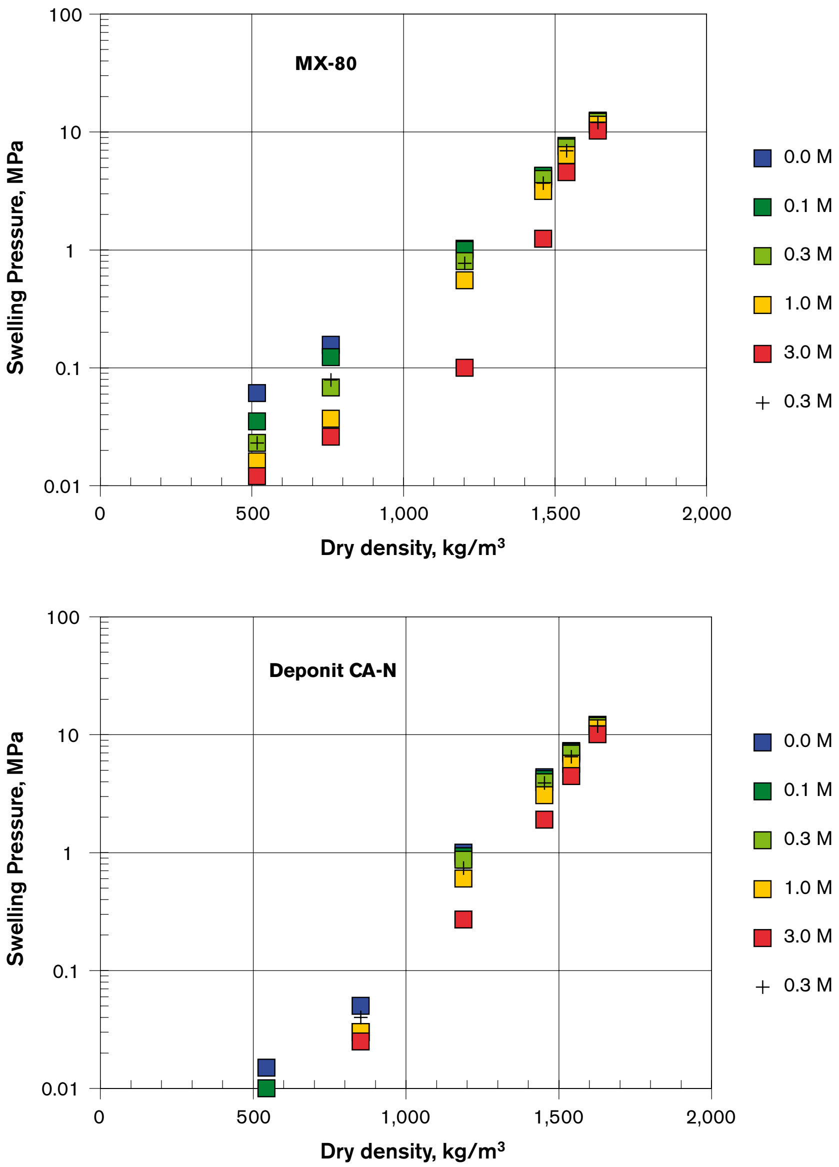


Figure 4-6. *Swelling pressures of MX-80 exposed to NaCl solutions (upper) and Deponit CA-N exposed to $CaCl_2$ solutions (lower).*

The figure also indicates that if the dry density exceeds 1,400 kg/m^3 (1,890 kg/m^3 saturated), the requirement that the buffer swelling pressure should be above 1 MPa is fulfilled even in the case of a 3 M solution, i.e. for all relevant groundwater compositions. For a dry density of 1,300 kg/m^3 (1,830 kg/m^3 saturated), or less, fulfilment of this requirement cannot be claimed for these extreme salt concentrations.

The relation between swelling pressure/hydraulic conductivity and ionic strength in the solution can be described by a so called Donnan equilibrium. Using the model described by /Karnland et al. 2006/ the drop in swelling pressure as a function of ionic strength can be calculated. Figure 4-7 shows the results of such a calculation /Karnland et al. 2006/. The model confirms the conclusions from the experiments mentioned above.

Figure 4-8 shows the hydraulic conductivity for the MX-80 and Deponit CA-N materials exposed to NaCl and $CaCl_2$ solutions, respectively.

This figure indicates that if the dry density exceeds 1,200 kg/m^3 (1,760 kg/m^3 saturated), the requirement that the buffer hydraulic conductivity should be below 10^{-12} m/s (see further section 7.3.2) is fulfilled even in the case of a 3 M solution for Depont CA-N and for a 1 M solution for MX-80 (good data for low densities and high salinities are lacking for MX-80).

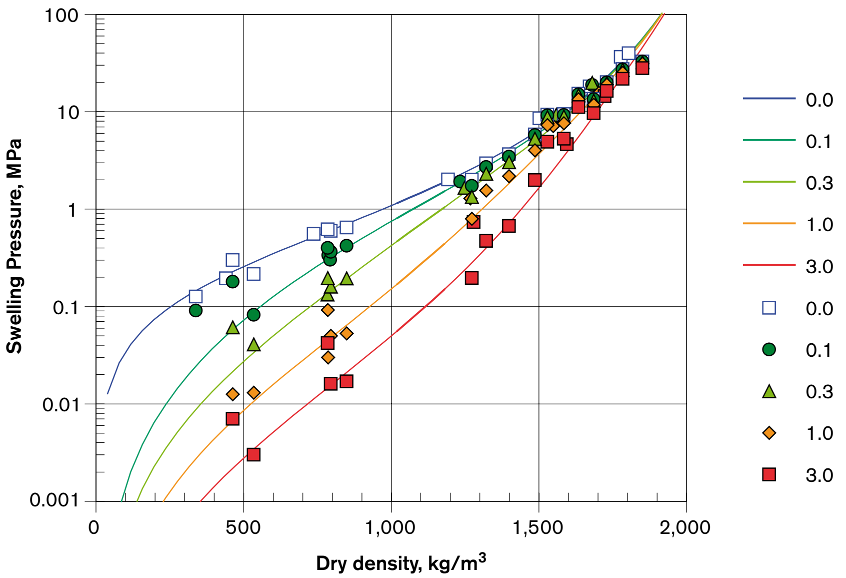


Figure 4-7. *Measured (squares) and calculated (lines) swelling pressure versus clay dry density for different concentrations in a NaCl solution in equilibrium with the Na-montmorillonite. Legends show external solution concentration in mole/L.*

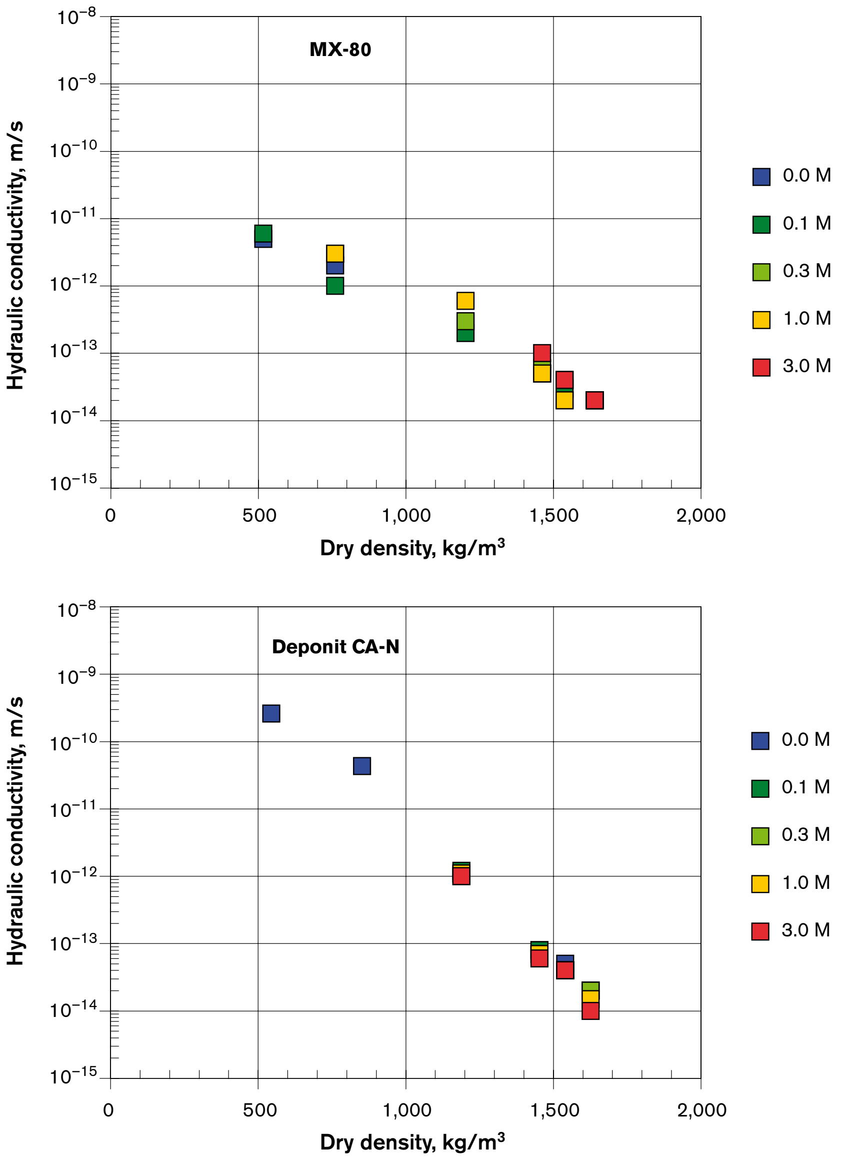


Figure 4-8. *Hydraulic conductivities of MX-80 exposed to NaCl solutions (upper) and Deponit CA-N exposed to $CaCl_2$ solutions (lower).*

The backfill has a lower content of swelling material and is thus more sensitive to an intrusion of saline water. The reference backfills analysed in SR-Can have dry densities of 1,928 kg/m^3 for 30/70 mixture and 1,780 kg/m^3 for Friedland clay.

Laboratory studies by /Johannesson and Nilsson 2006/ show that hydraulic properties of the Friedland clay are rather insensitive to the groundwater composition. Figure 4-9 shows the swelling pressure as a function of dry density for different NaCl concentrations. These tests were not performed with samples all the way up to the reference backfill. However, a density of 1,780 kg/m^3 for Friedland clay would lead to a hydraulic conductivity of around 10^{-12} m/s and a swelling pressure of roughly 3 MPa. These values have been derived from oedometer test /Johannesson and Nilsson 2006/.

Mixtures of 30/70 bentonite with crushed rock are more sensitive to the effect of saline water. Figure 4-10 shows the effect of different NaCl concentrations on the swelling pressure of different mixtures. Mix 1 and Mix 6 are representative of the 30/70 mixtures with MX-80 and Deponite CA-N, respectively.

The results from the laboratory studies show that the required swelling pressure of 0.1 MPa (section 7.3.3) of a Friedland backfill will be maintained with good margin even in the case of the intrusion of saline water. Figure 4-9 shows that a dry density of 1,400 kg/m^3 would give a swelling pressure of 0.1 MPa even at a salinity of 3 M NaCl.

The swelling pressure of the 30/70 mixture would also fulfil the requirements in the case of the intrusion of saline water as long as the reference density is maintained. However a drop in density to below 1,850 kg/m^3 would result in a swelling pressure very close to 0.1 MPa.

The results from the laboratory studies also show that the required hydraulic conductivity of 10^{-10} m/s (section 7.3.3) of a Friedland backfill would be maintained with good margin even in the case of a 3 M saline water, see Figure 4-11. The 30/70 mixtures would maintain the required hydraulic conductivity at reference density even at 7% (1.2 M) NaCl, see Figure 4-12. However, a small drop in density would lead to a substantial increase in the hydraulic conductivity for these materials.

4.2.9 Backfill of other repository cavities

The extent of this sub-system is defined in geometrical terms as all rock excavation volumes except those in the deposition tunnels and deposition holes. The definition thus includes the volumes of, e.g. access ramp and shafts, transport and main tunnels, ventilation shafts, and the central area, which together make up the necessary space for access to and operation of the underground facility and its deposition areas.

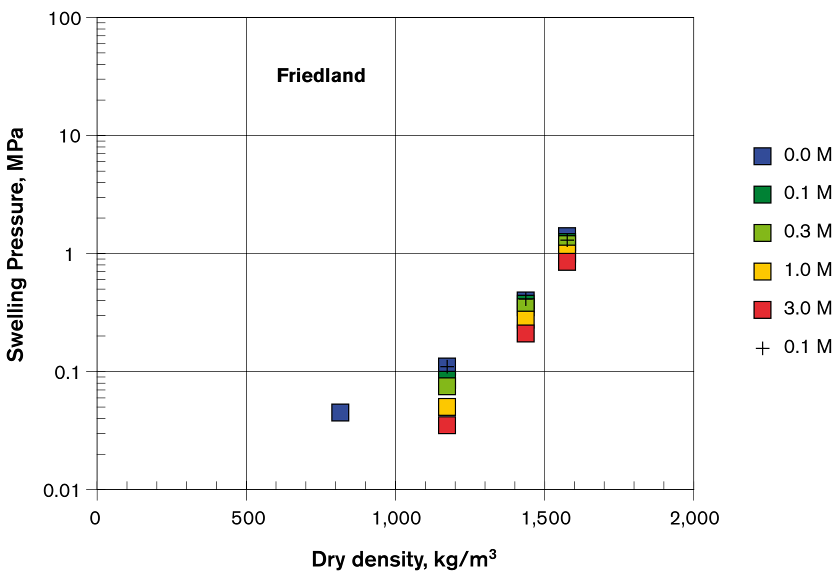


Figure 4-9. *Swelling pressure of Friedland clay as a function of dry density for different NaCl concentrations.*

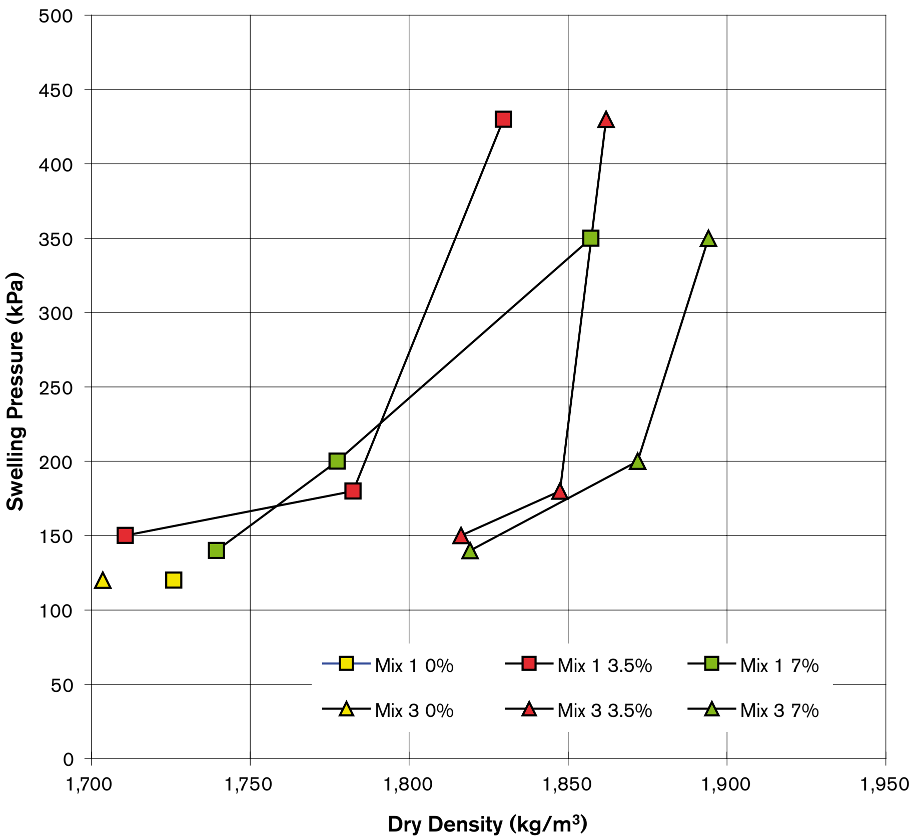


Figure 4-10. *Swelling pressure of different bentonite/crushed rock mixtures at 3.5% and 7% NaCl. Mix 1 represents MX-80 and aggregates and Mix 3 Deponit CA-N and aggregates (3.5% and 7% corresponds to 0.6 and 1.2 M, respectively).*

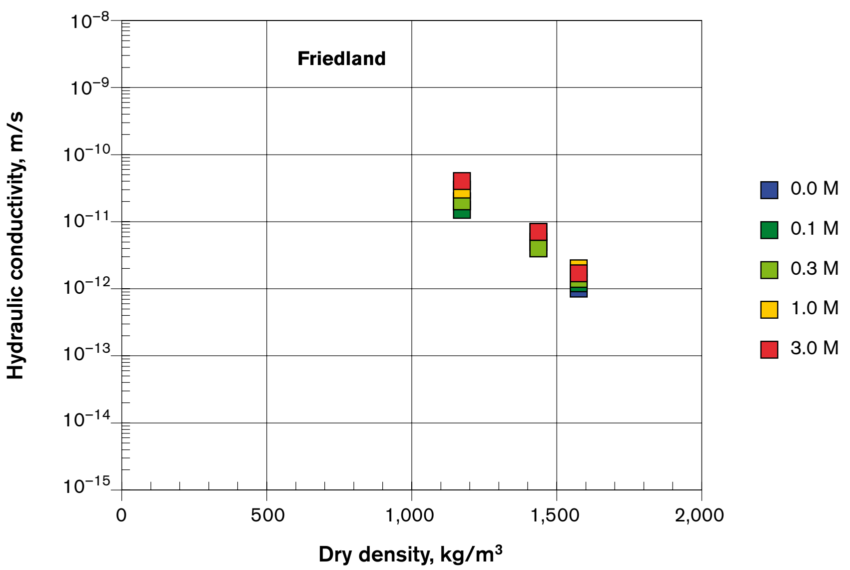


Figure 4-11. *Hydraulic conductivity of Friedland clay as a function of dry density for different NaCl concentrations.*

For the purpose of SR-Can, it is assumed that the same backfill concept will be used in these cavities as in the deposition tunnels. It is further assumed that the same working methods for application and quality control of the backfill are used.

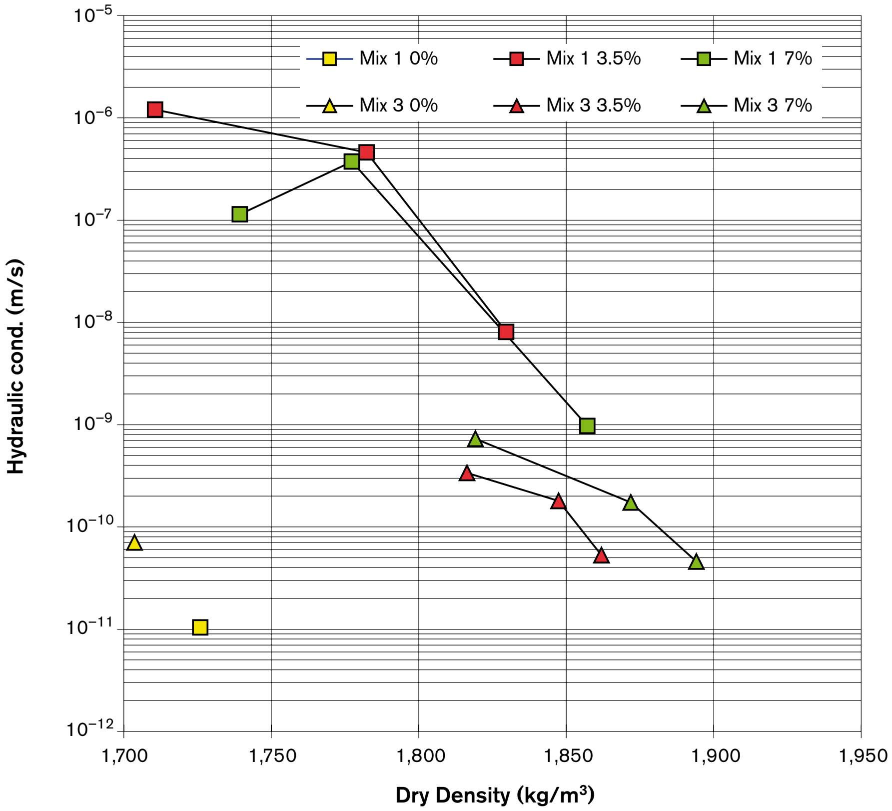


Figure 4-12. *Hydraulic conductivity of different bentonite/crushed rock mixtures at 3.5% and 7% NaCl. Mix 1 represents MX-80 and aggregates and Mix 3 Deponit CA-N and aggregates (3.5% and 7% corresponds to 0.6 and 1.2 M, respectively).*

As part of the decommissioning of the facility and as for the deposition tunnels, installations and building components will be stripped out prior to the backfilling of the underground facility. Materials like roadbeds will be removed, whereas rock supports like shotcrete and rock bolts, as well as grout in grout holes, will be left.

4.2.10 Materials for grouting and shotcreting

In SR-Can it is assumed that "low" pH cement, or other low pH grouting material, will be used for grouting of deposition holes and of deposition tunnels and also for potential shotcreting of deposition tunnels. These "low" pH materials are expected to have porewaters with pH ≤ 11. The development of low pH materials is ongoing meaning that their final compositions are not available.

4.2.11 Plugs

Each backfilled deposition tunnel needs to be sealed awaiting the backfilling of the main tunnel. The prime function of the plug is to take the hydraulic gradient from ambient pressure at the level to atmospheric pressure in the open drift system under ground, and by that prevent piping in the backfill. The hydrostatic pressure is the dominating construction requirement. The plug provides a mechanical support to the backfill material and it is sized to be strong enough to withstand the combined pressure from groundwater and the swelling of the bentonite. The plug is also required to prevent water flow.

The plug considered is a reinforced concrete plug grouted with low pH cement anchored in a slot in the rock. The design considered is similar to the reinforced plugs installed in the Prototype Repository in Äspö HRL.

The plugs will be left in the repository at its closure, but they have no long-term safety functions.

4.2.12 Borehole seals

A number of more or less vertical surface-based investigation or characterisation boreholes are to be drilled during site investigations in order to obtain, e.g. data on the properties of the rock. These boreholes will be sealed, no later than at the closure of the final repository. Some holes will be bored from the repository tunnels during the construction phase, meaning that horizontal and upwards-directed holes also have to be sealed.

The borehole seals must prevent short-circuiting of flow of potentially contaminated groundwater from the repository. They should, therefore, not be more transmissive than the undisturbed, surrounding rock. Time-dependent degradation must be accepted, but the goal is to use plug materials that maintain their constitution and tightness for a long time.

Seals for boreholes are under development as part of SKB's RD&D programme. The concept adopted for surface-based boreholes in SR-Can comprises the following materials at different depths: compacted till (0–3 m), close-fitting rock cylinders from the site (3–50 m), compacted till (50–60 m), smectite pellets (60–100 m), and highly compacted smectite clay contained in perforated copper tubes (below 100 m). Tunnel-based boreholes are assumed to be filled with highly compacted smectite clay in perforated copper tubes. These boreholes are to be plugged with concrete at the tunnel.

4.3 Initial state of geosphere and biosphere

4.3.1 From site data to SR-Can

The initial state of the geosphere is determined from the Site Investigations at the two sites explored and is generally described in the site descriptive model reports /SKB 2005c, 2006b/. The information transfer from field investigation to the safety assessment application involves several steps:

- Field data are obtained from various investigation activities like air borne and surface-based geophysics, borehole drilling and borehole testing. The data are quality controlled and then entered into the SKB measurement data base, Sicada.
- The field data are interpreted and evaluated into a cross-disciplinary Site Descriptive Model (SDM) being a synthesis of geology, rock mechanics, thermal properties, hydrogeology, hydrogeochemistry, bedrock transport properties and surface system properties, see Figure 4-13. The SDM provides a description of the current understanding of the site properties within the different discipline areas. It also provides an assessment of the uncertainty in these descriptions. The SDM is reported in a SDM report, i.e. /SKB 2005c/ for the Forsmark site and /SKB 2006b/ for the Laxemar subarea.
- The site description, and references therein, cannot always be used directly in the safety assessment. There may be a need to also consider non-site specific information, to add judgements on how to handle the uncertainties identified in the SDM and to make final selections of model input data. For this reason, all site data used in SR-Can is assessed in the **Data report**, using the SDM as input. The role of the **Data report** is explained in section 2.2. The format of the **Data report** is further discussed in chapter 8.

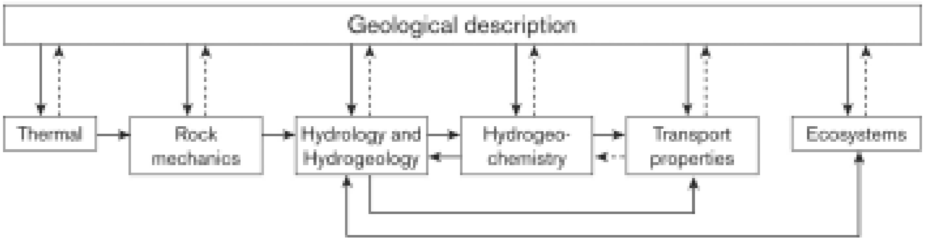


***Figure 4-13.** The field data are interpreted and evaluated into a cross-disciplinary Site Descriptive Model (SDM) being a synthesis of geology, rock mechanics, thermal properties, hydrogeology, hydrogeochemistry, transport and surface system properties.*

- Also a repository design including a site specific layout is developed based on the site description, as further discussed in section 4.4. As already stated in the introduction to this chapter, the initial state in SR-Can is defined as the state at the time of beginning of excavation of the repository for the geosphere and the biosphere. The evolution of the natural system, including the potential development of an Excavation Damaged Zone (EDZ) will thus, at least in some aspects, be followed from the time of beginning of excavation in the safety assessment, see section 9.2.

In short, the quantitative site-specific input to SR-Can is handled in the **Data report**, and is not repeated here in the main report. There is, however, a need to outline the main characteristics of the sites and to assess the current level of understanding of them. The remainder of this section provides an overview with this in mind. To minimise duplication of very similar material, different aspects of the site description are emphasized for the two sites while still giving enough information to allow the reader to appreciate the similarities and differences between the sites. Detailed input data (with rationale) are found in the SDM reports and the **Data report**.

4.3.2 The Forsmark site

Data input from the Forsmark site to the **Data report** are from version 1.2 of the SDM, but the overview given below also takes into account site understanding developed during analyses of more recently collected site data that have been carried out within the framework of step 2.1 of the site descriptive modelling for Forsmark /SKB 2006e/.

Setting

The Forsmark site is located in northern Uppland within the municipality of Östhammar, about 170 km north of Stockholm. The candidate area for site investigation, approximately 6 km long and 2 km wide, is located along the shoreline of Öregrundsgrepen (see Figure 4-14).

The north-western part of the candidate area has been selected as the target area for a potential repository. Characterisation of the bedrock in the target area is undertaken by both surface-based investigations and by investigations in boreholes, see Figure 4-14. The site information available for establishing version 1.2 of the Forsmark SDM is further exemplified below and fully described in the SDM report /SKB 2005c/.

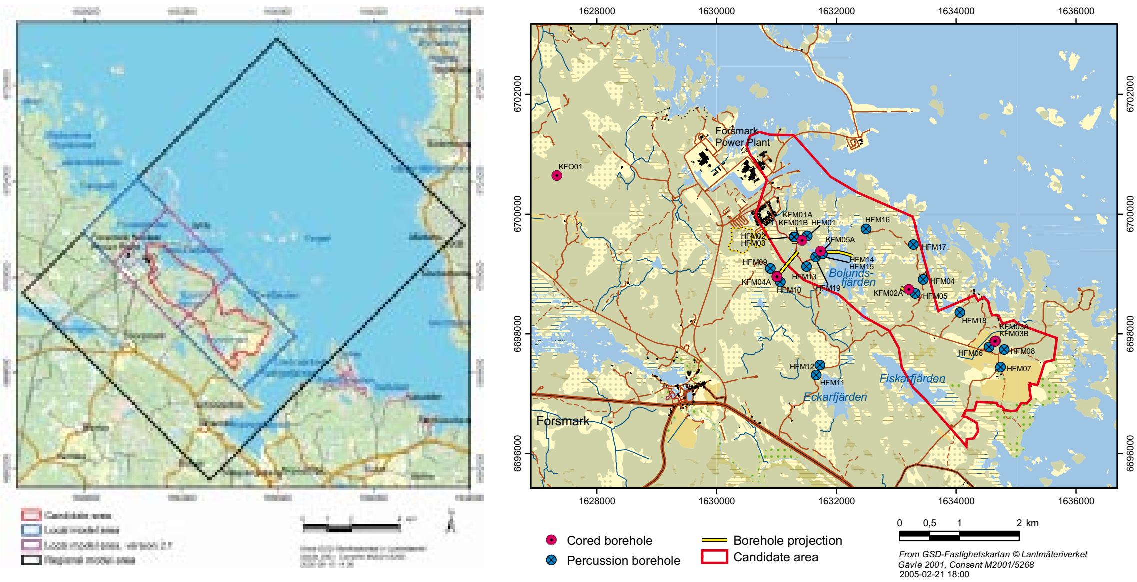


Figure 4-14. Geographical setting of the Forsmark site and location of deep boreholes defining the input to Forsmark SDM version 1.2 /SKB 2005c/.

Lithology and associated thermal and rock mechanics properties

The site lithology, i.e. the distribution of rock types, reveals important aspect of the structure of the site. Furthermore, it directly affects the ore potential as well as thermal and rock mechanics properties of the intact rock. In the SDM, the lithology is described by rock domains, defined based on composition, grain size, homogeneity, and style and inferred degree of ductile deformation.

Lithology and division into rock domains

The bedrock in the Forsmark region has been affected by both ductile and brittle deformation. The ductile deformation has resulted in large-scale ductile high-strain zones. Tectonic lenses, in which the bedrock is much less affected by ductile deformation, are enclosed in between the ductile high-strain zones. The candidate area is situated within the north-westernmost part of one of these tectonic lenses. This lens extends along the Uppland coast from north-west of the nuclear power plant south-eastwards to Öregrund (Figure 4-15) and it is c 25 km long and up to c 4 km wide.

In the regional structural context of the coastal area in northern Uppland, the tectonic lens in which the candidate area is located is considered to be well established. The lens developed more than 1,850 million years ago, when the rock units were situated at mid-crustal depths and were affected by penetrative but variable degrees of ductile deformation under amphibolite-facies metamorphic conditions. The bedrock inside the lens is relatively homogeneous and is dominated by a metagranite, whereas the lithology and deformation characteristics are more complex outside the lens.

A substantial amount of geologic data, both at the surface (mapping and geophysics) and from depth in the form of information from cored (5,600 m at six sites) and percussion (2,850 m at 19 sites) boreholes, underpins version 1.2 of the rock domain model. Cored borehole data confirm that the character of the bedrock at c 1,000 m depth inside the candidate area is similar to that observed at the surface. Hence, the surface geology is the key to the geology at depths down to at least 1,000 m in the candidate area at Forsmark.

The site investigation data confirm that the tectonic lens makes up the larger part of the candidate area and, due to its internal homogeneity, most of the lens can be described as a single "rock domain" denoted RFM029 (see Figure 4-16). The dominant rock type in this rock domain is medium-grained granite to granodiorite (c 75% of the domain volume). Subordinate rock types are fine- to medium-grained metagranodiorite or metatonalite, amphibolite, pegmatitic granite or pegmatite, and fine- to medium-grained granite. The dominant rock type and the subordinate rock types, except for amphibolite, have high quartz content, c 20 to 50%. A foliation within the metagranite is folded and both fold axis and mineral stretching lineations plunge towards the south-east.

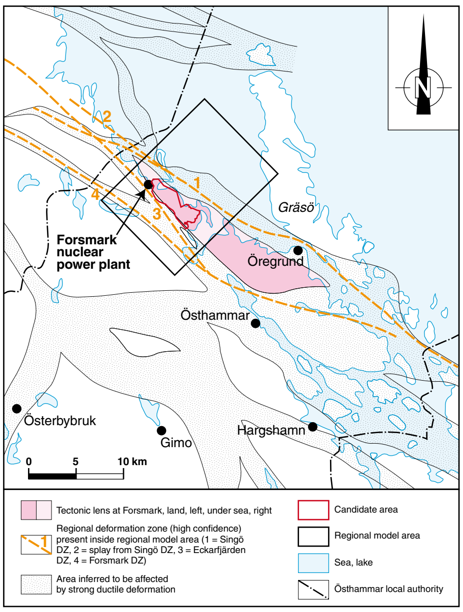


Figure 4-15. *Structural geological map of the coastal area in the local authority of Östhammar showing the extension of the tectonic lens within which the candidate area at Forsmark is situated.*

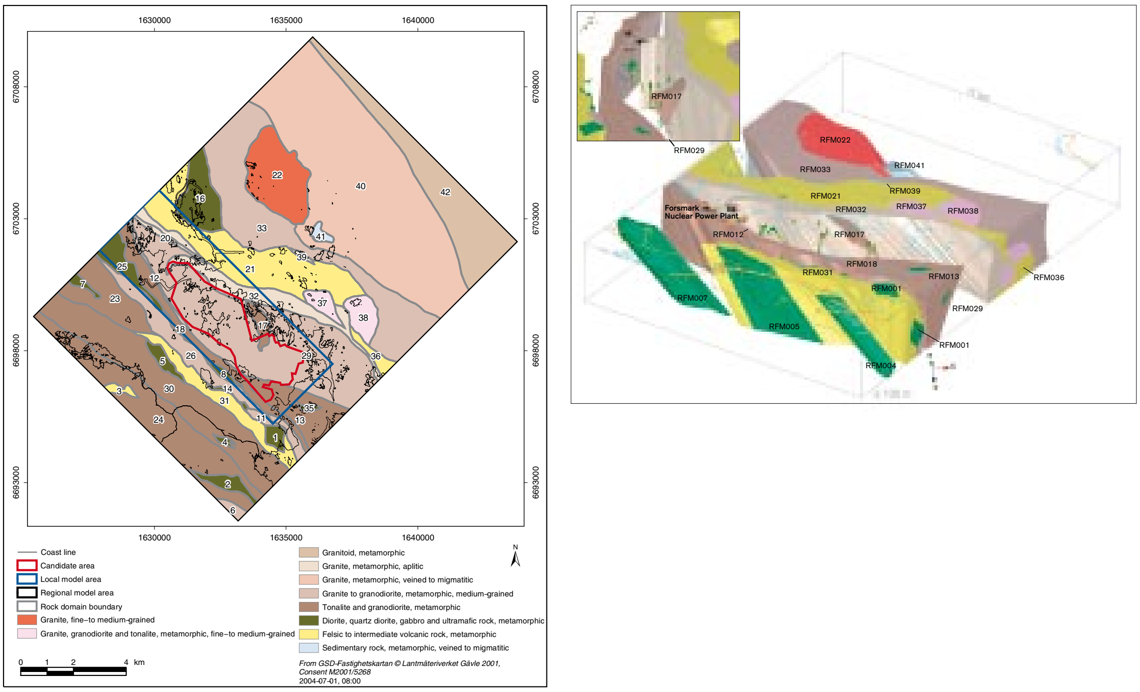


Figure 4-16. *Surface view (left) and 3-D view (right) of the rock domain model. The colours indicate the dominant rock type in each domain.*

The lens is surrounded by various domains that strike north-west, dip steeply to the south-west and are dominated by SL-tectonites, i.e. contain both planar and linear ductile mineral fabrics. In general, the rocks in these domains show a considerably higher degree of ductile deformation relative to that observed inside the tectonic lens and the bedrock is heterogeneous and composed of various types of felsic to intermediate metavolcanic rocks and metagranitoids. In the model, this is described as rock domains with strongly deformed, and also in part, banded and inhomogeneous rocks that occur along the south-western (e.g. RFM012, RFM018) and the north-eastern (e.g. RFM021, RFM032) margins of the lens. The rocks in these marginal domains dip steeply towards the south-west.

Ore potential

The ore potential is correlated to the rock types and their characteristics. An assessment of the ore potential carried out in support of model version 1.1 came to the conclusion that there is no potential for metallic and industrial mineral deposits within the candidate area at Forsmark. A potential for iron oxide mineralisation was recognised in an area south-west of the candidate area, predominantly in the felsic to metavolcanic rock, but the mineral deposits are small and have been assessed to be of no current economic value /Lindroos et al. 2004/.

Based on data from the islands offshore of the Forsmark candidate area, a new rock domain (RFM021), dominated by felsic to metavolcanic rock, was recognised in version 1.2 of the site descriptive model. This rock domain is located north of the candidate area (Figure 4-16). There is no documented iron mineralisation in data available from the islands, but since most of this rock domain is located beneath the Baltic Sea from where no mineralogical data exist, the potential for iron oxide mineralisation in rock domain RFM021 cannot be totally excluded.

Thermal properties

The thermal properties, i.e. thermal conductivity and heat capacity, of the rock are closely related to the lithology, since these properties depend on the mineral composition, and especially the quartz content. The thermal conductivity of the rock has been assessed from direct measurements and by calculations based on mineral composition from modal analyses. These two methods give consistent results.

The rock types in rock domain RFM029 have typically high quartz content, which favours high values of the thermal conductivity. Measurements at the cm-scale show values in the range 3.4 to 4 W/(m·K) for the dominant rock type in rock domain RFM029 and in rock domain RFM012 located southwest of RFM029, whereas some subordinate rock types yield significantly lower values. Upscaling of the thermal conductivity from rock type level to rock domain level at a scale of 0.8 m, i.e. the scale relevant to assess the thermal evolution in a deposition hole, retains the picture although the impact of subordinate rock types with lower conductivity is seen in the resulting distribution histograms (Figure 4-17). These facts are considered in the **Data report**, section 6.2, when defining the uncertainty and spatial variability ranges for thermal conductivity.

There is generally a high confidence in the modelled distribution of the thermal properties, due to their strong correlation with the well-understood lithology and also supported by the low spatial variability of the data, see Figure 4-17. The main remaining uncertainties in thermal properties of the rock in the target area concern the impact of subordinate rock types, both in terms of their thermal conductivity and their spatial distribution. In addition, some measured data indicate anisotropy in thermal conductivity in foliated parts of the rock with higher conductivity parallel to the foliation. This is being investigated further in larger-scale near-surface studies. However, the interpretation of these data is uncertain; the anisotropy may be overestimated in the small-scale measurements relative to its significance at the canister scale.

Rock mechanics properties of intact rock

Lithology also directly affects the thermal expansion, deformation modulus and mechanical strength of the unfractured rock (called intact rock in rock mechanics). Measurements of the mechanical strength of the dominant rock type (granite to granodiorite) within rock domain RFM029 show relatively high values for the uniaxial compressive strength (UCS) of intact rock (Figure 4-18) sampled at the depth interval 400 to 550 m in boreholes in the candidate area. The mean values for samples in boreholes from the target area (north-western part of the candidate area) are all above 220 MPa. The calculated

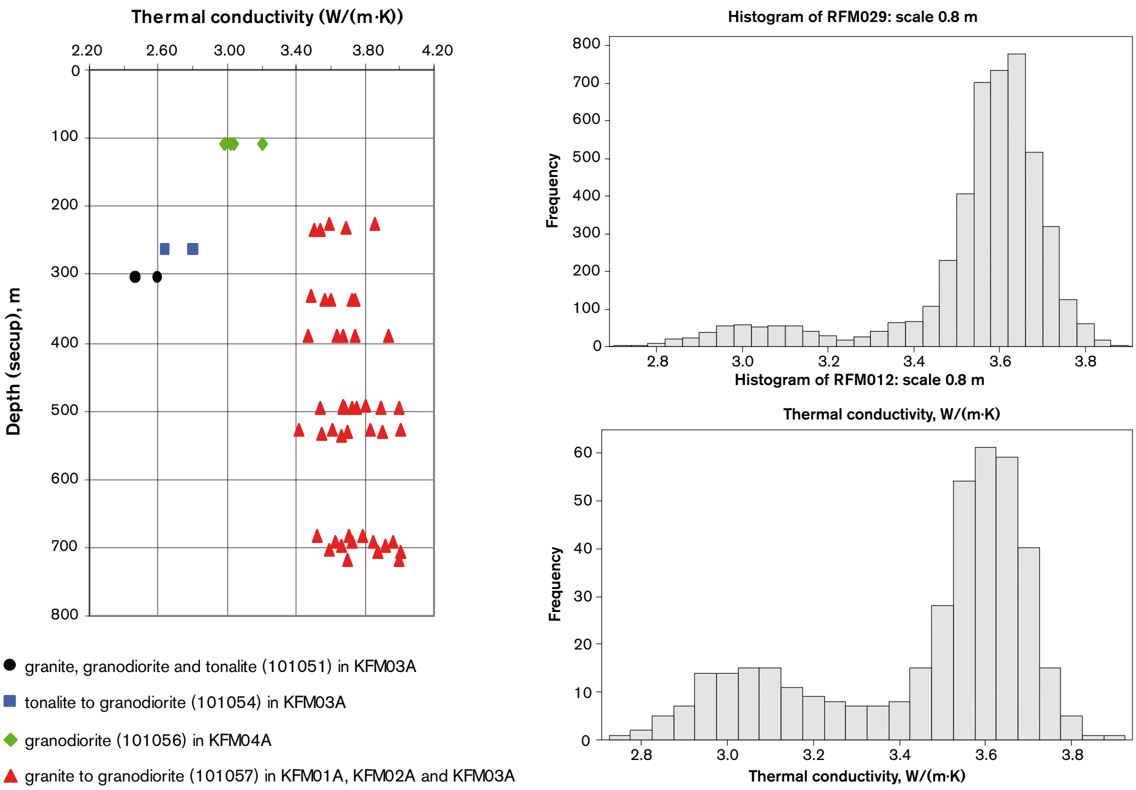


__Figure 4-17.__ Measured thermal conductivity at the cm-scale for different rock types (left) and modelled thermal conductivity for rock domain RFM029 (upper right) and RFM012 (lower right) at a scale of 0.8 m /Sundberg et al. 2005/. The resulting bi-modal distribution is a result of the lower thermal conductivity of subordinate rock types. Otherwise the thermal properties show little spatial variation.

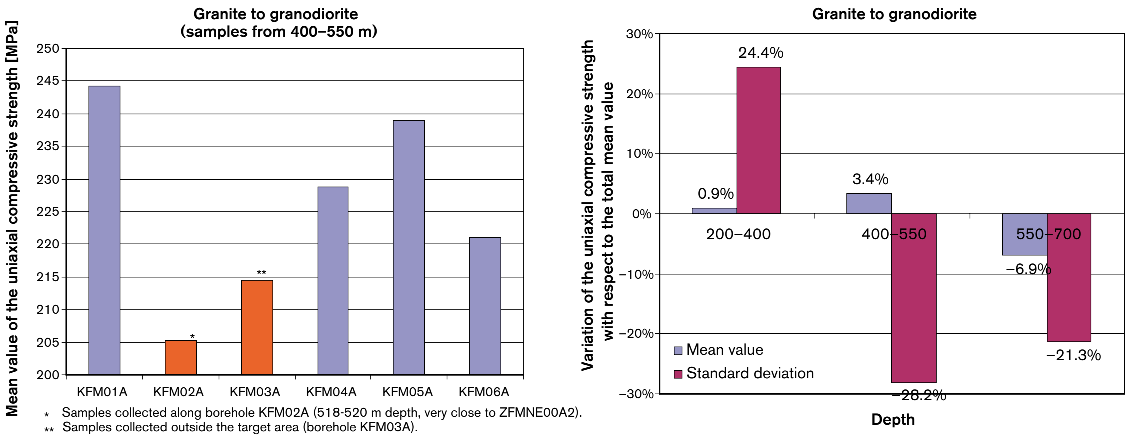


__Figure 4-18.__ Mean value of the uniaxial compressive strength measured in samples from 400 to 550 m depth in boreholes in the candidate area (left) and deviation in the mean value for different depth intervals from the overall mean value at all depths in rock domain RFM029 (= 225 MPa).

mean value of the UCS for intact rock in rock domain RFM029 is 225 MPa. Comparing the average value for different depth intervals with the overall average for rock domain RFM029 indicates a decrease of the UCS for intact rock by about 10% at depths below 500 m (Figure 4-18). This depth coincides with the depth where micro-cracking due to stress relief is expected.

Data for use in SR-Can are assessed in the Data report. There is generally a high confidence in the modelled distribution of the strength of the intact rock, at least inside rock domain RFM029, due to its strong correlation to the well understood lithology and also supported by the low spatial variability of the data, see Figure 4-18.

Deformation zones and fractures

Deformation zones and fractures are themselves important characteristics of the site as they affect the possible location of the repository, the mechanical stability and the groundwater flow. Furthermore, the deformation history and the geometry of the deformation zones affect the rock stress distribution and thereby also the properties of fractures in the volume. Understanding the deformation zones is thus key to understanding the fracturing, the in situ stress and the hydraulic properties.

Deformation zones and deformation history

Three major sets of deformation zones with distinctive orientations that have been recognized with high confidence at the Forsmark site are represented in the models. Vertical and steeply, SW-dipping zones with WNW and NW strike show complex, ductile and brittle deformation. Regional zones longer than 10 km (e.g. Forsmark, Singö and Eckarfjärden deformation zones at the boundary of the candidate volume) are restricted to this set which is the master set at the site (Figure 4-19). Vertical and steeply-dipping, brittle deformation zones with NE strike transect the candidate volume at Forsmark and are prominent in the Bolundsfjärden area (Figure 4-19 and Figure 4-20). This set is strongly dominated by sealed fractures and sealed fracture networks. Gently SE- and S-dipping brittle deformation zones occur more frequently in the south-eastern part of the candidate volume (Figure 4-20). Relative to the other two sets, there is an increased frequency of open fractures along the gently dipping set. These gently dipping zones seem to play an important role in determining the properties of the Forsmark site, such as the distribution of stress, fracturing and the transmissivity distribution of the fractures (see further below).

A fourth set of zones that strikes NS and is vertical or steeply dipping has also been recognized. However, only one local minor zone with a medium confidence of existence and a subordinate number of zones with a low confidence of existence have been included in model version 1.2. Relative to the other three sets, there is a limited number of such zones and a higher degree of uncertainty concerning the existence of this set of deformation zones.

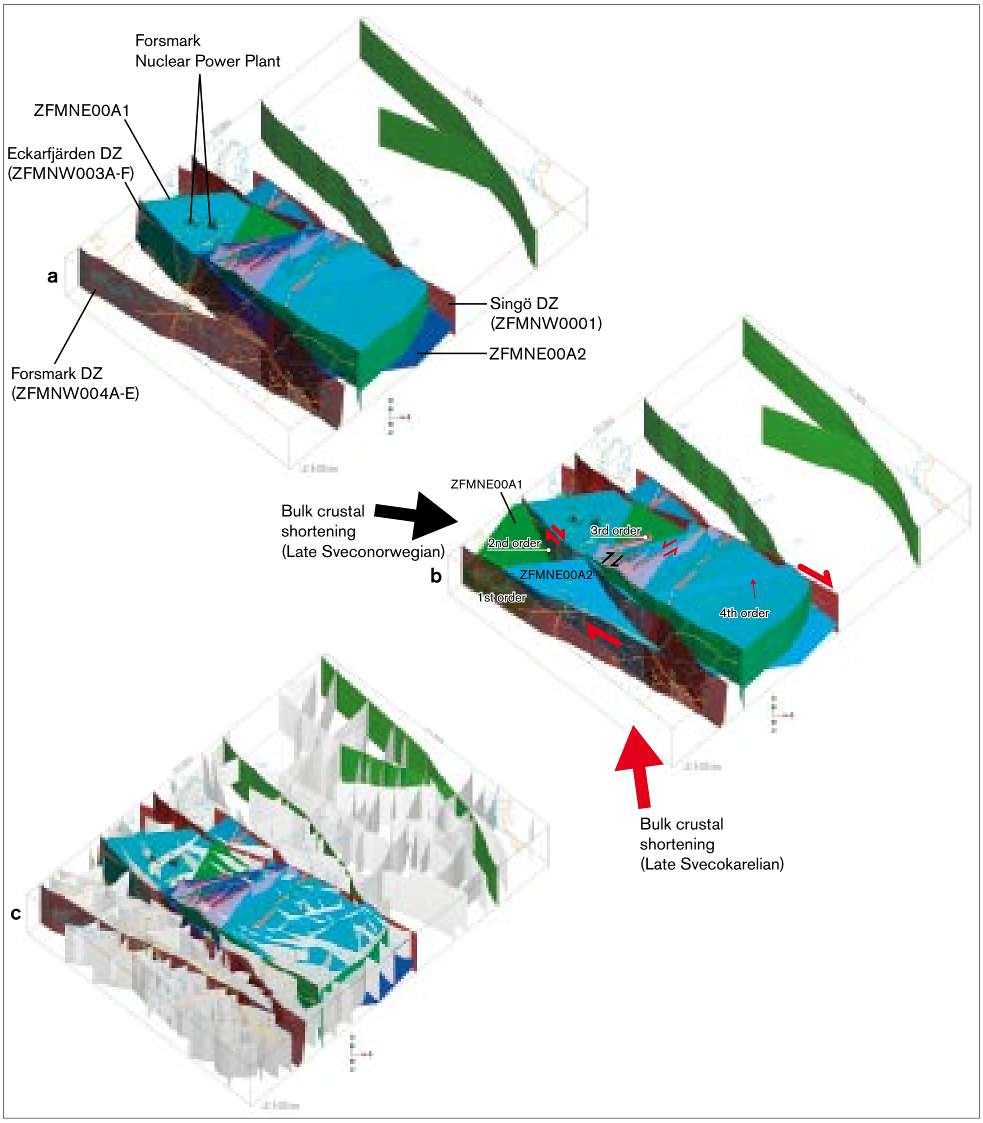


Figure 4-19. *a) Base model for deterministic deformation zones, viewed to the north. The zones coloured in red-brown shades are vertical and steeply dipping zones with high confidence of existence, the zones coloured in blue shades are gently dipping zones with high confidence of existence, and the zones coloured in green shades are medium confidence zones irrespective of their dip. b) Base variant model. c) Alternative model, where the zones coloured in grey shades are vertical and steeply dipping zones with low confidence of existence. The inferred sense of displacement and orientation of the maximum principal stress direction, during both the formation and an important phase of reactivation of these deformation zones, are shown in (b).*

Because of uncertainties concerning the geometry and character of deformation zones interpreted with the help of linked lineaments, mainly in the regional domain outside the candidate area, as well as in the extension of the gently dipping deformation zones, three alternative deformation zone models were developed in version 1.2 of the site descriptive model. These are referred to as the base model, the base model variant and the alternative model, see Figure 4-19abc. The difference between the base model and its variant only concerns the size of four gently dipping zones (ZFMNE00A1, ZFMNE00A2, ZFMNE00C1, ZFMNE00C2). In the alternative model (Figure 4-19c) vertical and steeply-dipping zones that are generally longer than 1,000 m are described as deterministic features within the whole regional model volume. Outside the “target area” (a volume in the north-western part of the candidate area that has been the focus for more detailed investigations, see Figure 4-50) virtually all these features have been identified solely on the basis of expression of lineaments and have been assigned a low level of confidence in existence. It should be noted that the alternative model essentially only differs from the base model outside the “target area”.

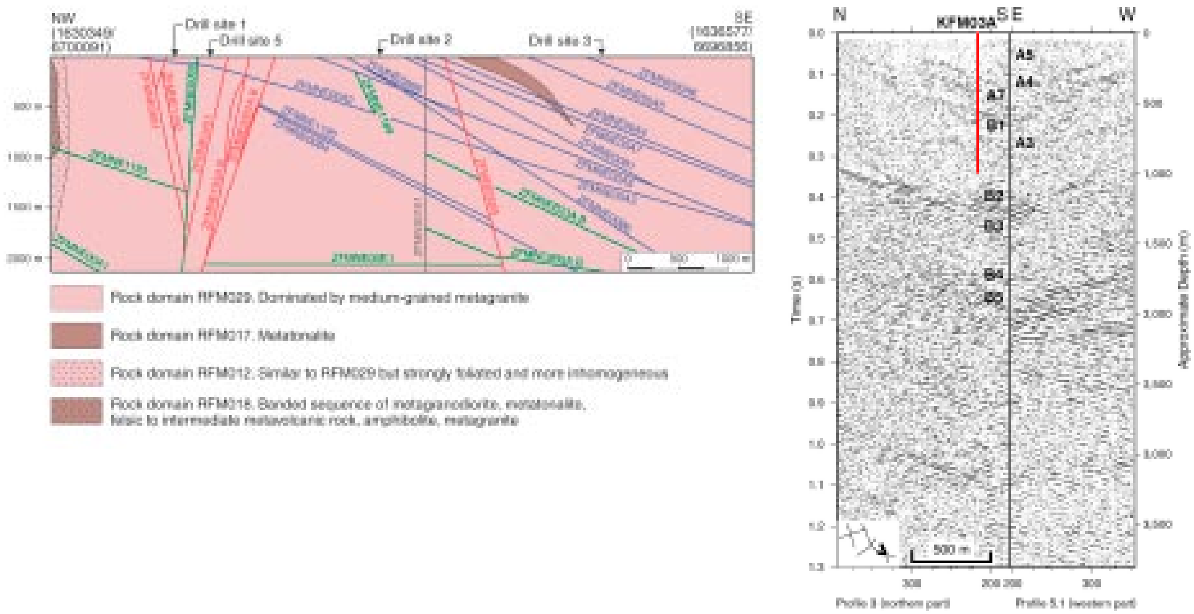


Figure 4-20. *Confidence in the gently dipping deformation zones is enhanced by combining reflection seismic data with borehole data. Left: NW-SE cross section through the candidate area in the structural model showing vertical and steeply dipping zones with high confidence (red), gently dipping zones with high confidence (blue), medium confidence zones (green) and a vertical zone with low confidence (grey). Right: Gently dipping seismic reflectors identified in the south-eastern part of the candidate area.*

The deterministic deformation zone model builds on the integration of the understanding of the deformation history with surface seismic reflection data, lineament interpretations, and fracture orientation, fracture mineralogical and bedrock alteration data from especially the cored boreholes. Gently dipping zones have mainly been detected by an integration of data from boreholes with the interpretation of seismic reflectors (Figure 4-20). By contrast, vertical and steeply dipping zones have been recognised by an integration of data from boreholes and the surface with the interpretation of, mainly magnetically identified, lineaments.

The properties of the deformation zones and geochronological data have been used to establish a conceptual model for the formation and reactivation of these zones in order to explain the order of creation of the different sets and how they terminate against each other. This model attempts to address the deformation zones in the context of changes in stress regimes from the later part of the Svecokarelian orogeny, c 1,800–1,750 million years ago, until the current time (Quaternary). The conceptual model, Figure 4-21, suggests that all three sets of deformation zones formed during the waning stages of the Svecokarelian orogeny, i.e. as a result of the stress changes caused by the variety of processes occuring during the Svecokarelian mountain-building. The regionally important Forsmark and Singö deformation zones with WNW strike, and the NW splays from these zones (e.g. Eckarfjärden deformation zone), are ranked as first-order and second-order structures, respectively, in a strike-dip fault system. It is proposed that these deformation zones formed in response to bulk crustal shortening in a N to NNW direction. The steeply dipping NE zones initiated as third-order structures and the gently SE- and S-dipping structures are fourth-order structures in the same system. Therefore, these sets terminate on the first- and second-order structures.

The conceptual model also addresses the reactivation and character of these different deformation zones. Among other things, the model suggests that the character of the gently dipping zones, with increased frequency of open fractures, incohesive breccias and clay minerals, is the result of rapid unloading during the removal of ice and significant changes in the magnitude of differential stress during the Quaternary.

The understanding of the tectonic evolution of the site, as expressed above, has had several implications for the development of a deterministic deformation zone model. For example, deformation zones and most of the fractures are inferred to be geologically ancient structures and the inferred structural hierarchy has provided a procedure for truncation of deformation zones. It is proposed that more than

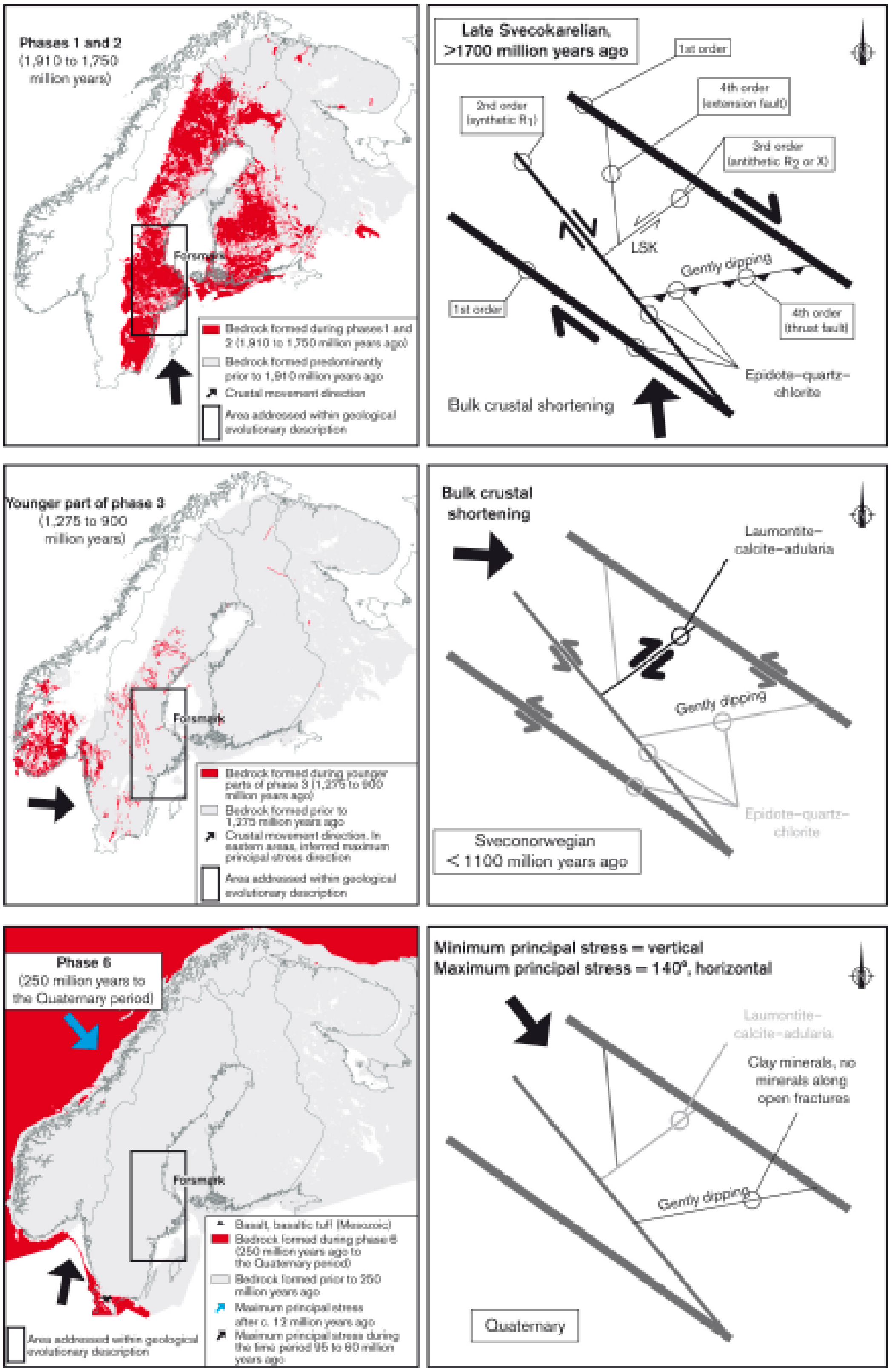


Figure 4-21. *Conceptual model for the formation and reactivation of the three major sets of deformation zones recognised at Forsmark.*

one fracture set is present along a deformation zone. Furthermore, rapid changes in the magnitude of the differential stress, during the Quaternary, can explain the increased frequency of open fractures and the increased hydraulic transmissivity of the gently dipping zones.

The upper few tens of metres of the bedrock contain fractures with a large aperture that are more or less parallel to the ground surface. Some of these fractures are filled with glacial sediments. It is suggested that they formed or reactivated as a result of stress release in connection with the removal of ice during the last glaciation and/or, at an earlier stage, in connection with the removal of the Phanerozoic sedimentary cover (younger than 545 million years). However, there is no evidence of faulting or major earthquakes since the disappearance of the last ice sheet.

The main uncertainties remaining in the version 1.2 of the deformation zone model are summarised below.

- The presence of undetected deformation zones cannot be ruled out, since there has been a strong focus in the geological programme on use of indirect data in the initial site investigation stage. However, all the larger deformation zones (> 3 km) have probably already been found, especially inside the target area.
- Continuity, dip and thickness of deformation zones, interpreted with the help of data on linked lineaments, are uncertain. There are poor constraints on the termination of a linked lineament and for dip and thickness, there are restricted amounts of data. However, in the "target area", the uncertainty is limited since some percussion and cored boreholes go through some of the deformation zones.
- The continuity and thickness of the gently dipping zones assessed, to a large extent, on the basis of seismic reflection data, are uncertain.

Since the publication of version 1.2 of the Forsmark SDM /SKB 2005c/, new data have been analysed as part of modelling step 2.1 /SKB 2006e/. In essence, these new data support the modelling of gently dipping fracture zones in the version 1.2 base model for deterministic deformation zones. However, the along-strike extension of virtually all these zones is reduced relative to that envisaged in the version 1.2 base model. The new data also show that a separate group of reflectors that strike NE and ESE and dip moderately southwards characterise the domain south-west of the tectonic lens.

Fractures and fracture domains

Smaller zones and fractures, not covered by the deformation zone model, are handled in a statistical way through discrete fracture network (DFN) models. The descriptions are based on fracture observations in the boreholes, mapped fractures at outcrops and from interpretation of lineaments. The DFN model captures both the open and the sealed fractures since also the sealed fractures are potential planes of weakness and could be planes where there exist flow channels. However, this approach probably overestimates the fracture frequency since many of the sealed fractures are mechanically and hydrogeologically indistinguishable from the intact rock.

Analyses of fracture data indicate a large spatial variability in the size, intensity and properties between different rock domains, but also within rock domain RFM029. For example, the frequency of open and partly open fractures, fractures that by the mapping geologists are judged to have an aperture in their natural state, is markedly higher in the upper part (c 300 m) of the bedrock in the north-western part of rock domain RFM029 relative to that observed in deeper sections in this part of domain RFM029. By contrast, there is no simple depth dependence in the frequency of such fractures in the south-eastern part of rock domain RFM029. Furthermore, fracturing is affected by the proximity to deformation zones. This is indicated, for example, by the higher frequency of fractures immediately beneath the gently dipping deformation zone ZFMNE00A2 that outcrops in the target area, and very few fractures at greater depth below this zone. This suggests that rock domain RFM029 should be subdivided into different fracture domains.

The possible need for division into fracture domains was identified as a result of the version 1.2 modelling work, but the version 1.2 DFN model does not make that division of rock domain RFM029 into sub-domains. Instead, one DFN model is produced for the entire rock domain RFM029. This is also the model used within SR-Can. More details of this model and associated uncertainties are given in the **Data report**, section 6.3.

As part of the work within step 2.1 of the site descriptive modelling /SKB 2006e/, a conceptual model for the division of the bedrock at Forsmark into fracture domains has been developed (Figure 4-22). Potentially, the uncertainties in the DFN-model as assessed within SR-Can, building on the version 1.2 DFN-model, could be reduced in the future through application of this conceptual model and thereby improve the representation of the repository rock.

Stress conditions

The state of stress in rock domain RFM029 is estimated based on overcoring and hydro-fracturing results obtained in boreholes KFM01A, KFM01B, KFM02A and KFM04A and from old overcoring measurements in a borehole drilled during the construction of the nuclear power plants (borehole DBT-1). The results show that the maximum horizontal stress trends NW-SE, sub-parallel to the plate-ridge push and to the regional deformation zones at the site, and that the magnitude is significantly higher, at least at some 200–500 m depth, than at other sites in Scandinavia (Figure 4-23). The geomechanical and stress data also show that the upper crust, down to about 100–200 m depth, exhibits a more varying stress state characterised by local changes in magnitude and orientation.

The orientation of the major deformation zones relative to the current regional stress orientation, given by the plate ridge push, offer a conceptual explanation for the high stress levels found. Especially the rock volume below deformation zone ZFMNE00A2, see Figure 4-20 and Figure 4-22, would be subject to the full thrust of the regional stress, whereas rock volumes above the zone would be relatively relaxed and thus show lower stress levels. A higher rock stiffness inside the lens attracting higher stresses may also be a factor that needs to be considered. However, it should be noted that all stress data collected so far in the candidate area are from the rock below the gently dipping deformation zone ZFMNE00A2. More stress data, especially above deformation zone ZFMNE00A2, are needed before a high confidence stress model could be established. Such data are being acquired as part of the complete site investigation programme and will be available in time for SR-Site.

Nevertheless, data from borehole DBT-1 support the hypothesis in that they display a stress jump at the same depth at which a fracture zone has been detected (Figure 4-23). New reflection seismic data show that this, water-bearing, minor fracture zone at c 320 m depth in borehole DBT-1, corresponds to a gently dipping reflector potentially similar in character to ZFMNE00A2. The reflector dies out to the south-east and does not transect the candidate volume. Similar observations of variation of in situ stress across geologically old thrust faults have also been made in the URL in Canada where the rock above a gently dipping fracture zone at about 300 m depth is low-to moderately stressed and the rock below this zone is highly stressed /Martin et al. 2001 and references therein/.

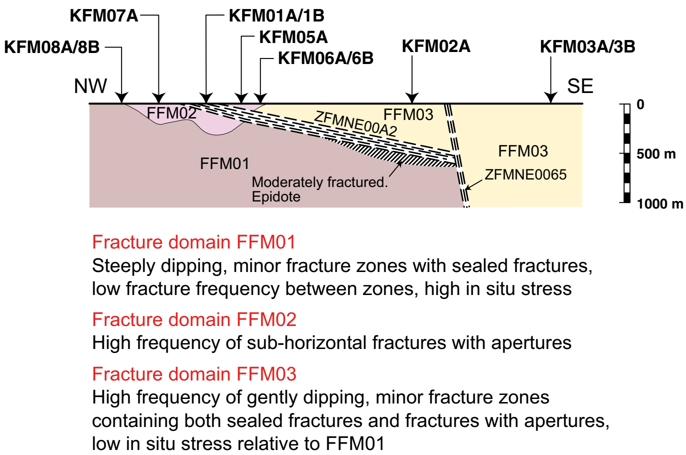


Figure 4-22. *A possible division of the candidate volume at Forsmark, which is dominated by rock domain RFM029, into three fracture domains. The domains are shown on a simplified NW-SE cross-section along the candidate volume. Only two fracture zones, the gently dipping zone ZFMNE00A2 and the steeply dipping zone ZFMNE0065, against which zone ZFMNE00A2 appears to truncate, is shown (Figure 3-7 in /SKB 2006e/). This volume division is not used in the DFN-model assessed within SR-Can, but it would probably be the basis for future DFN-models of the Forsmark site.*

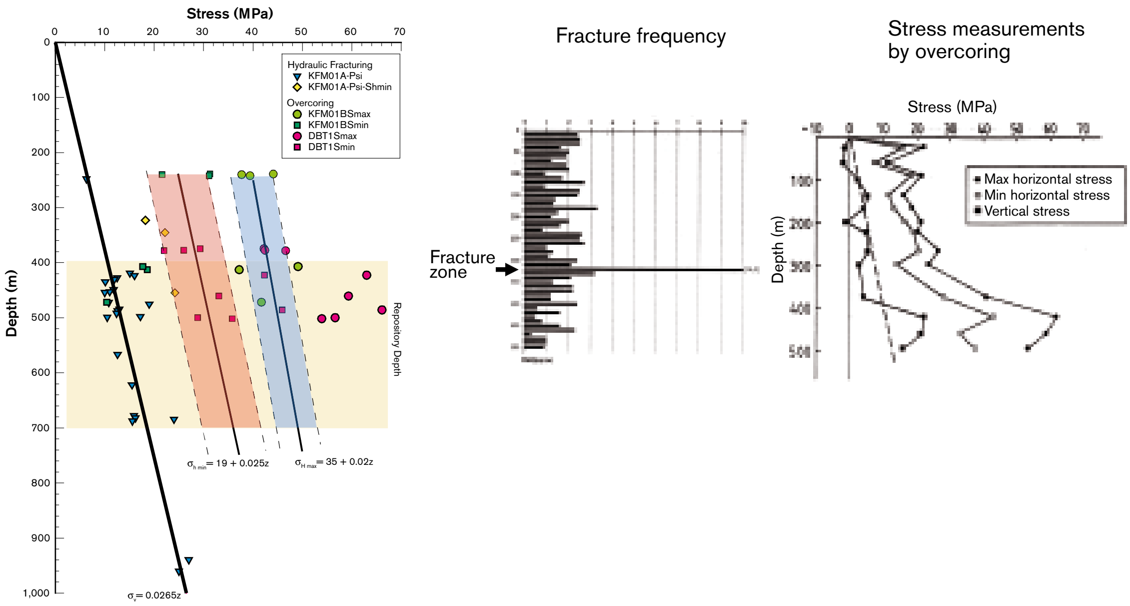


Figure 4-23. *Left: Stress measurements and stress modelling results for RFM029 at Forsmark (Figure 6-16 in Forsmark SDM version 1.2 /SKB 2005c/). Right: stress data and fracture frequency in borehole DBT-1 /Carlsson and Olsson 1982/.*

Hydraulic properties

Analyses of hydraulic data from the boreholes in the candidate area have shown that the geological structures in the uppermost part of the bedrock are highly transmissive in the horizontal plane and in good hydraulic contact over long distances (c 2 km). In contrast, the geological structures at depth beneath deformation zone ZFMNE00A2 appear to be of low permeability (Figure 4-24). This strongly suggests that the rock mass between the deterministically modelled deformation zones in rock domain RFM029 contains sub-domains with different hydraulic properties, and thus also supports the hypothesis of sub-division of the rock into fracture domains, as mentioned above.

Another observation made is that the transmissivity of deformation zones seems to depend on depth and dip, with higher transmissivity in the gently dipping zones than in the steeply dipping zones at comparable depths. It may also be noted that the least principal stress is vertical, which is consistent with higher transmissivity in gently dipping zones. However, down to c 60 m depth, the zones are hydraulically very heterogeneous with transmissivities that vary over three orders of magnitude. These observations are based on results of hydraulic testing of 27 of the 44 deformation zones included in the version 1.2 deformation zone base model (Figure 4-19a).

The hydraulic data from the boreholes strongly suggest that the rock mass inside rock domain RFM029 should be divided into volumes with different hydraulic properties as outlined in Figure 4-24. Such a division is also supported by the geological and stress model (see Figure 4-22), although the latter only suggests a stress jump over the deformation zone ZFMNE00A2. However, since there are few boreholes, the exact boundaries of the different volumes remain to be defined. In particular, it should be noted that although it is likely that most of the repository panels according to the layout would lie within volumes of very low permeability, it cannot yet be excluded that some parts will be in more permeable volumes.

The rock mass encountered below the foot wall of the gently dipping deformation zone ZFMNE00A2 has very low permeability, but the proper way of describing this rock volume is still developing. Data show that there are very few features with measurable transmissivity outside the deterministically modelled deformation zones. Depending on assumptions made in the DFN modelling, alternative interpretations are possible ranging from a sparsely connected fracture network with a rather high transmissivity field to a well connected fracture network with a very low transmissivity, i.e. close to the lower measurement limit of the hydraulic test equipment. As is further elaborated in the Preliminary Safety Evaluation of the Forsmark site /SKB 2005b/, the probability of intersecting narrow channels with boreholes is much lower than of intersecting a wide channel in a fracture. This makes the estimates of the frequency of occurrence of flow paths uncertain.

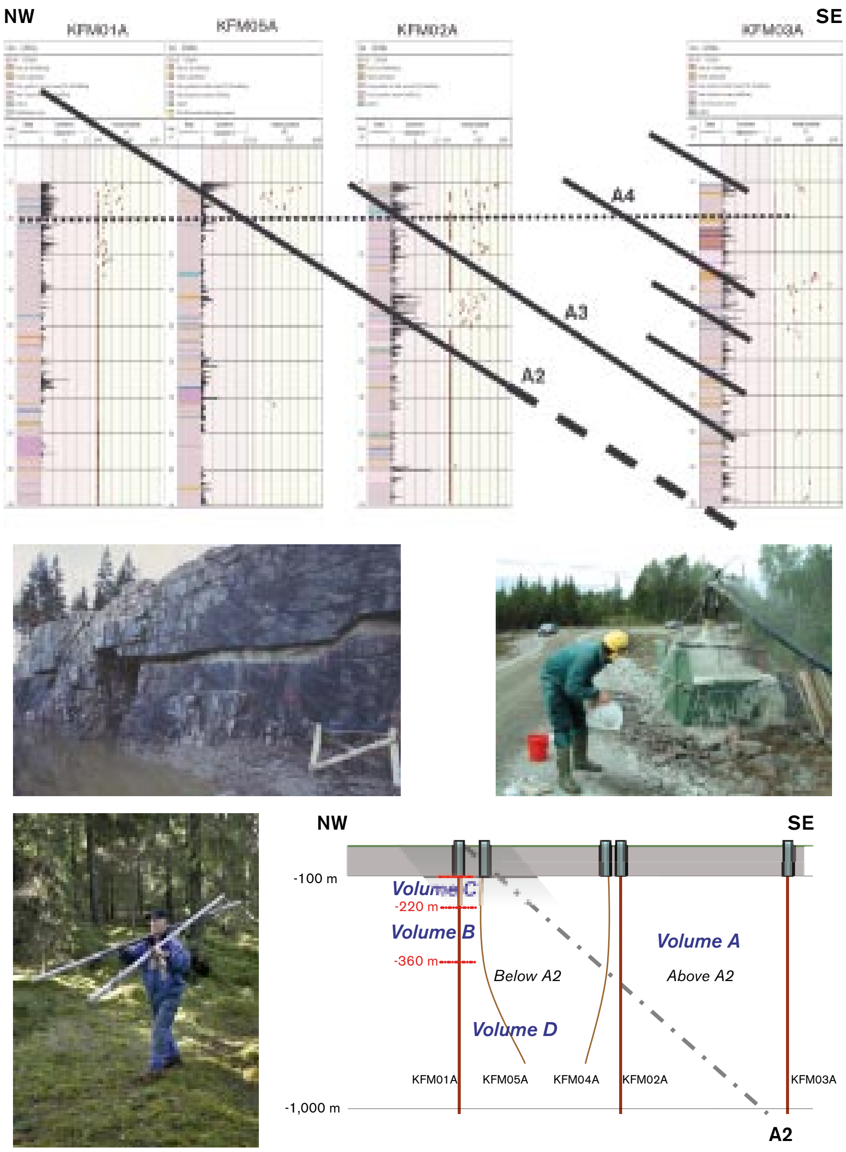


Figure 4-24. *Analyses of hydraulic data from the boreholes in the candidate area have shown that the near-surface rock contains highly transmissive structures, whereas the rock in rock domain RFM029 appears to be of low permeability at depth below the deformation zone ZFMNE00A2.*

A realistic base case for the rock mass is to assume that the volume is characterised by a low density fracture network. This DFN-model implies very few intersections between boreholes (or deposition holes) and water conductive fractures, but it is possible that the model volume contains some, still undetected, high transmissivity paths. At the current level of site understanding, the existence of such paths cannot be excluded (Figure 4-25). A conceptually different way of representing the low permeability region would be to describe the rock mass as a very low permeability continuum porous medium (CPM) intersected by the much more transmissive deformation zones. In this conceptualisation, there are no possibilities for high transmissivity paths outside the deterministically modelled deformation zones. Potentially, it may be found that this is indeed the most reasonable description of the low permeability rock, but currently the existence of the "stochastic" high transmissive paths cannot be ruled out. Furthermore, the CPM model is not correct in the volumes above the low permeability volume. There it is quite clear that the flow takes place in fractures and not in a homogeneous porous medium.

These and other uncertainties, as well as the quantitative implications for the uncertainty analysis of SR-Can, are discussed at length in the **Data report**, sections 6.5 and 6.6.

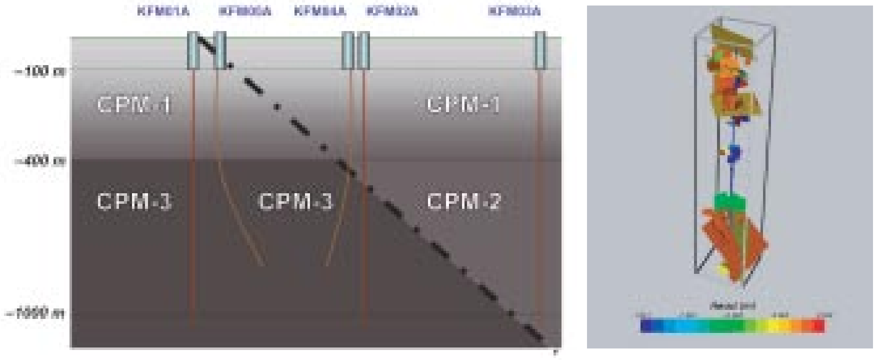


Figure 4-25. *There are different ways of describing the low permeability of the deeper rock volumes ranging from a low permeability porous medium CPM (left) to a poorly connected fracture network (right). Both these representations could be made to match the hydraulic data.*

Groundwater flow

Based on the hydraulic property description, the SDM version 1.2 also presents transient, density dependent, groundwater flow calculations in an equivalent porous medium representation at a regional scale. Figure 4-26 shows resulting groundwater flow paths, obtained from particle tracking in the present velocity field.

The analyses suggest that the flow field in the north-western part of the candidate volume is mainly local. The presence and properties of deformation zones outside RFM029 have little effect on flow and salt transport inside the rock domain. In contrast, deformation zone heterogeneity within the candidate area has a clear effect on the local flow distribution. However, it should be noted that these simulations do not consider the anisotropy and heterogeneity of the hydraulic properties of the near-surface rock as indicated by the hydraulic data from the site. More details are given in /Hartley et al. 2005a/ and /Follin et al. 2005/. Furthermore, additional simulations have been carried out within the framework of SR-Can, as discussed in chapter 9.

Groundwater composition

Explorative analyses of measured groundwater chemistry data and hydrogeochemical modelling have been used to evaluate the hydrogeochemical conditions at the site in terms of the origin of the groundwater and the processes that control the water composition.

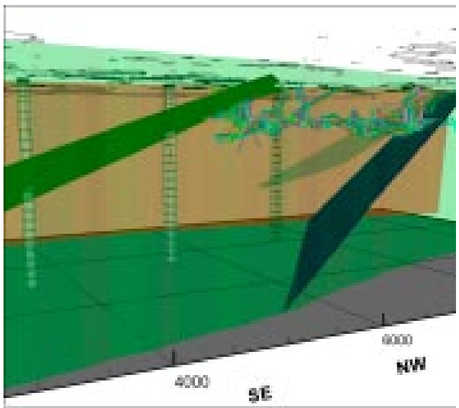


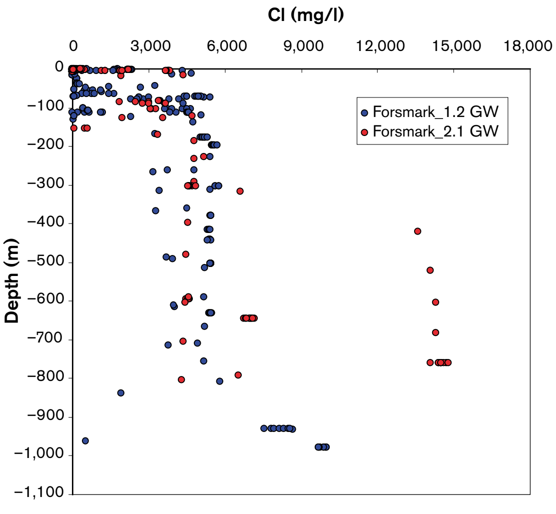
Figure 4-26. *Regional groundwater flow simulations strongly suggest that the groundwater flow field in the target volume is local and is determined by the local geometry and features within rock domain RFM029.*

Data on groundwater composition show an increase in salinity down to a depth of about 200 m (Figure 4-27). This combined with the finding that ^3H data show no input of modern water at depths greater than 200 m indicates that groundwaters in the uppermost parts of the rock are of meteoric origin. At depths between 200 and 800 m, the salinity remains fairly constant at a level between 5,000 and 6,000 mg·L^{-1}, which together with high Mg concentrations indicate input of Littorina Sea waters at these depths (Figure 4-27). The Littorina Sea stage is one of the main stages in the development of the Baltic Sea since the last deglaciation (see also Figure 4-28). At depths between 800 and 1,000 m, the salinity increases to high values and there are some weak indications that the salinity is higher at large depths in the rock in the north-western part of the candidate area (i.e. in the target area) as compared with the south-eastern part.

Analyses of groundwater chemistry data have also revealed an anomaly in uranium concentration. Large variations in uranium content in surface waters are common and are usually ascribed to various redox states (oxidation will facilitate mobilization of uranium) and various contents of complexing agents, normally bicarbonate (which will keep the uranium mobile). Lower uranium content with depth is expected due to decreasing redox potential and decreasing bicarbonate content. This trend is not seen in the data collected so far at Forsmark. Instead, most of the data indicate high values at depths between 200 and 600 m (Figure 4-27). The reason for this anomaly is presently under investigation.

According to current understanding of the past evolution, the Forsmark site has been transgressed by different non-saline and brackish lake/sea stages since c 11,000 years BP, which have affected the hydrogeochemical conditions at the site (see Figure 4-28). Of these periods, the Littorina Sea period, with a salinity maximum of about twice the present salinity of the Baltic Sea, is judged to have had largest impact by penetrating down into the rock and by mixing with glacial/brine groundwater already present in the bedrock. During the last 1,500 years, the Forsmark region has gradually emerged above the sea and recharging fresh meteoric water has formed a lens on top of the more saline water. Since the topography of the Forsmark area is relatively flat, and the time elapsed since the area emerged above the sea is short, the outflushing of saline water has been limited and the freshwater lens exists only at shallow depths.

The hydrogeochemical data evaluation and modelling has revealed that the main compositional changes in groundwater composition at Forsmark have been caused by mixing of waters of various origins, and that microbial processes and rock-water interactions are important in controlling certain parameters such as redox, pH and some trace element concentrations.



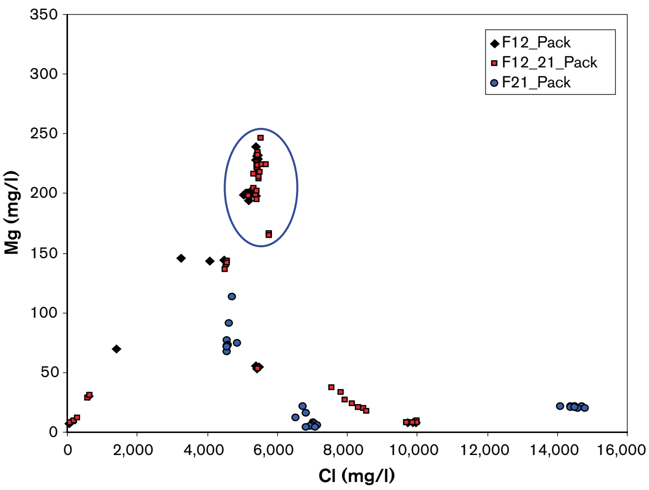


***Figure 4-27.** Salinity versus depth (left) and magnesium versus chloride (right) (data from SDM versions 1.2 /SKB 2005c/ and modelling step 2.1 /SKB 2006e/). The cluster of high magnesium concentrations at chloride concentrations at about 5,000–6,000 mg·L^{-1} is an indication of Littorina Sea water input since these concentrations are higher than in Baltic Sea water.*

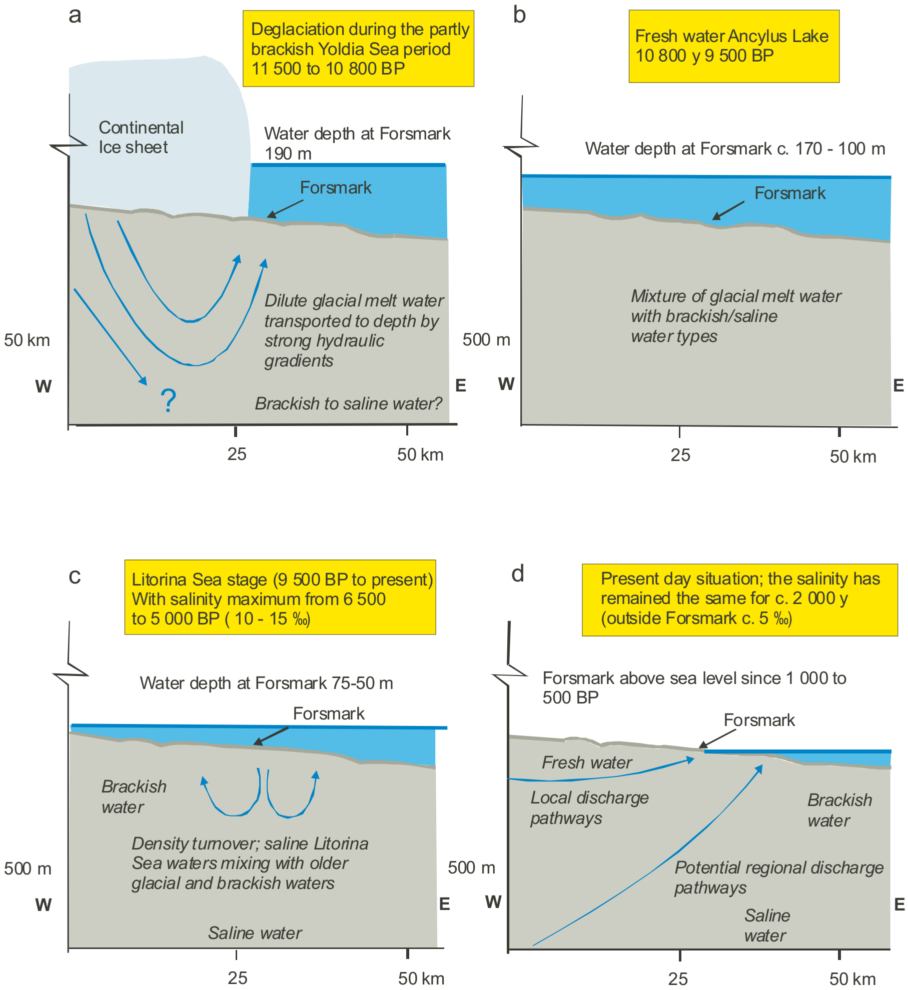


Figure 4-28. *Conceptual model for the postglacial evolution at the Forsmark site. The figures show possible flow lines, density driven turnover events, and non-saline, brackish and saline water interfaces. The possible relation to different known post-glacial stages such as isostatic land uplift, which may have affected the hydrochemical evolution of the site is shown; a) Yoldia Sea stage including deglaciation, b) Ancylus Lake stage, c) Littorina Sea stage, and, d) present-day Baltic Sea stage. From this conceptual model it is expected that glacial meltwater and deep and marine water of various salinities have affected the groundwater distribution.*

Four main groundwater types are present at Forsmark (Figure 4-29). A shallow Na-HCO_3 (Type A) groundwater forms a distinctive horizon at the centre of the transect in Figure 4-29. It lenses out towards the SE Baltic Coast where discharge of deeper groundwater probably occurs. From Lake Bolundsfjärden to the NW, a less marked horizon is indicated, but data are few. In addition, the influence of the deformation zone A2 on the groundwater chemistry is not clear at this near-surface locality, but may represent some kind of boundary between Type A and the deeper Type B Littorina groundwaters.

Bordering the shallow Na-HCO_3 groundwaters, and extending from close to the surface (near the SE coast) to depths of around 500 m (e.g. along the gently dipping deformation zone A2), are the Type B Littorina Sea groundwaters. An explanation for the preservation of Littorina water beneath Lake Bolundsfjärden could be the low permeability of the bottom sediments of the lake, which, together with the flat topography, would limit flushing out of the water from the rock. Also the presence of horizontal conductive zones in the uppermost part of the bedrock is important in this respect (see below).

The distribution of the deeper, more saline groundwaters (Type C) is based on few data, but these appear to represent much older groundwaters of deep origin (> 1,000 m) that have undergone mixing with cold climate glacial waters at least down to around 1,000 m depth, but it should be noted that

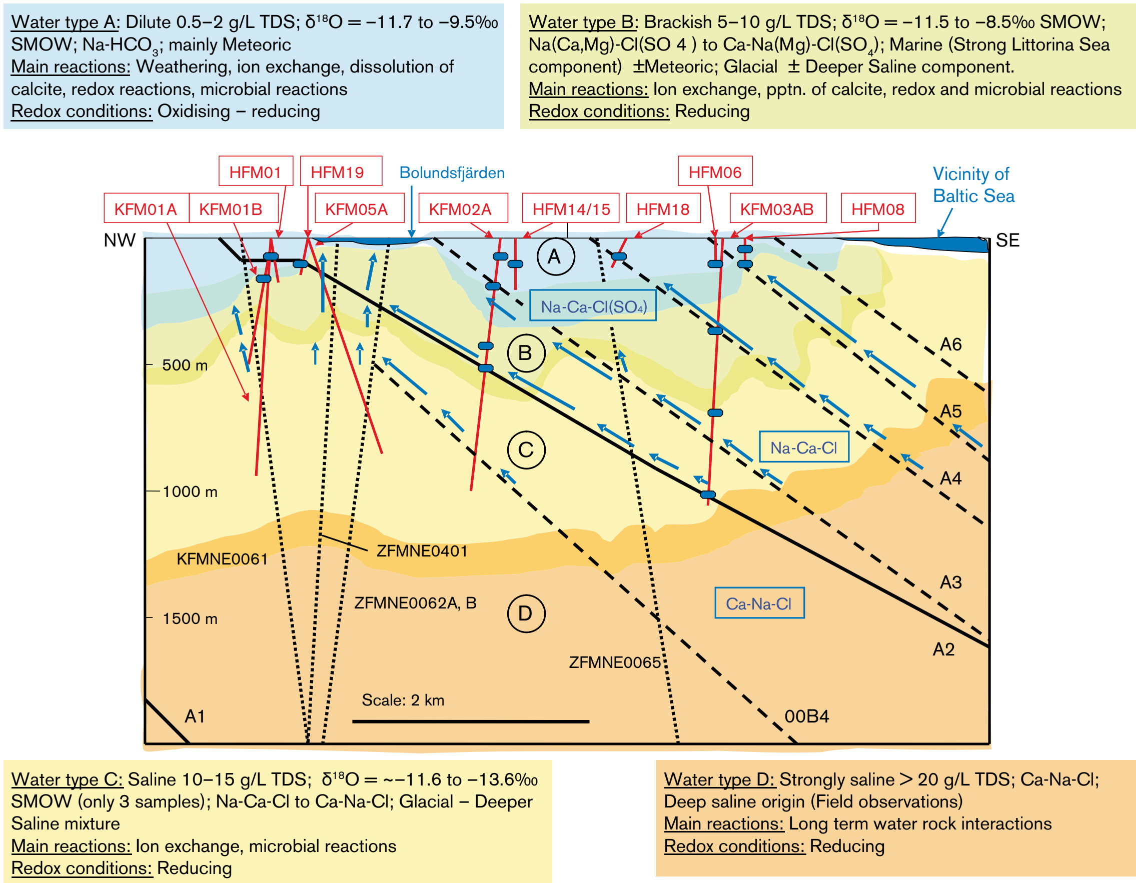


***Figure 4-29.** Schematic 2-D cross-section, along the current shoreline, integrating the major structures, the major groundwater flow directions and the variation in groundwater chemistry (Types A–D) from the sampled boreholes (indicated in blue). The blue arrows are estimated groundwater flow directions. Note, this cross-section is essentially perpendicular to the main flow direction.*

chemical data are sampled in the highly transmissive deformation zones only. Lack of data precludes a more specific interpretation. At still greater depths (> 1,000 m), strongly saline, non-marine groundwater (Type D) is probably dominating. However, so far this is suggested by field observations during pumping tests only.

Hydrogeological simulations of the past evolution of groundwater composition show some agreement between simulated and measured hydrogeochemical data at depth, whereas poorer matches were obtained in the upper 100 m of the rock (Figure 4-30). Furthermore, these hydrogeological simulations support the occurrence of Littorina Sea water in the upper 500 m of the rock. An explanation for the poor match in the upper part of the rock can be that the uppermost part of the bedrock is much more anisotropic and hydraulically heterogeneous (highly transmissive in the horizontal plane) than predicted in the version 1.2 hydrogeological model. Point-water head data suggest a “hydraulic cage” scenario where the recharge of meteoric water from above is short circuited by sub-horizontal fractures/fracture zones/sheet joints in the uppermost part of the of the rock and the outcropping gently dipping deformation zones. This hypothesis and the implications of dividing the rock into different hydraulic domains (see sub-heading ‘Hydraulic properties’ above) will be further elaborated and tested in coming site modelling work.

Remaining uncertainties in the hydrogeochemical description of the Forsmark site, including the anomaly in uranium concentration data, mainly concern the groundwater composition in the low-conductive parts of the rock as well as the spatial variability in composition and interactions between surface waters and groundwater. Details of the groundwater composition and the implications for SR-Can are given in the **Data report**, section 6.1.

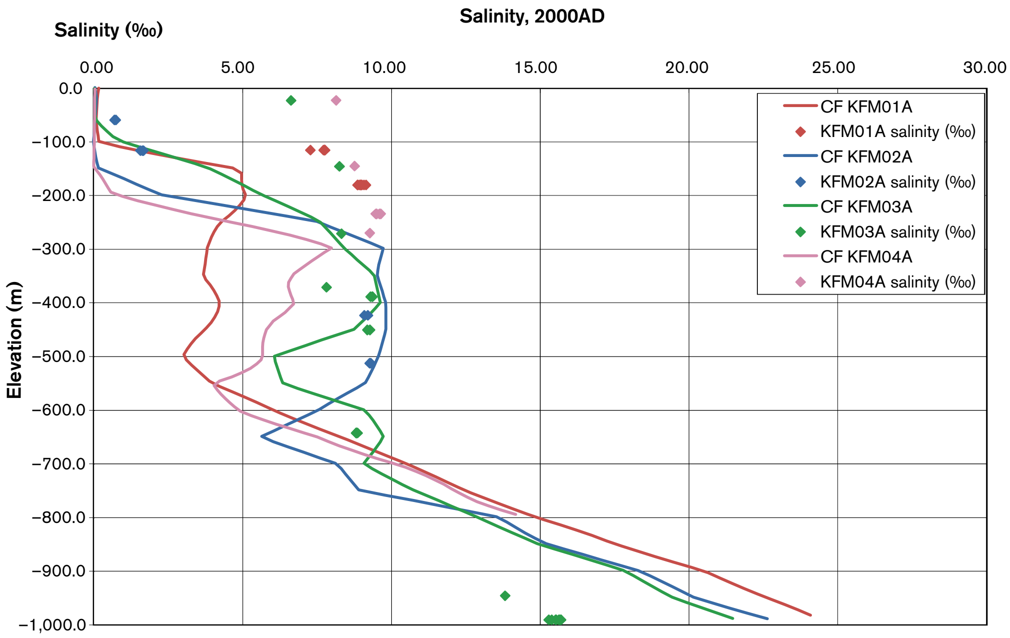


Figure 4-30. *Results of hydrogeological simulations of salinity (lines) and measured data (dots).*

Bedrock transport properties

The version 1.2 site descriptive modelling of transport properties in Forsmark only considers retardation parameters (porosity, diffusivity and sorption coefficients), whereas the flow-related migration properties are assessed as part of SR-Can, see section 6.6 of the **Data report**. Also, in section 6.7 of the **Data report** the retardation properties are further assessed and uncertainty ranges for use within SR-Can are quantified.

Site investigation data from porosity measurements and diffusion experiments (in situ and in the laboratory) were available for the version 1.2 site descriptive modelling. The work has included evaluation of data from the geological and hydrogeochemical descriptions, in addition to the evaluation of transport data. Porosities, as well as diffusivities and formation factors (the ratio between the effective matrix diffusivity and the free diffusivity in water), determined by electrical resistivity measurements, have been determined for core samples in the laboratory. In addition, electrical resistivity measurements in the cored boreholes have provided in situ formation factors.

The data clearly demonstrate the existence of a connected pore space, with limited variability in the rock matrix. This generally gives strong, site-specific, support for the existence of matrix diffusion. However, a complicating factor in the present analysis is that considerable systematic differences are obtained between the in situ formation factor measurements and the corresponding laboratory measured formation factors. Both methods involve methodological uncertainties; there is only very limited information concerning the pore liquid composition in the in situ measurements, whereas the laboratory samples show indications of having been exposed to stress release. Additional information and analysis is needed for a better quantification of the uncertainties and biases associated with the different methods.

Flow-related migration parameters

The Formark SDM does not provide any estimates of the transport resistance (F-factor). However, such estimates are derived in the Prelimary Safety Evaluation of Forsmark /SKB 2005b/. It is noted that assessing a realistic site-specific value for the transport resistance is dependent upon correctly predicting the transmissivities, extents, frequencies, and connectivity of conductive features in the rock volume being investigated. It is clear from borehole hydraulic tests that there is a broad distribution of flow rates and transmissivities that characterise different flowing features. Furthermore, the F-factor is dependent not only on the hydraulic characteristics of individual flowing features comprising a flow path, but also on their interconnectivity in the extended network of fractures surrounding the repository.

Nevertheless, the first order analysis of the Preliminary Safety Evaluation, assuming that all measured flowing features extend throughout the model volume suggest a F value higher than 10^7 y/m in the repository volume and values in the range between 10^6 y/m and 10^7 y/m in the volume above. However, it should be noted that, for safety assessment, the relevant issue is the spatial distribution of migration paths related to the scale of individual deposition holes. The percentile of deposition holes with a low F-factor would not exactly equal the percentile of individual flow paths with this low F-factor in the rock volume as a whole, as a deposition hole could be intersected by a number of migration paths (varying from zero to several for each hole). Moreover, the F-factor for a deposition hole would be dominated by the path with lowest F-factor value intersecting the hole. (Another reason that would increase the F-factor in practice is that deposition holes with high inflows and, therefore, likely high outflows may not be used.) Therefore, upscaling using various assumptions in the DFN-model is needed to provide more quantified uncertainty ranges for application within the safety assessment. Such upscaling is performed as part of SR-Can, see section 6.6 of the **Data report** and chapter 9.

The surface ecosystem

The site description for the surface systems is presented in /Lindborg 2005b/ and underlying reports, here a short overview is presented.

The landscape in Forsmark is a relatively flat peneplain, that dips gently towards the east. The whole area is situated below the highest coastline associated with the last deglaciation and today's landscape is strongly influenced by the ongoing shore-level displacement of c 6 mm per year. Most of the area has been raised above the sea during the last 1,000 years, which means that processes such as chemical weathering and peat formation have affected the area over a relatively short period of time. The till and glacial clay are rich in $CaCO_3$ derived from Palaeozoic limestone, which outcrops at the sea bottom north of the area.

Hydrology

The conceptual and descriptive modelling of the meteorological, surface hydrological and near-surface hydrogeological conditions in the Forsmark area is presented in /Johansson et al. 2005/. The model area is characterised by low relief and small-scale topography; almost the whole area is located below 20 m above sea level. The corrected mean annual precipitation is 600–650 mm and the mean annual evapotranspiration can be estimated to be a little more than 400 mm, leaving approximatley 200 mm/year for runoff. In total, 25 "lake-centered" catchments, ranging in size from 0.03 to 8.67 km^2 have been delineated and described within the model area. The 25 mapped lakes range in size from 0.006 to 0.752 km^2. The lakes are very shallow, with maximum depths ranging from 0.4 to 2.0 m. No major watercourses flow through the model area. Wetlands are frequent and cover 10–20% of the areas of the three major catchments, and up to 25–35% of some sub-catchments.

Chemistry

The glacial till in the Forsmark area is characterised by its high content of calcium carbonate. The calcite originates from Ordovician limestone present at the sea bottom north of the Forsmark area. The tills with a clay content higher than 5% have a slightly higher content of calcite (average content 24%, n=84) in the fine fraction (grain sizes < 63 µm) compared with the sandy till (average content 18%, n=52). Results from quantitative XRD analyses show small variations in the contents of most silicate minerals in the till. The samples contain almost 40% of quartz, which is similar to most of the bedrock in the investigated area. The results show that the chemical and mineralogical compositions of the till mainly reflect those of the local bedrock. The high $CaCO_3$ content of the till shows, however, that one fraction of it has been transported several tens of kilometres.

The sea

The marine system in the Forsmark modelling area is located in Öregrundsgrepen, Southern Bothnian Sea. The marine area in Forsmark has been divided into seven basins (Figure 4-31).

The marine system in the Forsmark area is a relatively productive coastal area in a region of otherwise fairly low primary production. This is due to up-welling along the mainland /Eriksson et al. 1977/. The surface water has a nutrient concentration ranging from 330 to790 µg/l tot-N and 12 to 25 µg/L tot-P

Figure 4-31. *The Forsmark model area including its seven basins with Basin SAFE-area and Stånggrundsfjärden indicated. In the map the location of the drainage area for catchment Bolundsfjärden (Forsmark 2) is indicated.*

/Nilsson et al. 2003/. The seabed mainly comprises erosion and transport bottoms with heterogeneous and mobile sediment consisting mainly of sand and gravel, but with varying fractions of glacial clay /Mo and Smith 1988/. The seabed close to the mainland has some areas of rocky bottoms, which are partly covered with coarse till /Sigurdsson 1987/.

The water in the Basin Öregrundsgrepen is estimated to have an annual average retention time (ART) of approximately 4.4 days (see Table 4-7), whereas the retention times for the smaller individual basins vary between 0.2 and 1.6 days. Basin SAFE-area and Basin Stånggrundsfjärden have ART values of 0.6 and 0.3 days, respectively. Annual averages of pH, salinity, oxygen concentration and light penetration depth for the area are 7.9, 3.9‰, 11.6 mg/l and 2.4 m, respectively /Nilsson and Borgiel 2004/.

Table 4-7. ART-time [days] estimates for seven of the nine SBs. SB2 is the major coastal basin that to a large extent but not exactly coincides with Öregrundsgrepen. These data are computed with all water outside an individual SB considered as exogenous. The vertically integrated (averaged by volume) statistics for SB15 through SB19 are calculated directly from 3D-model results, which have a temporal resolution of one hour. Two of the SBs were not sufficiently resolved by the 3D grid and the corresponding calculation has been deferred until their basin and strait hypsographies are available.

	Trivial name	Min	Mean – S D	Mean	Mean + S D	Max
SB1	Kallrigafjärden	0.48	1.29	1.67	2.05	2.45
SB2	Öregrundsgrepen (major coastal sub-basin)	1.88	4.46	6.32	8.19	10.40
SB15	Asphällsfjärden	0.30	0.73	0.82	0.92	1.10
SB16	Norra Asphällssundet	0.34	0.38	0.45	0.52	1.06
SB17	Stånggrundsfjärden	0.07	0.24	0.29	0.34	1.00
SB18	Tixelfjärden	0.03	0.12	0.15	0.19	1.00
SB19	SAFE-area	0.08	0.35	0.66	0.96	1.63

Data from the detailed marine geological survey of the sea bottom outside Forsmark gives information regarding the horizontal and vertical distribution of Quaternary deposits on sea bottoms situated at water depths greater than 3 m /Elhammer and Sandkvist 2005/. This information is presented in a map of the Quaternary deposits on the sea bottom /Lindborg 2005b/.

Many studies on flora and fauna have been carried out in the Öregrundsgrepen area, of which several were conducted in the defined modelling area. In the photic zone, the seabed is to a large extent covered with a layer of micro algae, mainly diatoms, and is characterised by a relatively high species diversity and large amount of macrophytes (macroalgae and vascular plants) /Kautsky et al. 1999, Snoeijs 1985, 1986/. The macrophyte species that contribute most to the macrophyte biomass in the benthic community in Forsmark are the red algae *Polysiphonia nigrescens*, the brown algae bladderwrack, *Fucus vesiculosus* and *Sphacelaria arctica* and the vascular plant pondweed, *Potamogeton filiformis* /Kautsky et al. 1999/. Herbivorous gastropods together with both herbivore and omnivore crustaceans dominate the grazing macrofauna and the most common filter feeder in the area has been found to be the bivalve clam, *Cardium spp* /Kautsky et al. 1999/. The major meiofauna taxa present in the area are nematodes, acarins, cladocerans, copepods and ostracods /Snoeijs and Mo 1987/. The most common fish species in Öregrundsgrepen are herring (*Clupea harengus*), roach (*Rutilus rutilus*) and perch (*Perca fluviatilis*) /Neuman 1982/.

Lakes

The characteristics of the limnic system in the Forsmark regional model area is to a great extent determined by the small topographic gradients in combination with the ongoing shore displacement and a short distance to the sea, and by the occurrence of calcium-rich deposits. A total of eight small water systems situated partly or entirely within the SKB site investigation area have been identified, and the total number of lakes and ponds within these catchments is 25 /Brunberg et al. 2004/. Some of the lakes have not yet been completely separated from the sea, and in these lakes saline water from the Baltic Sea may occasionally intrude during low pressure weather conditions. Many of the streams in the area are ephemeral, due to small catchment areas and low precipitation.

All investigated lakes in the area can be classified as oligotrophic hardwater lakes. This means that they show very unusual chemical conditions, with high alkalinity, conductivity, pH-value and nitrogen concentrations and very high concentrations of slightly coloured dissolved organic carbon (DOC), whereas phosphorus concentrations are very low. Preliminary measurements of primary production in the lakes show that whereas the production in the pelagial zone is always low, the production in the microbial mat may potentially be very high /Blomqvist et al. 2002/.

General characteristics of lakes in the Forsmark area

The dominant habitat in the larger lakes in the area is the littoral with submerged vegetation (Littoral type III). In Lake Eckarfjärden, Bolundsfjärden and Fiskarfjärden this habitat makes up at least 50% of the lake area, whereas 20 of the other 22 lakes in the area have a larger percentage of the littoral with emergent and floating-leaved vegetation (Littoral type I, cf Table 4-8 and /Brunberg et al. 2004/). This is not surprising since these lakes are smaller, shallower and at a later successional stage. The extreme is Lake Labboträsket where 96% of the area consists of littoral with emergent and floating-leaved vegetation.

No major water courses flow through the area. The water courses downstream of Lake Gunnarsboträsket in catchment Forsmark 1 and downstream of Lake Eckarfjärden and Lake Gällsboträsket in catchment Forsmark 2 carry water most of the year, but they can be dry for long periods during dry years such as 2003.

Land (terrestrial part)

The vegetation is affected by the bedrock, the Quaternary deposits and human land use. Outcrop is not a widely distributed substrate, making pine forest on felsic rocks quite scarce. The Quaternary deposits are mainly wave-washed till, where conifer forests are common. In depressions, a deeper regolith layer is found, with a fairly high lime content. The calcareous influence is typical for the north-east part of the county of Uppland and is manifested in the flora. The Forsmark area has a long history of forestry, which is seen today as a fairly high percentage of younger and older clear-cuts in the landscape. The spatial distribution of different vegetation types is presented in a vegetation map /Boresjö Bronge and Wester 2002/.

Table 4-8. Depth, surface and volume characteristics of importance for primary production in the lakes in the drainage area Forsmark 2 (data from /Brunberg et al. 2004/).

	Eckar-fjärden	Bolunds-fjärden	N. Bassängen	2:2	Graven	Fräken-gropen	Vambörs-fjärden	Kungs-träsket	Gällsbo-träsket	Stock-sjön	Puttan
Depth (m)											
Average	0.9	0.6	0.3	0.3	0.1	0.2	0.4	0.2	0.2	0.2	0.4
Maximum	2.1	1.8	0.9	0.6	0.4	0.8	1	0.5	1.5	0.8	1.3
Surface area (m^2)											
Littoral I	95,318	206,719	44,395	4,954	42,185	16,913	29,781	4,755	178,344	31,012	56,230
Littoral II											
Littoral III	188,532	404,593	31,675	4,975	7,902	2,510	19,796	2,978	8,704	5,468	26,511
Chara area	142,330	305,443	23,913	3,756	5,966	1,895	14,945	2,248	6,571	4,128	20,014
Chara coverage	0.75										
Profundal											
Pelagial	188,532	404,593	31,675	4,975	7,902	2,510	19,796	2,978	8,704	5,468	26,511
Total lake area	283,850	611,312	76,070	9,929	50,087	19,423	49,577	7,733	187,048	36,480	82,741
Volume (m^3)											
Photic	257,000	374,000	24,000	3,000	6,000	4,000	21,000	2,000	32,000	8,000	30,000
Aphotic											
Total	257,000	374,000	24,000	3,000	6,000	4,000	21,000	2,000	32,000	8,000	30,000

The forests are dominated by Scots pine (*Pinus sylvestris*) and Norway spruce (*Picea abies*) forests situated on till. The spruce becomes more abundant where a deeper soil cover is found along with more mesic-moist conditions. The field layer is here heavily influence by the calcareous content and is characterised by herbs and broad-leaved grasses along with a number of orchid species. The deciduous tree species are dominated by Birch, *Betula pendula*, Alder, *Alnus glutinosa* and Rowan, *Sorbus acuparia*, but also Maple, *Acer platanoides* and Ash, *Fraxinus excelsior* are fairly common. In particular, *F excelsior* may be abundant along sheltered seashores. Oak, *Quercus robur* and Elm, *Ulmus glabra* are close to their northern limit and are very scarce.

Arable land, pastures and clear cuts dominate the open land. Arable land and pastures are found close to settlements. The pastures were earlier intensively used, but are today a part of the abandoned farmland that arose following the nationwide general regression of agricultural activities.

Wetlands are frequent and cover 10%, 12% and 17% of the major catchments Forsmark 1, 2 and 8, respectively. In some of the sub-catchments, wetlands cover between 25% and 35% of the area. The distribution of wetlands according to the vegetation map is shown in Figure 4-32. The wetlands are characterised by a strong calcareous influence, making the extremely to moderate rich fen types common in this area. These fen types lack the dominance of peat moss (*Sphagnum*) species in the ground layer and are instead dominated by brown mosses, e.g. *Scorpidium scorpioides*. However, bogs are also present in the more elevated parts of the area, but are rare, partly because of the short time since these areas emerged from the Baltic. Roughly, wetlands may be classified in two types: those accumulating peat and those where decomposition is fairly high, thereby minimising peat formation. The distribution of these two types is illustrated by over-laying the wetlands on the Quaternary deposit map, see Figure 4-33.

Water flow is an important factor contributing to temporal variations in ecosystem properties, with a large variation within the year.

Humans and land use

In total, 168 people lived in Forsmark parish in 2002. The population density has been low but fairly stable over the last ten years. The density has on average been 1.8 inhabitants per square kilometre. In 2002, the population density in Forsmark parish was 24 times lower than in Uppsala County. 52% of the inhabitants were over 45 years, compared to 40% in Uppsala County as a whole. The dominant employment sector within the Forsmark parish is electricity-, gas- and water supply, sewage and refuse

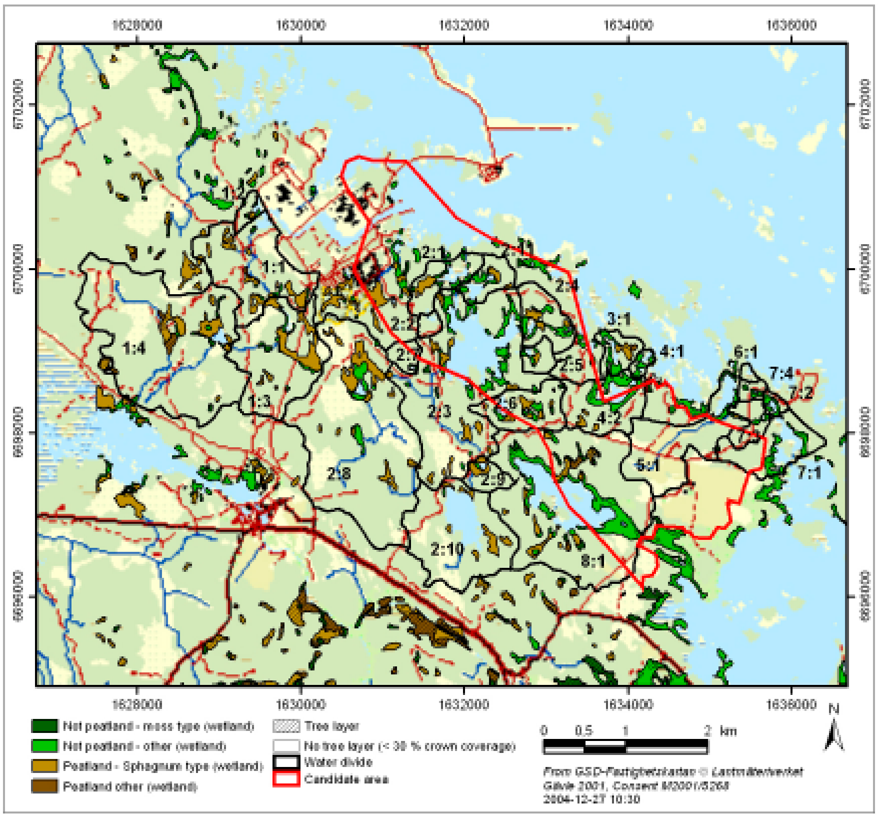


Figure 4-32. *Wetlands of different types within the Forsmark area based on the vegetation map /Boresjö Bronge and Wester 2003/.*

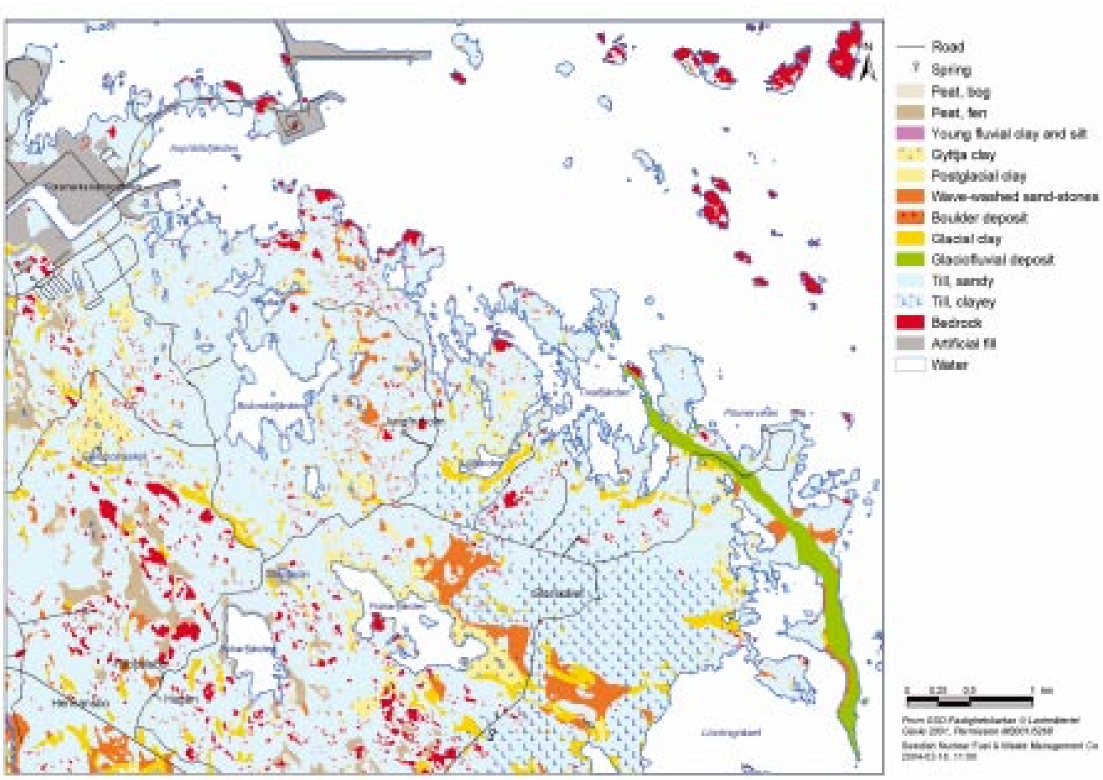


Figure 4-33. Map showing the spatial distribution of Quaternary deposits in the central part of the Forsmark regional model area, from /Sohlenius et al. 2004/.

disposal and it involves 79% of the employed day-time population (working in the area). In the case of the employed night-time population (living in the area) on the other hand, only 19.7% work in that sector. Thus, there is a major ongoing commuting activity due to presence of the Forsmark nuclear power plant. The net commuting is positive in Forsmark parish, meaning that immigration is larger than emigration /Miliander et al. 2004/.

The land use in Forsmark parish is assumed to be similar to the land use in Forsmark area. The land use within the Forsmark area differs from the average land use in Uppsala County, as there is proportionally more forest, wetlands and water in the Forsmark area and the fractional area of agricultural and developed land is smaller.

There are approximately 20 licensed fishermen in Östhammar municipality and they undertake coastal small-scale fishing for consumption, and sell their catch to local grocery stores. None of them seem to live in Forsmark parish. According to the figures from The County Administrative Board of Uppsala, moose hunting is currently more intensive in Forsmark parish than in the municipality and county as a whole (0.53 individuals·km^{-2} harvested compared with 0.37 respectively 0.35, in 2003). No obvious trend can be seen in the data between 1999 and 2003. The harvest was almost equal in Forsmark parish, Östhammar municipality and Uppsala County in 1999, but since then the harvest has been more intensive in Forsmark parish /Miliander et al. 2004/.

4.3.3 The Laxemar site

The Laxemar site is part of the Simpevarp candidate area located in the municipality of Oskarshamn, about 300 km south of Stockholm. The Simpevarp candidate area is divided into two parts, the Simpevarp subarea, concentrated on the Simpevarp Peninsula and the Laxemar subarea located on the mainland west of the Simpevarp Peninsula, see Figure 4-34. Thus the Simpevarp subarea forms part of the regional environment of the Laxemar site.

The initial stage of site investigation has been completed for the Simpevarp and Laxemar subareas. SKB has decided to continue with a complete investigation only of the Laxemar subarea. Here results from the analysis of Laxemar is presented based on the preliminary SDM version 1.2 for the Laxemar subarea /SKB 2006b/.

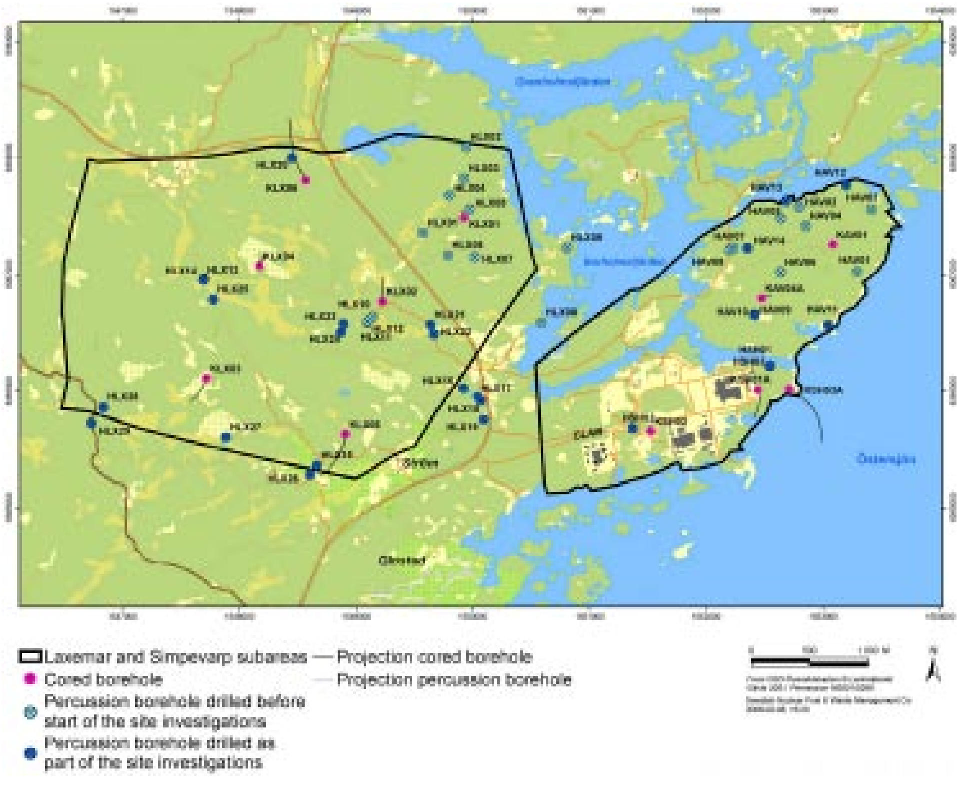


Figure 4-34. *Overview map of the locations of core-drilled and percussion-drilled boreholes in the Laxemar (on the left hand side) and Simpevarp subareas, at data freeze 1.2.*

The Simpevarp candidate area, including Laxemar, is characterised by a relatively flat topography (c 0.4% overall topographic gradient), which largely reflects the surface of the underlying bedrock and is characterised by a high degree of bedrock outcrop (38%). Although flat, the landscape is interrupted by occasional narrow valleys, often associated with deformation zones in the bedrock. Till is the dominant Quaternary deposit and covers about 45% of the Laxemar subarea.

Lithology and associated thermal and rock mechanics properties

The site lithology, i.e. the distribution of rock types, reveals important aspects of the structure of the site. Furthermore, it directly affects the ore potential as well as thermal and rock mechanics properties of the intact rock. In the SDM, the lithology is described by rock domains, defined based on composition, grain size, homogeneity, and style and inferred degree of ductile deformation.

Lithology and division into rock domains

According to the Laxemar site description, the majority of the rocks at the present day erosional level in southeastern Sweden were formed during a period of intense igneous activity c 1,810–1,760 Ma ago during the waning stages of the Svecokarelian orogeny. The dominant rocks comprise granites, syenitoids, dioritoids and gabbroids, as well as spatially and compositionally related volcanic rocks. This generation of igneous rocks belongs to the so-called Transscandinavian Igneous Belt (TIB). Locally, fine- to medium-grained granite dykes and minor massifs, and also pegmatite occur frequently. Though volumetrically subordinate, these rocks constitute essential lithological inhomogeneities in parts of the bedrock in the Oskarshamn region. After the formation of the TIB rocks, the next rock forming period in south-eastern Sweden, including the Oskarshamn region, did not take place until c 1,450 Ma ago. It was characterised by the local emplacement of granitic magmas in a cratonized crust. In the Oskarshamn region, the c 1,450 Ma magmatism is exemplified by the occurrence of the Götemar, Uthammar and Jungfrun granites.

In late Precambrian and/or early Cambrian time, i.e. c 600–550 Ma ago, arenitic sediments were deposited and subsequently transformed to sandstones. The remainder of these formerly extensively occurring sedimentary rocks covers the Precambrian crystalline rocks along the coast of the Baltic Sea from the area south of Oskarshamn in the north to north-eastern Blekinge in the south. Furthermore, during the ongoing site investigation in Oskarshamn, sandstone of presumed Cambrian age has been documented in a cored borehole. The sandstone occurs in a deformation zone and occupies ca 0.1 m of the drill core.

The bedrock history explains the rather complex lithology of the bedrock of the Laxemar subarea. In the model, the site is divided into different rock domains. The Laxemar subarea, see Figure 4-35, is mainly domain RSMA, primarily composed of Ävrö granite and dominant in the northern and central parts of the subarea, domain RSMD, consisting mainly of quartz monzodiorite, and a mixed domain RSMM (diorite to gabbro) dominant on the surface in the southwest and in an arc-shaped fashion dipping to the north with the concave side to the north. A conspicuous rock domain (RSMP) is related to the north-easterly oriented set of shear zones that make up the eastern boundary of the subarea. Lithological heterogeneity in the bedrock occurs in the Laxemar subarea in the form of subordinate rock types (dikes, enclaves or minor bodies in the dominant rock type, mainly fine-grained granite and pegmatite). An additional contribution to heterogeneity is provided by a general mixture of different rock types of different composition and character, compositional variations within a dominant rock type, and combinations of these contributions.

A conspicuous characteristic of the gabbroid-dioritoid-syenitoid-granite rocks of the Simpevarp candidate area is their low quartz content. The higher the quartz content the higher the thermal conductivity. The quartz content also shows a large variability as evidenced by Figure 4-36, which indicates that the diorite to gabbro and quartz monzodiorite domains (RSMBA and RSMD) have the lowest quartz content.

Ore potential

The potential for ore, industrial minerals and commercial stone at the site has been assessed by an exploration geologist /Lindroos 2004/. In that work, ore potential was defined as mineralisations considered worthwhile exploring today or over a longer period. It was concluded that the Simpevarp regional model area is dominated by intrusive rocks and granites, belonging to the c 1,810–1,760 Ma generation of the Transscandinavian Igneous Belt (TIB), which by experience are more or less devoid of metallic mineralisation.

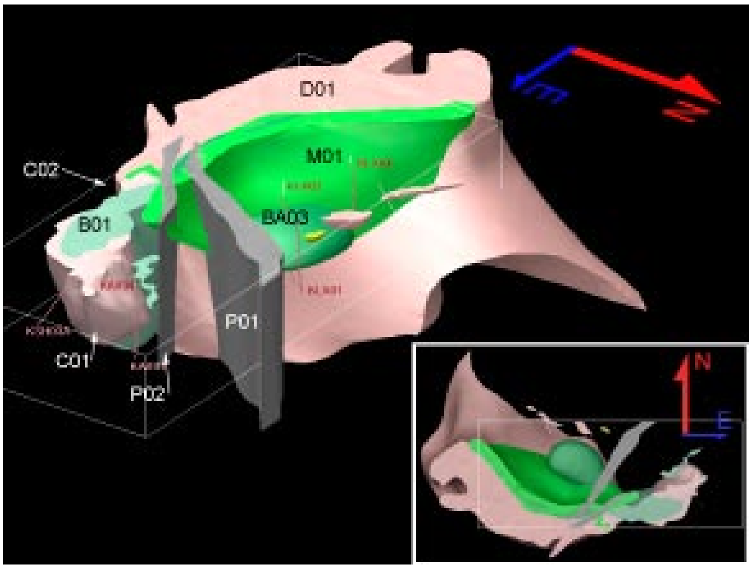


Figure 4-35. *Rock domain model of the Laxemar subarea, viewed from the north east. Rock domains are indicated by short notation (i.e. B01, BA03, etc where the number indicate different geometrical units of the same domain). Rock domain RSMA is unshaded in order to show some of the major three-dimensional characteristics. The insert shows the model from above.*

The only candidate for metallic mineralisation in the Simpevarp regional model area is the c 1,450 Ma old Götemar-type granite, which is judged to have a potential for tin (Sn) and tungsten (W), although no mineralisations of this type have so far been found. Consequently, the whole Simpevarp regional model area may be considered as sterile concerning metallic mineralisations and ores. Furthermore, the only real potential for quarrying building- and ornamental stone is associated with the Götemar and Uthammar granite intrusions in the north and south, respectively, i.e. well outside the Laxemar subarea.

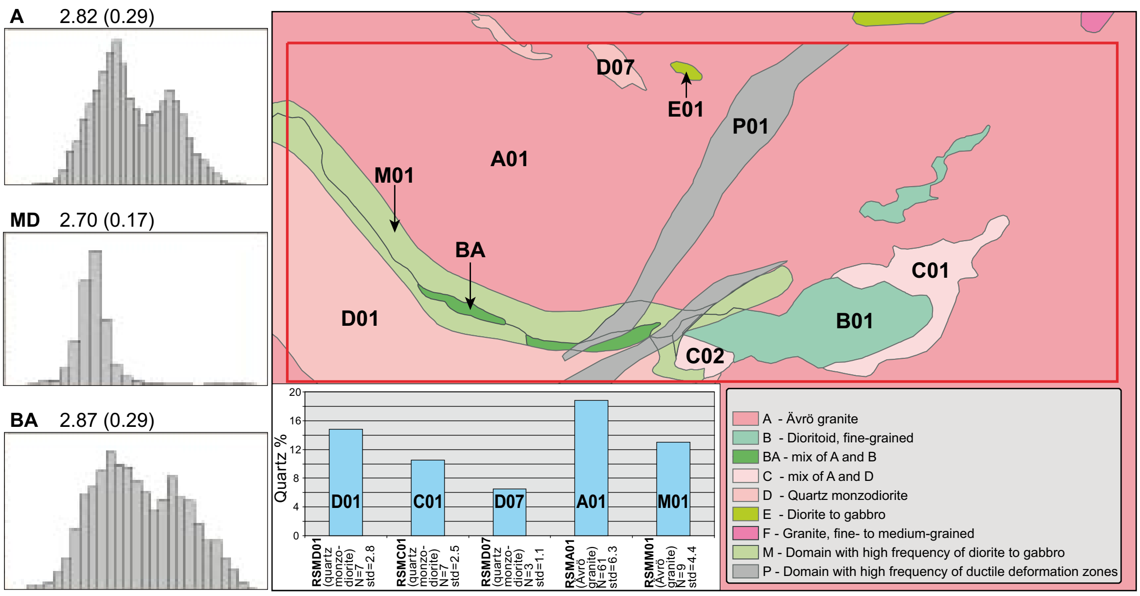


Figure 4-36. *Composite showing rock domain model (upper right), differences in quartz content between rock domains (as inferred from surface samples) (lower central) and modelled distributions with mean and standard deviation by rock domain of thermal conductivity at the 0.8 m scale (left).*

Thermal properties

The thermal properties, i.e. thermal conductivity and heat capacity, of the rock are closely related to lithology, since these properties depend on the mineral composition, and especially the quartz content. The thermal conductivity of the rock has been assessed from direct measurements and by calculations based on mineral composition from modal analyses. These two methods give consistent results.

As already stated, many of the rock types of the Laxemar subarea have a low and spatially varying quartz content, Figure 4-36. This results in relatively low and varying thermal conductivity. The results of the modelling of thermal conductivity, show mean values on the 0.8 m, i.e. the scale relevant to assess the thermal evolution in a deposition hole, scale in the order of 2.45 to 2.9 W/(m·K) in the different rock domains and with a high variability, which may also be bimodal in the RSMA and RSMBA domains. This suggests that these domains can be further divided into quartz-rich and quartz-poor sub-domains and the possibility for such further subdivision will be pursued in future modelling. As also noted in /SKB 2006b/, the modelled thermal properties are uncertain due to potentially poor representativity of the samples taken for laboratory testing, uncertainty in the density logging method used to estimate thermal conductivity along boreholes and uncertainties in its upscaling. There are few data from rock domains RSME and RSMM and no representative boreholes in those domains. Data for use in SR-Can are given in the **Data report**, section 6.2.

Rock mechanics properties of intact rock

Lithology also directly affects the thermal expansion, deformation modulus and mechanical strength of the unfractured rock (called intact rock in rock mechanics). The rock mechanics properties of the intact rock have been estimated from new laboratory tests on drill cores. Especially, the uniaxial strength depends on rock type. The mean uniaxial compressive strength (UCS) ranges between 165–210 MPa and is thus relatively low in most of the rock types and also shows a quite large spread, probably reflecting the relatively low and spatially varying quartz content at the site.

As also noted in /SKB 2006b/, the rock mechanics properties for intact rock of rock type quartz monzodiorite and the Ävrö granite in the southern part of the Laxemar subarea are possibly biased, since only laboratory tests from the Simpevarp subarea and northern Laxemar were available at the time of producing the site description. The Ävrö granite in southern Laxemar is expected to have lower quartz content than the available samples of Ävrö granite, and the quartz content may affect the mechanical properties. New data will reduce these biases in future model versions. Data for use in SR-Can are presented in the **Data report**, section 6.4.

Deformation zones and fractures

Deformation zones and fractures are important characteristics of the site as they affect possible location of the repository, the mechanical stability and the groundwater flow. Furthermore, the deformation history and the geometry of the deformation zones affect the rock stress distribution and thereby also the properties of fractures in the volume. Understanding the deformation zones is thus key to understanding the fracturing, the in situ stress and the hydraulic properties.

Deformation zones and deformation history

The bedrock in the Simpevarp candidate area, which generally is well preserved and undeformed, has been exposed to a series of tectonic events that have involved shifts in the direction and magnitude of compressional forces exerted on the rock mass. Characteristic ductile features in the Simpevarp candidate area are the occurrences of low-grade brittle-ductile shear zones made up of the northeasterly belt of zones associated with deformation zones ZSMNE005A (Äspö shear zone) and ZSMNE004A, which also make up the rock domain RSMP discussed above, see Figure 4-37. In addition, there is also a subhorizontal zone (ZSMNW928A) interpreted from reflection seismics and borehole data, and shown to be located well below typical repository depth (> 770 m, compared with 500 m) in the central parts of the Laxemar subarea.

In the Simpevarp subarea the distributional pattern of deformation zones largely aligns with the belt of shear zones in the western part of the Simpevarp subarea, see Figure 4-37. In the Laxemar subarea, north of zone ZSMNW42 and the contact between the Ävrö granite and the quartz monzodiorite, the geometrical pattern of interpreted deformation zones is more irregular, although the principal orientations of the deformation zones are NS and EW. Currently ongoing kinematic and fracture

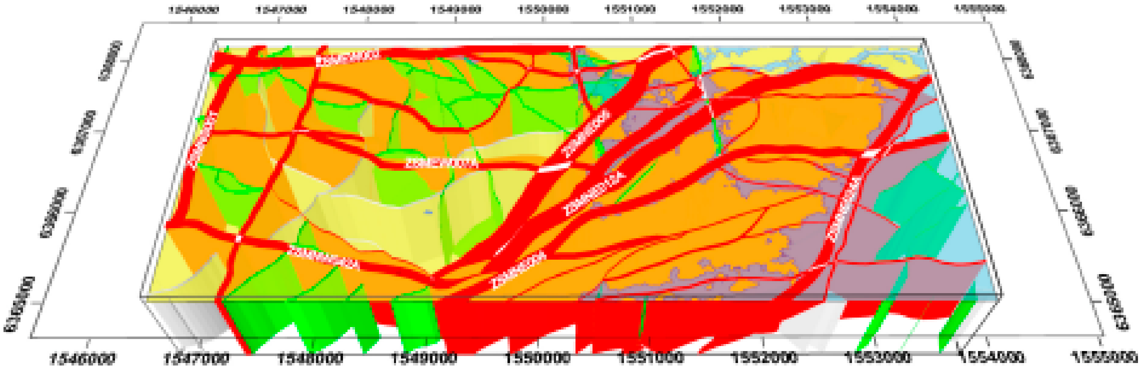


Figure 4-37. *Local scale model of deformation zones. In the Simpevarp subarea, to the south east, the major deformation zones largely align with the belt of shear zones ZSMNE005A (Äspö shear zone) and ZSMNE004A. In the Laxemar subarea, to the west, there is a strong element of NS and EW zones. Red, green and grey indicate high, medium and low confidence zones, respectively.*

mineralogical studies are expected to shed more light on the evolution of the deformations in the area, and why the current differences exist. Current understanding, however, indicates that the Simpevarp subarea is more strongly affected by the occurrence of the above shear zones than the Laxemar subarea, supported by a more banded pattern in the magnetic anomaly map of the Simpevarp subarea, and suggesting that the two subareas may be structurally different, at least in respect of the occurrence and frequency of ductile overprinting.

It is judged that most local major, steeply dipping zones have been identified at the surface. Good support to the general validity of the underlying lineament map is provided by an independent alternative lineament interpretation /Korhonen et al. 2005/. The interpretations are general similar although there are some differences in details. Potentially there are deformation zones not included in the model. This mainly relates to local minor and minor sub-horizontal zones as these are harder to detect. However, although it is clear that gently dipping regional zones do not exist within the local model domain, it is more difficult to observe smaller gently dipping zones, if they were to exist, since this would require a high data density. One gently dipping deformation zone has been proposed and included in the geometric framework for Laxemar 1.2, primarily based on reflection seismics.

The existence of deformation zones ranges between high, medium and low. High confidence zones are established by interpretation of different independent data, e.g. both indirectly through lineament or geophysical data, and directly through field mapping, borehole or tunnel observations. When the data support is lower the confidence in the existence is lower, but the number of zones in the model (i.e. including the medium and low confidence zones) is judged realistic. However, the continuity, and thus the size estimate, along strike and dip at depth and the termination of the deformation zones are uncertain and also the character and properties of the zones are uncertain, even for the high confidence zones.

Fractures and fracture domains

Smaller zones and fractures, not covered by the deformation zone model, are handled in a statistical way through discrete fracture network (DFN) models. The descriptions are based on fracture observations in the boreholes, mapped fractures at outcrop and from interpretation of lineaments.

Also, the analysis of the fracturing in the rock mass between interpreted larger deformation zones, and the variation in local fracture orientations suggests, together with results from the deformation zone model, that the Simpevarp subarea is located within a belt of shear zones and exhibits significantly different fracture behaviour from that of the Laxemar subarea which is located outside of this belt.

The analysis and display of fracture orientations reveal five sets; three regional sets (S_A, S_B, S_C) observable in both outcrop and in deformation zone traces in the two subareas and two local sets typical of their respective subareas (S_d and S_f /S_e, respectively), where S_d represents the subhorizontal set in each subarea.

The Laxemar 1.2 geological DFN orientation model is based solely on fracture patterns observed at outcrop, and may not necessarily match conditions found at depth. Fracture size analysis shows that regional fracture sets can be approximated by power-law size models. Local fracture sets are censored by the outcrop sizes such that alternate size models have a better statistical fit, but this would not necessarily be the case if the spatial extent of the exposures was larger.

Fracture intensity has been shown to be dependent on subarea, somewhat dependent on the rock domain, and locally dependent on host rock lithology, fracture ages, degree of alteration, and presence of ductile or brittle deformation zones. This is indicated by intensites (total fracture area per unit volume of rock, P_{32}, of all fractures) of the regional sets in the domain RSMA of the Laxemar subarea varying between 1.4 and 1.7 m^{-1}, and the corresponding intensities in the Simpevarp subarea being some 30–100% higher.

Verification exercises on the average show a fair correspondence with observations at outcrop, but also show that the model cannot match outcrop and borehole intensity data simultaneously at present, cf Figure 4-38. This shows the need for further assessment of the assumptions made in the DFN-model. However, the finding also suggest that the core mapping captures very short features – of little significance for rock mechanics and flow. Most of the fractures mapped in the core would not be important for flow – and the measured fracture frequency thus has little relevance for the migration properties of the rock.

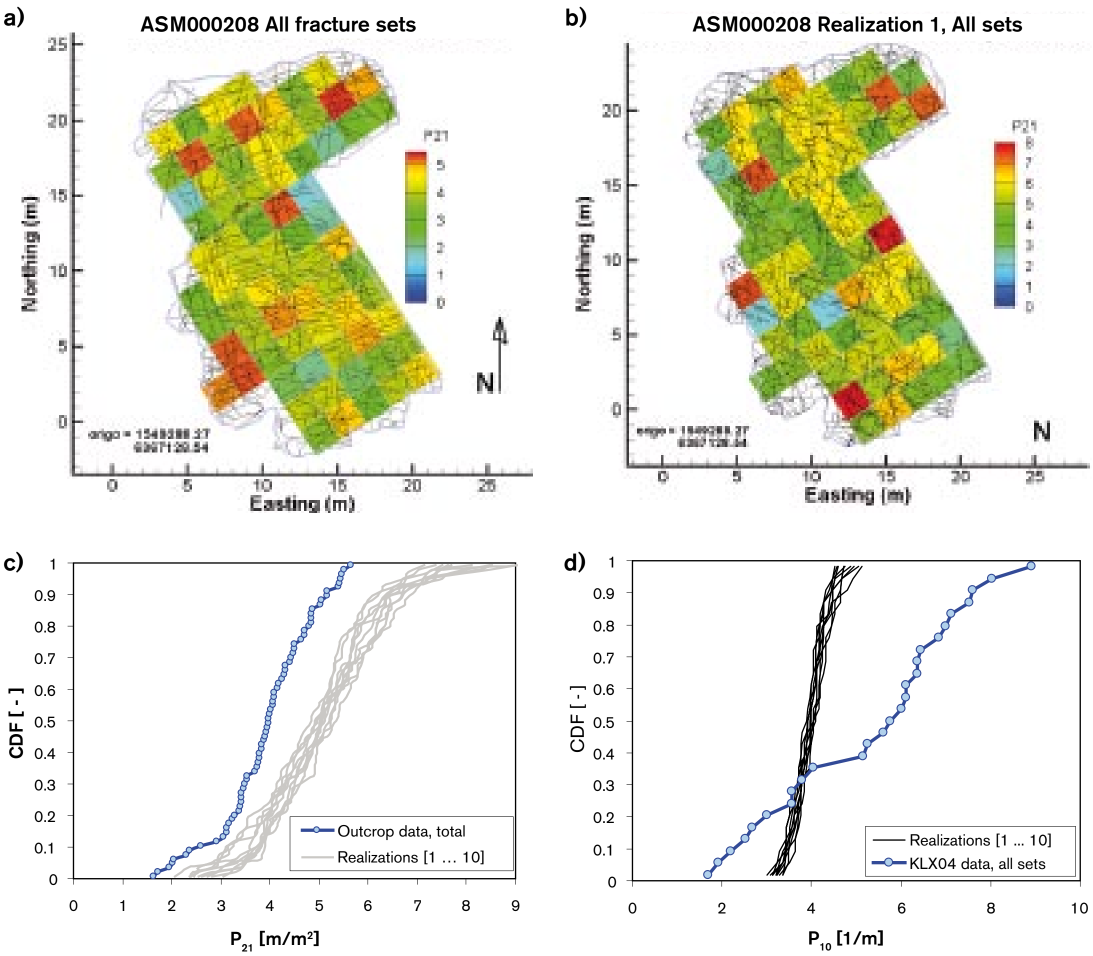


Figure 4-38. *Evaluation of Laxemar subarea, RSMA, all fracture sets. Traces of outcrop ASM000208 compared with one realisation. Simulated fracture properties (grey lines) are compared with field data (blue), in terms of total fracture trace length per unit area, P_{21} and fracture frequency (number of fractures per unit length, P_{10}).*

In fact, there are several uncertainties in the DFN Model. Possibly, the most important uncertainties concern the fracture intensities and the size distribution of the subhorizontal sets. There is a high variability in borehole fracture intensity, even in sections not identified as deformation zones. A more stable model could possibly be obtained by applying different geological controls, such as dividing the DFN-model into smaller subdomains based on lithology, alteration or closeness to deterministic zones. Another uncertainty concerns the size distribution of the sub-horizontal set. These uncertainties and potential alternatives have not been fully developed for the current version of the Laxemar site description. This matter is further discussed in the **Data report**, section 6.3.

Stress conditions

Both data and stress modelling results suggest that the Laxemar subarea can be divided into two different stress domains (I and II), where Stress Domain II has lower stresses. It is recognised that the essentially northeast trending deformation zones on either side of the Simpevarp peninsula-Hålö-Ävrö (i.e. zones ZSMNE012A and ZSMNE024A) can be interpreted to form a wedge-shaped body of rock that may represent a different stress regime from that prevailing at Äspö, see Figure 4-39. Similarly, the rock volume above zones ZSMEW007 and ZSMEW002 forms a wedge in the Laxemar subarea. Although these two domain II volumes are physically separated, the reasons for lower stress are assumed similar in both volumes. When the measured stress data are sorted into two different groups representing these assumed geographical domains, it is noted that the spread within each group is significantly reduced compared with the combined spread of the two groups of data in combination, see Figure 4-39.

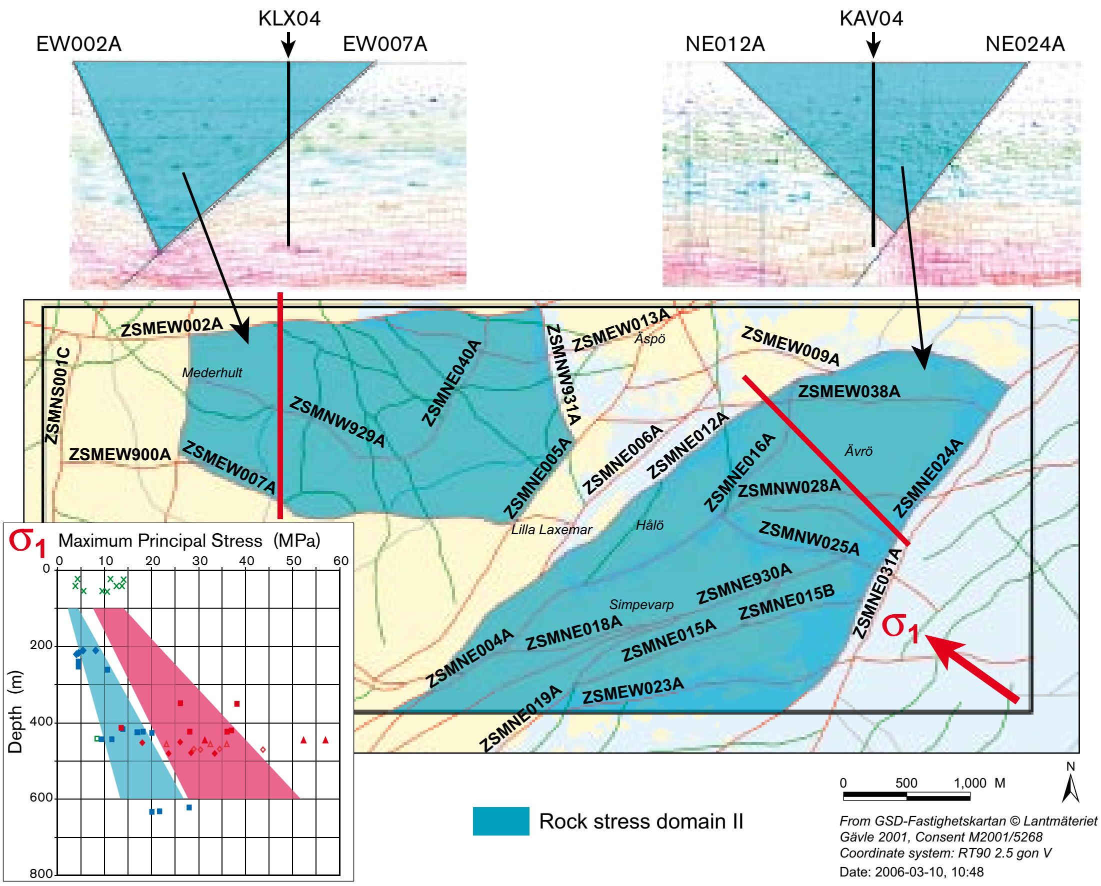


***Figure 4-39.** Both data and stress modelling, based on the deformation zone model, suggest that the Laxemar subarea can be distinguished into two different Stress Domains (I and II). Stress domain II, the domain with lower stresses, is indicated in blue.*

The hypothesis of a structure-controlled explanation for the noted stress variation in the local-scale model volume was evaluated using a numerical model, see /Hakami and Min 2006/. The applied stress boundary conditions, simulating tectonic compression in the direction NW-SE, are assumed to have prevailed during the most recent evolutionary period. From the modelling results, it can be seen, as expected, that wedge-shaped rock masses surrounded by deformation zones with reduced strength properties, are not able to sustain high horizontal stresses, and the stress consequently becomes lower inside the wedge and higher in areas outside, as also illustrated in Figure 4-39. The results, although subject to uncertainty, thus support a conceptual stress model describing the stress state in the modelled area as being characterised by two different stress domains. The stress conditions applied in SR-Can are presented in the **Data report**, section 6.4.

Hydraulic properties

Analyses of hydraulic data from the boreholes in the area have shown great variation, with sections of high intensities of highly transmissive features, followed by long sections with few transmissive fractures. Much of the measured high transmissivity can be attributed to the deterministic deformation zones in the geological model. The hydraulic tests confirm that the deformation zones usually are more conductive than the surrounding rock and the measured hydraulic conductivity of the deformation zones, assessed by dividing the zone transmissivity by the zone thickness, is about an order of magnitude higher than the hydraulic conductivity of the rock mass if test sections intersected by deformation zones are excluded. Therefore, all deformation zones in the geological model are treated as particularly transmissive features (hydraulic conductor domains; HCDs) in the hydraulic model. However, some HCDs in the current model may have low transmissivity (and hydraulic conductivity) and many of the deformation zones have not been tested hydraulically. Furthermore, there are several measured high transmissivities that cannot be attributed to the modelled deformation zones. In the hydraulic model, the rock mass between the deformation zones is described by a hydraulic DFN-model.

Analysis of the hydraulic test data from deformation zones and intervening rock mass shows indications of hydraulic conductivity decreasing with depth, Figure 4-40. This is unlike the situation at Äspö HRL where no such dependence has been noted. Hydraulic properties have been assigned to hydraulic rock domains (HRDs) defined based on the underlying rock domains defined by geology.

The tectonic and structural differences between the Simpevarp and Laxemar subareas are also reflected in the model description of the hydraulic rock domains where e.g. HRD(A) (Ävrö granite) in the Simpevarp subarea has been assigned an increased hydraulic conductivity compared with the remainder of the Ävrö granite in the Laxemar subarea. Young granitic intrusions (Götemar and Uthammar) and fine-grained granites are assigned an increased hydraulic conductivity compared with Ävrö granite. Rock domains including quartz monzodiorite and diorite (HRD(D), HRD(M) and HRD(B,C)), which dominate the southern parts of the Laxemar subarea (see Figure 4-35) are all assigned hydraulic conductivity values lower than HRD(A). However, the borehole transmissivity data do not indicate that the intensity of flowing fractures varies significantly between rock domains, apart from a lower intensity estimated for domain D and the mixed domain M. The few borehole data and the strong variability in hydraulic properties found in and between boreholes does not allow a robust evaluation to be made of the representativity of either the depth dependence or domain-related differences.

Furthermore, the use of one single transmissivity model for all fracture sets is questionable. Posiva flow log (PFL) data from the Laxemar subarea (KLX04) indicate that Sets A (NE) and B (NNE) have 0.5 to1 orders of magnitude lower transmissivity than Set d (Subhorizontal), whereas Set C (WNW) has up to 0.5 to 1 orders of magnitude higher mean transmissivity than Set d. However, the current analysis is essentially based on data from borehole KLX04, and can at this time be regarded as indicative only. The noted anisotropy, with a higher hydraulic conductivity in the WNW(-NW) fracture set, is in accord with the principal horizontal stress direction, and also corroborates earlier findings on hydraulic anisotropy from the Äspö HRL, although much less pronounced.

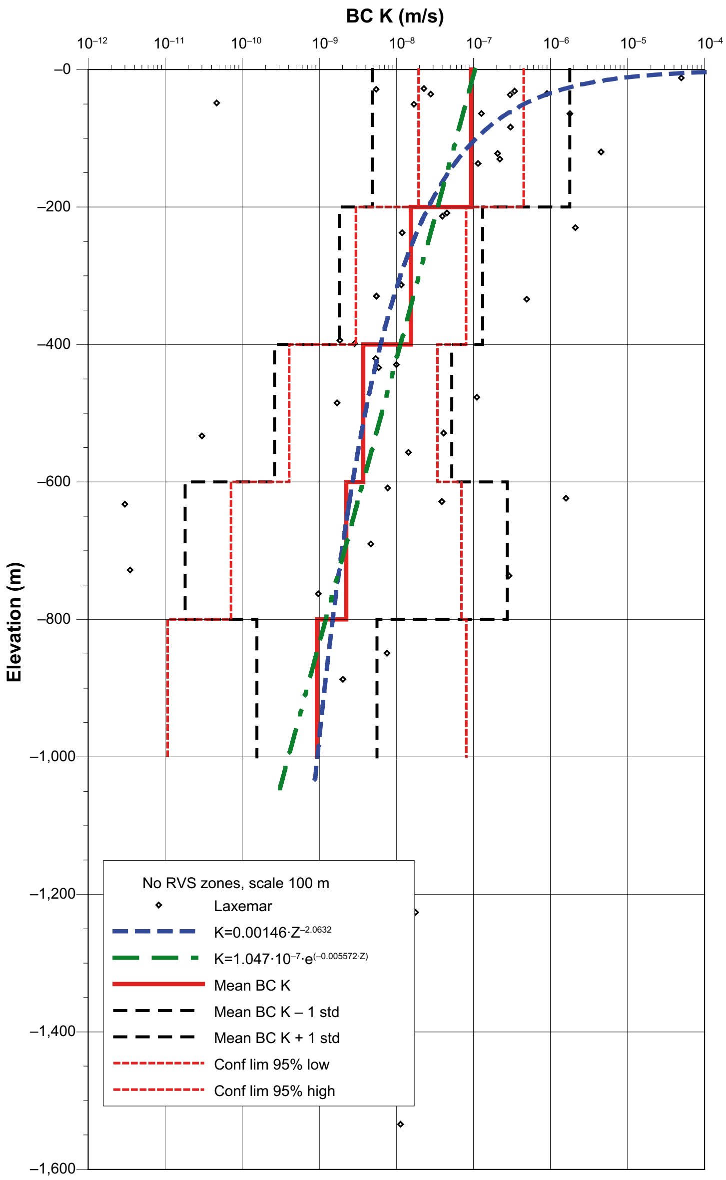


Figure 4-40. *Depth trend of the hydraulic conductivity in HRDs. Test scale 100 m. Data, statistics and depth trends based on data from the Laxemar subarea alone. Data representing deterministically interpreted deformation zones are excluded. Based on Boreholes HLX01–09, -32, KLX01–KLX06 (In KLX05 and KLX06 , only data from hydraulic tests during drilling using the WireLineProbe (WLP) measurements are included). BC= Best choice value.*

As mentioned above, the limited number of boreholes and small amounts of data available for Laxemar 1.2 do not adequately justify distinguishing the volume into hydraulic rock domains with different and depth-dependent hydraulic properties. However, new data, which have become available after data freeze Laxemar 1.2, support both the depth dependence and that the rock domains in southern Laxemar, Figure 4-41, have lower hydraulic conductivity than those in northern Laxemar, Figure 4-42. Figure 4-43 shows locations of the boreholes and the surface expression of the rock domains. These new data show a higher degree of lithological homogeneity and also distinctly lower hydraulic conductivity in the depth interval 300–700 m, cf new data from boreholes KLX05, KLX10A, KLX11A and KLX12A in Figure 4-41. It should also be noted that many of the boreholes in northern Laxemar (KLX06, KLX07 and KLX08) are affected by their proximity to the deformation zones EW007A and EW002A. Consequently, it is highly likely that the hydraulic conductivity of the Laxemar area is lower than indicated by the hydrogeological model derived for Laxemar version 1.2.

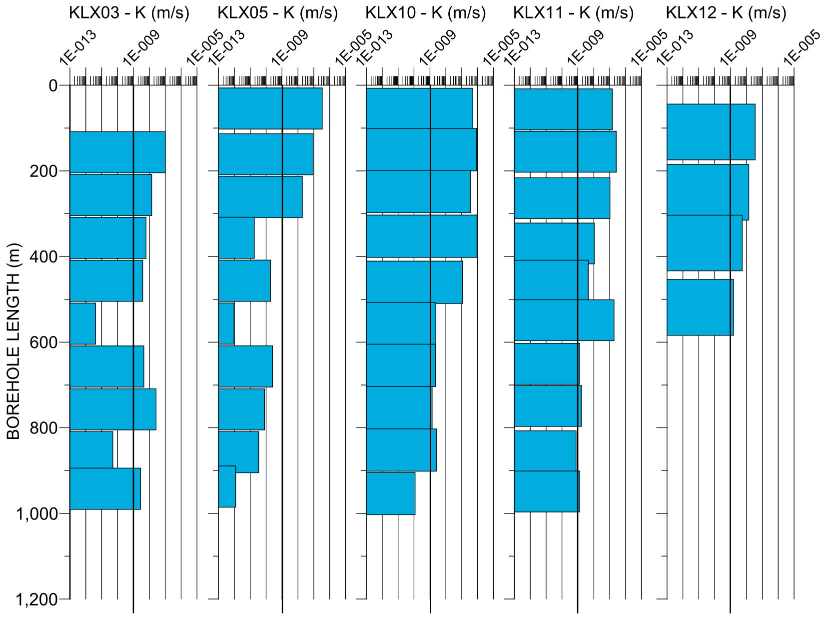


Figure 4-41. *Laxemar South – Hydraulic conductivity at a 100 m test scele. Results from injection tests (PSS) in KLX03 and KLX05. Preliminary results from WLP tests during drilling in KLX10, KLX11 and KLX12, see Figure 4-43 for location of the boreholes. Depth is given as borehole length.*

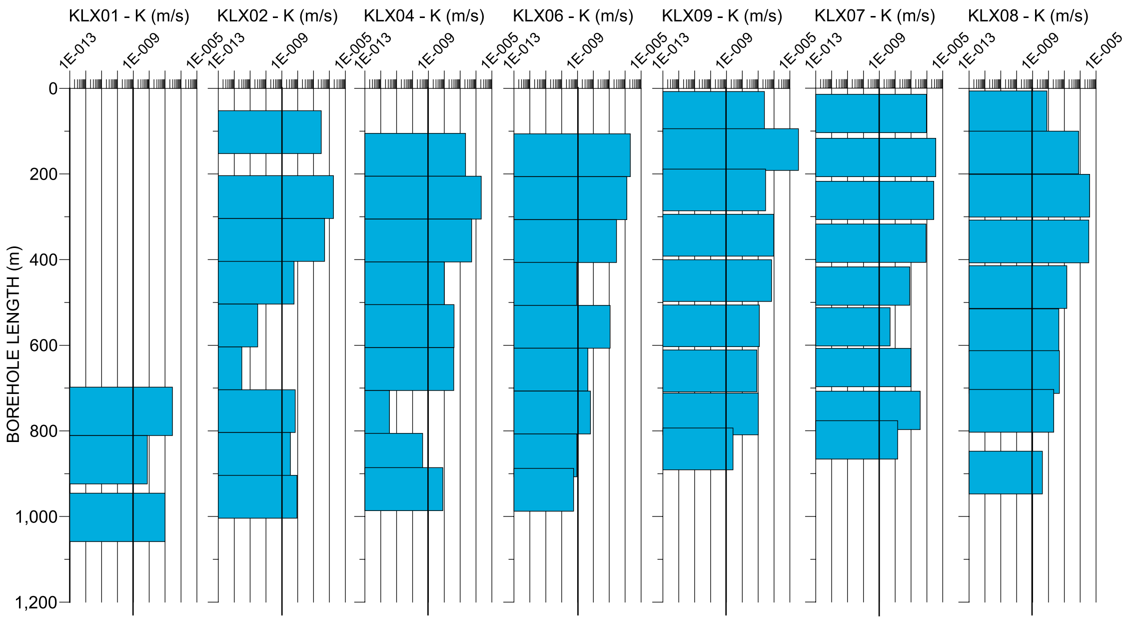


Figure 4-42. *Laxemar North – Hydraulic conductivity at a 100 m test scale. Results from injection tests (PSS) in KLX02, KLX04, KLX06 and KLX07. Preliminary results from WLP tests during drilling in KLX08 and KLX09. Old test methodology employed in KLX01. Depth is given as borehole length. (See Figure 4-43 for location of the boreholes).*

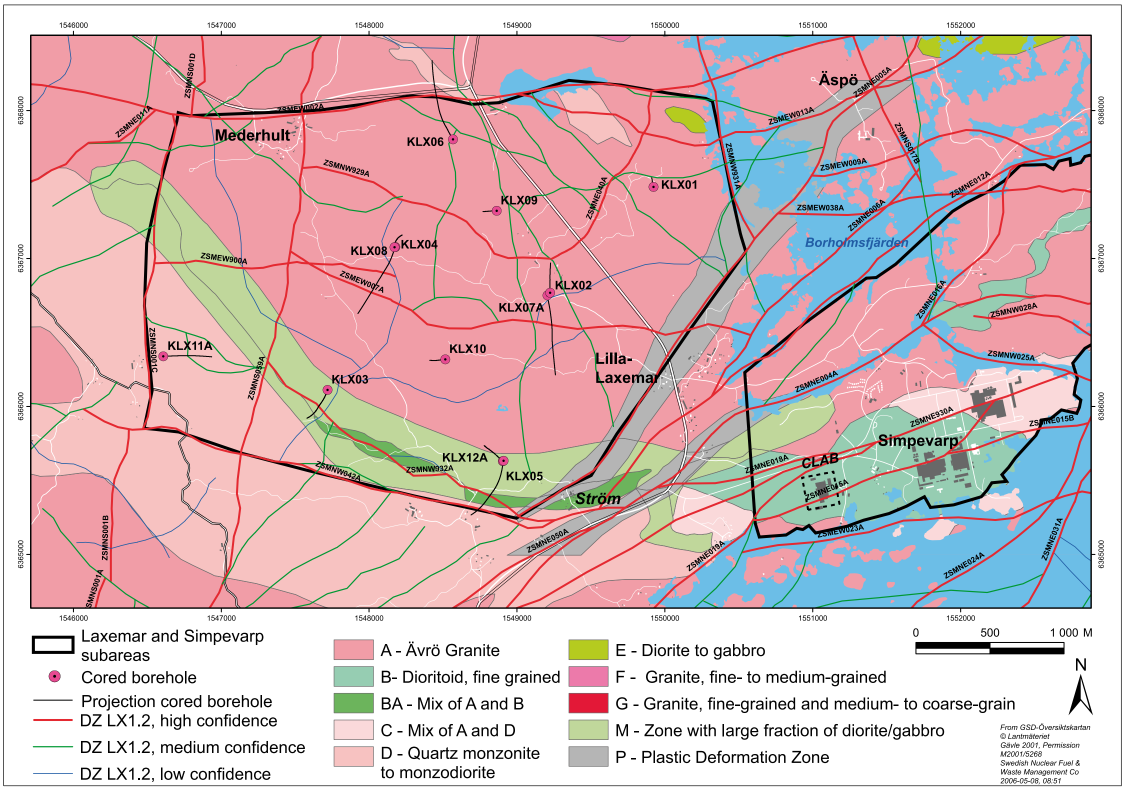


__Figure 4-43.__ Location of cored boreholes in the Laxemar subarea, including boreholes drilled after data freeze 1.2, draped on a combined rock domain and deformation zone model (model version Laxemar 1.2). It should be noted that rock domains D, E and M are more abundant at potential repository depth.

Groundwater flow

The general flow direction through the modelled area is determined by the overall topographic gradient towards the Balitic sea. The controls on the flow, apart from the hydraulic gradient, are also the geometry and properties of the hydraulic rock domains (rock mass) and the hydraulic conductor domains, as discussed above.

Based on the hydraulic property description, the SDM presents transient, density dependent, groundwater flow calculations in an equivalent porous medium representation at a regional scale. In accounting for the density driven flow also the effects of diffusional salt exchange between the rock matrix and the flowing water are accounted for. Flow paths are assessed for the velocity field simulated for the present day. An example of discharge points is shown in Figure 4-44.

The path lengths of the released particles are generally quite short. Localised flows are present as a result of the topography and the heterogeneous bedrock. Most released particles exit inside, or very close to, the local-scale model area, including the two release areas. The exit locations are located close to the shoreline and in the valleys with lower topographic elevation in the area. For more detail, see /Hartley et al. 2006c. Furthermore, additional simulations have been carried out within the framework of SR-Can, as discussed in chapter 9.

The flow model has also been used to predict the salinity and distribution of different water types as identified in the hydrogeochemical modeling, see next section. Figure 4-45 shows a comparison of simulated and measured salinity in boreholes KLX01, KLX02, KLX03 and KLX04 for the reference case of the hydrogeological model. It is noted that the overall representation of the distribution of salinity for the series of boreholes is generally good for the KLX and KSH boreholes, but there is certainly not a one-to-one fit. For example, the salinity measured for KLX01 at –220 m is calculated to occur at –500 m. The observed salinity for KLX02 at –390 m corresponds to the one calculated for –800 m. For KLX04 the measured salinity at –500 m is predicted to occur at –800 m. This could possibly be due to too high a conductivity in the hydrogeological model. The model also seems to simulate some moderate flushing of the deep Brine in KLX02, below about –1,200 m, suggesting possibly a little too high (vertical) conductivity at depth. The simulations nevertheless indicate the relatively fast migration of non-reactive species from the near surface to depth.

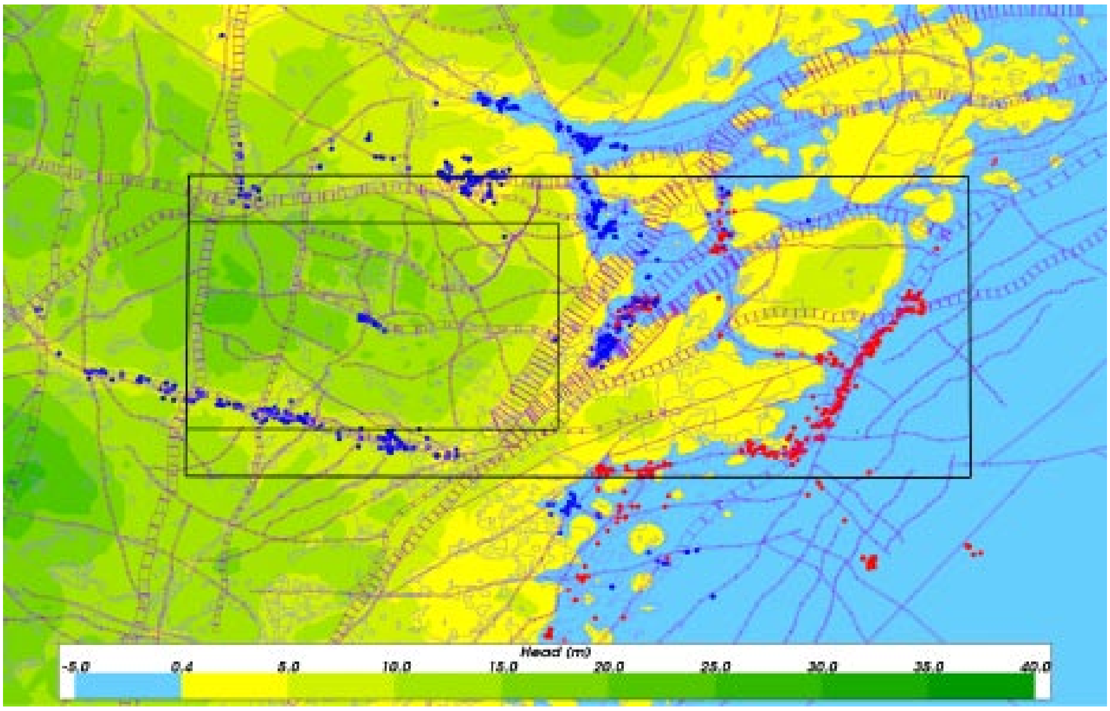


***Figure 4-44.** Close-up view of particle exit locations in the local-scale release area for the reference case of /Hartley et al. 2006c/. Particles released from the Laxemar release area are coloured in blue and particles from the Simpevarp release area are coloured in red. The Laxemar release area (the smaller black rectangle) is shown for orientation. Because of the limited view, not all particles are shown in the picture. (Updated from /Hartley et al. 2006c/ Figure 9-4).*

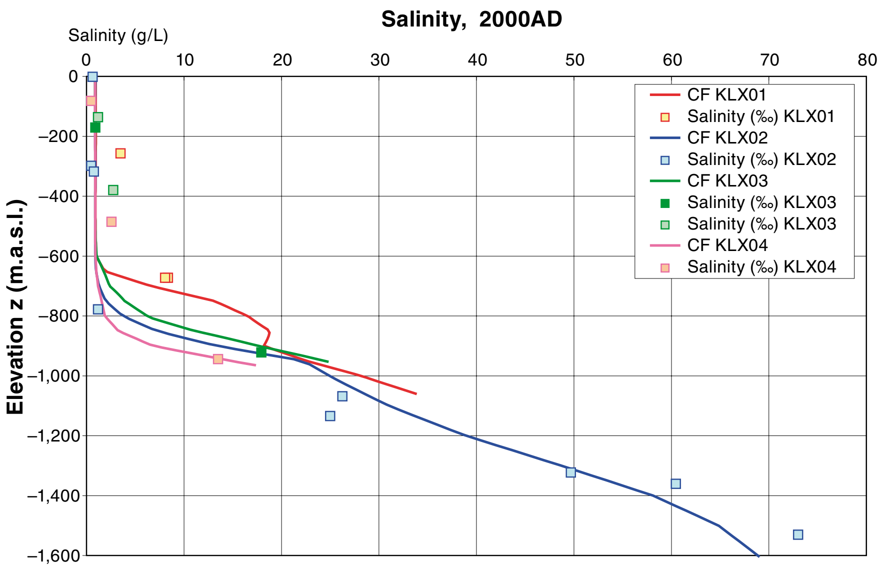


***Figure 4-45.** Comparison of simulated and measured salinity in KLX01, KLX02, KLX03 and KLX04 for the reference case of the hydrogeological model. The simulated salinity in the fracture system is shown by solid lines, and the data by points. Only representative data are shown.*

Groundwater composition

Explorative analyses of measured groundwater chemistry data and hydrogeochemical modelling are used to evaluate the hydrogeochemical conditions at the site in terms of the origin of the groundwater and the processes that control the water composition, cf Figure 4-46

The complex groundwater patterns in the Laxemar subarea are a result of many factors such as: a) the present-day topography and proximity to the Baltic Sea, b) past changes in hydrogeology related to glaciation/deglaciation, land uplift and repeated marine/lake water regressions/transgressions, and c) organic or inorganic modification of the groundwater composition caused by microbial processes and water/rock interactions. The sampled groundwaters reflect, to various degrees, processes relating to modern or ancient water/rock interactions and mixing.

According to the model, see Figure 4-47, four main groundwater types, Types A, B, C and D, are present. At the Laxemar subarea type A (dilute and mainly of Na-HCO_3) is found down to 800 m depths, Type B (brackish, mainly Na-Ca-Cl) is found at intermediate depths (500–950 m), Type C (saline (6,000–20,000 mg/L Cl, 25–30 g/L TDS), mainly Na-Ca-Cl) at intermediate to deep levels (900–1,200 m). Type D (highly saline, > 20,000 mg/L Cl, max TDS ~ 70 g/L), only seen in KLX02 at depths > 1,200 m.

The hydrogeochemical conceptual model has been developed in close collaboration with the hydrogeological modelling. The conceptual hydrogeochemical model is shown in Figure 4-47 together with a corresponding WNW section through the base case hydrogeological flow model mapping total dissolved solids (TDS).

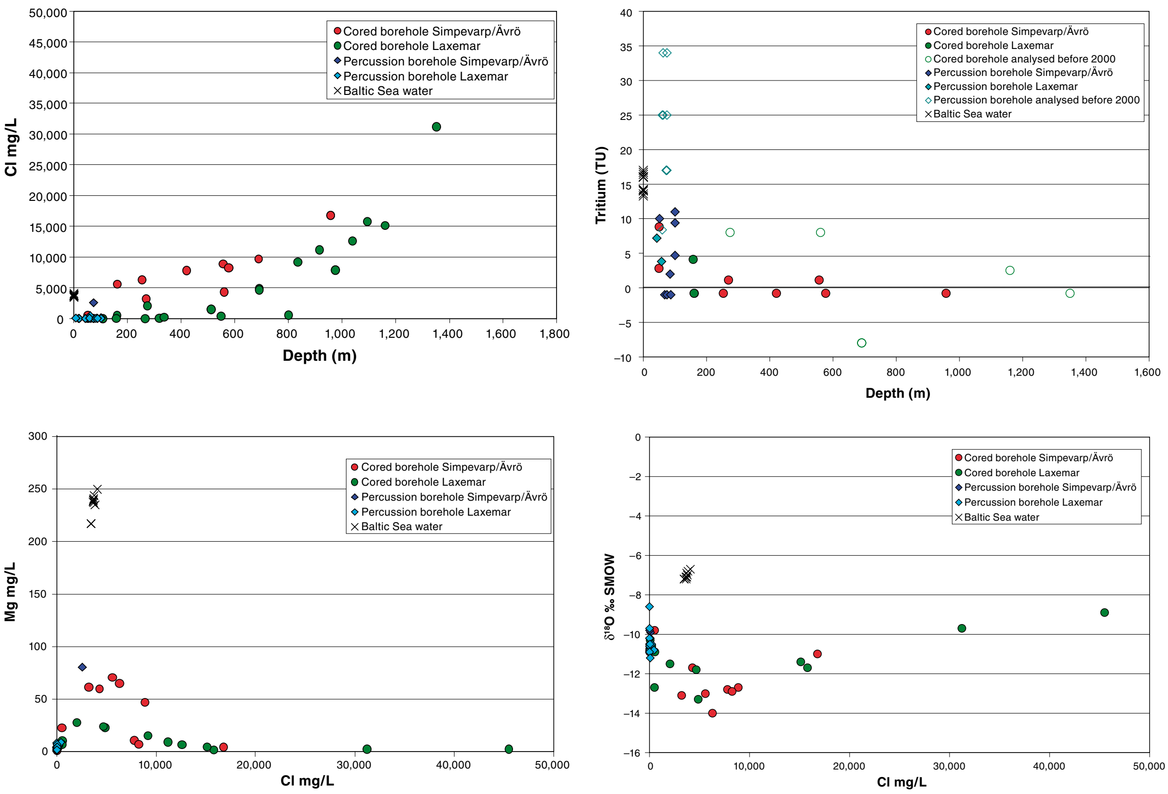


***Figure 4-46.** Salinty vs borehole depth (upper left), Tritium vs borehole depth (upper right), magnesium vs chloride (lower left), O-18 vs chloride (lower right) (extracted from Figures 9-2, 9-7, 9-4 and 9-6 of /SKB 2006b/).*

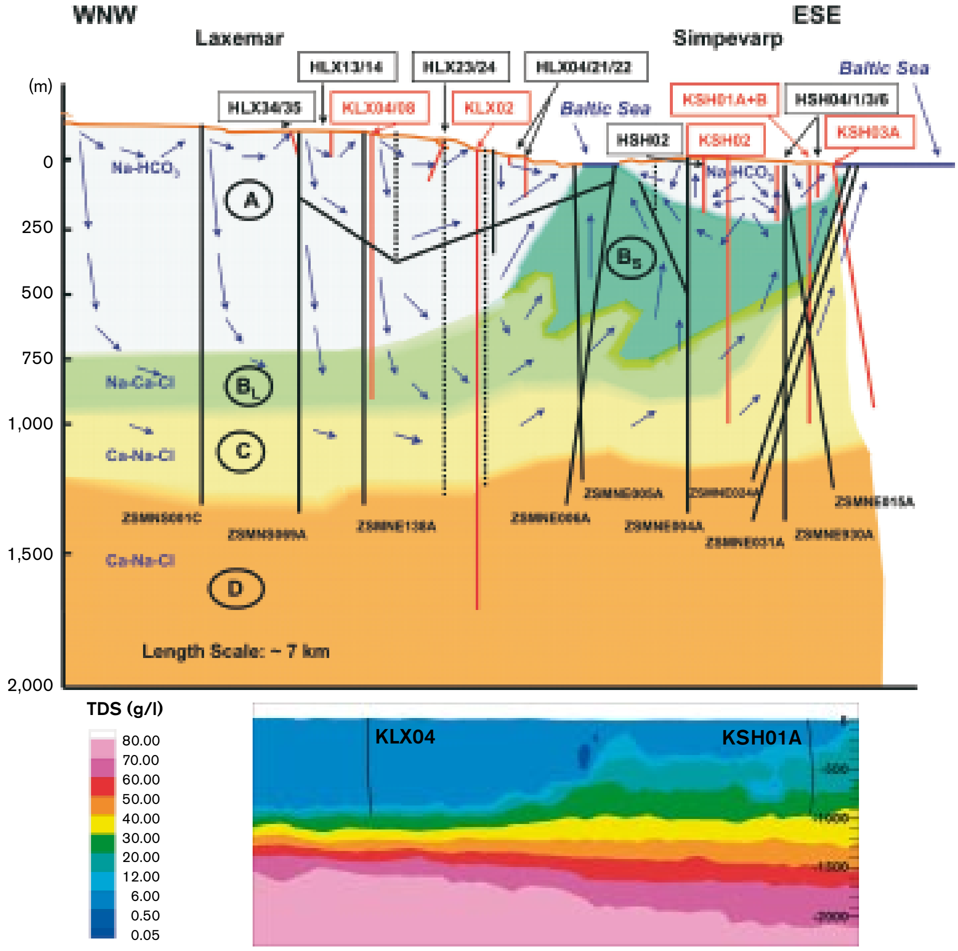


Figure 4-47. Composite showing a comparison between the conceptual hydrogeochemical WNW section (top) and the corresponding section through the regional scale base case hydrogeological model showing the distribution of total dissolved solids (TDS) (bottom).

Bedrock transport properties

Migration properties of the rock matrix

The diffusivity is quantified through the formation factor, F_m. Formation factors are obtained from through-diffusion experiments and electrical resistivity measurements both in the laboratory and in situ. The resistivity can be measured both in laboratory experiments (where the rock samples are saturated with 1 M NaCl) and in borehole in situ experiments. In contrast, all through-diffusion experiments are made at the laboratory scale. Although laboratory methods are more controlled, they could introduce a bias by potential fracturing of the cores due to stress release. The effective diffusivity assigned to the various rock types in the retardation model of the Laxemar subarea is currently based largely upon electrical resistivity measurements carried out in the laboratory. These measurements give effective diffusivities that possibly are up to a factor two larger than those obtained by in situ measurement of electrical resistivity. The differences, however, between in situ and laboratory measurements are not unequivocal when the data variance and overall measurement uncertainty are taken into account.

It is difficult to give a definitive estimation of relative diffusive properties as there is a considerable inequality in sample support amongst the different rock types and measurement methods. However, Ävrö granite appears to have the highest effective diffusivity (associated with higher retention) with a formation factor on the order of $Fm > 10^{-4}$. Other reported rock types appear to have essentially similar diffusive properties to each other (formation factors roughly 2–4 times lower than that for Ävrö granite) and any relative differences are speculative owing to the inherent data uncertainties.

At present, preliminary sorption measurement data exist only for Ävrö granite taken from a single location in borehole KLX03A. Many of these data are of a provisional nature, owing to the long times required for laboratory characterisation of the samples. Although there are no laboratory determined sorption measurements for other major rock types available at this time, specific surface area measurements indicate relative sorption strengths for different rock types. These data suggest that the differences between the rock types are typically very small and are often less than the estimated uncertainty in the sorption data. Consequently, sorption values for SR-Can are also based, in part, on generic data. This is further elaborated in the **Data report**, section 6.5.

Flow-related migration parameters

By various approaches, the Laxemar SDM, also provides estimations of the transport resistance (F-factor) and its distribution using site-specific data for Laxemar. It is noted that assessing a realistic site-specific value for the transport resistance is dependent upon correctly predicting the transmissivities, extents, frequencies, and connectivity of conductive features in the rock volume being investigated. It is clear from borehole hydraulic tests that there is a broad distribution of flow rates and transmissivities that characterise different flowing features. Furthermore, the F-factor is dependent not only on the hydraulic characteristics of individual flowing features comprising a flow path, but also their interconnectivity in the extended network of fractures surrounding the repository.

The uncertainty is partly assessed by scoping calculations to establish an envelope of possible behaviour using a channel network representation. Estimates are, however, model dependent and can vary between alternative model concepts. Despite these difficulties, it is still possible to provide bounding estimates of the variability of the F-factor for individual migration paths. This analysis suggests a mean value on the order of about 10^6 y/m, but based on the extreme assumptions of channel length and flow channel interdependence investigated, up to 10% of the migration paths could have an F-factor of less than 10^4 y/m. However, it should be noted that, for safety assessment, the relevant issue is the spatial distribution of migration paths related to the scale of individual deposition holes. The percentile of deposition holes with a low F-factor would not exactly equal the percentile of individual flow paths with this low F-factor in the rock volume as a whole, as a deposition hole could be intersected by a number of migration paths (varying from zero to several for each hole). Moreover, the F-factor for a deposition hole would be dominated by the path with lowest F-factor value intersecting the hole. (Another reason that would increase the F-factor in practice is that deposition holes with high inflows and, therefore, likely high outflows may not be used.) Therefore, upscaling using various assumptions in the DFN-model is needed to provide more quantified uncertainty ranges for application within the safety assessment. Such upscaling is performed as part of SR-Can, see the **Data report**, section 6.6, and chapter 9.

Near-surface hydrology

The conceptual-descriptive and quantitative modelling of the meteorological, surface hydrological and near-surface hydrogeological conditions in the Simpevarp candidate area is presented in /Werner et al. 2005/. The conceptual-descriptive model is based on three types of "elements": type areas, flow domains, and interfaces between flow domains. The identified type areas are (1) *high altitude areas* (dominated by exposed or very shallow bedrock), (2) *valleys* (with thicker Quaternary Deposits (QD) and postglacial sediments at the surface), (3) *glaciofluvial deposits* (of which the Tuna esker in the western part of the regional model area is the largest), and (4) *hummocky moraine areas* (primarily existing in the south-western part of the regional model area and in the central part of the Laxemar subarea). The Simpevarp candidate area has a relatively small-scale topographical undulation and shallow regolith. This implies that there are a large number of relatively small catchments with mostly small watercourses. There is a large degree of surface runoff taking place in the exposed/shallow bedrock areas, from which water is diverted into the valleys, and further into watercourses, lakes and wetlands. Considering a time period of one year, it was assumed that the storage change $\Delta S = 0$. The average (corrected) precipitation in the Simpevarp candidate area (P) is c 600–700 mm y^{-1}, and the average specific discharge (R) is estimated to be in the interval 150–180 mm y^{-1} /Larsson-McCann et al. 2002/. Hence, the evapotranspiration (E) was estimated to be in the interval 550 (700 minus 150) to 420 (600 minus 180) mm y^{-1}.

Near-surface chemistry

The chemistry of near-surface groundwater and surface water at Laxemar is described in /Tröjbom and Söderbäck 2006/ and /Lindborg 2006/.

The freshwater systems in the Simpevarp candidate area can generally be classified as mesotrophic, brown-water types. Most freshwaters are markedly coloured due to a high content of humic substances, indicating very high levels of dissolved organic carbon. Both streams and lakes are also relatively rich in nitrogen and phosphorus. These high levels of dissolved organic carbon and nutrients imply poor light penetration conditions in the lakes, and periodically also high levels of chlorophyll in the surface water and low oxygen concentrations in the bottom water of the lakes.

The chemical composition of shallow groundwater is an integrated consequence of both present and past processes. Shallow groundwater in the Simpevarp candidate area is characterised by neutral or slightly acid pH values, an alkalinity ranging from high to very low, and a normal or slightly elevated content of major constituents in a national context. The groundwater in the area is influenced by marine relics, resulting in elevated content of e.g. chloride and sulphate in both shallow groundwater and fresh surface waters.

When data on the chemical composition of till from the Simpevarp area are compared with regional and national data, only minor differences are revealed, indicating that the till in the Simpevarp area is relatively normal in a Swedish context.

The sea

The marine system is described in /Lindborg 2006/. The marine system at Laxemar encompasses three major habitats; semi-enclosed bays to a varying degree affected by fresh water discharges, the coastal archipelago with sheltered areas, and a Baltic Sea coastal habitat exposed to sea currents and wave action. The bays have a variable geometry; large shallow areas (less than 1 m) are found as well as depths down to 18 m. Area, volume and mean depth of the basins are listed in Table 4-9 The bay areas have an average surface salinity of 3.5–4.5‰ whereas the bottom water (16 m) has a salinity close to that of the adjacent coastal area of 6‰. The bay areas are characterized by humic, low transparency conditions, averaging a light penetration of 2–3 m in enclosed bays, 4–7 m in the archipelago and 12 m in the open sea. The Laxemar marine ecosystem has been divided in fourteen basins. The division is based on bathymetry and coincides with projected future drainage basins. Their characteristics are illustrated in Figure 4-48.

Table 4-9. Area, volume and mean depth of the basins in the Laxemar area.

Number	Name	Area (m^2)	Mean depth (m)	Volume (m^3)
1	Basin Borholmsfjärden	$1.37 \cdot 10^6$	1.6	$2.21 \cdot 10^6$
2	Basin Granholmsfjärden	$1.29 \cdot 10^6$	5.3	$6.88 \cdot 10^6$
3	Basin Getbergsfjärden	$3.61 \cdot 10^5$	3.2	$1.17 \cdot 10^6$
6	Basin Eköfjärden	$1.63 \cdot 10^6$	2.6	$4.30 \cdot 10^6$
8	Basin Talleskärsfjärden	$4.30 \cdot 10^6$	5.6	$2.40 \cdot 10^7$
9	Basin Fläsköfjärden	$1.03 \cdot 10^6$	0.6	$6.04 \cdot 10^5$
10	Basin Mjältnatefjärden	$2.85 \cdot 10^5$	0.7	$1.94 \cdot 10^5$
11	Basin Sketuddsfjärden	$1.56 \cdot 10^5$	0.9	$1.48 \cdot 10^5$
12	Basin Kråkefjärden	$8.99 \cdot 10^5$	5.7	$5.15 \cdot 10^6$
13	Basin Långvarpsfjärden	$8.91 \cdot 10^4$	estimated: 0.5	$4.58 \cdot 10^4$
14	Basin Hamnefjärden	$1.61 \cdot 10^5$	2.2	$3.58 \cdot 10^5$
15	Basin Ävrö Coastal	$2.02 \cdot 10^7$	11.9	$2.40 \cdot 10^8$
16	Basin Kalmarsund	$4.89 \cdot 10^8$	13.2	$6.44 \cdot 10^9$
17	Basin Finngrundsfjärden	$1.89 \cdot 10^6$	6.7	$1.27 \cdot 10^7$

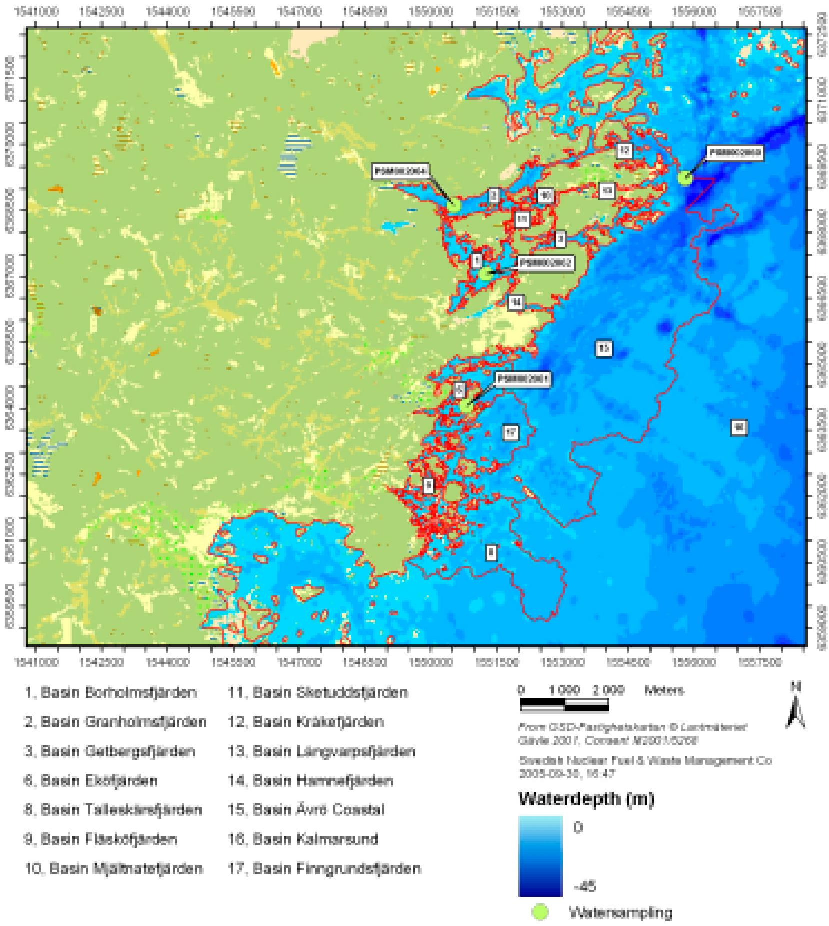


Figure 4-48. *The basins of the Laxemar area. The digital elevation model for the sea is displayed in increasing dark blue with depth.*

The inner, soft-bottom parts of the archipelago north of Laxemar (around Äspö) are dominated by stoneworts, *Chara spp*. West of Ävrö, a large area is covered by the algae, *Xanthophyceae Vaucheria sp*. On corresponding bottoms in the southern area, the vegetation is dominated by vascular plant communities, dominated by pondweed (*Potamogeton pectinatus)* and eelgrass (*Zostera marina)*. The sheltered inner coastal waters, particularly south of Laxemar, are dominated by *P pectinatus*. Further out towards more exposed areas *P pectinatus* and *Z marina* occurs together in a patchy appearance. On hard substrates, in shallow areas, the vegetation is dominated by the kelp-like bladderwrack (*Fucus vesiculosus)* and in deeper areas red algae covers the hard substrata /Fredriksson and Tobiasson 2003/. *Fucus sp* in low abundance is recorded to approximatey 10 m depth and red algae down to approximately 30 m /Tobiasson 2003/. The benthic fauna is dominated by filter feeders, blue mussel (*Mytilus edulis*) and detritivores, often the Baltic clam (*Macoma baltica*) or snails (*Hydrobia spp*). In the coastal hard bottom areas, filter feeders constitute up to 95% of the biomass /Fredriksson 2005/, whereas detritivores, on the other hand, constitute 50–80% of the biomass in the inner areas e.g. basin Borholmsfjärden. In total, 45 animal species associated with the vegetation occur in the area around Laxemar. The *Fucus sp* communities is the most diverse in respect of associated fauna and harbours 31 species or higher taxa, whereas in the soft bottoms without vegetation only 14 species have been found.

Primary producers in the pelagic habitat, which accounts for a relatively small part of the turnover of matter of the ecosystem (see chapter 5 in /Lindborg 2006/), seems to be dominated by the diatoms. Copepods are the dominant zooplankton, and zooplankton is more abundant in the inner bays than in the coastal areas.

Lakes

An overview of the lakes and lake sediment is found in /Lindborg 2006/, further information about the lakes in /Brunberg et al. 2004/ and a discussion of their chemistry in /Tröjbom and Söderbäck 2006/

The regional area of Simpevarp contains relatively few lakes. Totally six lakes, situated partly or entirely within the regional model area, have been investigated for habitat characterisation during the site investigations. For some of the lakes, other biotic data have also been collected, e.g. relating to plankton, macrophytes, fish, and invertebrates. Here an illustrative account is given based on data from lake Frisksjön.

Data have also been collected in streams, where a characterisation of the watercourses concerning vegetation, substrate, and encroachments has been performed. Moreover, invertebrate data have been collected in two of the streams.

The lake habitats have been characterised and the borders between different habitats within the lakes have been defined /Brunberg et al. 2004/. Furthermore, phytoplankton sampling for biomass estimation has been performed in Frisksjön over one year /Sundberg et al. 2004/. Macrophyte biomass was investigated in Frisksjön in August 2004 /Aquilonius 2005/, and macrophyte vegetation in watercourses has also been studied /Carlsson et al. 2005/.

The lakes in the Oskarshamn area have been distinguished into five different habitats according to /Brunberg et al. 2004/;

Littoral type I: The littoral habitat with emergent and floating-leaved vegetation. This habitat is developed in wind-sheltered, shallow areas where the substrate is soft and allows emergent and floating-leaved vegetation to colonise.

Littoral type II: The littoral habitat with hard substrate. This habitat develops in wind-exposed areas of larger lakes, but also in smaller lakes, where the lake morphometry includes rocky shores. The photosynthesising organisms colonizing these areas include species that are able to attach to the hard substrate, e.g. periphytic algae.

Littoral type III: The littoral habitat with submerged vegetation. This habitat is found in areas of the lakes without emergent or floating-leaved vegetation, but where the light penetration is enough to sustain photosynthetic primary production all the way down to the sediment.

The profundal habitat: This habitat develops at the sediments of the lakes where light penetration is less than needed to sustain a permanent vegetation of primary producers. Non-photosynthesising organisms dominate this habitat. The profundal organisms are dependent on carbon supplies imported from other habitats of the lake or from allochtonous sources.

The pelagic habitat: This habitat includes the open lake water, where a pelagic food-web based on planktic organisms is developed. Depending on the light availability, these plankton are dominated by either photosynthetic production (i.e. by autotrophic phytoplankton) or, if the water is strongly coloured or turbid, by heterotrophic carbon processing (e.g. by heterotrophic/mixotrophic bacterioplankton and phytoplankton). The pelagic habitat covers the same area as the sum of littoral type II, littoral type III and profundal habitats within a lake.

Table 4-10. Data sources concerning primary producers in the limnic systems in the Oskarshamn regional model area.

Parameter	Lake	Year	Reference
Habitat borders	6 lakes in the Oskarshamn area (e.g. Lake Frisksjön)	2003	/Brunberg et al. 2004/
Phytoplankton biomass	Lake Frisksjön	July 2003–June 2004	/Sundberg et al. 2004/
Macrophyte biomass	Lake Frisksjön	August 2004	/Aquilonius 2005/
Bottom vegetation (coverage and species)	Mederhultsån, Kåreviksån, Ekerumsån, Laxemarsån	2004	/Carlsson et al. 2005/

Below, the habitat characterisations for one of the investigated lakes, Lake Frisksjön, is presented.

Lake Frisksjön

All five major habitats are present in Lake Frisksjön, see Table 4-11 and Figure 4-49. Despite the relative shallowness of this lake (maximum depth 2.8 m), the brown colour of the water prevents light from penetrating down to the bottom in large parts. Thus, the profundal habitat covers a substantial part of the bottom area (41%). The dominant littoral habitat is of type III.

Macrophyte biomass in Lake Frisksjön was studied in August 2004, when the vegetation had reached its maximum biomass for the season. The calculations were often based on only one weight of each plant species and are, therefore, to be considered as rough estimates. In Littoral III, no vegetation was found. Littoral II hosted low vegetation biomass, whereas the biomass was higher in Littoral I. This indicates that the bottom area with light conditions below the compensation level, i.e. where it is too dark to enable primary production, is larger than the area classified as Profundal in /Brunberg et al. 2004/.

Table 4-11. Distribution of major habitats in Lake Frisksjön /Brunberg et al. 2004/.

Habitats	Area (%)	Area (m²)
Littoral type I	18	24,200
Littoral type II	< 2	1,430
Littoral type III	38	49,130
Pelagial	82	107,270
Profundal	41	52,250
Sum		127,010

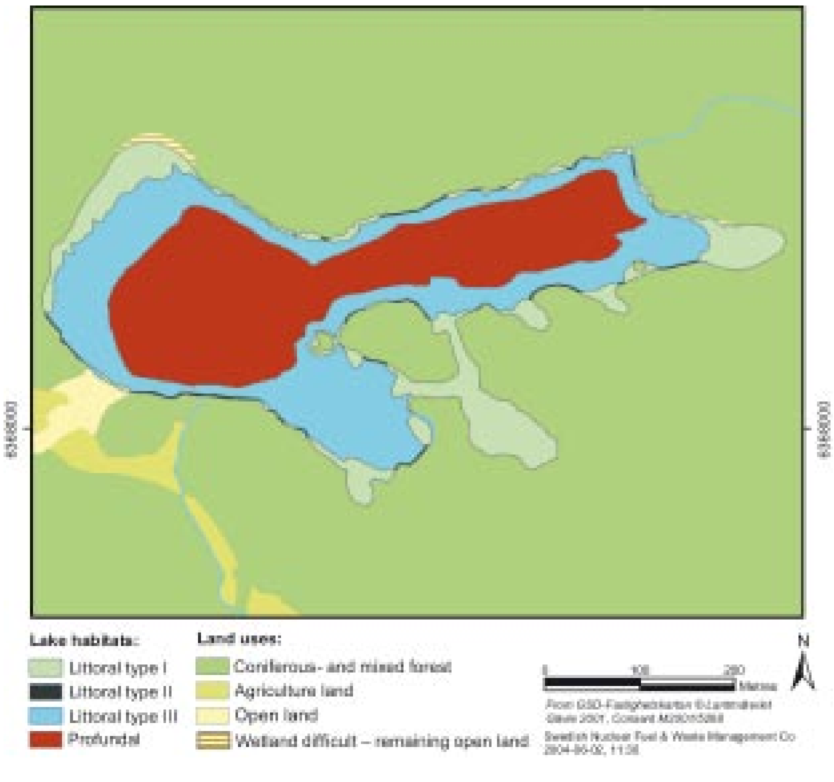


Figure 4-49. Distribution of major habitats in Lake Frisksjön /Brunberg et al. 2004/.

Terrestrial ecosystems

An overview of the ecosystems on land is provided in /Lindborg 2006/.

The terrestrial vegetation is highly influenced by the bedrock composition, Quaternary deposits and human land management. Bedrock mainly consists of granites. The Quaternary deposits are mainly wave-washed till, but silt and clay have been deposited in the valleys. This distribution of deposits is reflected in the vegetation, as pine forests dominate on the till and all the arable land and pastures (abandoned arable land) are found in the valleys. Human management has been restricted to agricultural activities in the valleys, whereas forestry has been the dominating activity elsewhere. The spatial distribution of different vegetation types is presented in the vegetation map /Boresjö Bronge and Wester 2003/.

The forests are dominated by dry Scots pine (*Pinus sylvestris*) forests situated on bedrock or nutrient poor thin soils with shrubs, mostly heather (*Calluna vulgaris*), and grasses, such as *Deschampsia flexuosa*, *Agrostis vinealis* and *Festuca ovina*, and with lichens and mosses dominating the ground layer. When these pine forests get moister cowberries (*Vaccinium vitis-idaea)* and biberries (*Vacinium myrtillus)* becomes more common in the field layer. Norway spruce (*Picea abies*) becomes abundant where a deeper soil cover is found, while deciduous tree species are an important constituent near the coast, i.e. mainly oak (*Quercus robur*) but also hazel (*Corylus avelana*), rowans (*Sorbus aucuparia*, *S intermedia* and maple (*Acer platanoides*), making the mixed forest the second commonest forest type. *Q robur* is often the dominant tree species when more or less pure deciduous forests are found. The character of these forests is a function of boulder frequency, nutrient availability and earlier history of management.

Arable land, pastures and clear cuts dominate the open land. Arable land and pastures are found in the valleys close to settlements. The pastures were earlier intensively used, but are today a part of the abandoned farmland that arose following the nationwide general regression of agricultural activities. As a consequence of the forestry activities in the area many clear-cuts of different successional stages are found. Birch (*Betula pendula)* is the dominant species in many of the earlier successional stages until it is replaced by young *P abies* or *P sylvestris* depending on soil type and/or management.

The dominant wetland type is a nutrient-poor mire that is accumulating peat /Rühling 1997, SNV 1984/. A special type of semi-wetland is found on the pine-dominated bedrock, where water-filled depressions, rock pools (Sw: *hällkar*), are formed /Lundin et al. 2005/. These obtain all their water from precipitation and have, therefore, a peat moss (S*phagnum)*-dominated community, very bog-like, with labrador tea *Rhododendron tomentosum* and *P sylvestris*, and a peat layer accumulating on the bedrock.

Human population

In /Miliander et al. 2004/ the human population is described in detail. In total, 2,709 people lived in Misterhult parish in 2002. The population is slowly decreasing, with a maximum over the last ten years in 1993, with 2,987 inhabitants. The density has on average been 7.1 inhabitants per square kilometre.

The dominant employment sector within Misterhult parish is electricity-, gas- and water supply, sewage and refuse disposal and it involves 60% of the employed day-time population (working in the area). Within the employed night-time population (living in the area) on the other hand, only 11.7% work in that sector.

The land use in Misterhult parish differs substantially from the average land use in Kalmar County. The forest area is far more dominant in the Laxemar area than in Kalmar County. The proportion of arable land is considerably lower in the Laxemar area, 4.4% compared with 11.6% in Kalmar County. The same holds for wetlands.

Agricultural activities are limited in Misterhult parish compared with Kalmar County. The farm density in Misterhult parish is on average only 0.2 farm·km^{-2}, which is half of the density in Kalmar County as a whole (0.4 farms·km^{-2}). The main part of the arable land (64%) is used for fodder production. Barley is by far the dominant crop in Misterhult parish, according to data from 1999. The standard yield of spring barley in the harvest area in which the Misterhult parish is located, is slightly below the county average (90%) and clearly below the national average (79%).

The number of cattle, sheep and fowl (Sw: *höns*) in Misterhult parish has decreased between 1990 and 1999. In 1999, the number of cattle was 1,207. In the case of cattle the number of breeding cows has increased, whereas the numbers of dairy cows and heifers, bulls and bullocks have decreased. The number of pigs has increased by 50%, from 292 (the average between 1990 and 1999) to 422 in 1999.

Representativity of the Laxemar version 1.2 Site Description

Although the Laxemar 1.2 SDM is based on a significant amount of data, the size of the area and the initial focus on exploring the deformation zones and rock volumes outside the repository volume, imply that the model is only based on a few data representing the potential repository volume. This is especially evident for the fracture data (the DFN-model), for the thermal data and for the hydraulic property description.

Data obtained after data freeze 1.2 contain much more information from the potential repository volume and more boreholes are also planned in this volume within the ongoing complete site investigation programme /SKB 2006f/. Furthermore, these data show more favourable hydraulic characteristics (cf Figure 4-41) than those presently used in the hydraulic flow models derived from the version 1.2 site description. This means that the current flow models may be somewhat biased and that they do not fully capture the actual variability in the hydraulic properties.

For these reasons, the SR-Can team decided to carry out a limited set of analyses of the Laxemar site in SR-Can and it was not judged meaningful to explore different variants based on the Laxemar 1.2 data set.

4.4 Site-specific layout

A site-specific repository layout is produced as part of the repository design work. The design premises and methodology for application in the preliminary design of underground excavations within the framework of SKB's site investigations are presented in "Deep Repository: Underground Design Premises. Edition D1/1", /SKB 2004b/. The design work is made in stages, where a preliminary design. D1, is produced after the Initial Site Investigations (ISI) and an updated design, D2, is produced based on the Complete Site Investigation (CSI). According to these design premises the goals of the design work during the Initial Site Investigation are to:

- Test and evaluate the design methodology.
- Determine whether the deep repository can be accommodated within the studied site.
- Identify site-specific facility-critical issues and provide feedback to design organisation regarding additional studies that needs to be done; the site investigation organization regarding further investigations; and safety assessment regarding which factors control the extent of the repository.
- Provide material for consultations according to chapter 6 of the Environmental Code regarding: the location of the surface facility; the location and extent of the underground facility; theoretical impact (e.g. groundwater draw down).
- Provide supporting material for Preliminary Safety Evaluation (PSE), as well as SR-Can, regarding theoretical extent of deposition areas; estimation of the quantity of injection grout and other "foreign" materials.

Feedback from this step is given to the continued site modelling work, see e.g. /Janson et al. 2006/.

During the Complete Site Investigations (CSI) the design goals are further refined to

- Present a facility description for the chosen site with a proposed layout for the final repository facility's surface and underground components as a part of the supporting material for an application. The description shall present an evaluation of constructability, technical risks, costs, environmental impact and the reliability and effectiveness of the operational phase. The underground layout shall be based on information from the CSI phase and serves as a basis for the safety assessment.
- Provide a basis for the Environmental Impact Assessment (EIA) and consultation regarding the siting of the final repository facility's surface and underground parts with proposed final locations of ramp and shafts, plus the environmental impact of construction and operation.
- Carry out the design work for the entire final repository facility to the point that it is possible to plan for the construction phase.

Ultimately, the design work should lead to a layout D2, to be used in the application for the final repository, which will be submitted after the CSI. The design premises, including the goals, will be updated before the D2 step is taken, and will consider the feedback from SR-Can.

4.4.1 Methodology

For the design step D1, a design methodology was developed in the design premises document /SKB 2004b/. This has been applied to all sites now being investigated by SKB. The design methodology identifies and characterises several design tasks. Each task addresses a particular design issue. In a first stage of the D1 design work, the following issues and tasks have been addressed (for further detail, see /SKB 2004b/, which also contain flow charts expressing the logical sequence for the assessment of the questions).

A: What locations and depths within the site may be suitable for hosting the final repository?

B: Is it reasonable to consider that the total required repository area can be accommodated, taking into account current respect distances to deformation zones and preliminary assumed losses of deposition holes because of local unfavourable geological conditions?

C: How can the deposition areas be designed with a view towards achieving sufficient space and long-term safety? With the sub-issues:

- C1. How can deposition tunnels, deposition holes and main tunnels be designed considering the equipment and activities that they are required to accommodate?
- C2. What distance may be required between deposition tunnels and between deposition holes in order to conform with the maximum permissible temperatures?
- C3. What orientation may be suitable for deposition tunnels taking into account both water seepage and mechanical stability in deposition tunnels and deposition holes?
- C4. How large a proportion of the deposition holes may be excluded as unusable during the excavation, based on the minimum permissible distance to fractures or fracture zones of too large size, excessive water inflow and instability? How is the loss affected by different criteria for rejection?
- C5. Based on the evaluations made in previous steps, at what depth or over what depth range may it be suitable to build the final repository?

D: How can other underground openings, especially the central area's rock caverns, be designed to achieve stability and to accommodate the required equipment and activities?

E: How can the layout of the entire hard rock facility be configured?

The answers to these questions have potential safety implications, since the issues to be solved by the Rock Engineering team to a large extent concern adapting the layout in order to meet safety requirements and preferences.

Subsequent steps in the D1 design work concern engineering implications of the suggested design, like estimates of potential upconing and grouting needs.

It should be noted that there are several important layout aspects that were not specified for the layout step D1. These include designing the the access to the underground via ramp and shafts, location of ventilation shafts, and developing practical approaches to the grouting work. These aspects will be considered in layout step D2.

Application of deposition hole rejection criteria in SR-Can

The layout work considers that some potential canister positions may be found unsuitable. A degree-of-utilisation is estimated by considering the mechanical stability, the probability of deposition holes intersecting fractures or deformation zones with radius $R > 75$ m (see section 9.4.5 for details), and the inflow of water to tunnels and deposition holes, using criteria defined in the design premises document /SKB 2004b/. The degree-of-utilisation affects the layout of the repository both in terms of extent and configuration, i.e. the repository is made large enough to find space for 6,000 accepted canister positions. However, due to the stochastic and uncertain nature of the site description, the layout cannot identify which actual positions would be rejected. The criteria used were intended to ensure selection of canister positions favouring safety. However, they are preliminary and it is neither clear that they are necessary nor that it is sufficient to apply them for achieving a safe repository.

A potentially important feedback from SR-Can to rock engineering, therefore, concerns an evaluation of the significance of applying different deposition hole rejection criteria. Within SR-Can the importance, with respect to both safety and degree-of-utilisation, of some examples of such criteria is, therefore, explored. Clearly, criteria resulting in very poor degree-of-utilisation would be impractical.

As is further discussed in the following sections there are essentially two different criteria of interest:

- criteria addressing canister deposition hole intersections with large fractures,
- criteria addressing the flow conditions in and around a deposition hole.

A key factor to consider is not only how effectively the criteria contribute to safety, but also their practical applicability. The criteria need to be related to observable properties during deposition tunnel and deposition hole construction.

A recently developed criterion concerning the avoidance of deposition holes intersected by large fractures and utilising observations of fractures in the corresponding deposition tunnel states the following /Munier 2006a/: If a fracture is observed over the entire perimeter of the deposition tunnel, then no deposition hole should be located such that it would be intersected by the (assumed) extension of that fracture. This so called full perimeter intersection criterion (FPC) has been evaluated using data from the Forsmark and Laxemar sites /Munier 2006a/. The results suggest a high efficiency in reducing the number of deposition holes intersected by large fractures at the expense of a moderate increase in total deposition tunnel length. The FPC method addresses part of issue C4 above and will be fully implemented in layout step D2.

Since the method is straight-forward to implement and since its efficiency has been quantified site specifically, it is assumed that the FPC rule has been implemented when the layouts of the two sites presented below are used in SR-Can. This has important implications for the safety evaluation concerning i) the hydraulic and transport properties associated with the ensemble of deposition holes and ii) the consequences of potential post-glacial major earthquakes in the vicinity of the repository.

Concerning flow conditions it is likely that practical criteria would relate to results of hydraulic tests in pilot holes in deposition tunnels or deposition holes or relate to inflows measured in deposition holes. However, the practicalities or effectiveness of such hydraulic criteria have not yet been assessed by SKB. For this reason, SR-Can has explored a much simpler, but potentially much less effective, criterion related to the transmissivity of the fractures intersecting the deposition hole. This is further discussed in section 9.3.6.

4.4.2 Preliminary layout for the Forsmark area

A type D1 design, reported in /Brantberger et al. 2006/ has been developed focusing on the “target area” of the Forsmark candidate area, see Figure 4-50. The selection of the target area is justified in the Forsmark Site Investigation Programme for further investigations of geosphere and biosphere /SKB 2005d/.

The design considers a repository for 6,000 canisters, based on current estimates of the final amount of spent fuel being produced in Sweden, including a margin of 1,500 canisters in case the final amount of spent nuclear fuel should exceed current estimates. Layouts are presented both for the −400 m and −500 m levels – the former is the reference option, as explained by /Brantberger et al. 2006/.

Layout adaptation to deformation zones, rock stress and thermal properties

For deformation zones longer than 3 km, the repository layout developed in the D1 design work for the Forsmark area /Brantberger et al. 2006/ applies a respect distance equal to the zone width, including the transition zone, or at least 100 m, i.e. in accordance with the rules defined in /Munier and Hökmark 2004/. For zones shorter than 3 km, a *margin for construction* is applied that equals the zone width plus a safety margin based on potential construction problems, i.e. the applied rule is somewhat stricter than the safety related respect distance as given by /Munier and Hökmark 2004/. In the layout, canister deposition tunnels may intersect these shorter zones, whereas the margin for construction applies to the individual deposition holes. This means that in a deposition tunnel intersecting a short deformation zone, no deposition holes are allowed to be placed within the margin for construction of this zone. Other tunnels, such as ramp shaft, access and transport tunnels may pass the larger deformation zones provided they do not pose a construction problem.

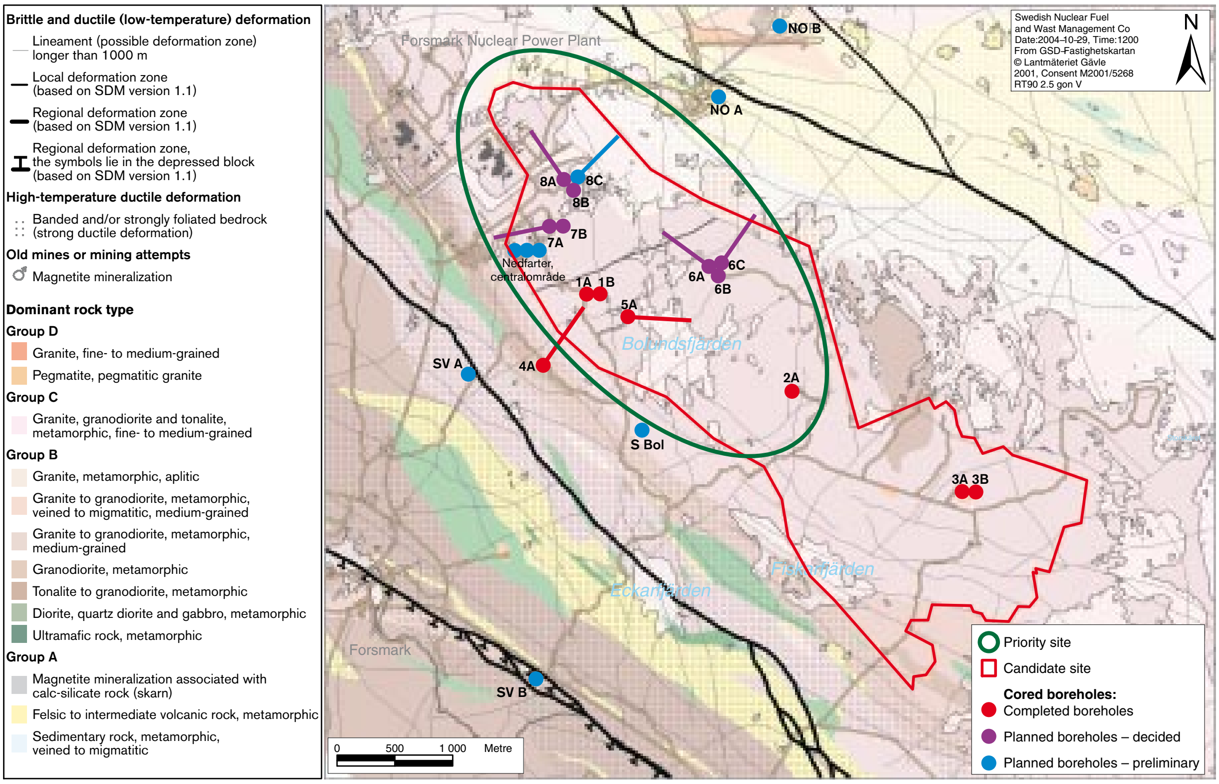


***Figure 4-50.** The D1 design work for Forsmark has focused on the "target area" indicated in green.*

Figure 4-51 shows resulting respect distances, indicating potentially available deposition areas, at the −400 m level within the target area. Both high and medium confidence zones are considered. There is little difference in the available area between the −400 m and the −500 m level. All deposition areas are located within rock domain RFM029 and between the gently dipping deformation zones ZFMNE1193 and ZFMNE00A2, see chapter 5 of SDM F1.2.

The potential repository layouts presented for the Forsmark area are based on the current Site Description. Later versions of the layout will need to incorporate any modifications of the Site Description, including changes of the deformation zone geometry.

The area of the rock actually needed for the repository depends on the number of canisters, the thermal properties of the rock and the degree-of-utilisation. A minimum canister separation distance is determined based on the thermal properties. In addition to that, some potential canister positions may be found unsuitable. The degree-of-utilisation depends on the mechanical stability, the probability of deposition holes intersecting fractures or deformation zones with radius R > 75 m and the inflow of water to tunnels and deposition holes, see the design premises document /SKB 2004b/.

The thermal properties and the initial temperature of the different rock domains are used to calculate the necessary distance between deposition holes, in order to ensure that the temperature criteria are met. The design rule is provided in the Underground Design Premises document /SKB 2004b/. The rule is based on the analyses performed by /Hökmark and Fälth 2003/. According to the procedure specified, the layout should be based on 40 m separation between the deposition tunnels, whereas canister spacing should be adapted to the site properties. The designed minimum canister spacing is based on a constant value of the thermal conductivity and thermal properties taken from the SDM. This analysis implies a canister spacing in the range 4.9 to 5.6 m. However, given remaining uncertainties and also considering potential construction difficulties with small canister separation distances, the design work adopts a reference canister spacing set to 6 m. (In revised designs, it may also be possible to adjust the tunnel separation, in order to more optimally use the repository volume.)

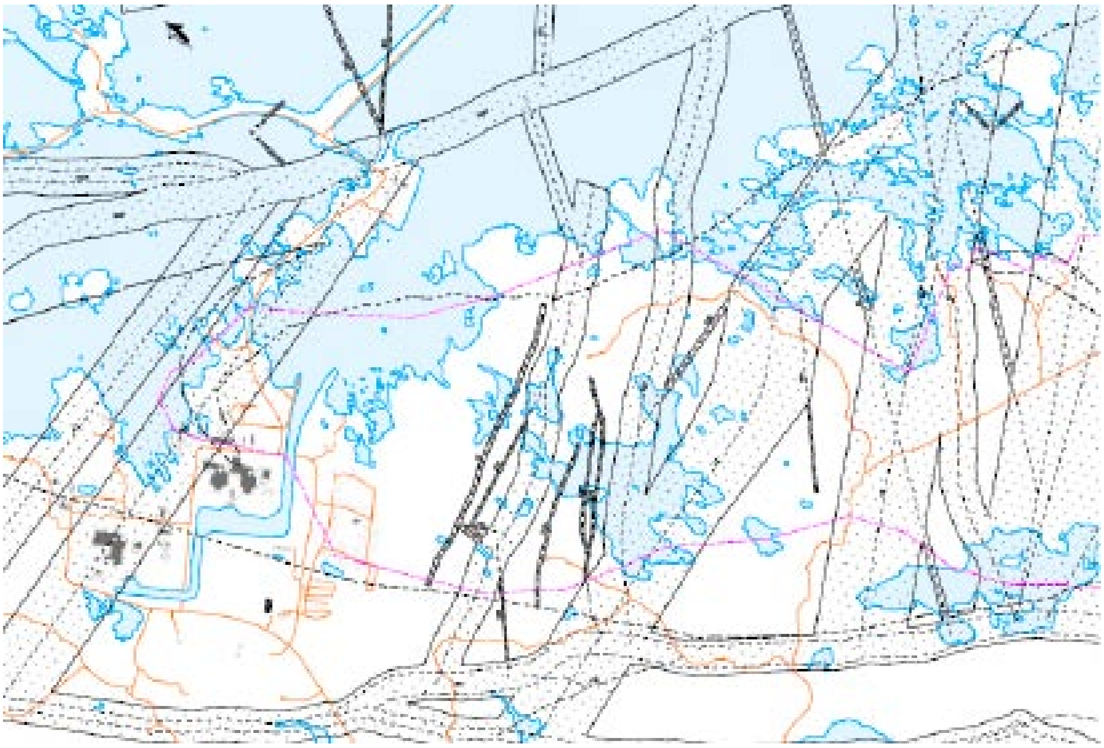


***Figure 4-51.** Respect distances from the large (> 3,000 m) high and medium confidence deformation zones at the –400 m level.*

The risk of spalling of deposition tunnels and deposition holes during construction, assessed using the stress and intact rock properties, is based on the assessment by /Martin 2005/. In order to minimize the risk of spalling in deposition tunnels, the deposition tunnel directions should be parallel with the main principal stress orientation.

Using this information and an assessment of degree of utilisation, the layout D1 design work for the Forsmark area /Brantberger et al. 2006/ presents potential layouts adapted to the respect distances. Figure 4-52 shows a potential layout at the −400 m level. At this level, the degree of utilisation, which depends on rock stability and potential water problems, is estimated to be around 89%. Layouts at the −500 m level have also been developed and those need about the same area, but the degree of utilisation decreases to 86%, due to expected problems of rock spalling in deposition holes. It is also noted that the use of the FPC criterion to avoid deposition positions intersected by large fractures (see section 9.4.5), to be implemented in layout D2, suggests a degree-of-utilisation of around 90% /Munier 2006a/. (In obtaining this figure, a slightly extended version of the FPC, denoted EFPC, was applied, see /Munier 2006a/ for details.)

The layout D1 design work for the Forsmark area /Brantberger et al. 2006/ also presents a limited sensitivity study varying the length of some deformation zones (affecting whether they have respect distance or not), varying the degree of utilisation for various reasons, varying the dip of the deformation zones in accordance with the uncertainties provided in the SDM Forsmark 1.2, varying the margin for construction, varying the distances between deposition holes and deposition tunnels and varying the maximum length of deposition tunnels (from 300 m to 600 m). Of these changes, the size of deformation zones, the uncertainty in dip, the degree of utilisation and the distance between deposition holes have the largest influence. It is generally found that there is sufficient space, with margin, to host a repository within the target area. Furthermore, the target area is only a subset of the Forsmark candidate area. Additional space is, therefore, available.

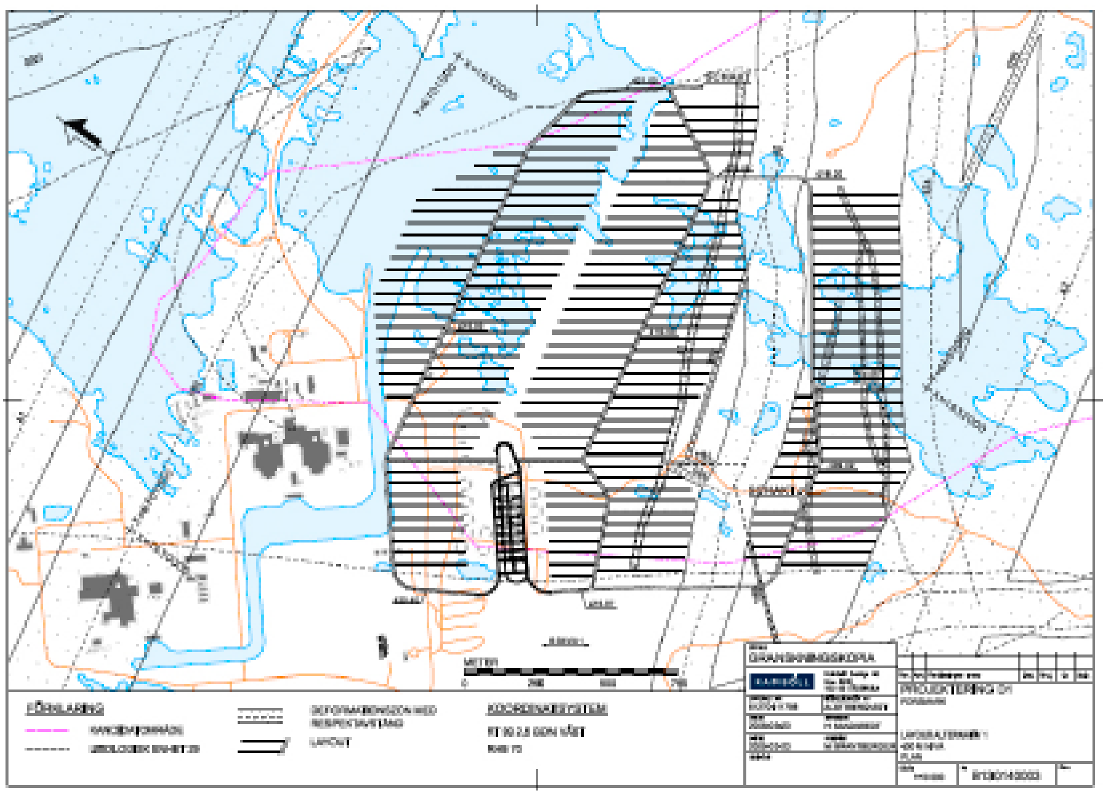


Figure 4-52. *Potential Layout at the –400 m level.*

4.4.3 Preliminary layout for the Laxemar subarea

A type D1 design, reported in /Janson et al. 2006/ has also been developed for the Laxemar subarea, see Figure 4-34. As for Forsmark, the design considers a repository for 4,500 canisters, based on current estimates of the final amount of spent fuel being produced in Sweden, but also assesses the space needed for an additional 1,500 canisters, in case the final amount of spent nuclear fuel should exceed current estimates. Layouts are presented both for the –500 m and –600 m levels, the former is the reference option. SKB decided not to develop a layout for the –400 m level, although there was nothing in the data suggesting this would not be possible.

Layout adaptation to deformation zones, rock stress and thermal properties

For deformation zones longer than 3 km, the repository layout developed in the D1 design work for the Laxemar subarea /Janson et al. 2006/ applies a respect distance equal to the zone width, including the transition zone, or at least 100 m, i.e. in accordance with the rules defined in /Munier and Hökmark 2004/. For zones shorter than 3 km, a *margin for construction* is applied that equals the zone width plus a safety margin based on potential construction problems, i.e. the applied rule is somewhat stricter than the safety related respect distance as given by /Munier and Hökmark 2004/. Furthermore, in contrast to the Forsmark layout, the designer decided that these minor zones were not allowed to intersect the deposition tunnels, although this is not formally required by the mechanical respect distance rules. As for Forsmark, other tunnels, such as ramp shaft, access and transport tunnels may pass the lager deformation zones provided they do not pose a construction problem.

Figure 4-53 shows resulting respect distances, indicating potentially available deposition areas, at the −500 m level. Both high and medium confidence zones are considered. The impact of low confidence zones has been assessed in a sensitivity analysis.

The area of the rock actually needed for the repository depends on the number of canisters, the thermal properties of the rock and the degree-of-utilisation. A minimum canister separation distance is determined based on the thermal properties. In addition to that, some potential canister positions may be found unsuitable. The degree-of-utilisation depends on the mechanical stability, the probability

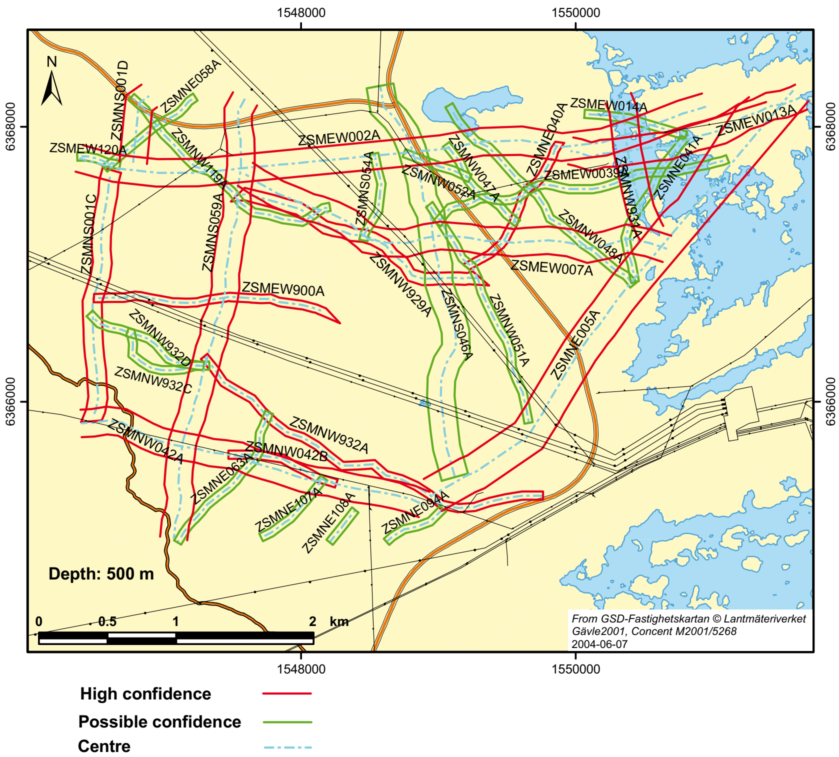


***Figure 4-53.** Respect distances from the large (> 3,000 m) high (red) and medium (green) confidence deformation zones at the −500 m level.*

of deposition holes intersecting fractures or deformation zones with radius R > 75 m and the inflow of water to tunnels and deposition holes, see the design premises document /SKB 2004b/.

The thermal properties and the initial temperature of the different rock domains are used to calculate the necessary distance between deposition holes, in order to ensure that the temperature criteria are met. The design rule is provided in the Underground Design Premises document /SKB 2004b/. The rule is based on the analyses performed by /Hökmark and Fälth 2003/. According to the procedure specified, the layout should be based on 40 m separation between the deposition tunnels, whereas canister spacing should be adapted to the site properties. The designed minimum canister spacing is based on a constant value of the thermal conductivity and other thermal properties taken from the SDM. Based on these analyses, the suggested layout at 500 m depth adopts a mean canister separation distance of 7.4 m. However, this distance is based on a maximum temperature of 100°C on the canister surface. This temperature criterion has subsequently been relaxed, as discussed in section 7.3.1. This would most likely imply that a shorter canister separation than 7.4 m would be possible.

The risk of spalling of deposition tunnels and deposition holes during construction, using the stress and intact rock properties is based on the assessment by /Martin 2005/. The analyses suggest a negligible risk of spalling in the deposition tunnels at the –500 m level, but an increased risk at the –600 m level.

Using this information, the modelled thermal properties and the assessment of degree of utilisation, the layout D1 design work for the Laxemar subarea /Janson et al. 2006/ presents potential layouts adapted to the respect distances. Figure 4-54 shows a potential layout at the –500 m level. Due to the negligible risk of spalling in the deposition tunnels, tunnel orientations are selected to make best use of available space without consideration of stress orientation. At this level the degree of utilisation is estimated to lie between 75 and 80%. Layouts at the −600 m level have also been developed, but the degree of utilisation decreases to 50 to 60%, due to expected problems of rock spalling in deposition holes. It should also be remembered that the potential repository layouts presented for the Laxemar subarea are based on the current Site Description. Later versions of the layout will need to incorporate any modifications of the Site Description, including changes of the deformation zone geometry.

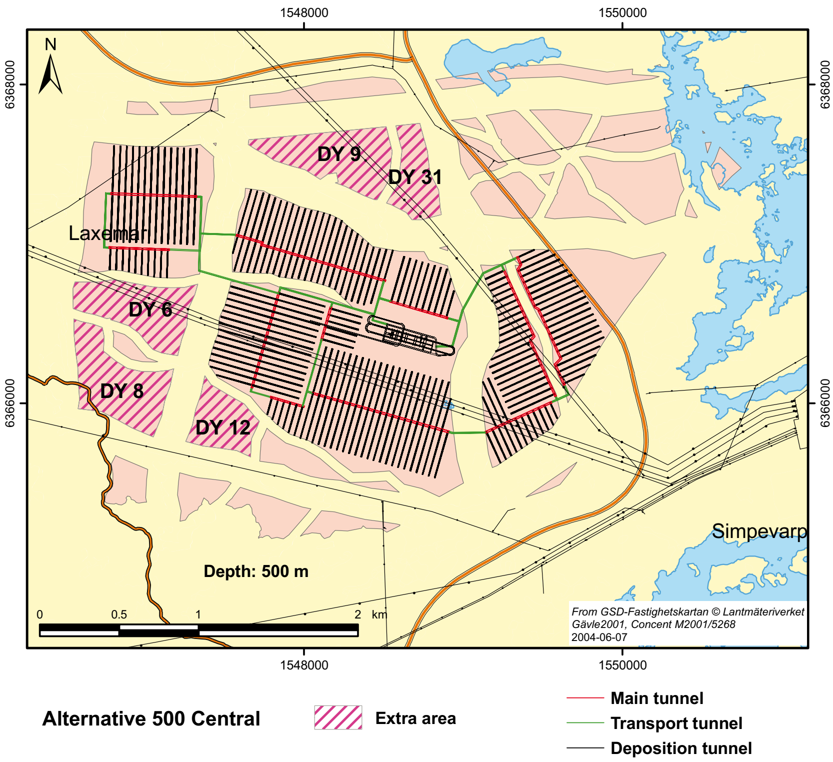


Figure 4-54. *Potential Layout at Laxemar at the –500 m level. Due to the negligible risk of spalling in the deposition tunnels, tunnel orientations are selected to make best use of available space without consideration of stress orientation.*

It should also be noted that the use of the FPC criterion to avoid deposition positions intersected by large fractures (see section 9.4.5), to be implemented in layout D2, suggests that a degree-of-utilisation of slightly less than 90% would be achieved /Munier 2006a/. (In obtaining this figure, a slightly extended version of the FPC, denoted EFPC, was applied, see /Munier 2006b/ for details.) Additional canister positions may be lost due to application of hydraulic criteria, as discussed previously.

The layout D1 design work for the Laxemar subarea /Janson et al. 2006/ also presents a limited sensitivity study varying the length of some deformation zones (affecting whether they have respect distance or not), varying the degree of utilisation for various reasons, varying the dip of the deformation zones in accordance with the uncertainties provided in the site descriptive model /SKB 2006b/ and varying the distances between deposition holes and deposition tunnels (based on different assumptions concerning mean thermal conductivity).

Of these changes, the change in thermal conductivity, potential increase in loss of deposition hole positions and the inclusion of low confidence deformation zones has a large impact on the available space. In contrast, changing the orientation of the high-confidence and intermediate confidence deformation zones affects the geometry of the base layout, but has no or little impact on the available space. Given the size of the Laxemar subarea, it is found that there is sufficient space, with margin, to host a repository within the subarea under all the sensitivity variations studied.

4.5 Monitoring

Repository construction and operation will cause significant disturbances of the site. The safety relevant aspects of these will be handled in the assessment. Monitoring these disturbances will be important for advancing the understanding of the site and the envisaged repository. Monitoring may also be considered after repository closure. The monitoring strategy of SKB is evolving, but /Bäckblom and Almén 2004/ summarise the current SKB strategy on these matters.

Monitoring for the baseline description

Many of the investigated site parameters like precipitation and groundwater levels, will show a pattern of more or less pronounced temporal variation. One reason for such variation is seasonal fluctuations in temperature and precipitation. There may, however, also be other and more unpredictable reasons, such as long-term variations or trends in meteorological parameters, which can cause variation in one or several of the parameters. Furthermore, investigations and underground activities themselves may give rise to changes or variation in values of some parameters.

The site descriptive model produced after completion of the site investigations is also the baseline description of the site. As set out in the overall SKB strategy for monitoring /Bäckblom and Almén 2004/, the general idea with establishing the Baseline conditions during the site investigations from surface is to define a reference against which the changes caused by repository development can be recognised and distinguished from natural and man-made temporal and spatial variations in the repository environment.

The baseline description is essentially identical to the site descriptive model and is based on the data obtained from the site characterisation programme. Part of this characterisation concerns properties that vary in time. Therefore a monitoring programme is needed. Specifically, monitoring results should be seen as inputs to an integrated site description, and not as individual indicators of site properties.

Understanding temporal variation is important when establishing the baseline conditions. However, this does not imply that all aspects of natural time variation need to be characterised. As discussed by /Andersson et al. 2004/ site-specific monitoring can hardly reveal more than "within-year" variation, whereas longer-term variation needs to be assessed through more generic ("regional") knowledge and modelling.

Even if extensive sampling programmes for the collection of time series data are restricted to one or two years, the programmes would not be terminated after this period. Instead, a reduced number of carefully selected sampling points would be included in long-term monitoring programmes. Data collected in these monitoring programmes would, together with the initially collected baseline data, form the reference against which any changes caused by repository construction could be recognised and distinguished from natural and man-made temporal and spatial variations in the repository environment.

Monitoring impact of repository construction

The detailed characterization of site-specific conditions and processes planned to be carried out during the Site Investigation Phase will, for most parameters, ensure the establishment of undisturbed baseline conditions with sufficient accuracy. Before repository construction commences, a monitoring programme covering key parameters potentially affected by investigation and construction activities will be set up. Monitoring aspects of the engineered barriers may also be considered /see Bäckblom and Almén 2004/.

Monitoring after waste emplacement

Repository closure is a stepwise process from consecutively closing a deposition tunnel to closing one or several deposition areas before the whole repository is closed. As stated by /Bäckblom and Almén 2004/ rationales for monitoring of the post-closure phase, such as verification of safeguard requirements, may develop. The extent of the post-closure monitoring programme will essentially be determined by decisions made at, or in lead up to, closure and it is appropriate that any decisions on post-closure monitoring are taken by the generation that is the decision-maker at the time of closure. As the responsibility for the repository is transferred to the State after closure, it is also necessary to clarify the responsibility for execution of the post-closure monitoring. In SR-Can, no consideration is given to monitoring after waste emplacement, and it is also assumed that such monitoring, were it to be performed, would not have any detrimental impacts on the safety functions. Nor is any credit taken for the potential indications of performance arising from such monitoring.

5 Handling of external conditions

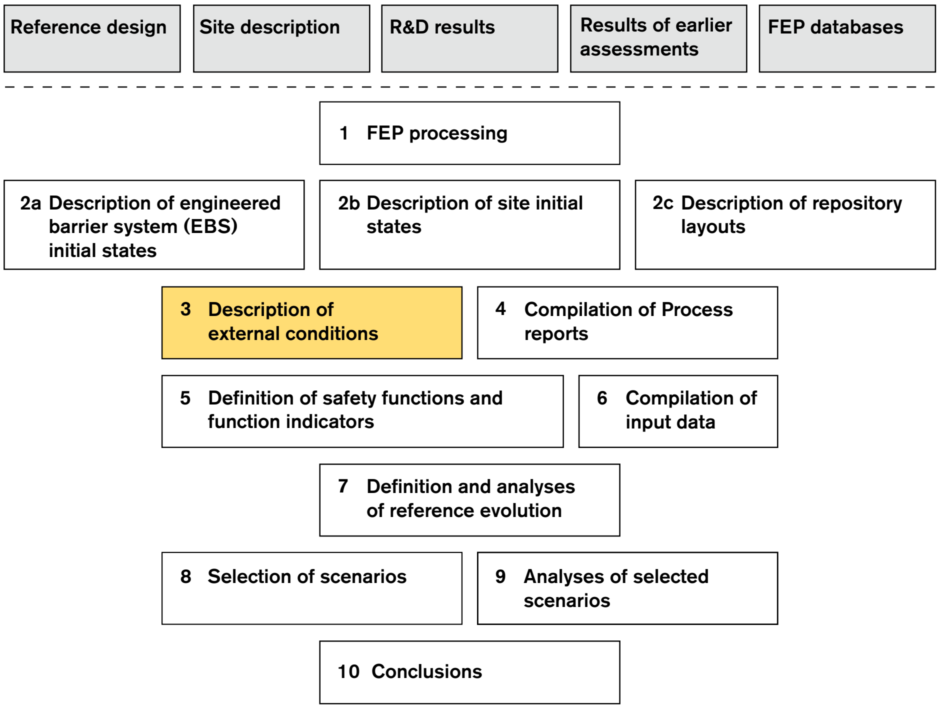


Figure 5-1. *The SR-Can methodology in ten steps (section 2.2), with the present step highlighted.*

5.1 Introduction

The external conditions at the repository site are expected to change considerably over the time scale of the safety assessment. External FEPs are one of the three main categories in the SR-Can FEP catalogue, see chapter 3 and the **FEP report**. The external FEPs are further sorted into the following groups:

1. Climate related issues.
2. Large-scale geological processes and effects.
3. Future human actions.
4. Other (only meteorite impact identified in this group).

The geological processes that can be regarded as external include weathering, erosion and tectonic uplift (other than those induced by glacial loading and unloading, see below) and plate tectonics. In very long time perspectives, millions to hundreds of millions of years, plate tectonic movements, uplift or downwarping, and downwearing of the bedrock surface through weathering and erosion, will affect both the geosphere and the Earth climate system.

The tectonic uplift events that formed the present large-scale Fennoscandian topography mainly occurred in the Tertiary (1.8–65 Ma ago), events that raised the Scandinavian mountain range and the South Swedish Dome centred over the Småland county /e.g. Lidmar-Bergström and Näslund 2002/. Although the uplift centres were located west of Forsmark and Laxemar, the sites were probably to some extent affected by the uplift. Through increased erosion and weathering, the Tertiary uplift events re-exposed an ancient smooth bedrock surface formed in crystalline bedrock prior to the Cambrian period. Although this smooth bedrock surface, called the Sub-Cambrian peneplain, is somewhat dissected along major fracture zones in these two regions, it has been subject to relatively stable large-scale tectonic conditions during the past 1.8 million years e.g. /Lidmar-Bergström and Näslund 2002/. During this period, isostatic changes due to glacial loading and unloading have dominated the vertical displacement of the two sites. /Riis 1996/ suggests that the general rate of bedrock lowering due to erosion and weathering during the Pliocene-Pleistocene (a 5 million year long period ending close to present) has been less than 100 metres per million years for the coastal areas in Sweden where Forsmark and Oskarshamn are situated. This value describes the general lowering of the bedrock surface, and thus excludes higher erosion rates along for example valleys and bedrock fracture zones. In light of the above, the alterations of external conditions caused by processes such as tectonic movements, weathering and erosion are of minor importance for repository safety within the assessment period of one million years. Their impact on the geosphere in the vicinity of the repository and on the current state of the Baltic shield are reported in the **Geosphere process report** and are not further discussed in this chapter.

Climate changes or climate-related changes, such as the ongoing shore-level displacement, are the most important naturally occurring external factors affecting the repository in a time perspective from tens of years to hundred of thousands of years. Most of the safety relevant long-term processes occurring in the biosphere and the geosphere are affected by climate and climate-related changes. A safety assessment must thus address the potential impact of climate changes on repository safety. Climate-related issues are further discussed in section 5.2.

Another main category of external FEPs that may impact the repository is future human actions. These can be divided into actions at or close to the repository site like utilisation of resources from the bedrock and regional or global actions, e.g. those resulting in severe pollution. Future human actions are further discussed in section 5.3.

The third group of external FEPs in the FEP catalogue contains the only FEP "Meteorite impact". Meteorite impacts have been excluded from further analyses, since the probability that a meteorite, large enough to damage the repository, will actually hit can be demonstrated to be extremely low. Furthermore, the direct effects of the event, namely a destruction of the local or regional biosphere including humans, are deemed to be much more severe than its possible radiological consequences.

5.2 Climate-related issues

5.2.1 General climatic evolution

Climate change is caused by factors external to the Earth's climate system and by the complex response of the climate system's components and internal dynamics to those forces. Examples of external natural factors affecting climate in the time perspective of interest for the safety assessment are volcanism, solar variability and changes in insolation due to variations of the Earth's orbital parameters. Another example of an external, but anthropogenic, factor is the burning of fossil fuel, increasing concentrations of greenhouse gases in the atmosphere. Internal dynamics affecting the climate include those associated with atmospheric and ocean circulation, the waxing and waning of ice sheets and feedback processes such as those relating to temperature – water vapour, ice – albedo, vegetation – albedo and vegetation – precipitation.

The Earth climate system is also closely linked to the carbon cycle, i.e. the continued exchange and reactions of carbon in the terrestrial biosphere, atmosphere, hydrosphere, and sediments, the latter including fossil fuels. There are important feed-back mechanisms in the carbon transfer processes between these carbon reservoirs, many of which have an impact on climate. Global warming could for example suppress terrestrial carbon uptake, which would result in higher carbon dioxide levels in the atmosphere /e.g. Cox et al. 2006/. This is a topic within climate research that is developing rapidly. A recent update on this and related issues is found in /Thorne and Kane 2006/.

Past climate

For the past ~2.5 million years, several cycles of growth and decay of ice sheets have occurred. Periods during which ice sheets gradually grow to a maximum extent are known as glacials. Periods with warm climate when the ice sheets wane to an extent similar to that at the present day are called interglacials. A glacial cycle consists of a glacial and an interglacial. Glacial cycles also include colder and warmer stages denominated stadials and interstadials, respectively.

Over the last 700,000 years about 100,000 year long glacial-interglacial cycles have dominated climate variation. These cycles consist of a long period of cooling followed by a fast transition to a warm climate. During the cold period, ice sheets and glaciers have successively – by repeated advances and decays – grown world wide to a maximum extent and during the following transition to a warm climate they have melted away rapidly to residual extents similar to that of the present. At the maximum extent during these cold periods, ice sheets covered about one third of the total land area of Earth (nearly 47 million km^2), compared to at present with ice sheets and glaciers covering about 10% (15 million km^2) of the land surface. Global climate change during the past 700,000 years is shown in Figure 5-2.

Glacials in Sweden

During periods of cold climate, the glaciers in the Scandinavian mountains expand, eventually forming ice caps that will expand into an ice sheet. In front of the ice sheet, permafrost may develop. As the ice sheet grows, the weight of the ice causes an isostatic depression of the Earth's crust. Simultaneously, as ice sheets and glaciers expand globally, a eustatic lowering of global sea level occurs as water is transported from the oceans to the land-based ice sheets and glaciers. The net result of the eustatic component (sea-level fluctuations) and isostatic component (vertical changes of the lithosphere) gives a particular development of vertical shore-level displacement. Depending on the relative rate of the two processes, the shore-level can either rise or fall, which in turn gives a transgression or regression, respectively. During a deglaciation after a period of major ice sheet coverage, large portions of the coastal regions of Sweden experience a dominant isostatic recovery component with a general regression as result, interrupted by shorter periods of transgressions.

The changes in the position of the shore-line due to the eustatic and isostatic processes will alter the hydrological conditions at the candidate sites. The ice load and isostatic process will also alter the rock stresses. When an ice sheet of great thickness overlies the bedrock, an increase of vertical stress is expected along with an increase of horizontal stresses. The change in the non-isotropic stress states introduced by glacial loading and unloading may lead to bedrock instability. Further, the basal conditions of the ice sheet are important for the hydrological boundary conditions as well as for effective stresses. Figure 5-3 shows the course of events as an ice sheet grows and decays along a schematic transect from the Norwegian coast towards the east.

Human-induced climate change

In addition to naturally occurring processes, human emissions of greenhouse gases have been identified as a potentially significant cause of climate alterations. Recent studies utilising both so called Earth Models of Intermediate Complexity and more conventional Global Circulation Models have projected a very long period of warm climate similar to the climate seen in the warm phases of past interglacials /BIOCLIM 2003/. In these model simulations, the emission of greenhouse gases is assessed to result in a long-term perturbation of the pattern of glacial cycles observed in the past. The perturbation is envisaged to remain until the emitted greenhouse gases have been removed from the surface ocean-atmosphere system and sequestered in the lithosphere. Within the BIOCLIM project,

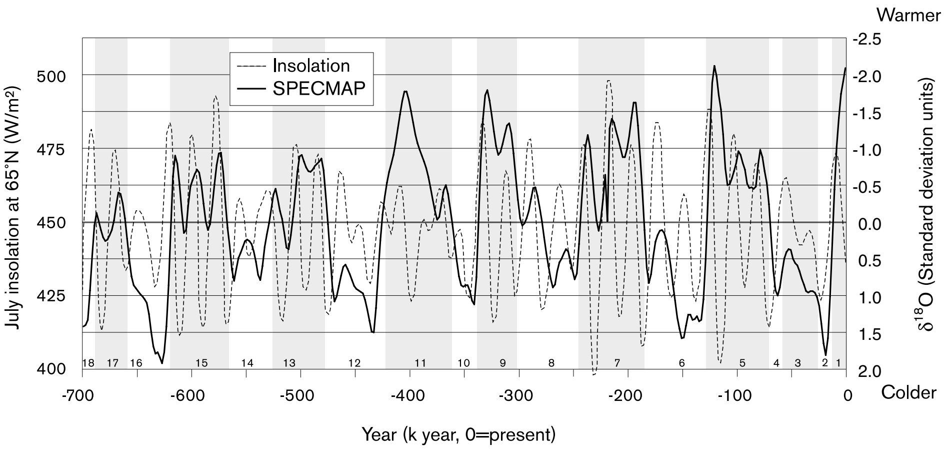


Figure 5-2. *δ^{18}O variation from five drill cores of deep sea sediments expressed as number of standard deviations from the long-term mean /from Imbrie et al. 1984/. δ^{18}O variations reflect the temperature of the sea and, more importantly, the volume of water that has been bound in land-based ice sheets and glaciers all over the world. The grey and white fields and the figures at the bottom edge indicate warm and cold periods denoted by their corresponding marine isotopic stages (MIS) number.*

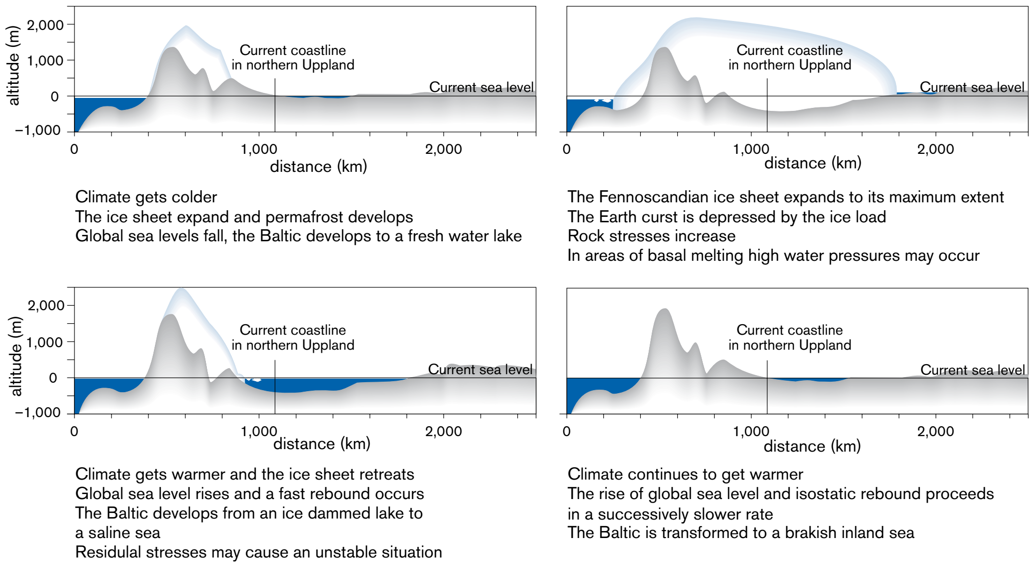


Figure 5-3. *The course of events as an ice sheet expands and decays along a schematic transect from the Norwegian coast towards the east.*

this timescale has been estimated at 200,000 years or more. However, these topics are subject to large uncertainty, for example the knowledge of the carbon cycle is incomplete and both the total emissions and the recirculation to the lithosphere are uncertain.

5.2.2 Impact on repository safety

Climate-related changes such as shore-level migration, development of permafrost and the growth and decay of ice sheets will alter not only surface but also subsurface conditions. Freezing, shore-level displacement and the presence of ice sheets will change permeability, water turnover, groundwater pressures, groundwater flow and composition. The ice load will alter rock stresses and during different phases of a glaciation the principal stresses will change in magnitude and in some cases also in direction. This will alter bedrock permeability and may also cause glacially induced faulting. In general, the integrated effects of continuous climatic evolution need to be considered, but there are also a number of more specific phenomena of importance for repository safety that require special attention. Based on the results of earlier assessments, these include:

- The maximum hydrostatic pressure and rock stress occurring at repository depth for glacial conditions.
- The maximum permafrost depth throughout a glacial cycle.
- The possible penetration of oxygen to deep groundwaters during glacial conditions.
- The possible occurrence of dilute groundwaters during glacial conditions potentially causing erosion of buffer and backfill.
- The groundwater salinity occurring at repository depth.
- Faulting (or more particularly movement on existing faults) associated with glaciations.
- Factors affecting retardation in the geosphere, like high groundwater fluxes and mechanical influences on permeability.

5.2.3 Handling the uncertain long-term climatic evolution

The timing and extent of climate changes are uncertain due to the complexity and non-deterministic aspects of the climate system. Additional uncertainty regarding climate evolution is introduced by the uncertain impact and duration of human influence on the climate due to emissions of greenhouse gases. It is currently not possible to predict the evolution of future climate and any presented climate evolution is associated with large uncertainties. However, the extremes within which the climate of Sweden may vary can be predicted with reasonable confidence. Within these limits characteristic climate conditions can be identified. The conceivable climate conditions can be represented as climate-driven process domains /Boulton et al. 2001/, where such a domain is defined as; a climatically determined environment in which a set of characteristic processes of importance for repository safety appear. The identified domains are:

- The glacial domain.
- The permafrost domain.
- The temperate domain.

The purpose of identifying climate domains is to create a framework for the assessment of climate-related processes of importance for repository safety associated with a particular climatically determined environment. Both the extent of the climate domains and the specific conditions within them will vary in time and space. The duration of each domain depends both on global climate changes and on the location of the site. The succession of climate domains will generally follow a cyclic pattern, see Figure 5-4, even if all domains will not necessarily occur at all sites for all possible evolutions. If it can be shown that a repository for spent nuclear fuel fulfils the safety requirements independent of the prevailing climate domain, and the possible transitions between them, then the uncertainty regarding their extent in time and space is of less importance.

Even if predictions of the future long-term climate are currently not possible to make it is highly likely that the three climate domains will appear repeatedly during the one million year assessment period, i.e. any reasonable evolution will have to cover them. It is furthermore possible to put bounds on the conditions that could reasonably occur during each type of domain. The main scenario of the safety assessment includes a reasonable succession of the identified climate domains and variants based on possible differences in domain duration and conditions.

For compliance purposes, it is particularly important to include sequences covering external conditions yielding, with a high likelihood, the highest risk during the assessment period for a specified scenario of radionuclide release from the repository. Based on results of earlier analyses, the highest risks are likely to occur during temperate periods. Typical situations are i) a terrestrial system that has accumulated radionuclide releases over a long time, possibly in sea sediment prior to its emergence and that is later used for agriculture and ii) a well intruding into the host rock and used for domestic purposes.

It is also important to include the climate domains and sequences having the greatest impact on repository safety through impairment of barrier safety functions. Phenomena that may impact barrier safety functions are mentioned above; the most severe potential effects are related to the development of permafrost and the advance and decay of ice sheets.

The handling of the climate evolution in SR-Can is further developed in chapter 11 in conjunction with scenario selection.

Figure 5-4. *The climate domains succeed each other in a cyclic pattern.*

5.2.4 Documentation

The climate-related conditions and processes identified as relevant for the long-term safety of a KBS-3 repository are identified and described in the **Climate report**, one of the supporting documents for the safety assessment SR-Can, see section 2.2.1. The purpose of the **Climate report** is to provide a concise description of the Earth climate system and to document the scientific knowledge of the climate-related conditions and processes relevant for the long-term safety of a KBS-3 repository to a level required for an adequate treatment in the safety assessment. The report includes three main parts/chapters:

- The climate system.
- Climate-related issues.
- A reference evolution of climate-related conditions for the safety assessment.
- Variants of the reference evolution, of importance for the long-term safety of a KBS-3 repository

"The climate system" part includes an overview of the knowledge of the Earth's climate system and the climate conditions that can be expected to occur in Sweden on a 100,000 year time perspective. Based on this summary, climate-related issues relevant to the long-term safety of a KBS-3 repository are identified. These are documented in part two "climate related issues" to a level required for an adequate treatment in the safety assessment. In part three, "a reference evolution of climate related conditions for the safety assessment" an evolution comprising a 120,000 year period and including a characterisation of identified climate-related issues of importance for repository safety is presented. Finally, relevant variants of the reference evolution are presented, describing for example situations of maximum ice load or permafrost depth. The Climate report also includes the strategy to accommodate long-term climate changes presented above.

As further described in the **FEP report**, the content of the **Climate report** has been audited by comparison with FEP databases compiled in other assessment projects. The **Climate report** follows as far as possible the template for documentation of processes regarded as internal to the repository system, see section 6.3. However, rather than single processes, a number of more comprehensive climate related issues are treated. The issues are i) development of permafrost, ii) ice-sheet dynamics, iii) ice-sheet hydrology, iv) isostatic adjustment and shore-level migration and v) glacially induced faulting. Each climate-related issue includes a set of processes together resulting in the behaviour of a system or feature. For instance "ice-sheet dynamics" is the result of several thermal, hydrological and mechanical processes, but, considering the interaction of an ice sheet with its bed, it can be regarded as one entity.

5.3 Future human actions

A great number of external FEPs related to future human actions (FHA) were identified in the SR-Can FEP database, as a result of an audit against the NEA international database, see further the **FEP report**. These include actions like rock drilling, mining, severe pollution, underground excavations in relation to urbanisation and intentional or inadvertent repository intrusion. The identified FEPs were further briefly audited against the results of the analyses of scenarios based on future human actions carried out in the SR 97 assessment /SKB 1999a/. The majority of the identified FEPs were included in the SR 97 analyses. The latter study was carried out without reference to the NEA database.

In the work for SR-Can, the strategy for managing and analysing future human actions developed for SR 97, which previously had only been reported in Swedish, was translated into English. In parallel to the translation, the text was updated based on experience from SR 97, the FEP audit and a review of some relevant literature published after SR 97. This updated version of the SR 97 work is documented in the **FHA report**.

The further handling of FHA FEPs is presented in conjunction with the scenario analyses in chapter 12, section 12.10.

6 Handling of internal processes

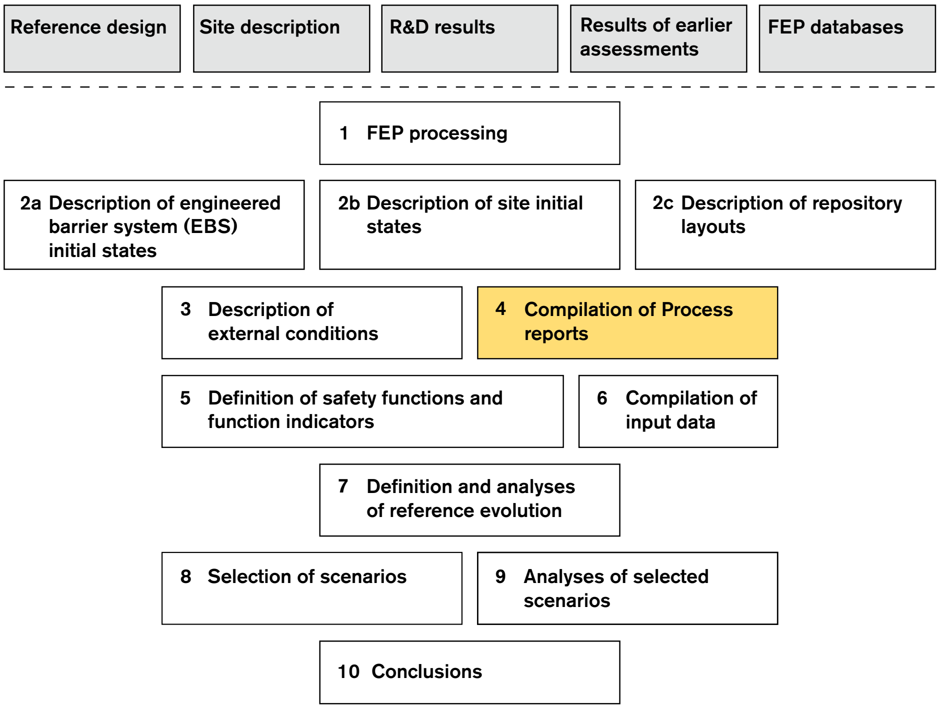


Figure 6-1. *The SR-Can methodology in ten steps (section 2.2), with the present step highlighted.*

6.1 Introduction

A thorough understanding and handling of the processes occurring over time in the repository system is a fundamental basis for the safety assessment. The basic sources of information for this are the results of decades of R&D efforts by SKB and other organisations. In a broader sense, these are based on the knowledge accumulated over centuries of scientific and technological development. The R&D efforts have led to the identification and understanding of a number of processes occurring in the engineered barriers and the natural systems relevant to long-term safety. For the purpose of the safety assessment, the relevant process knowledge for the engineered barriers and the host rock is compiled in a number of process reports which also, for each process, contains a prescription for its handling in the safety assessment. Also short-term geosphere processes/alterations due to repository excavation are included.

This chapter describes how processes are documented in the SR-Can process reports, including the principles for their handling in the safety assessment taking into account relevant uncertainties. Formats for graphically illustrating the system of coupled processes are discussed in section 6.2. The format for process documentation in the SR-Can Process reports is described in section 6.3. section 6.4 gives an overview of the handling of all processes in SR-Can, based on the material in the SR-Can Process reports.

6.1.1 Identification of processes

The identification of relevant processes has been a continuing effort over many years, based on R&D results, findings in earlier safety assessments etc. In SKB's most recent safety assessment, SR 97, an identification of the set of processes to be managed in the safety assessment was made /Pers et al. 1999/ and this set was the starting point for process identification in SR-Can.

As mentioned in chapter 3, in an audit against the contents of the international FEP database, a large number of FEPs were mapped to the set of relevant processes in the SKB database leading also to the identification of a few additional processes relevant to the engineered barriers or the geosphere.

Furthermore, the division of the system into components was revised and refined, see section 4.1.1. The deposition tunnel backfill has been included as a distinct system component, rather than being described together with the buffer as in SR 97. Also, the components “bottom plate in deposition hole”, “plugs”, “borehole seals” and “backfill of other repository cavities” have been added. The new components are, however, in general not crucially linked to safety, and processes reports for these have not been developed in SR-Can.

6.1.2 Biosphere processes

As mentioned in section 3.3, biosphere processes were not included in the SR 97 Process report and there is, therefore, not the same basis for updating these descriptions as for the engineered barriers and the geosphere. All biosphere FEPs have, therefore, been collected in a single category to be further handled in the safety assessment.

In the SAFE project, a biosphere interaction matrix was developed /Kautsky 2001/. The results of that work and its further development have been used for setting up the site investigation program and for the development of models. It has also aided in developing a structure for a biosphere process report. Such a biosphere process report is currently (October 2006) being developed, but is not available as a basis for SR-Can.

6.2 Format for process representations

For the purpose of the safety assessment, the repository system is divided into several system components and each component is characterised by a number of specified time-dependent physical variables, section 4.2.2. Within a specific system component, a number of processes act over time to alter the state of the system, i.e. changing the variables. Examples from the buffer are heat transport, water uptake, swelling, chemical decomposition and ion exchange.

The coupling between the processes is expressed by the network of connected processes and variables and the system of coupled processes need to be managed in the safety assessment. Couplings between system components are handled via the time-dependent boundary conditions at the component interfaces.

Variables, processes and their dependencies may be graphically represented in different ways. In SR 97, the representation was in the form of Process Diagrams, one for each system component. Figure 6-2 shows the SR 97 process diagram for the buffer. The diagram also shows which variables influence each process as well as the influences a particular process has on the set of variables. Also, interactions across the boundaries of the system component are described. Another example of graphical representation is the Interaction Matrix, e.g. /Skagius et al. 1995/. Both these representations condense a vast amount of information graphically. Both interaction matrices and process diagrams have been used to force the analyst to work in a structured way in identifying relevant processes and barrier properties and their dependencies.

The benefits of the structured treatment of processes and variables in the process diagrams are utilised in the process documentation in the SR-Can process reports. For each process, a table is given describing, for each variable in the system component, if it influences or is influenced by the process in question, see further section 6.3. For a given process, the table will thus correspond to the arrows for that process in Figure 6-2. The table format also allows comments to be included and thus gives a fuller description than the arrows in the diagram. In conjunction with the table, the influences are documented.

Both interaction matrices and process diagrams do, however, share a difficulty: It is difficult to grasp even the main features of system evolution by studying these graphical representations. The graphical information in the diagrams or matrices has, therefore, not been utilised directly in the safety assessment, e.g. for illustrating the evolution of the system. Rather than clarifying the important features of system dynamics, the interaction matrices and the process diagrams convey a (true) impression of complexity, but with no guidance as to the relative importance of different traits of system evolution. This is partly related to the lack of distinction between the different time frames of repository evolution. Most processes and influences on barrier properties are only relevant in some of the several time frames that need to be considered in the safety assessment. The SR-Can FEP catalogue can generate process diagrams, and, if required, be developed so that interaction matrices can also be generated, but neither of these representations has a central role in the further analyses in SR-Can.

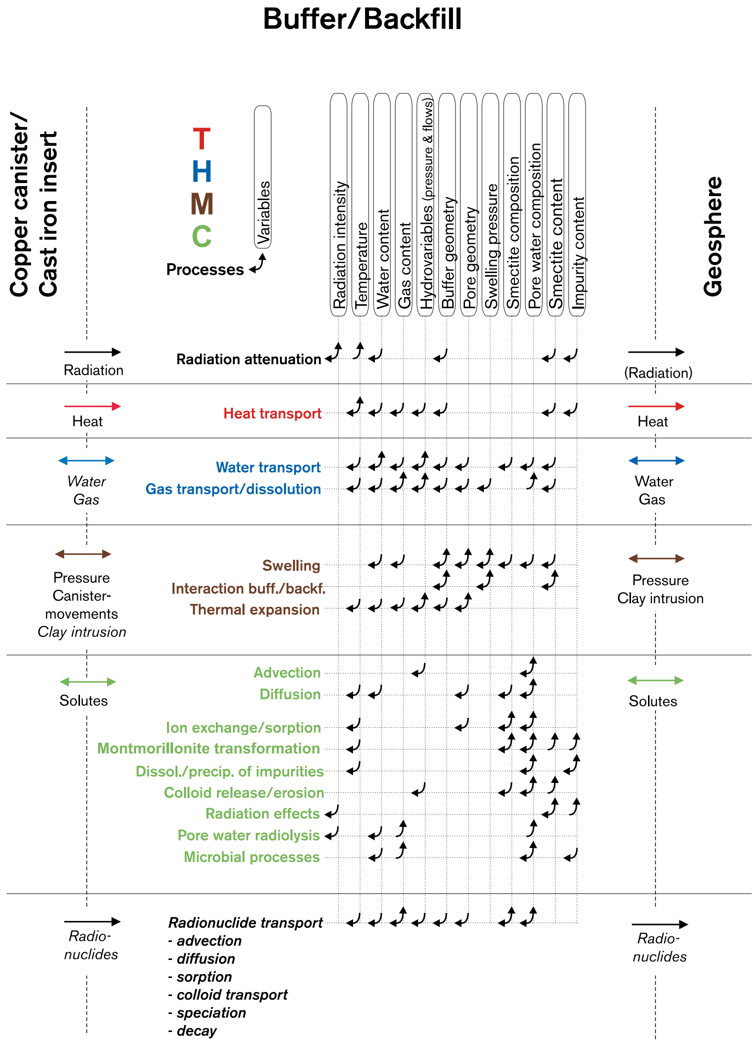


Figure 6-2. *The SR 97 version of the process diagram for the buffer. Thermal, hydraulic, mechanical and chemical processes are listed in the left column, the variables are given in the top row. Influences between variables and processes are shown by arrows in the diagram. Processes and interactions in italics only occur if isolation of the copper canister is broken.*

The graphical representation of processes in SR-Can is in the form of tables, where the handling of the processes in different time frames is explained. This mode of presentation is further developed in section 6.4.

6.3 Format for process documentation

The SR-Can process reports document all processes in the fuel, the canister, the buffer, the backfill and the host rock identified as relevant for long-term safety of a KBS-3 repository as discussed in section 6.1.1.

The purpose of the process reports is to document the scientific knowledge of the processes to a level required for an adequate treatment in the safety assessment SR-Can. The documentation is, therefore, from a scientific point of view not fully comprehensive nor highly detailed, since such a treatment is neither necessary for the purposes of the safety assessment nor possible within the scope of an assessment.

The purpose is further to determine an approach to the handling of each process in the safety assessment and to demonstrate how uncertainties are taken care of given the adopted handling.

All identified processes are documented using the following template, where many of the headings are the same as those used in the SR 97 process report.

Overview/general description

Under this heading, a general description of the knowledge regarding the process is given. For most processes, a basis for this is the contents of the SR 97 process report. All that text has, however, been reviewed and updated as necessary.

Also, an influence table is produced documenting how the process is influenced by the specified set of physical variables in the relevant system component and how the process influences the variables, see Table 6-1 for an example.

Several reasons for neglect of an influence can be distinguished. These include:

- Little intrinsic significance.
- Little significance compared with other influences.
- Can be subsumed into another influence (without necessarily judging which is the more significant).
- Cautious to neglect an influence that may be significant, but cannot readily be quantified.

Boundary conditions

The boundary conditions for each process are discussed. These refer to the boundaries of the relevant system part. For example, for buffer processes the boundaries are the buffer interfaces with the canister, the walls of the deposition hole and the backfill. The processes for which boundary conditions need to be described are, in general, related to transport of material or energy across the boundaries. For example, for chemical processes occurring within a system component, like illitisation in the buffer, the discussion of boundary conditions relates to the boundary conditions of the relevant transport processes occurring in the buffer, i.e. advection and diffusion.

Model studies/experimental studies

Model and experimental studies of the process are summarised. This documentation is the major source of information for many of the processes.

Natural analogues/observations in nature

If relevant, natural analogues and/or observations in nature regarding the process are documented under this heading.

Time perspective

The time scale or time scales on which the process occurs is documented, if such timescales can be defined.

Handling in SR-Can

Under this heading, the handling in the safety assessment SR-Can is described. Typically, the process is:

- neglected on the basis of the information under the previous headings,
- neglected provided that a particular condition is fulfilled, e.g. that the buffer density is within a specific range,
- included by means of modelling.

The following aspects are covered, although no prescribed format for the documentation is given.

Time periods: Over what time periods is the process relevant for the system evolution? In e.g. the case of the buffer, relevant time periods might be:

- the resaturation phase extending from the time of deposition until the time when the buffer is fully water saturated,
- the so called thermal phase extending from the time of deposition and throughout the approximately 1,000 year time period of elevated temperature in the buffer, or
- the long-term time scale extending throughout the one million year assessment period and including the varying conditions in the bedrock caused by long-term climate and other environmental variations.

Table 6-1. Influence table for the process "heat transport" in the geosphere.

Variable	Variable influence on process			Process influence on variable		
	Influence present?	Time period	Handling of influence	Influence present?	Time period	Handling of influence
Temperature in bedrock	Yes. Temperature gradients are the driving force for heat transport. Thermal conductivity and heat capacity are temperature dependent.	Excavation/ operation	Heat transport neglected (see section 2.1.7 in **Geosphere process report**).	Yes.	Excavation/ operation	Heat transport neglected (see section 2.1.7 in **Geosphere process report**.
		Temperate	Site-specific temperature and thermal properties. Thermal properties for constant T.		Temperate	Output from calculations.
		Permafrost Glaciation	See Temperate above and **Climate report**.		Permafrost Glaciation	Output from calculations, see also section 2.2 in **Geosphere process report** and **Climate report**.
Groundwater flow	Yes.	Excavation/ operation	Heat transport neglected (see section 2.1.7 in **Geosphere process report**).	No. But indirectly through temperature.		See section 3.1 Groundwater flow in **Geosphere process report**.
		Temperate Permafrost Glaciation	Influence of convection neglected; little significance.			
Groundwater pressure	Yes.	Excavation/ operation	Heat transport neglected (see section 2.1.7 in **Geosphere process report**).	No. But indirectly through temperature.		See section 3.1 Groundwater flow in **Geosphere process report**.
		Temperate	Influence neglected; little significance.			
		Permafrost Glaciation	See Temperate above and **Climate report**.			
Gas flow	Yes.	Excavation/ operation	Heat transport neglected (see section 2.1.7 in **Geosphere process report**).	No.	–	–
		Temperate	Influence neglected; little significance.			
		Permafrost Glaciation	See Temperate above and **Climate report**.			
Repository geometry	Yes. Affects heat flux from repository. Canister spacing particularly important in the near field.	Excavation/ operation	Heat transport neglected (see section 2.1.7 in **Geosphere process report**).	No.	–	–
		Temperate	Included in model.			
		Permafrost Glaciation	Included in permafrost model (see **Climate report**).			
Fracture geometry	Yes.	Excavation/ operation	Heat transport neglected (see section 2.1.7 in **Geosphere process report**).	No. But indirectly through rock stresses and temperature.		See mechanical processes in chapter 4 in **Geosphere process report**.
		Temperate	Influence neglected; little significance.			
		Permafrost Glaciation	Influence neglected; little significance.			

Variable	Variable influence on process			Process influence on variable		
	Influence present?	Time period	Handling of influence	Influence present?	Time period	Handling of influence
Rock stresses	No.	–	–	No. But indirectly through temperature.		See mechanical processes in chapter 4 in **Geosphere process report**.
Matrix minerals	Yes. Determines thermal properties.	Excavation/ operation	Heat transport neglected (see section 2.1.7 in **Geosphere process report**).	No.	–	–
		Temperate	Use of site-specific thermal properties.			
		Permafrost Glaciation	Use of site-specific thermal properties in permafrost model (see **Climate report**).			
Fracture minerals	Yes. Marginally and locally.	Excavation/ operation	Heat transport neglected (see section 2.1.7 see **Geosphere process report**).	No. But indirectly through temperature and groundwater composition.	–	See chemical processes in chapter 5 in **Geosphere process report**.
		Temperate	Influence neglected; little significance.			
		Permafrost Glaciation	Influence neglected; little significance (**Climate report**).			
Groundwater composition	No.	–	–	No. But indirectly through temperature.	–	See chemical processes in chapter 5 in **Geosphere process report**.
Gas composition	No.	–	–	No.	–	–
Structural and stray materials	No.	–	–	No.	–	–
Saturation	Yes. Affects scope and extent of convective heat transport	Excavation/ operation	Heat transport neglected (see section 2.1.7 in **Geosphere process report**).	No. But, indirectly through temperature.	–	–
		Temperate	Influence neglected; little significance.			
		Permafrost Glaciation	See Temperate above and **Climate report**.			

By documenting the relevance of the process for applicable time periods, the process system can be simplified by omitting the process in time periods during which it is not relevant.

Boundary conditions: How are the boundary conditions handled? Are e.g. spatially and temporally varying chemical and hydraulic conditions considered?

Influences and couplings to other processes: The handling of the documented influences is discussed as are couplings to other processes within the system component.

The special cases of a failed canister and of earthquakes altering deposition hole or tunnel geometry: These special cases imply altered conditions that could influence many processes in particular for the fuel, the canister, the buffer and the backfill and they therefore need to be discussed separately. Canister failures and earthquakes of a magnitude that could affect the deposition hole or tunnel geometry are not expected during the several thousands of years after deposition when temperate conditions are likely to prevail, meaning that the special cases are not relevant for many "early" processes.

As a result of the information under this subheading, a mapping of all processes to method of treatment and, in relevant cases, applicable models is produced, see further section 6.4.

Handling of uncertainties in SR-Can

Given the adopted handling in SR-Can, as described above, the handling of different types of uncertainties associated with the process are summarised.

Uncertainties in mechanistic understanding: The uncertainty in the general understanding of the process is discussed based on the available documentation and with the aim of answering the question: Are the basic scientific mechanisms governing the process included and understood to a level necessary for the adopted handling? Alternative models are sometimes used to illustrate this type of uncertainty.

Model simplification uncertainties: In most cases, the quantitative representation of a process contains simplifications. These may result in a significant source of uncertainty in the description of the system evolution. Alternative models or alternative approaches to simplification for a particular conceptual model are sometimes used to illustrate this type of uncertainty.

Input data uncertainties: The set of input data necessary to quantify the process for the suggested handling is documented. The further treatment of important input data and input data uncertainties is described in the **Data report**, to which reference is made if relevant.

References

A list of references used in the process documentation.

6.3.1 Documentation of participating experts and decisions made

Generally, all arguments including bases for decisions, and underpinning references are provided in the process description under the appropriate headings. In addition, a short record is generated for each process detailing which expert(s) assembled the basic information on the process, which expert(s) were involved in the decision regarding treatment in the safety assessment.

6.4 Process mapping/process tables

To summarise the handling of processes in the safety assessment, a table showing the handling of each process was produced, based on the handling documented in the process reports. The description is broken down in different time frames where relevant. One table per system component is provided. In the table, the process is either "mapped" to a model by which it is quantified or associated with a brief verbal description of how it is to be handled. The SR-Can process tables for the fuel, the canister, the buffer, the deposition tunnel backfill and the geosphere are presented in sections 6.4.1 to 6.4.5.

In section 6.5, two flow charts demonstrate how the different modelling activities are connected.

6.4.1 Fuel and canister interior

Table 6-2. Process table for the fuel and canister interior describing how fuel processes and processes occurring in the canister interior are handled for intact canisters and in the special cases of failed canisters. Green fields denote processes that are neglected or irrelevant for the period of interest. Red fields denote processes that are quantified by modelling in the safety assessment. Orange fields denote processes that are neglected subject to a specified condition. Motives for handling are given in the Fuel and canister process report. An overview of all modelling activities, with references to sections in this main report where the results are discussed, is given in section 6.5. Much of this information is also given in the "notes" column in the table.

	Intact canister	FEP chart item intact can (see section 7.6)	Failed canister	Notes
F1 Radioactive decay	Thermal model	Decay, heat generation	COMP23	In thermal calculation, see section 9.3.4, in nuclide transport calculations section 10.4.1.
F2 Radiation attenuation/heat generation	Thermal model	Decay, heat generation	Neglected as long-term releases occur after period of elevated temperatures	In thermal calculation, see section 9.3.4.
F3 *Induced fission (criticality)*	Neglected since there will be insufficient amounts of moderator inside the canister prior to failure	–	Neglected since the probability is negligibly small if credit is taken for the burn-up of the fuel	See further section 10.3.
F4. Heat transport	Thermal model	Heat conduction	Neglected as long-term releases occur after period of elevated temperatures	In thermal calculation, see section 9.3.4.
F5 *Water and gas transport in canister cavity, boiling/ condensation*	Not relevant	–	Description in Main report, integrated with other relevant processes	Section 10.5.2.
F6 Cladding failure	Not relevant	–	Pessimistic assumption	
F7 Structural evolution of fuel matrix	Not relevant	–	Neglected, since burn-up sufficiently low	
F8 *Advection and diffusion*	Not relevant	–	Description in Main report, integrated with other relevant processes	Refers to diffusion and advecion in the canister interior, see section 10.5.2. See also process F16.
F9 Residual gas radiolysis/acid formation	Neglected since negligible amounts of corrodants are produced	–	Not relevant	See **Fuel and canister process report**, section 2.5.2.

	Intact canister	FEP chart item intact can (see section 7.6)	Failed canister	Notes
F10 *Water radiolysis*	Neglected	–	Neglected except for fuel dissolution, see that process	Initial water consumed by nitric acid formation or cast iron corrosion.
F11 *Metal corrosion*	Not relevant	–	Pessimistic handling: a) No barrier function, all radionuclides instantaneously released upon water contact in COMP23. b) 1,000 years for complete corrosion if advective conditions in buffer	a) See section 10.4.1. b) See section 10.6.3, subheading "The pulse contribution".
F12 *Fuel dissolution*	Not relevant	–	Modelled as constant, pessimistic dissolution rate in COMP23	Sections 10.5.3 and 10.6.4.
F13 *Dissolution of gap inventory*	Not relevant	–	Pessimistic, instantaneous	See sections 10.4.1 and 10.6.3, subheading "The pulse contribution".
F14 *Speciation of radionuclides, colloid formation*	Not relevant	–	COMP23	Precipitation/dissolution handled by COMP23, concentration limits provided in **Data report**. Handling summarised in section 10.5.3, subsection "Concentration limits".
F15 Helium production	Neglected since the amount of helium produced will not increase the pressure inside the canister enough to affect its mechanical stability	–	Not relevant	See **Fuel and canister process report**, section 2.5.8.
F16 *Radionuclide transport*			COMP23	Canister interior treated as mixed tank in all transport calculations reported in chapter 10.

6.4.2 Canister

Table 6-3. Process table for the canister describing how canister processes are handled for intact canisters and in the special case of failed canisters. Green fields denote processes that are neglected or irrelevant for the period of interest. Red fields denote processes that are quantified by modelling in the safety assessment. Orange fields denote processes that are neglected subject to a specified condition. Motives for handling are given in the Fuel and canister process report. An overview of all modelling activities, with references to sections in this main report where the results are discussed, is given in section 6.5. Much of this information is also given in the "notes" column in the table.

	Intact canister	**FEP chart item intact can (see section 7.6)**	**Failed canister**	**Notes**
C1 Radiation attenuation/heat generation	Included in integrated modelling of thermal evolution; thermal model.	Decay, heat generation	Neglected as long-term releases occur after period of elevated temperatures.	See section 9.3.4.
C2 Heat transport	Included in integrated modelling of thermal evolution; thermal model.	Heat conduction	Neglected as long-term releases occur after period of elevated temperatures.	See section 9.3.4.
C3 Deformation of cast iron insert	Isostatic: Comparison of external pressure with probabilistically calculated isostatic collapse load. Uneven swelling: Neglect based on pessimistically simplified calculations and model calculations. Tectonic events: Criterion for canister failure provided in process report. Creep for all above cases: Not included. Creep testing of the insert is currently in progress.	Isostatic load Stress induced by rapid rock shear Creep insert	Not relevant	See sections 9.3.12 (temperate period), 9.4.5 (large earthquakes) and 9.4.9 (isostatic pressure for glacial load).
C4 Deformation of copper canister from external pressure	Initial deformation due to buffer swelling pressure until gap closed. Otherwise, deformation according to that of cast iron insert considering also creep.	Creep copper	Not relevant	See in particular section 9.4.5 (large earthquakes).
C5 Thermal expansion (both cast iron insert and copper canister)	Neglected since the thermal expansion will cause negligible strains in the materials.	–	Not relevant	
C6 *Copper deformation from internal corrosion products*	Not relevant	–	Description in Main report, integrated with other relevant processes.	Section 10.5.2.
C7 *Corrosion of cast iron insert*	Not relevant	–	Description in Main report, integrated with other relevant processes.	Section 10.5.2.
C8 *Galvanic corrosion*	Not relevant	–	Description in Main report, integrated with other relevant processes.	Section 10.5.2.

	Intact canister	FEP chart item intact can (see section 7.6)	Failed canister	Notes
C9 Stress corrosion cracking of cast iron insert	Neglected since stress corrosion cracking is considered unlikely and even if it occurred it would have no consequences for stability of the insert.	–	Not relevant	
C10 Radiation effects	Neglected since its effects on the mechanical properties if the insert would be negligibly low.	–	Not relevant	
C11 Corrosion of copper canister	Sulphide in buffer and backfill modelled. Microbially generated sulphide in buffer neglected if swelling pressure sufficiently high, otherwise pessimistically modelled (strictly a buffer process). Initial oxygen in buffer (strictly a buffer process): Pessimistically assumed that all oxygen corrodes copper, neglecting oxygen consumption by buffer pyrite and rock. Initial oxygen in tunnel backfill (strictly a backfill process): Consider consumption by rock and microbes. Potentially intruding oxygen: Integrated handling of rock, backfill and buffer conditions. Pitting (oxygen corrosion): Described as uneven general corrosion. Nitric acid corrosion: Neglected since only negligible quantities will be produced. Chloride corrosion: Neglected since it requires very low pH to proceed under reducing conditions.	Corrosion	Not relevant	See sections 9.3.12 and 9.4.9.
C12 Stress corrosion cracking, copper canister	Neglected due to the combined effect of very low (if any) concentrations of SCC promoting agents and the insufficient availability of oxidants.	–	Not relevant	
C13 Earth currents – Stray current corrosion	Neglected due to e.g. the high polarisation resistance of copper under reducing conditions.	–	Not relevant	
C14 Deposition of salts on canister surface	Process exists, but consequences negligible.	–	Not relevant	
C15 Radionuclide transport	Not relevant	–	COMP23	See chapter 10.

6.4.3 Buffer

Table 6-4. Process table for the buffer describing how buffer processes are handled in different time frames and for the special case of an earthquake. Green fields denote processes that are neglected or not relevant for the period of interest. Red fields denote processes that are quantified by modelling in the safety assessment. Orange fields denote processes that are neglected subject to a specified condition. Motives for handling are given in the Buffer and backfill process report. An overview of all modelling activities, with references to sections in this main report where the results are discussed, is given in section 6.5. Much of this information is also given in the "notes" column in the table.

	Resaturation/"thermal" period	Long-term after saturation and "thermal" period	Earthquakes	FEP chart item (see section 7.6)	Notes
Intact canister					
Bu1 Radiation attenuation/ heat generation	Neglected since dose rate is too low to be of importance for the buffer.	Neglected since dose rate is too low to be of importance for the buffer.	Not relevant.	–	
Bu2 Heat transport	Thermal model.	Thermal model.	Not relevant.	Heat conduction.	See section 9.3.4.
Bu3 Freezing	Neglected, since this requires permafrost conditions.	Neglected if buffer temperature > −5°C. Otherwise bounding consequence calculation.	Not relevant.	Freezing, expansion.	Repository temperature in long term obtained from permafrost depth modelling, see section 9.4.3.
Bu4 Water uptake and transport for unsaturated conditions	THM model.	Not relevant by definition.	Not relevant.	Saturation.	See section 9.3.8.
Bu5 Water transport for saturated conditions	Neglected under unsaturated conditions. For saturated conditions the treatment is the same as for "Long-term".	Neglected if hydraulic conductivity < 10^{-12} m/s since diffusion would then dominate.	See process Bu9.	Advection.	Regarding consequences of buffer colloid release, see section 9.4.9, subheading "Canister corrosion for a partially eroded buffer".
Bu6 Gas transport/dissolution	Through dissolution.	(Through dissolution) No gas phase is assumed to be present.	(Through dissolution) No gas phase is assumed to be present.	–	
Bu7 Piping/erosion	Scoping calculation.	Not relevant, see also Bu17.	Not relevant.	Piping/erosion	See section 9.2.4.
Bu8 Swelling/Mass redistribution	Analytical modelling of interaction buffer/backfill.	Integrated evaluation of relevant processes.	Part of integrated assessment of buffer/ canister/rock.	Swelling	Initial saturation/swelling: See section 9.3.9. Long-term temperate conditions: 9.3.11. Effects on swelling pressure from salinity are discussed in sections 9.3.9, 9.4.8 and 12.3.2. The effect of ion-exchange on swelling pressure is discussed in section 12.3.2 Earthquakes: See section 9.4.5, sub-heading "Canister failures due to postulated shear movements".

	Resaturation/“thermal” period	Long-term after saturation and “thermal” period	Earthquakes	FEP chart item (see section 7.6)	Notes
					Consequences of buffer colloid release (erosion) discussed in section 9.4.9, subheading “Canister corrosion for a partially eroded buffer” and covered by stylised case reported in section 9.3.9. Canister sinking is discussed in section 9.4.8 and 12.3.4.
Bu9 Liquefaction	Not relevant.	Neglected .	Neglected since lique-faction from a short pulse cannot occur in a high density bentonite, due to high effective stresses.	Liquefaction.	See section 9.4.8, subheading “Liquefaction”.
Bu10 Advection	Simplified assumptions of mass transport of dissolved species during saturation.	Neglected if hydraulic conductivity < 10^{-12} m/s.	See process Bu9.	Advection.	See process Bu5.
Bu11 Diffusion	PHAST (thermal, saturated phase; unsaturated phase disregarded).	PHAST		Diffusion	Thermal phase: section 9.3.10 Long-term temperate: section 9.3.11 Glacial cycle: section 9.4.8, subheading “Chemical evolution of buffer and backfill for altered groundwater compositions”.
Bu12 Sorption (including ion-exchange)	PHAST (thermal, saturated phase; unsaturated phase disregarded).	PHAST		Reactions in pore water and clay, sorption.	See process Bu11.
Bu13 Alterations of impurities	PHAST (thermal, saturated phase; unsaturated phase disregarded).	PHAST		Reactions in pore water and clay, sorption.	See process Bu11.
Bu14 Pore water speciation	PHAST (thermal, saturated phase; unsaturated phase disregarded).	PHAST		Reactions in pore water and clay, sorption.	See process Bu11.
Bu15 Osmosis	Pessimistically bounded in analytic modelling of buffer/backfill interaction.	Evaluation through comparison with empirical data.		Osmosis	Initial saturation/swelling: See section 9.3.9. Long-term temperate: section 9.3.11. Glacial cycle: section 9.4.8, subheading “Effects of saline water on buffer and backfill”.
Bu16 Montmorillonite transformation	Model calculations (thermal, saturated phase; unsaturated phase disregarded).	Model calculations.		Reactions in pore water and clay, sorption.	Thermal phase: See section 9.3.10, subheading “Mineral transformation”, covers also long-term temperate pase.

	Resaturation/"thermal" period	Long-term after saturation and "thermal" period	Earthquakes	FEP chart item (see section 7.6)	Notes
Bu17 Colloid release	Neglected if $[M^{2+}] > 1$ mM. Otherwise modelled.	Neglected if $[M^{2+}] > 1$ mM. Otherwise modelled.		Colloid release.	Long-term temperate: section 9.3.11 Glacial cycle: section 9.4.8, subheading "Colloid release from buffer and backfill".
Bu18 Radiation-induced transformations	Neglected since dose rate outside canister is too low to have any effect.	Neglected since dose rate outside canister is too low to have any effect.		–	
Bu19 Radiolysis of pore water	Neglected since dose rate outside canister is too low to have any effect.	Neglected since dose rate outside canister is too low to have any effect.		–	
Bu20 Microbial processes	Neglected under unsaturated conditions, since the extent of aqueous reactions is limited. For saturated conditions the treatment is the same as for "Long-term".	Neglected if swelling pressure > 2 MPa, otherwise quantitative estimate of sulphate reduction.		Microbial sulphate reduction.	Sulphate reduction included in corrosion calculation, section 9.4.9.
Failed canister					
Bu6 Failed canister. Gas transport/dissolution	Quantitative estimate based on empirical data *(no failures are expected this period).*	Quantitative estimate based on empirical data.		–	See section 10.5.2, subheading "Gas transport through the buffer".
Bu18 Failed canister. Radiation-induced transformations	Neglected since dose rate outside canister is too low to have any effect.	The effect of α-radiation from nuclides from a failed canister is estimated.		–	The effect of α-radiation from nuclides is estimated in the **Buffer and backfill process report**, section 2.5.11. There, it is concluded that the consequences can be neglected.
Bu21 Colloid transport	Neglected if density at saturation > 1,650 kg/m^3, otherwise bounding calculation *(no failures are expected this period).*	Neglected if density at saturation > 1,650 kg/m^3, otherwise bounding calculation.		–	See section 10.6.4, subheading "Fuel dissolution rate".
Bu22 Speciation of radionuclides	Assumptions based on empirical data *(no failures are expected this period).*	Assumptions based on empirical data.		–	Resulting concentration limits presented in section 10.5.3, subheading "Concentration limits".
Bu23 Transport of radionuclides in water phase	COMP23 Analytic *(no failures are expected this period).*	COMP23 Analytic	COMP23 Analytic Reduced diffusion path.	–	See chapter 10 Earthquake: See section 10.7.
Bu24 Transport of radionuclides in gas phase	Quantitative estimate *(no failures are expected this period).*	Quantitative estimate.		–	See section 10.9.

6.4.4 Backfill in deposition tunnels

Table 6-5. Process table for the backfill describing how backfill processes are handled in different time frames. Green fields denote processes that are neglected or not relevant for the period of interest. Red fields denote processes that are quantified by modelling in the safety assessment. Orange fields denote processes that are neglected subject to a specified condition. Motives for handling are given in the Buffer and backfill process report. An overview of all modelling activities, with references to sections in this main report where the results are discussed, is given in section 6.5.

	Resaturation/"thermal" period	Long-term after saturation and "thermal" period	FEP chart item (see section 7.6)	Notes
Intact canister				
BfT1 Heat transport	Simplified assumption.	Simplified assumption.	–	
BfT2 Freezing	Neglected, since this requires permafrost conditions.	Neglected if backfill temperature > 0°C. Otherwise bounding consequence calculation. Note that only deposition tunnels are considered in SR-Can.	Not included since freezing in backfill relates to retardation.	Less severe consequences than for buffer.
BfT3 Water uptake and transport for unsaturated conditions	THM model.	Not relevant by definition.	Saturation	The pellets are included in the model.
BfT4 Water transport for saturated conditions	Neglected under unsaturated conditions. For saturated conditions the treatment is the same as for "Long-term".	Included in geosphere modelling.	Advection	Evaluate effects on conductivity of chemical evolution and mass redistribution/loss and of possible changes of hydraulic gradients for permafrost and glaciation.
BfT5 Gas transport/dissolution	THM model.	(Through dissolution).		The presence of a trapped gas phase is considered in the modelling of the saturation of the backfill (not the case for the buffer).
BfT6 Piping/erosion	Model study.	Not relevant, see also BfT16.	Piping/erosion	See also water transport for saturated conditions.
BfT7 Swelling/Mass redistribution	Analytic modelling of interaction buffer/backfill.	Integrated evaluation of relevant processes.	Swelling (buffer)	Deviations in amount of buffer and backfill initially deposited and buffer saturating before tunnel backfill is discussed in section 9.3.9. The effect of salinity is discussed in section 9.3.9 and 9.4.8. The effect of erosion is discussed in section 9.4.8.
BfT8 Liquefaction	Not relevant.	Not relevant.	–	Less severe consequences than for buffer. Discussed in section 9.4.8
BfT9 Advection	Simplified assumptions of mass transport of dissolved species during saturation.	Included in geosphere modelling.	Advection	See "Water transport for saturated conditions".

	Resaturation/“thermal” period	Long-term after saturation and “thermal” period	FEP chart item (see section 7.6)	Notes
BfT10 Diffusion	The early stage is not studied specifically, since the conditions in the backfill will be about the same as for the long-term evolution.	PHAST	Diffusion	Thermal phase: section 9.3.10. Long-term temperate: section 9.3.11. Glacial cycle: section 9.4.8, subheading “Chemical evolution of buffer and backfill for altered groundwater compositions”
BfT11 Sorption (including ion-exchange)	The early stage is not studied specifically, since the conditions in the backfill will be about the same as for the long-term evolution.	PHAST	Reactions in PW and clay, sorption.	See process BfT10.
BfT12 Alterations of impurities	The effect on inorganic reduction of oxygen is modelled.	PHAST	Reactions in PW and clay, sorption.	See process BfT10.
BfT13 Pore water speciation	The early stage is not studied specifically, since the conditions in the backfill will be about the same as for the long-term evolution.	PHAST	Reactions in PW and clay, sorption.	See process BfT10.
BfT14 Osmosis	Hydraulic conductivity in THM model chosen so as to handle osmosis .	Evaluation through comparison with empirical data.	Osmosis	Handling of long-term intrusion of saline water.
BfT15 Montmorillonite transformation	Neglected since temperature only mildly elevated.	Neglected since temperature only mildly elevated.	Reactions in PW and clay, sorption.	
BfT16 Colloid release	Neglected if $[M^{2+}] > 1$ mM. Otherwise modelled.	Neglected if $[M^{2+}] > 1$ mM. Otherwise modelled.	Colloid release	Loss of backfill is discussed in section 9.4.8.
BfT17 Radiation-induced transformations	Neglected, since dose rate in backfill is too low to have any effect.	Neglected, since dose rate in backfill is too low to have any effect.	–	
BfT18 Microbial processes	Excluded, (the effect on oxygen consumption is not considered).	Excluded at this stage.		
Failed canister				
BfT5 *Failed can. Gas transport/ dissolution*	*Neglected, since gas volumes (from buffer) assumed to be too low to reach backfill during this period.*	*Neglected, pessimistically since transport would delay radioactive releases and decrease buffer pressure. The backfill would act as a sink for gas.*	–	*Gas release from canister.*
BfT19 *Colloid formation and transport*	*See geosphere (no failures are expected this period).*	*See geosphere.*	–	*Called “colloid transport” for buffer. Reference to corresponding geosphere process.*
BfT20 *Speciation of radionuclides*	*Assumptions based on empirical data (no failures are expected this period).*	*Assumptions based on empirical data.*	–	See chapter 10.
BfT21 *Transport of radionuclides in water phase*	*COMP23* *Analytic (no failures are expected this period).*	*COMP23* *Analytic.*	–	See chapter 10.
BfT22 *Transport of radionuclides in gas phase*	*By-passed (no failures are expected this period).*	*By-passed.*	–	See chapter 10.9.

6.4.5 Geosphere

Table 6-6. Process table for the geosphere describing how processes are handled in different time frames/climate domains and in the special case of earthquakes. Green fields denote processes that are neglected or irrelevant. Red fields denote processes that are quantified by modelling in the safety assessment. Orange fields denote processes that are neglected subject to a specified condition. Non-coloured fields denote processes for which basis for definite handling in SR-Can has not been developed. Motives for handling are given in the Geosphere process report. An overview of all modelling activities, with references to sections in this main report where the results are discussed, is given in section 6.5. Much of this information is also given in the "notes" column in the table.

Process	Excavation/operation	Temperate	Permafrost	Glaciation	Earthquakes	FEP chart item (see section 7.6)	Notes
Ge1 Heat transport	Neglected since sensitivity studies show that time evolution of heating is not sensitive to detailed pattern of deposition.	Modelling of peak canister temperature and temperature distribution in rock.	Site-specific 1-D estimations of permafrost depth.	Site-specific 1-D estimations of sub-glacial permafrost depth.	Not relevant.	Row "Temperature"	Temperate: section 9.3.4 Permafrost & glacial: section 9.4.3
Ge2 Freezing	Not relevant.	Not relevant.	Site-specific 1-D estimations of permafrost depth.	Site-specific 1-D estimations of sub-glacial permafrost depth.	Not relevant.	Row "Temperature"	Section 9.4.3
Ge3 Groundwater flow	Modelling of inflow and upconing assuming saturated flow (Darcy Tools). MIKE-SHE for simulating near-surface effects.	Modelling of resaturation (DarcyTools) and saturated flow at different scales (CONNECT-FLOW).	Modelling of flow pattern with Darcy Tools.	Modelling of groundwater flow pattern during advance and retreat of an ice sheet.	Not handled in SR-Can.	Row "GW flow"	Excavation/ operation: section 9.2.3. Temperate: section 9.3.6 Permafrost & glacial: section 9.4.6
Ge4 Gas flow/ dissolution	Neglected based on arguments supporting the assumption of small effects of unsaturated regions on inflows to tunnels.	Neglected provided that gas generated in the repository can rapidly escape through the geosphere without causing pressure build-up.	Not handled in SR-Can.	Not handled in SR-Can.	Not relevant.	(Row "GW flow")	Section 10.5.2, subheading "Gas transport through the buffer".
Ge5 Displacements in intact rock	3DEC stress modelling of near-field effects of excavation of tunnels and deposition holes.	3DEC modelling of thermal stresses and deformations.	Thermal effects neglected provided that only marginal changes in mechanical state occur.	3DEC stress modelling of near field.	Included in the modelling of shear movements.	Row "Rock stresses"	Excavation/ operation: section 9.2.2. Temperate: section 9.4.6 Permafrost & glacial: section 9.4.4

Process	Excavation/operation	Temperate	Permafrost	Glaciation	Earthquakes	FEP chart item (see section 7.6)	Notes
Ge6 Reactivation – displacement along existing discontinuities	3DEC modelling of construction-induced reactivation.	3DEC modelling of reactivation due to thermal load. Estimation of earthquake probability (consequence analysis, see Earthquake).	Thermal effects neglected provided that only marginal changes in mechanical state occur.	3DEC modelling of ice-load induced reactivation. Assessment of MH effects of hydraulic jacking. Estimation of earthquake probability (consequence analysis, see Earthquake).	Apply design rules (respect distances and canister spacing). Assessment of residual probability for canister failure due to shear displacement.	Row "Fracture structure"	See process Ge6. Integrated handling of effects of earthquakes in section 9.4.5
	Construction-induced seismicity neglected since construction induced stresses too limited and expected to be relaxed at the time of deposition.		Estimation of earthquake probability (consequence analysis, see Earthquake).			Row "Fracture structure"	
Ge7 Fracturing	Assessment of EDZ. Modelling (3DEC) and observations (APSE) of fracturing around deposition holes (spalling).	Modelling (3DEC) of potential for fracturing induced by thermal stresses. Estimations of effects of gas overpressure.	Thermal effects neglected provided that only marginal changes in mechanical state occur.	Modelling (3DEC) of potential for fracturing induced by ice load. Assessment of risk for hydraulic fracturing.	Neglected based on observations of eartquake-induced damage around open tunnels at shallow depth.	Row "Fracture structure".	See process Ge6.
Ge8 Creep	Not relevant. Covered by construction-induced reactivation.	Neglected because of insignificant convergence of deposition holes at expected rock stresses.	Neglected because of insignificant convergence of deposition holes at expected rock stresses.	Neglected because of insignificant convergence of deposition holes at expected rock stresses.	Not relevant.	–	–
Ge9 Surface weathering and erosion	Not relevant.	Neglected because of low erosion rates.	Neglected because of low erosion rates.	Neglected because of low erosion rates.	Not relevant.	–	–
Ge10 Erosion/ sedimentation in fractures	Neglected because of too low flow rates in non-grouted fractures.	Neglected based on site observations indicating limited significance at repository depth.	Neglected based on site observations indicating limited significance at repository depth.	Neglected based on site observations indicating limited significance at repository depth.	Not relevant.	–	–

Process	Excavation/operation	Temperate	Permafrost	Glaciation	Earthquakes	FEP chart item (see section 7.6)	Notes
Ge11 Advection/mixing	Advection of salt included in hydro-geological modelling. Composition of mixtures assessed from hydrogeological modelling and site understanding.	Advection of salt included in hydro-geological modelling. Composition of mixtures assessed from hydrogeological modelling and site understanding.	Modelling of transport of out-frozen salt.	Modelling of up-coning of saline water and transport of glacial meltwater to repository depth.	Not relevant.	Rows "GW flow and GW salinity".	Excavation/ operation: section 9.2.5. Temperate: section 9.3.7. Permafrost & glacial: section 9.4.7.
Ge12 Diffusion and matrix diffusion	Diffusion of salt between mobile and immobile groundwater included in hydrogeological modelling.	Diffusion of salt between mobile and immobile groundwater included in hydrogeological modelling.	Diffusion of salt between mobile and immobile ground-water included in modelling of transport of out-frozen salt.	Diffusion of salt included in modelling of groundwater flow pattern during advance and retreat of an ice sheet. Included in modelling of oxygen consumption.	Not relevant.	(Row "GW composition".)	See process Ge11.
Ge13 Speciation and sorption	Not relevant.	Simplified K_d-approach for modelling sorption of radio-nuclides. Speciation considered in the selection of K_d.	Simplified K_d-approach for modelling sorption of radio-nuclides. Speciation considered in the selection of K_d.	Simplified K_d-approach for modelling sorption of radio-nuclides. Speciation considered in the selection of K_d.	Not relevant.	Row "GW composition".	See the Data report.
Ge14 Reactions groundwater/rock matrix	Neglected since reactions are considered to take place at fracture surfaces only.	Neglected because of expected insignificant impact on ground-water composition and matrix porosity.	Neglected because of expected insignificant impact on groundwater composition and matrix porosity.	Included in modelling of oxygen consumption	Not relevant.	Row "GW composition".	Glacial: Section 9.4.7, subheading "Glaciation; redox condition"
Ge15 Dissolution/ precipitation of fracture-filling minerals	Modelling of mixing (M3) and of reactions (PHREEQC).	Modelling of mixing (M3) and of reactions (PHREEQC).	Not handled, but effects are judged to be less important than effects of e.g. salt exclusion.	Included in modelling of oxygen consumption. Assessment of impact on flow paths of calcite dissolution/ precipitation.	Not relevant.	Row "GW composition".	See process Ge11.
Ge16 Microbial processes	Mass balance calculations of organic matter and modelling of microbial processes coupled with solute transport and hydro-chemical equlibria calculations.	Mass balance calculations of organic matter and modelling of microbial processes coupled with solute transport and hydro-chemical equlibria calculations.	Not handled, but effects are judged to be less important than effects of e.g. salt exclusion.	Not handled.	Not relevant.	Row "GW composition".	Excavation/ operation: section 9.2.5. Temperate: section 9.3.7.
Ge17 Degradation of grout	Neglected since expected effects will occur during Temperate period.	Modelling of effects on chemis-try of fractures.	Not specifically handled. Extrapolation of results from Temperate period	Not specifically handled. Extrapolation of results from Temperate period.	Not relevant.	Row "GW composition".	Temperate: section 9.3.7

Process	Excavation/operation	Temperate	Permafrost	Glaciation	Earthquakes	FEP chart item (see section 7.6)	Notes
Ge18 Colloid formation and transport	Neglected because of insignificant impact on geochemical conditions.	Neglected because of insignificant impact on geochemical conditions.	Neglected because of insignificant impact on geochemical conditions.	Neglected because of insignificant impact on geochemical conditions.	Not handled in SR-Can.	–	See Geosphere process report.
	Impact on radionuclide transport not relevant because of intact barriers.	Not handled in SR-Can in terms of radionuclide transport.	Not handled in terms of radionuclide transport.	Not handled in SR-Can in terms of radionuclide transport.		–	–
Ge19 Formation/ dissolution/ reaction of gaseous species	Natural gases neglected since concentrations are expected to remain essentially unchanged.	Natural gases neglected since concentrations are expected to remain essentially unchanged.	Natural gases neglected since concentrations are expected to remain essentially unchanged.	Included in modelling of oxygen consumption.	Not relevant.		Glacial: Section 9.4.7, subheading "Glaciation; redox condition"
Ge20 Methane hydrate formation	Not relevant.	Not relevant.	Not handled in SR-Can.	Not handled in SR-Can.	Not relevant.	Row "GW composition"	–
Ge21 Salt exclusion	Not relevant.	Not relevant.	Modelling of transport of outfrozen salt.	Not relevant.	Not relevant.	Row "GW salinity"	Permafrost: Section 9.4.7, subheading "Salt rejection"
Ge22 Radiation effects (rock and grout)	Neglected because of too low radiation fluxes.	Neglected because of too low radiation fluxes.	Neglected because of too low radiation fluxes.	Neglected because of too low radiation fluxes.	Not relevant.	–	See Geosphere process report.
Ge23 Earth currents	Neglected since expected electrical potential fields are too small to affect groundwater flow or solute transport.	Neglected since expected electrical potential fields are too small to affect groundwater flow or solute transport.	Neglected since expected electrical potential fields are too small to affect groundwater flow or solute transport.	Neglected since expected electrical potential fields are too small to affect groundwater flow or solute transport.	Not relevant.	–	See Geosphere process report.
Ge24 Transport of radionuclides in the water phase	Not relevant since engineered barriers are intact.	Advection, dispersion, matrix diffusion, sorption, radioactive decay included in integrated modelling (FARF31).	Advection, dispersion, matrix diffusion, sorption, radioactive decay included in integrated modelling (FARF31).	Advection, dispersion, matrix diffusion, sorption, radioactive decay included in integrated modelling (FARF31).	No credit taken for radionuclide retention in the geosphere.	Not explicitly included in present version	See chapter 10, in particular section 10.4.2.
Ge 25 Transport of radionuclides in the gas phase	Not relevant since engineered barriers are intact.	Assessed neglecting the geosphere as a barrier.	Assessed neglecting the geosphere as a barrier.	Assessed neglecting the geosphere as a barrier.	Not relevant.	Not explicitly included in present version	Section 10.9.

6.5 Assessment model flow charts, AMFs

To give an overview of the models used in the evaluation of repository evolution, and the dependencies/interactions between them, two assessment model flow charts, AMFs, have been developed. The AMFs show models used in the assessment (grey rectangles), data to/results from model exercises (parallelograms) and assessments of data for further modelling based on model output and other information (yellow boxes). The latter symbol is used when the output from one model is not directly used as input to another model, but where an intermediate interpretation is first required. The assessment of the occurrence of thermally induced spalling is an example: Such spalling has been modelled (rectangle "fracturing" in Figure 6-3), but an interpretation of the result and, in this case, a pessimistic assumption regarding the occurrence of thermally induced spalling is made based on the modelling result, in order to produce input data to modelling of groundwater flow (rectangle "GW flow saturated repository").

One AMF concerns the excavation/operation and initial temperate period, Figure 6-3 and one represents permafrost and glacial conditions, Figure 6-4. The **Model summary report** describes the models represented in the AMFs. Table 6-7 provides links between the processes in the process tables, the modelling activities described by the AMF and the section of the reference evolution (chapters 9 and 10) where the modelling is reported.

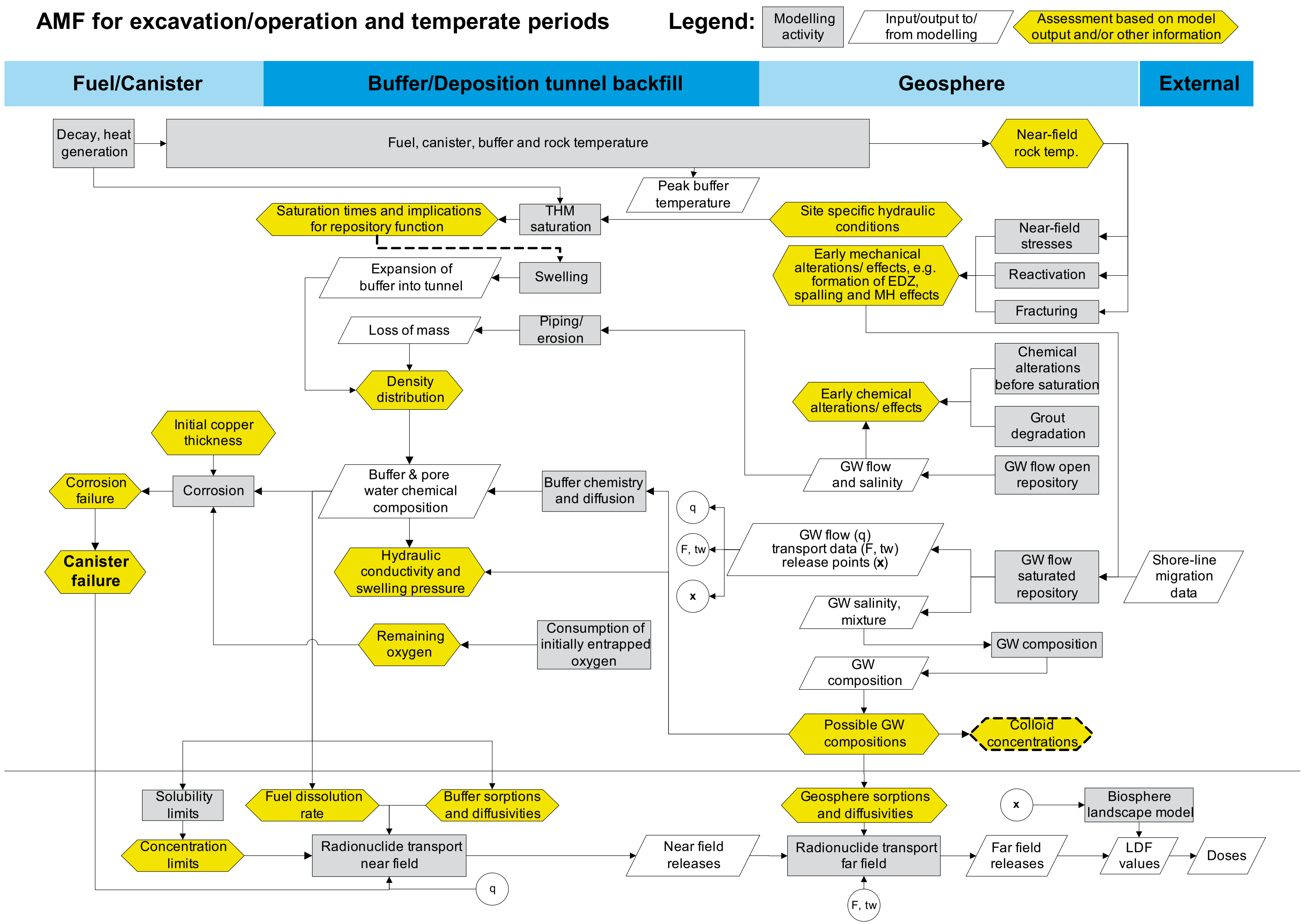


Figure 6-3. The assessment model flow chart for the excavation/operation period and the initial temperate period after closure. See main text for further explanations.

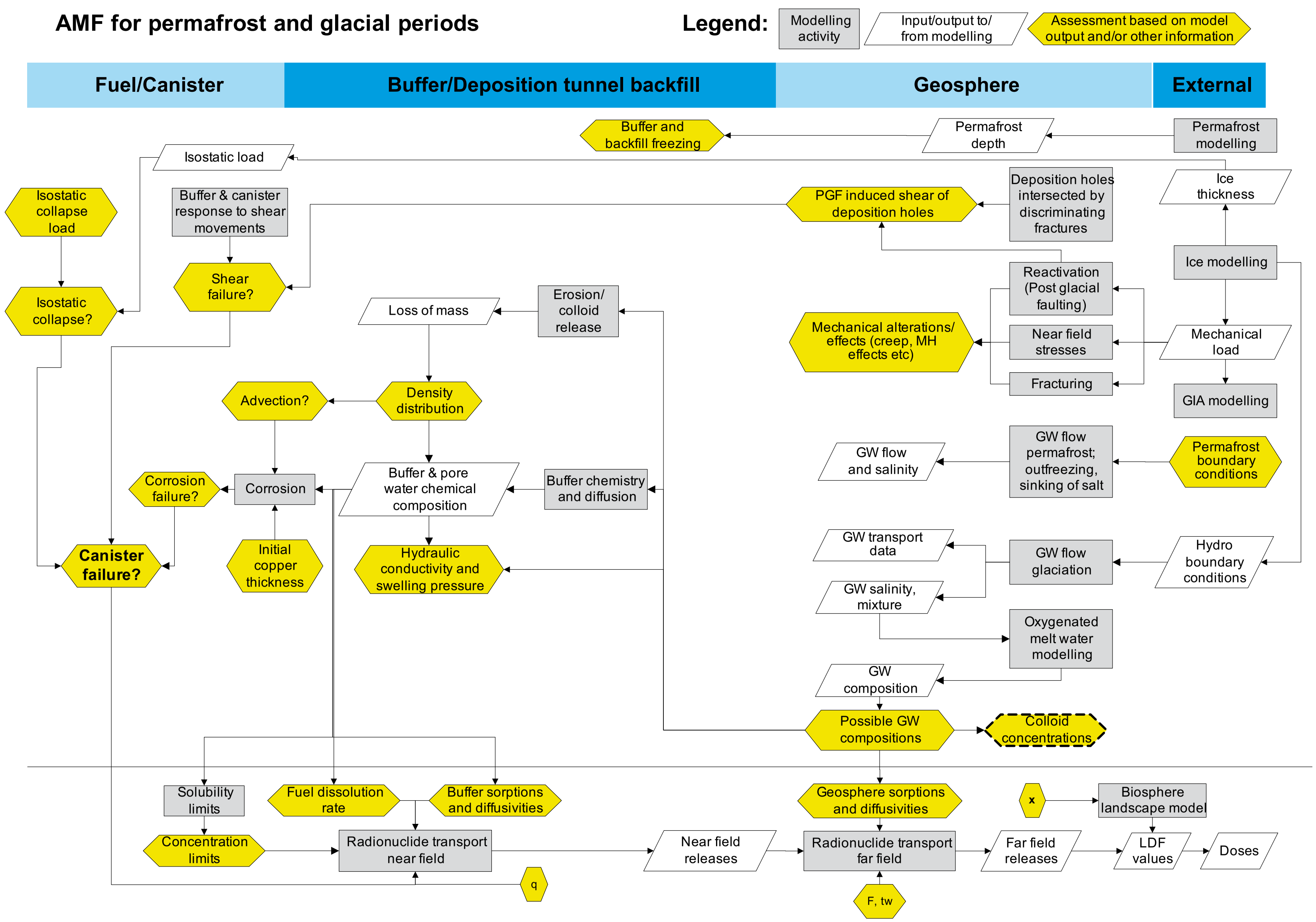


Figure 6-4. *The assessment model flow chart for permafrost and glacial conditions.*

Table 6-7. Links between process tables, AMF (Figure 6-3) and reporting in reference evolution, chapters 9 and 10. Excavation/operation and temperate periods.

Modelling activity in AMF	Included processes, as indexed in process tables in section 6.4	Code	Section(s) in reference evolution where modelling is reported	Note	Full modelling report
Decay, heat generation	F1, F2	Scale 4-3, ORIGEN-S, CASMO 4	–		/Håkansson 2000/
Near field temperature	F1, F2, C2, Bu1, Bu2, Ge1	Ansys Analytical model (Excel)	9.3.4	Decay and heat generation modelled as exponential expressions fitted to results of detailed calculations	–
THM Saturation (buffer and backfill)	Bu2, Bu4, BfT3	ABAQUS	9.3.8		/Börgesson et al. 2006/
Near-field stresses (geosphere)	Ge5	3DEC	9.2.2 (Excavation/operation) 9.3.5 (Initial temperate)		/Hökmark et al. 2006/
Reactivation	Ge6	3DEC	9.2.2 (Excavation/operation) 9.3.5 (Initial temperate)		/Hökmark et al. 2006/
Fracturing (spalling)	Ge7	3DEC	9.2.2 (Excavation/operation) 9.3.5 (Initial temperate)		/Hökmark et al. 2006/
Chemical alterations before saturation (geosphere)	Ge13, Ge15	PHAST	9.2.5		/Domènech et al. 2006/
Grout degradation	Ge17	PHAST	9.3.7 (Initial temperate) (Mentioned also in 9.2.5 Excavation/operation)		/Luna et al. 2006/
Groundwater flow open repository	Ge3	DarcyTools	9.2.3		/Svensson 2005, 2006ab/
Groundwater flow saturated repository	BfT4, Ge3, Ge11	ConnectFlow	9.3.6		/Hartley et al. 2006a/
Groundwater chemistry	Ge13, Ge14, Ge15, Ge19	PhreeqC	9.3.7 (temperate period)		/Auqué et al. 2006/
Piping/erosion	Bu7, BfT6	Simple scoping calculation	9.2.4		/Börgesson and Sandén 2006/
Swelling	Bu8, BfT7	ABAQUS, CodeBright	9.3.9		/Börgesson et al. 2006/
Buffer chemistry and diffusion	Bu11, Bu12, Bu13, Bu14	PHAST	9.3.10 (elevated temperatures), 9.3.11 (long-term)		/Arcos et al. 2006/
Consumption of initially entrapped oxygen (buffer and backfill)	BfT12	PHAST	9.2.5		/Grandia et al. 2006/
Corrosion	C11	Analytical expressions (Excel)	9.2.5 (excavation/operation) 9.3.12 (initial temperate)		–
Concentration limits	F14	PhreeqC			/Duro et al. 2006/

Modelling activity in AMF	Included processes, as indexed in process tables in section 6.4	Code	Section(s) in reference evolution where modelling is reported	Note	Full modelling report
Radionuclide transport near field	F16, Bu23, BfT21 (The above three include, as sub-processes, F1, F12, F13, F14, Bu11, Bu12, BfT9, BfT10 and BfT11)	COMP23, Analytic model (Excel)	10.5 through 10.8		–
Radionuclide transport far field	Ge24, consisting of sub-processes Ge11, Ge12, Ge13 and F1.	FARF31, Analytic model (Excel)	10.5 through 10.8		–
Biosphere landscape model	Biosphere processes	Eikos, MIKE_SHE, Pandora, Statistica	10.2		/SKB 2006hi, Avila et al. 2006/

Table 6-8. Links between process tables, AMF, Figure 6-4 and reporting in reference evolution, chapters 9 and 10. Permafrost and glacial periods.

Modelling activity in AMF	Included processes, as indexed in process tables in section 6.4	Code	Section(s) in reference evolution where modelling is reported	Note	Full modelling report
Permafrost modelling	F1, F2, Ge1	Numerical permafrost model	9.4.1, 9.4.3	Decay and heat generation modelled as exponential expressions fitted to results of detailed calculations	In **Climate report**
Ice modelling	External processes, see SR-Can **Climate report**	UMISM	9.4.1		In **Climate report**
GIA modelling	External processes, see SR-Can **Climate report**	Numerical GIA model	9.4.1		In **Climate report**
Deposition holes intersected by discriminating fractures	Initial state issue	Matlab, Analytical expressions (Excel)	9.4.5		/Munier 2006a, Hedin 2004b/
Near-field stresses (geosphere)	Ge5	3DEC	9.4.4		/Hökmark et al. 2006/
Reactivation	Ge6	3DEC	9.4.4		/Hökmark et al. 2006/
Fracturing	Ge7	3DEC	9.4.4		/Hökmark et al. 2006/
GW flow permafrost; outfreezing, sinking of salt	Ge3, Ge11, Ge12, Ge21	DarcyTools	9.4.7		/Vidstrand et al. 2006/
Groundwater flow, glaciation	Ge3, Ge11	ConnectFlow	9.4.6		/Jacquet and Siegel 2006/
Oxygenated melt water modelling	Ge11, Ge15	PhreeqC	9.4.7		/Guimerà et al. 2006/
Erosion/colloid release	Bu17	Analytical expression	9.4.8		–
Buffer chemistry and diffusion	Bu11, Bu12, Bu13, Bu14	PHAST	9.4.8		/Arcos et al. 2006/
Buffer and canister response to shear movements	C3, C4, Bu8, (Ge6)	ABAQUS	9.4.5		/Börgesson and Hernelind 2006/

Modelling activity in AMF	Included processes, as indexed in process tables in section 6.4	Code	Section(s) in reference evolution where modelling is reported	Note	Full modelling report
Corrosion	C11	Analytical expressions (Excel)	9.4.9		Appendix B
Solubility limits	F14	PhreeqC			/Duro et al. 2006/
Radionuclide transport near field	F16, Bu23, BfT21 (The above three include, as sub-processes, F1, F12, F13, F14, Bu11, Bu12, BfT9, BfT10 and BfT11)	COMP23, Analytic model (Excel)	10.5 through 10.8		–
Radionuclide transport far field	Ge24, consisting of sub-processes Ge11, Ge12, Ge13 and F1	FARF31, FVFARF, Analytic model (Excel)	10.5 through 10.8		–
Biosphere landscape model	Biosphere processes	Eikos, MIKE_SHE, Pandora, Statistica	10.2		/SKB 2006hi, Avila et al. 2006/

7 Safety functions and safety function indicators

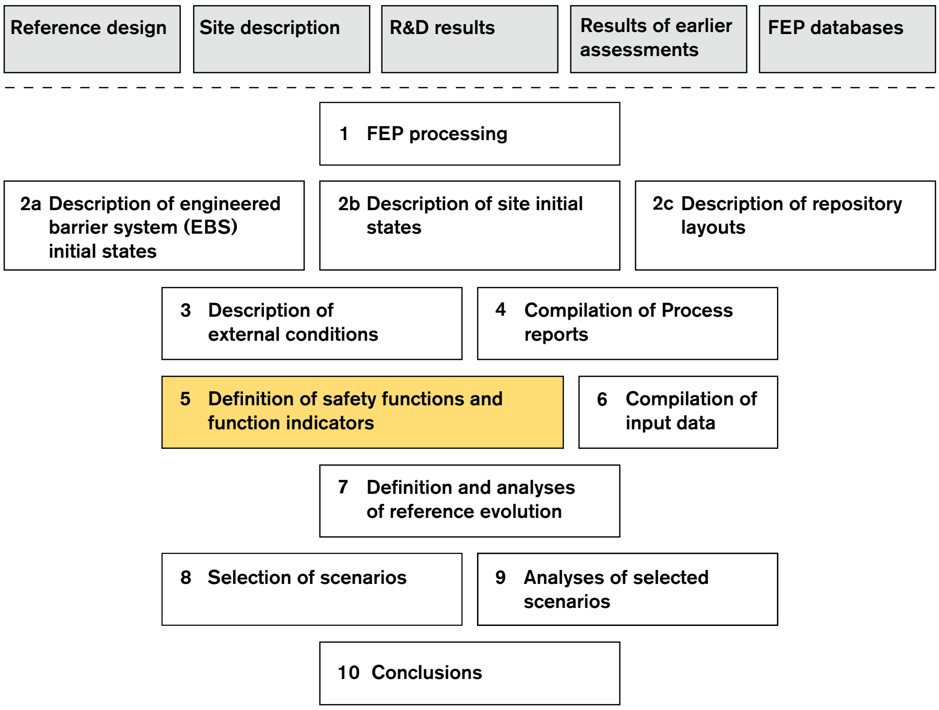


Figure 7-1. *The SR-Can methodology in ten steps (section 2.2), with the present step highlighted.*

7.1 Introduction

As mentioned in section 2.1, the primary safety function of the KBS-3 concept is to completely isolate the spent nuclear fuel within copper canisters over the entire assessment period, which is one million years in SR-Can. Should a canister be damaged, the secondary safety function is to retard any releases from the canisters. The two issues of isolation and retardation are thus of primary importance throughout the assessment. It should be noted that the isolation function is more prominent in the KBS-3 concept than in many other repository concepts for spent nuclear fuel or high level waste e.g. /Nagra 2002, ONDRAF/NIRAS 2001/. This is also reflected in the methodology and structure of the safety assessment, which focuses to a comparatively large extent on the isolating capacity of the repository.

This chapter deals with differentiation of safety functions for a KBS-3 repository. Safety function indicators and criteria for these indicating safe conditions in the repository are introduced in section 7.2. Safety function indicators and criteria related to isolation and retardation are developed in sections 7.3 and 7.4, respectively. In section 7.6, a FEP chart is developed. The chart describes the connections between important initial state conditions, long-term processes and safety functions and thus integrates much of the information given in this chapter, chapters 4 and 6, and external factors described in chapter 5.

The safety functions and their indicators and criteria are used to structure and differentiate the evaluation of safety when the long-term evolution of the repository is evaluated in chapter 9. They also play a key role in the selection and analyses of scenarios in chapters 11 and 12, respectively.

Immediately below follows a brief discussion of dilution, that has sometimes been regarded as a safety function for repositories.

7.1.1 Approach to dilution

Dilution is sometimes seen as a safety function in the context of waste management. Dilution is, however, not seen as a safety function for the KBS-3 system. The main reasons for this are that dilution essentially can not be controlled by the design of the repository and only to some extent by site selection. Nevertheless, dilution will play an essential role in a realistic estimate of the consequences of a potential release from the repository. A coastal site can be expected to be submerged for extended periods of time and dilution of potential releases in sea water could dramatically lower the calculated annual effective doses and thus the associated radiological risks.

The future evolution of climate and climate-related conditions, which will be determining factors for dilution, is however highly uncertain. Although marine discharges can be predicted to exist intermittently, these will also with high likelihood be interrupted by periods during which releases occur to terrestrial ecosystems, or when earlier releases accumulated in sea sediments will be present in terrestrial systems due to shore-line migration. These latter conditions will likely be associated with the highest individual risks as the contaminated terrestrial systems could be used for, e.g. agriculture. The compliance discussion for a repository has to be based on these unfavourable but, in a long-term perspective, not unlikely conditions where dilution in large water bodies will not occur.

Inevitably, dilution will have to be included in quantitative assessments of wells but also in this case many of the data will have to be generic and will not be amenable to control by repository design or site considerations.

A related phenomenon concerns the fact that the repository is distributed in space and that the host rock and the near-surface hydrological systems will redistribute potential releases from the repository before they cause human exposure. These phenomena will have to be included in the quantification of consequences of potential releases. The redistribution effects cannot however be straightforwardly described as positive or negative.

7.2 Safety functions, safety function indicators and safety function indicator criteria; general

The overall criterion for evaluating repository safety is the risk criterion issued by SSI, which states that "the annual risk of harmful effects after closure does not exceed 10^{-6} for a representative individual in the group exposed to the greatest risk". This is a "top level" criterion that requires input from numerous analyses on lower levels, and where the final risk calculation is the integrated result of various model evaluations using a large set of input data.

Safety functions

A detailed and quantitative understanding and evaluation of repository safety requires a more elaborated description of how the main safety functions of isolation and retardation are maintained by the components of the repository. Based on the understanding of the properties of the components and the long-term evolution of the system, a number of subordinate safety functions to isolation and retardation can be identified.

In this context, a *safety function* is defined qualitatively as a role through which a repository component contributes to safety. For example, copper corrosion could in the long term jeopardise the isolation function of the canisters. Certain species of microbes in the buffer could transform sulphate to sulphide, a copper corroding agent. A safety function related to the buffer and subordinate to isolation would therefore be the ability of the buffer to *eliminate microbes*.

Safety function indicators

In order to quantitatively evaluate safety, it is desirable to relate or express the safety functions to measurable or calculable quantities, often in the form of barrier conditions.

In the case of the buffer safety function of eliminating microbes, current understanding indicates that a high buffer swelling pressure prevents the survival of microbes in the buffer. The buffer swelling pressure is thus a suitable quantity to use in order to evaluate the extent to which this safety function is fulfilled. The buffer swelling pressure is said to be a *safety function indicator*[5] for the mentioned buffer safety function. A safety function indicator is thus a measurable or calculable quantity through which a safety function can be quantitatively evaluated.

Safety function indicator criteria

In order to determine whether a safety function is maintained or not, it is desirable to have quantitative criteria against which the safety function indicators can be evaluated over the time period covered by the safety assessment.

The situation is however different from safety evaluations of many other technical/industrial systems in an important sense: The performance of the repository system or parts thereof do not, in general, change in discrete steps, as opposed to e.g. the case of a pump or a power system that could be characterised as either functioning or not. The repository system will evolve continuously and in many respects there will be no sharp distinction between acceptable performance and a failed system on a sub-system level or regarding detailed barrier features.

There are thus many safety function indicators on which no limit for acceptable performance can be given. The groundwater concentrations of canister corroding agents or agents detrimental to the buffer are examples of this kind of factor related to isolation. Usually, they enter in more complex analyses where a number of parameters together determine, e.g. the corrosion rate of the canister. Most of the factors determining retardation are also of this nature.

Nevertheless, as will be demonstrated in this chapter, there are some crucial barrier properties on which quantitative limits can be put. Regarding isolation, an obvious condition is the requirement that the copper canister should nowhere have a penetrating defect, i.e. there should, over the entire surface of the canister, be a non-zero copper thickness. In addition to this direct measure of isolation performance, a number of quantitative supplementary criteria can also be defined. These relate, for example, to the peak temperature in the buffer and to requirements on buffer density and buffer swelling pressure giving favourable buffer properties for maintaining isolation. Most of them determine whether certain potentially detrimental processes can be excluded from the assessment. Relating to the above example of microbes in the buffer, current information indicate that the buffer should have a swelling pressure higher than 2 MPa for microbial survival in the buffer to be excluded The requirement that the buffer swelling pressure should exceed 2 MPa is thus a safety function indicator criterion in this case. More studies are, however, underway and future results will show if the threshold level of 2 MPa can be substantiated further.

Relation between global safety and individual safety functions

It is emphasised that the breaching of a safety function indicator criterion does not mean that the repository is unsafe, but rather that more elaborate analyses and data are needed in order to evaluate safety.

The criteria are an aid in determining whether safety is maintained. If the criteria are fulfilled, the safety evaluation is facilitated. If all criteria related to canister failures are fulfilled, this implies that the overall risk criterion is fulfilled, provided that all canister failure modes have been identified. Fulfilment of all criteria related to the buffer, the backfill and the host rock is not a guarantee for compliance with the overall risk criterion. On the other hand, compliance with the risk criterion could well be compatible with a violation of one or several of the criteria. A violation would be an implication of caution; further analyses could be required in order to determine the consequences on a sub-system level or a system level.

An example is the criterion that the groundwater concentration of divalent cations should exceed 1 mM in order for buffer erosion to be excluded. If this criterion is breached, buffer erosion must be quantitatively evaluated and its consequence, in terms of reduced buffer density, needs to be propagated to assessments of buffer swelling pressure and hydraulic conductivity. Alterations of the latter factors could, in turn, influence e.g. canister corrosion. A chain of assessments is thus initiated by the breaching of the first safety function, but the final outcome of a possibly increased corrosion rate is not necessarily an unacceptable impact on isolation.

[5] In choosing the term “function indicator”, it was observed that the two terms “performance indicator” and “safety indicator” in this context normally refer to releases of radionuclide or resulting dose consequences /EU 2002/. Those terms were thus avoided.

Approach to margins

Related to the above, a criterion may be defined so that it includes a considerable margin from unacceptable performance.

The peak temperature criterion for the buffer, set to 100°C in order to avoid mineral transformations, is an example of a criterion with a considerable margin as documented in the **Buffer and backfill process report**, section 2.5.9. One reason for this is that the extent of mineral transformation increases gradually with temperature and it is not possible to determine a sharp limit below which no transformation occurs. Rather, a criterion is determined below which transformation can, for all practical purposes and for extremely long time spans, be neglected in the safety assessment.

An example of a criterion with a smaller margin is the above mentioned requirement that the buffer swelling pressure should exceed 2 MPa in order to eliminate microbes. Here, a sharper onset of the safety function exists and it is possible to formulate the criterion with a smaller margin.

For the safety function indicator criteria used in SR-Can, there has been no systematic approach to margins when determining the criteria. The only requirement applicable to all safety function indicator criteria is that the safety function to which it relates should be fulfilled if the criterion is satisfied, based on the scientific understanding of the phenomenon in question.

Quantities for safety function indicators

There is, for some safety functions, a certain degree of freedom in the choice of quantities for the indicators used to represent the safety function.

For example, in the presently developed version, the indicator used to quantify the buffer safety function "prevent colloid transport through buffer" is the buffer density, whereas one could also have chosen the buffer pore size, a more direct measure of the safety function. For a specific bentonite material, the pore size is however directly related to the density and the buffer density is of interest in many other aspects of the safety assessment. Therefore, the density was chosen as the safety function indicator in this case.

There are other similar examples, in particular for the buffer for which many characteristics are dependent and thus to some degree interchangeable.

Derivation of safety functions, indicators and criteria

For the set of safety functions, their indicators and criteria to be useful in the evaluation of safety, they need to be as comprehensive as possible. It is therefore important to have a systematic approach to the derivation of these entities.

The pillars on which the derivation of safety functions is built are:

- The two principal safety functions isolation and retardation on which the design of the KBS-3 repository is based.
- The scientific understanding of the long-term evolution of a KBS-3 repository.

Throughout the decades of research related to the long-term safety of a KBS-3 repository, safety functions or barrier requirements have been discussed and established successively.

In SR-Can, the results of these efforts have been utilised. Also, all processes identified as relevant for long-term safety and documented in the **Process reports** have been considered with the aim of determining if a safety function relating to the process could be defined, ideally accompanied by an indicator and a criterion. For example, the knowledge related to item Bu20 "Microbial processes" in Table 6-4 on buffer processes, has led to the definition of the buffer safety function "eliminate microbes" and the related swelling pressure criterion of 2 MPa, mentioned above.

As for the set of processes identified as important for long-term safety, completeness can never be unequivocally claimed for the set of safety functions in the evaluation of safety. The set of safety functions can be more or less mature, as a reflection of the maturity of the scientific understanding of the system analysed. The safety of the KBS-3 system has been studied for decades and new detrimental processes, that could form a basis for the formulation of additional safety functions, have not been identified in recent years. Furthermore, the principle of designing a relatively simple system using naturally occurring materials with well known long-term properties, as in the case of KBS-3, favours the derivation of a comprehensive and mature set of safety functions.

Safety function indicator criteria are not the same as design criteria

It is noted that safety function indicator criteria are not the same as design criteria. Safety function indicator criteria are meant to be fulfilled throughout the one million year assessment period, whereas design criteria relate to the initial state of the repository. Design criteria need to be defined with sufficient margin to allow deterioration of the system components over the assessment period so that safety is still fulfilled, i.e. so that, ideally, all the safety function indicator criteria are fulfilled also at the end of the assessment period. A clear example of this is the copper thickness of the canister: It is designed with a 50 mm copper thickness to allow for corrosion, whereas the safety function indicator criterion requires that it is nowhere zero, as this is the criterion for the breaching of isolation.

Furthermore, several of the safety function indicators and their criteria are related to future geosphere conditions, which can only to a limited extent be controlled by design or siting choices.

Relations between safety functions

The safety functions are related. All safety functions of the buffer either support a safety function of the canister, or contribute to retardation in the buffer. For example, the safety function "limit advective transport" in the buffer supports the canister safety function "provide corrosion barrier", and also contributes to retardation in the buffer since advection is a more efficient transport mechanism than diffusion. Similarly, all safety functions of the host rock either support a safety function of the canister directly or indirectly via a buffer safety function, or contribute to retardation in the rock.

Summary

The following definitions have been introduced:

- A safety function is a role through which a repository component contributes to safety.
- A safety function indicator is a measurable or calculable property of a repository component that indicates the extent to which a safety function is fulfilled.
- A safety function indicator criterion is a quantitative limit such that if the safety function indicator to which it relates fulfils the criterion, the corresponding safety function is maintained.

Safety functions are an aid in evaluation safety, but the fulfilment of all safety function indicator criteria is neither necessary nor sufficient to argue safety. The different safety function indicator criteria are furthermore determined with varying margins to acceptable performance.

Safety functions are related to, but not the same as, design criteria. Whereas the latter relate to the initial state of the repository and primarily to its engineered components, the former should be fulfilled throughout the assessment period and relate, in addition to the engineered components, to the natural system.

The set of safety functions used in SR-Can has been derived based on the documented experience accumulated over decades of research related to the long-term safety of the KBS-3 repository.

7.3 Safety function indicators for isolation

The criteria presented below are often selected from a cautious perspective and further studies and engineering development may show that some of the criteria presented here could be relaxed for future safety assessments. Also, additional criteria may be added.

7.3.1 Canister

Minimum copper thickness

The canister integrity can be threatened either mechanically or chemically. An obvious requirement regarding canister integrity is that the copper shell of the canisters should not be penetrated. This can be expressed such that the minimum copper thickness taken over the entire canister surface shall be larger than zero:

$$d_{min}^{Cu} > 0$$

As long as this criterion is strictly fulfilled for all canisters, isolation is complete and no releases occur.

Isostatic load

Mechanical loads on the canister can be complex and, for some load situations, it is not straightforward to define a single criterion to which a load can be compared in order to determine if integrity is maintained. However, for the isostatic pressure on the cast iron insert, it is possible to formulate such a criterion. Maximum isostatic pressures in a repository have in previous assessments been estimated to be in the range of 40–45 MPa, composed of the bentonite swelling pressure and the hydrostatic pressure at the disposal depth during a glaciation, see e.g. the SR 97 assessment /SKB 1999a/.

A probabilistic study based on statistics of measured materials data from real canister inserts has shown that the probability for failure is insignificant ($\sim 2 \cdot 10^{-9}$) for a baseline case with an isostatic pressure of 44 MPa. This is the case even though several pessimistic assumptions are made both in the underlying deterministic analyses and the probabilistic analysis /Dillström 2005, Andersson et al. 2005/.

The probabilistic analysis of collapse only considers the first local collapse event; total collapse of the insert will occur at much higher pressure. Deterministic calculations of total collapse indicate that this will occur at pressures above 100 MPa.

In parallel to the statistical test programme and the probabilistic analysis, two pressure tests of canister mock-ups were performed to demonstrate the actual safety margins /Nilsson et al. 2005/. Two mock-ups representative of a complete KBS-3 canister were therefore manufactured and loaded to high hydrostatic pressure in a cold isostatic press to determine the failure load and failure mechanism.

The first mock-up was loaded to 130 MPa. At this load, the canister had undergone plastic deformation but retained its overall integrity. A detailed experimental post-test analysis programme indicated that some defects had grown up to 10 mm in stable tearing, but there were no through-wall cracks. The second mock-up was loaded to 139 MPa when it failed by plastic collapse.

The safety function indicator criterion is formulated such that the isostatic pressure in the buffer/canister interface should be smaller than the isostatic collapse pressure of the canister insert.

$$P_{Isostatic}^{Canister\,/\,Buffer\ interface} < P_{Isostatic\ collapse}^{Can}$$

The isostatic collapse pressure will vary between the canisters, but the probability for local collapse at 44 MPa is vanishingly small according to the above. Total collapse occurs at much higher pressures. These issues are discussed in more detail in the **Fuel and canister process report**, section 3.4.2.

Shear movements

Cases of loads due to shear movements on the canister are more complex to analyse. Limited shear loads may occur as a consequence of uneven swelling of the buffer at early stages of the repository evolution. More severe load situations may occur as a consequence of earthquakes that could induce secondary movements in fractures intersecting a deposition hole. The response of the canister to these latter loads depends on a number of factors:

- The rupture limit of the canister insert.
- The magnitude and location of the earthquake.
- The length over which the intersecting fracture is sheared.
- The angle of intersection of the fracture with the deposition hole.
- The velocity of the fracture shear movement.
- The buffer material properties, many of which depend strongly on the buffer density.

The combined effect of all these factors determines if a canister failure will occur. It is not straightforward to formulate criteria for the factors involved since they are dependent. Nevertheless, integrated modelling efforts have demonstrated that bounding guidelines can be formulated on at least the buffer density and the rock shear distance, thereby facilitating the analysis of this complex problem. These guidelines are mentioned in the buffer and rock sections below. A full account of the analysis of the shear movement problem, with site-specific rock data, estimates of the occurrence of large earthquakes, integrated modelling of buffer and canister response to postulated shear movements etc is given in the analysis of the reference evolution, section 9.4.5.

Formally, for the canister the criterion is that the rupture limit of the canister must exceed the shear stresses to which it is exposed, i.e.

$RuptureLimit^{Canister} > ShearStress$

Temperature

To ensure chemical stability of the buffer, it is required that its temperature nowhere exceeds 100°C, see section 7.3.2 below. As discussed in the **Fuel and canister process report**, section 3.5.7, exposures of the canister surface to temperatures well over 100°C are not expected to have an effect on the corrosion behaviour of the copper canister (or any other detrimental defect). Since the inner parts of the buffer and the canister surface will experience similar peak temperatures, it has not been seen necessary to set a limit on the peak temperature of the canister surface.

7.3.2 Buffer

Limit advective transport

An important safety function of the buffer is to limit transport of dissolved copper corroding agents to the canister and potential radionuclide releases from the canister. The material of the buffer surrounding the canister has been chosen so as to prevent advective transport in the deposition hole. A guideline is that the hydraulic conductivity of the buffer should fulfil /Buffer and backfill process report, section 2.5.2/:

$K^{Buff} < 10^{-12}$ m/s

The requirement refers to all parts of the buffer, i.e. the variability within the buffer must be such that the requirement is everywhere fulfilled.

For any reasonable hydraulic gradient in the repository, this condition will mean that transport in the buffer will be dominated by diffusion. The hydraulic conductivity is strongly related to the density of the buffer, to the adsorbed ionic species and to the ionic strength of the surrounding groundwater.

The buffer homogeneity is ensured partially by the fact that the buffer is made of a clay material that swells when water saturated. A swelling pressure criterion is therefore formulated /Buffer and backfill process report, section 2.4.1/:

$P_{Swell}^{Buff} > 1$ MPa

The requirement refers to all parts of the buffer, i.e. the variability within the buffer must be such that the requirement is everywhere fulfilled.

Resist transformations (requirement on temperature)

The buffer temperature should not exceed 100°C in order to limit chemical alterations /Buffer and backfill process report, section 2.5.9/.

$T^{Buffer} < 100°C$

Freezing

If the buffer freezes, its properties will change drastically. Therefore, the buffer temperature should not fall below the freezing temperature of a water-saturated buffer. The minimum buffer temperature will occur at the buffer/rock interface, therefore the limit is applied to this boundary. As the heat released from the canisters may, depending on the elapsed time after closure, play a role, it is necessary to consider deposition holes at the edge of the deposition area where the temperature will be the lowest. The criterion is the following /Buffer and backfill process report, section 2.2.2/:

$T^{Buffer} > -5°C$

A number of important buffer properties are related to the buffer density. It affects the thermal conductivity (of importance for the canister temperature), the swelling pressure and the hydraulic conductivity. These influences of density are addressed through the requirements set out above.

Eliminate microbes

The buffer should furthermore have a sufficient swelling pressure to prevent bacteria from surviving in it. Past and ongoing studies indicate that this will occur at swelling pressures exceeding 2 MPa. This leads to the criterion below /Buffer and backfill process report, section 2.5.13/ This is, however, still subject to studies and future results will show if this criterion can be further substantiated.

$P_{Swell}^{Buff} > 2$ MPa (Eliminate microbial activity).

The requirement refers to all parts of the buffer, i.e. the variability within the buffer must be such that the requirement is everywhere fulfilled.

It is also noted that this criterion is formulated to prevent microbes initially present in the buffer from surviving. If the buffer has once reached this swelling pressure, microbes are not expected to exist in it or on the canister wall. For additional bacteria to intrude, a buffer density much less than the reference density is required.

Prevent canister sinking

Also, the swelling pressure should be sufficient to prevent the canister from sinking in the deposition hole since this would render the canister in direct contact with the rock thus short-circuiting the buffer.

The main determinant of the creep rate is the magnitude of the mobilised shear strength. The shear strength decreases with decreasing swelling pressure. Recent calculations /Börgesson and Hernelind 2006/ of canister sinking in a deposition hole for a range of buffer densities and hence swelling pressures indicate that the sinking will be less than 2 cm for swelling pressures down to 0.1 MPa, see further the Buffer and backfill process report, section 2.4.1. Based on these calculations, the following safety function indicator criterion is cautiously formulated:

$P_{Swell}^{Buff} > 0.2$ MPa (Prevent canister sinking).

Damp rock shear movements

Another safety function of the buffer is to protect the canister from rock movements, in particular from the consequences of rock shear movements. Also here the buffer density plays a critical role, and the following criterion/guideline has been determined:

$\rho_{Bulk}^{Buff} < 2{,}050$ kg/m^3 (Ensure protection of canister against rock shear)

This is further discussed in section 9.4.5.

Liquefaction

A related phenomenon concerns the possible liquefaction of the buffer in the event of high ground-water pressures. Although the occurrence of this phenomenon is related to the buffer density, a quantitative criterion cannot be formulated based on current understanding. The phenomenon is being investigated experimentally, possibly facilitating the formulation of a criterion, see further section 9.4.8.

Other requirements

The buffer should allow gas produced within a potentially damaged canister to escape. The gas transport properties are related to the buffer swelling pressure, where a lower swelling would be an advantage, but quantitative limits for favourable buffer function in this respect cannot be formulated. The buffer issues related to gas transport are dealt with in analyses of the assessment of the evolution of a defect canister in section 10.5.2.

The content of canister corroding agents in the buffer should be low. Apart from unavoidable initial amounts of oxygen, the pyrite content could pose a long-term problem, as pyrite, if not oxidised by initially present or intruding oxygen, will release sulphide, a canister corroding agent. There is, however, no absolute criterion placed on this amount; the corrosion effects of measured amounts will have to be evaluated quantitatively. As pyrite could also act as a scavenger for any initially present or intruding oxygen in the repository, the evaluation of the effects of the presence of this material in the buffer is complex.

7.3.3 Backfill in deposition tunnels

The buffer swelling will cause an upward expansion with a resulting compression of the backfill. This needs to be counteracted by the backfill in order to keep the buffer density within the desired limits. This is covered by the evaluation of the safety function indicators for hydraulic conductivity and swelling pressure for the backfill, see below.

The concentration of canister-corroding agents in the backfill should be low. As for the buffer, a certain amount of initially entrapped oxygen is unavoidable in the backfill, and the pyrite concentration could pose a long-term problem. There is, however, no specific constraint placed on this concentration; the corrosive effects of the measured concentrations will have to be evaluated quantitatively.

7.3.4 Geosphere

Many aspects of the host rock safety functions cannot be captured by simple criteria, but require more complex analyses where the combined effect of a number of factors determine the outcome. This is discussed in a report on geoscientific suitability indicators and criteria for siting and site evaluation /Andersson et al. 2000/.

In the following, some critical constraints on groundwater composition useful in the safety assessment are provided.

Chemically favourable conditions

Several characteristics of the groundwater composition are essential for providing chemically favourable conditions for the repository.

Reducing conditions

A fundamental requirement is that of reducing conditions. A necessary condition is the absence of dissolved oxygen, because any evidence of its presence would indicate oxidising conditions. The presence of reducing agents that react quickly with O_2, such as Fe(II) and sulfide is sufficient to indicate reducing conditions. Other indicators of redox conditions, like negative redox potential, are not always well defined and thus less useful as a basis. Nevertheless, redox potential is a measure of the availability of all kinetically active oxidising species.

This requirement ensures that canister corrosion due to oxygen dissolved in the groundwater is avoided. Furthermore, should a canister be penetrated, reducing conditions are essential to ensure a low dissolution rate of the fuel matrix, to ensure favourable solubilities of several radioelements and, for some elements, also redox states favourable for sorption in the buffer, the backfill and the host rock.

In addition to dissolved O2, other oxidising groundwater components could be considered, for example nitrate and sulphate. However, whereas dissolved oxygen may react directly e.g. with the copper canister or the spent fuel, nitrate and sulphate can only be reactive by the intervention of microbes, which require both nutrients and reduced species such as dissolved hydrogen, methane or organic matter in order to be able to reduce nitrate or sulphate.

Ionic strength, salinity

The salinity of the groundwater should neither be too high, nor too low. The total concentration of divalent cations should exceed 1 mM in order to avoid colloid release from buffer and backfill, hence /Buffer and backfill process report, section 2.5.10/:

$\Sigma[M^{2+}]^{GW} > 10^{-3}$ M

Groundwaters of high ionic strengths would have a negative impact on the buffer and backfill properties, in particular on the backfill swelling pressure and hydraulic conductivity. In general, ionic strengths corresponding to NaCl concentrations of approximately 70 g/l (1.2 M NaCl) are a safe limit for maintaining backfill properties whereas the corresponding limit for the buffer is around 100 g/l (1.7 M NaCl). The limit of tolerable ionic strength is however highly dependent on the material properties of these components, (see section 4.2.8) and since, in particular for the backfill, alternative materials are to be evaluated in the assessment, no specific criterion is given here.

Colloid concentrations

The concentration of natural colloids should be low to avoid transport of radionuclides mediated by colloids. The stability of colloids is much decreased if the concentration of divalent cations exceeds 1 mM, a condition that, as discussed above, is also required for the stability of the buffer and backfill.

Concentrations of detrimental agents

Regarding canister corrosion, there should be low groundwater concentrations of other canister-corroding agents, in particular sulphide, HS^-. For sulphide to pose a problem, earlier assessments demonstrated that considerably higher concentrations than have ever been observed in Swedish groundwaters would be required. The quantitative extent of such corrosion also depends on the groundwater flow around the deposition hole and on the transport properties of fractures intersecting the hole.

Furthermore, low groundwater concentrations of agents detrimental to long-term stability of the buffer and backfill, in particular potassium and iron, are desirable /Buffer and backfill process report, section 2.5.9/.

pH

Regarding pH, a criterion can be formulated from the point of view of buffer and backfill stability /Buffer and backfill process report, section 2.5.9/:

$pH^{GW} < 11$

This is fulfilled for any natural groundwater in Sweden. However, construction and stray materials in the repository, in particular concrete, could contaminate the groundwater such that high pH values are reached.

Inflow to deposition holes

Mechanical erosion (piping) of the buffer and in backfill during and shortly after deposition is a possible concern. A criterion for that process is discussed in chapter 9. Currently knowledge indicates that, for preventing piping, water flows to a deposition hole must not exceed 0.1 l/min.

Avoiding chloride corrosion

A further requirement is that the combination of low pH values and high chloride concentrations should be avoided in order to exclude chloride corrosion of the canister. In quantitative terms, the requirement is assigned a preliminary criterion

$pH^{GW} > 4$ or $[Cl^-]^{GW} < 3$ M

The basis for this criterion is documented in the Fuel and canister process report, section 3.5.4.

Mechanically stable environment

The mechanical stability of the host rock cannot, in most respects, be simply evaluated. However, two main reasons for potential mechanical failure of the canisters can be identified. These are isostatic collapse and failure due to earthquakes causing secondary movements on fractures intersecting deposition holes, see section 7.3.1. A strongly contributing factor to the former could be high groundwater pressures such as might occur during a glaciation. Addressing the latter failure mode requires a complex evaluation of shear movements for a range of mechanical load situations. For assessing the consequences of such movements, a pessimistic limit on a maximally allowed shear displacement of a fracture intersecting a deposition hole can be formulated for canister integrity to be maintained.

/Börgesson and Hernelind 2006/ have analysed the impact of shear movements on the canister. For a saturated buffer density of 2,000 kg/m^3 and a 0.1 m shear movement, the plastic strain in the cast iron insert was calculated to be 1.6%. For a 0.2 m shear movement, the plastic strain was 4.4%. Both these values are lower than the lowest allowed ductility for the cast iron insert. The plastic strains in the copper shell were larger, but well below the specifications for the ductility of the copper material.

Based on these results, a failure criterion of 10 cm is used in SR-Can. In view of the current knowledge cited above, this criterion is robust and possibly overly pessimistic. See section 9.4.5 for more details.

It is thus required that

d_{shear} < 10 cm.

7.4 Safety function indicators for retardation

Several of the above criteria are related only to the isolation properties of the system. This is e.g. the case for the minimum copper coverage, the isostatic collapse load, the peak canister temperature, etc.

However, should a canister be breached, a number of additional phenomena and processes become relevant. The further evolution of a failed canister will depend on the geometry of the defect in the copper shell which will determine the influx of water to the canister interior, the corrosion of the cast iron insert as it is contacted by intruding water and the fate of the hydrogen gas generated due to the corrosion. Furthermore, alterations in the mechanical properties of the corroding cast iron insert and the copper canister will potentially lead to enlargement of the initial damage, collapse of the insert and establishment of a continuous water pathway between the fuel and the canister exterior. All these processes are discussed in section 10.5.2.

Should release of radionuclides occur, release limitation and retardation is provided by:

- the slow dissolution of the ceramic waste form,
- the low solubilities of several of the most hazardous radionuclides,
- transport resistances in the fuel cladding and the damaged canister,
- slow transport in the buffer (avoiding advection and providing sorption),
- transport resistances between the buffer and fractures intersecting the deposition hole,
- slow transport in the backfill (limiting advection and providing sorption), and
- slow transport in particular in the near-field host rock (limited groundwater flow, diffusion into the rock matrix where also sorption is provided).

Some of these release limiting and retarding phenomena are such that they can be evaluated through comparisons to criteria. This is e.g. the case for the avoidance of advective transport in the buffer (the same criteria as for the corresponding safety function above).

The buffer should furthermore be dense enough to prevent transport of colloids through it. This requirement is put on the buffer so that fuel colloids should not be able to escape a defective canister. Thereby, the releases of several key radionuclides will be limited by their solubilities. This requirement has led to the following criterion /Buffer and backfill process report, section 2.5.4/.

ρ_{Wet}^{Buff} > 1,650 kg/m^3 (Prevent colloid transport)

The backfill should not be a preferred pathway for radionuclide transport. For this to be fulfilled the backfill should have a certain swelling pressure to assure tightness and homogeneity and a limited hydraulic conductivity. The quantitative criteria are the following:

$P_{Swell}^{Backfill}$ > 0.1 MPa

and

$K^{Backfill}$ < 10^{-10} m/s

The basis for these criteria is documented in the Buffer and backfill process report, sections 3.3.1 and 3.4.1, respectively.

As for the buffer, there is also a requirement that the backfill in the deposition tunnels should not freeze, thus:

$T^{Backfill}$ > 0°C

For the deposition tunnel backfill, this requirement is primarily related to the retardation function, since i) freezing may damage the walls of the tunnel thus creating new transport paths for radionuclides and ii) the transport properties of a frozen and thawed backfill may be less favourable than those before freezing.

Another quantitative and general criterion also mentioned above is that of reducing conditions which is of particular importance for maintaining a stable fuel matrix and low solubilities.

Most other properties relating to the retarding capacity of the system will change gradually and be present to some degree, requiring a more detailed and integrated evaluation where the total outcome can be compared with the primary risk criterion.

Table 7-1 provides a list of key properties related to the release limiting and retarding factors mentioned above.

The fuel properties and geometrical arrangement in the canister should further be such that criticality is avoided if water should enter a defective canister, but there is no meaningful simple criterion to use for such an evaluation. The issue has to be addressed in an integrated analysis.

The buffer should allow passage of gas formed by corrosion of the cast iron insert of a defective canister at a certain maximum gas pressure, but it is presently not possible to formulate a quantitative criterion, see further section 10.5.2.

7.5 Summary, key issues to evaluate over time

The material presented above aims at defining in qualitative and quantitative terms a number of criteria that indicate safe performance of the repository. These safety function indicator criteria are mainly related to isolation and to the engineered parts of the repository. The idea is to compare calculated results of barrier evolution at later stages of the analysis to the criteria, and so obtain a quantitative evaluation of safety performance, both overall and by component.

It is emphasised that the criteria are an aid in determining whether safety is maintained. If the criteria are fulfilled, the safety evaluation is facilitated, but fulfilment of criteria alone (other than that of minimum copper coverage) is not a guarantee that the overall risk criterion is fulfilled. On the other hand, compliance with the risk criterion could well be compatible with a violation of one or several of the criteria. A violation would be an implication of caution; further analyses could be required in order to determine the consequences on a sub-system level or a system level.

Figure 7-2 summarises the safety function indicators and the criteria they should fulfil. The Figure thus points to a number of key properties that need to be evaluated as the repository system evolves in time. As is also evident from the presentation in this chapter, there are aspects of the repository evolution and barrier performance that can not be readily captured by a simple comparison to a criterion.

Table 7-1. Key properties related to release limitation or retardation.

Release limiting or retarding factor	Parameter
Slow dissolution of the ceramic waste form	Fuel dissolution rate
Low radionuclide solubilities	Solubilities of radioelements
Transport resistances in the fuel cladding and the damaged canister	Damage geometries
Slow transport in the buffer (avoiding advection and providing sorption)	Buffer hydraulic conductivity, radioelement diffusivities and sorption coefficients
Transport resistance between the buffer and fractures intersecting the deposition hole	Groundwater flow, (fracture geometry)
Slow transport in the backfill (limiting advection and providing sorption)	Backfill hydraulic conductivity, radioelement diffusivities and sorption coefficients
Slow transport in host rock (limited groundwater flow, matrix diffusion and sorption)	Transport resistance (F factor), diffusivities, sorption coefficients

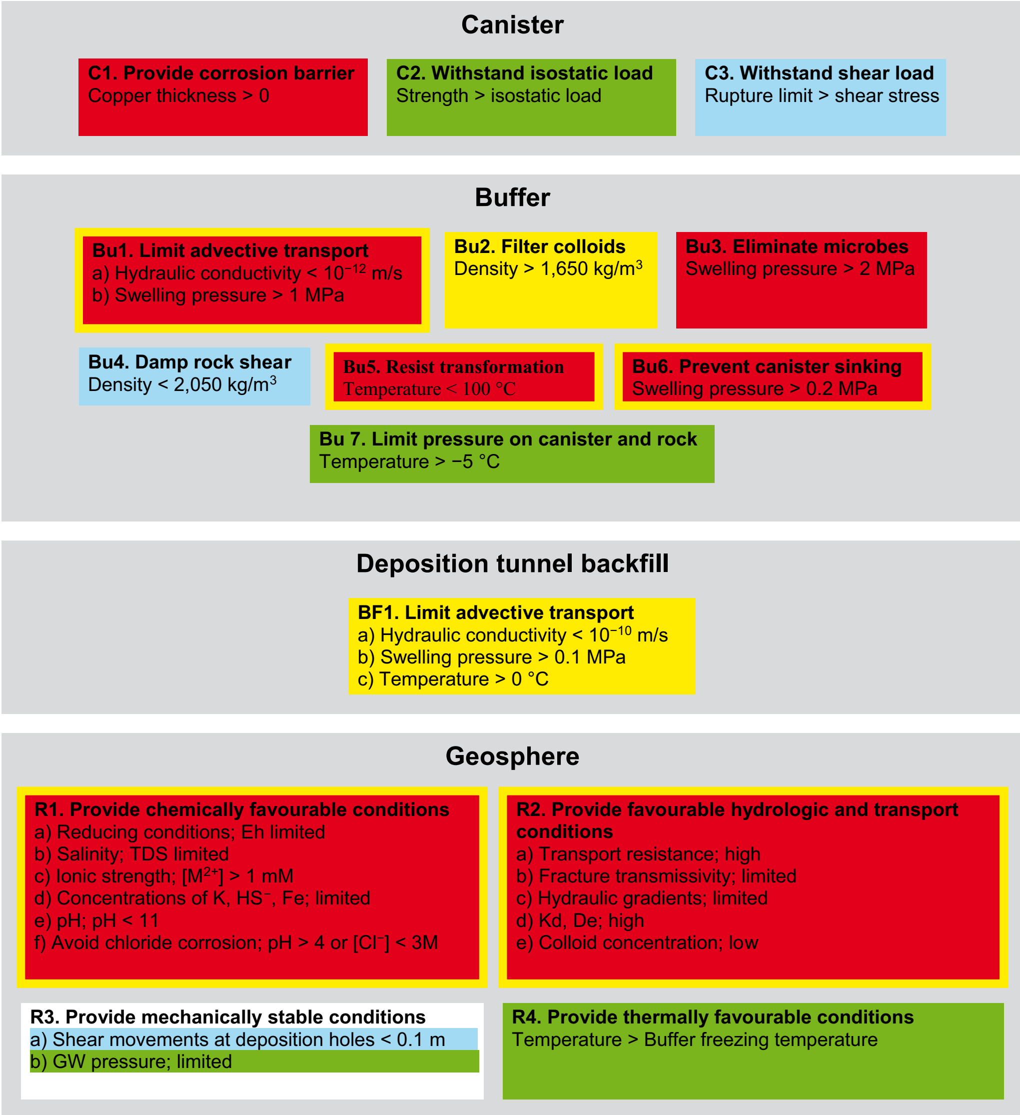


Figure 7-2. *Safety functions (bold), safety function indicators and safety function indicator criteria. When quantitative criteria cannot be given, terms like "high", "low" and "limited" are used to indicate favourable values of the safety function indicators. The colour coding shows how the functions contribute to the canister safety functions C1 (red), C2 (green), C3 (blue) or to retardation (yellow). Many functions contribute to both C1 and retardation (red box with yellow board).*

7.6 Factors affecting temporal evolution of safety function indicators – FEP chart

As has been mentioned earlier, the general evolution of the repository system, and that of the safety function indicators in particular, is determined by the initial state of the system, by a number of coupled, internal processes and by external influences on the system.

For the purposes of the safety assessment, it is desirable to have an overview of all these factors and their interdependencies. This is, in the SR-Can assessment, obtained through the development of a FEP chart.

A FEP chart contains important initial state properties, important processes, external influences, safety function indicators and the relations between these.

Figure 7-3 shows a first version of a FEP chart for a KBS-3 repository. The figure shows initial state factors (e.g. the initial copper thickness), processes (e.g. corrosion), safety function indicators (e.g. copper thickness over time) and the safety function indicator criterion (e.g. thickness > 0). Dashed lines indicate influences that occur if a safety function indicator criterion is violated.

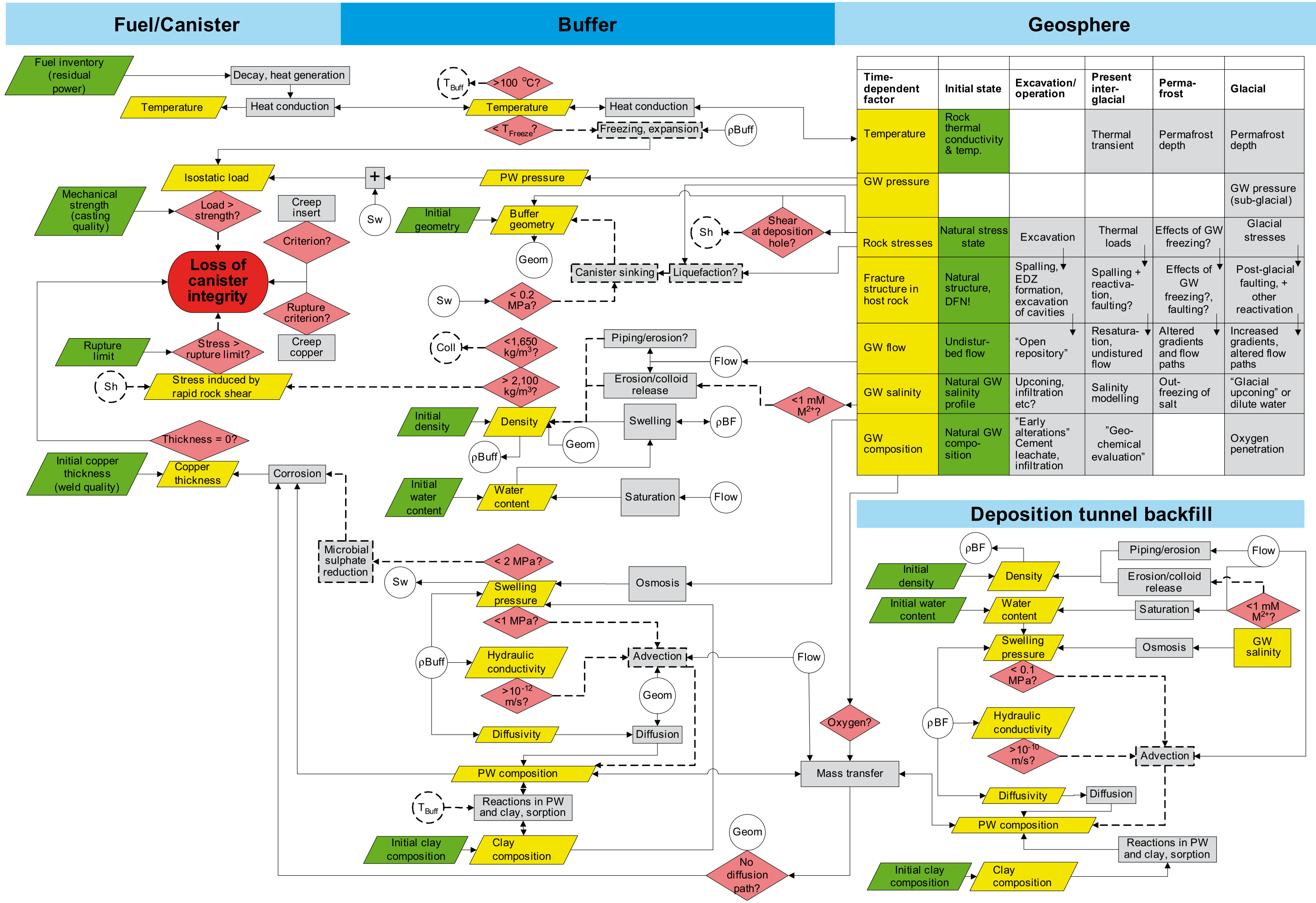


Figure 7-3. *The SR-Can FEP chart. Colour coding: Initial state factors, Variables, Processes, Safety function indicators. Solid lines: Influences that always occur. Dashed lines: Influences if there is safety function indicator violation. Circles: Interrupted influence lines (to increase readability).*

The FEP chart contains the following components.

- All variables defined as safety function indicators and their criteria, i.e. those given in Figure 7-2. However, all variables that express a component of the groundwater composition are collectively described as "groundwater composition" in the FEP chart, rather than being listed individually.
- Additional variables necessary to describe system evolution and safety, but which are not regarded as safety function indicators, e.g. the pore water pressure of the buffer.
- All identified fuel, canister, buffer and backfill processes related to *isolation*, except those which may be neglected according to the Process reports. However, some processes in the process tables are lumped into a single process, as explained in the process tables, Table 6-2 through Table 6-5.
- Gesophere processes and variables lumped into a limited number of phenomena that control the system evolution. The lumping is described in the geosphere process table, Table 6-6. The lumping also includes external influences on the system through the division of geosphere process descriptions into those applicable in the temperate, permafrost and glacial climate domains.
- Couplings and influences between the variables and the processes.

The FEP chart is useful in providing an overview of all major safety related factors, e.g. in the selection (chapter 11) and analysis (chapter 12) of scenarios based on safety function indicators.

In the present version of the FEP chart, the biosphere is not represented. The geosphere is less detailed than the engineered parts of the system since most of the safety function indicator criteria are related to the engineered part. Factors related purely to retardation are not included in the present version. Most retardation factors are, however, important also for isolation (boxes with yellow boards in Figure 7-3) and are thus included. The present version covers all time periods of the assessment. To improve clarity, it would be possible to develop a separate FEP chart for e.g. each time frame covered in the analysis of the reference evolution in the next chapter.

In summary, the FEP chart provides an overview of the relationships between initial state factors, variables, processes and safety function indicators. It aids an expert in analysing the system qualitatively, and is used, in combination with other sources, for scenario selection and analysis in SR-Can. The FEP chart may be further developed for future safety assessments.

8 Compilation of input data and data uncertainty

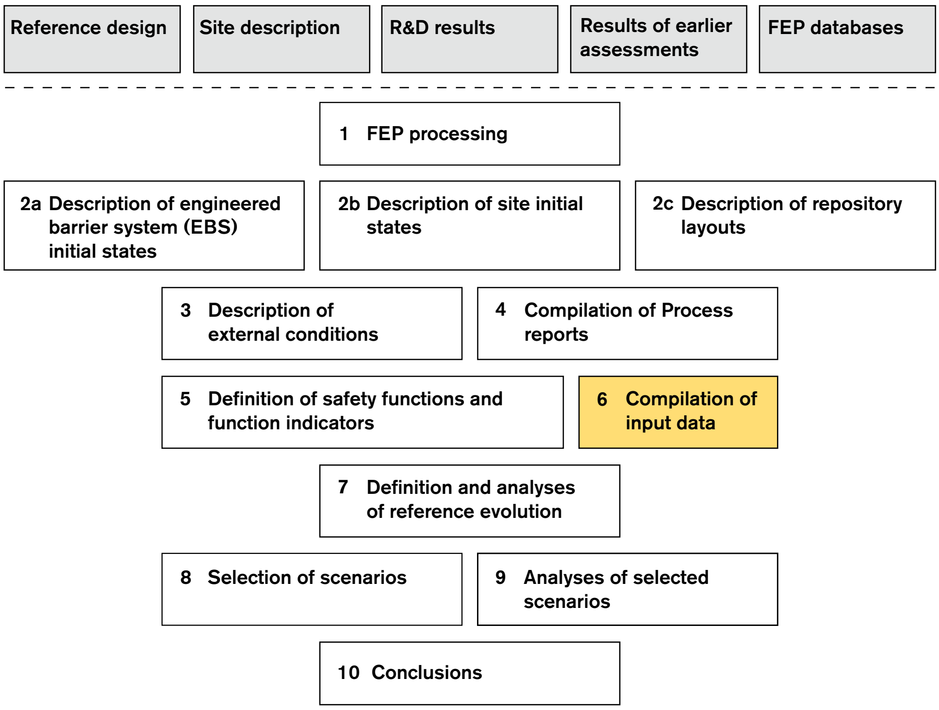


Figure 8-1. *The SR-Can methodology in ten steps (section 2.2), with the present step highlighted.*

8.1 Introduction

All input data used in quantitative aspects of the safety assessment have uncertainties. The quality of the results of any calculation in the assessment will, among other factors, depend on the quality of the input data and on the rigor with which input data uncertainties have been handled. A methodological approach for the determination of input data with uncertainties and the subsequent handling of the uncertainties is, therefore, required.

The set of input data parameters for the safety assessment is very large. Some input data uncertainties will have a substantial influence on safety related output uncertainty, whereas others will essentially not influence output uncertainty at all. An example of the latter are transport properties of those radionuclides that never give a significant contribution to the total dose. It is thus appropriate to identify input data to which output is sensitive and use these insights in allocating resources to the determination and, where feasible, reduction of input data uncertainties. It is also important to have a high degree of confidence in the data that are used to conclude that particular nuclides will never contribute to dose.

8.2 Objectives of the SR-Can Data report

In the safety assessment SR 97, a standardised procedure was employed for the derivation of all input data relevant to radionuclide transport calculations. These data were presented in the SR 97 Data Report /Andersson 1999/ which was reviewed by the authorities as part of the general SR 97 review /SKI/SSI 2001/. Following SR 97, both SKB /Hedin 2002a, 2003/ and the authorities /Wilmot and Galson 2000, Wilmot et al. 2000, Hora 2002, Hora and Jensen 2002/ have performed investigations relevant to the data derivation process in safety assessment calculations.

The results of these studies and the general development work related to data derivation were described in the interim version of the Data report /SKB 2004c/.

The procedure presented in the interim version is essentially unchanged in the final Data report. The objective of the latter is to compile input data, with uncertainties, for the SR-Can assessment calculations and for a wide range of conditions. In contrast to SR 97, data are provided not only for the radionuclide migration calculations, but also for important aspects of quantification of repository evolution.

8.3 Inventory of data

The mapping of safety relevant processes to models, see section 6.4, yields a set of models that are used to quantify the system evolution, including models for radionuclide transport and risk calculations. The data requirements of these models in principle constitute the input data inventory to be managed in the safety assessment. The importance of the various parameters, however, differs markedly. While data for all the several hundred input parameters must be quality assured, only a limited sub-set are uncertain to an extent critical to the safety evaluation, thus requiring a detailed quantification of uncertainty. These data are identified by sensitivity analyses of calculation results using preliminary input data ranges, often from earlier assessments. A number of calculation end-points regarding both isolation and retardation have been considered and sensitivities of these to input parameter uncertainty have been determined. Preliminary evaluations of calculation end-points and sensitivity analyses regarding general evolution and radionuclide dose and risk were provided in the SR-Can Interim report. These, and more developed results from later stages of the SR-Can project, have been used to continuously update the list of data needing rigorous qualification for the SR-Can assessment. The final list for SR-Can is provided in the Data report.

It is also important to understand some general features of how the models transform input to output. The output dose distributions in the SR 97 assessment /SKB 1999a, chapter 9/ are typically highly skewed, as is often the case in this type of calculation. The skewness is not primarily due to the way in which the input data are transformed by the model, but rather attributed to the fact that significant releases only occur for values of the tail ends of the input distribution. The skewness and other properties of the output distributions are only slightly affected by the selection of different input data distributions. This is an aid in the determination of input data, since it informs the analyst that calculation results are often not sensitive to the detailed shapes of the tails of input distributions. There are, however, also examples where only the extreme values of an input distribution have an effect on calculation results.

8.4 Procedure for assigning values

The new procedure, based on the one used in SR 97 and taking into account review comments, takes the form of a protocol to be used for all relevant data for the safety assessment. The full protocol is given in the Data report and is also part of the SR-Can QA procedures, see further section 2.8. The protocol is flexible so that anything from a well-motivated estimate of a single data value to a full expert elicitation of probability distributions can be handled, depending on the nature of the input data and needs of the safety assessment.

The data and uncertainty estimations are made for various subject areas. The evaluation of uncertainties and the final selection of input data for various conditions are presented in a standard form in the Data report. Each subsection in that presentation summarises input from experts and shows the judgements made by the SR-Can team. The standard form and the substance of the instructions to the experts are provided below. Experts are included in the SR-Can expert database, see further section 2.6.1.

In subject areas where data may have a large impact on assessment results, specific subject area data assessment reports are produced. These special reports follow a fixed outline with instructions to the author on how to address uncertainty, and clearly differentiate between input provided by identified experts and input provided by the SKB SR-Can team.

Expert input and judgement by SR-Can team

The individuals providing the expert input are identified in the respective supporting document and are also included in the SR-Can Expert Database, see section 2.6.

The data report distinguishes between expert inputs and judgements made by the SR-Can team. This is achieved both through clear referencing and by specific subsections entitled "Expert Input" and "Judgement by SR-Can Team". Although the experts may suggest values, the SR-Can team makes all the final judgements on which values, ranges and distributions to use in the assessment calculations. However, the concerned experts have the opportunity to review these judgements and their review comments and how they were dealt with by the SR-Can team are documented.

In some cases, the external expert input requires substantial further evaluation by the SR-Can team. Then it has not been judged possible to keep separate subsections relating to "Expert Input". Instead, this input is clearly identified through standard referencing.

Modelling in SR-Can

Each subject section of the data report starts with a brief explanation of how the data to be supplied are used in models applied in SR-Can. This information is provided for precisely defining the input data and explaining the context in which the data are to be used. Motivation for the use of these models in the assessment is formally given in the Model summary report.

Conditions for which data are supplied

The next section, according to the protocol for data uncertainty discussion, lists the various "conditions" for which parameter values and uncertainty estimates are needed. "Conditions" refer to boundary conditions, barrier states and other circumstances, which potentially may affect the values of the parameters to be estimated. Alternative "conditions" may arise because of various initial states, evolution within a scenario or under different scenarios.

Sensitivity to assessment results

As appropriate, the next section, according to the protocol, explains what sensitivity analyses have been performed in order to prioritise uncertainty assessments for those parameters and conditions judged to be potentially important to performance (both for overall endpoints such as risk and in terms of influencing conditions affecting the state of the system). In cases where the impact of a parameter on safety is difficult to judge the parameter would provisionally be regarded as sensitive to safety.

If sensitivity analyses have been performed, the following are discussed:

- For what ranges of the parameter is the impact on safety significant and are there ranges where the impact is negligible?
- Is the impact monotonic, i.e. is there a unidirectional relationship between the parameter value and performance, or is there an "optimal" value, or is the impact complexly dependent upon the values of other input parameters?
- If the parameter affects several different safety functions, do the effects on these different functions occur in different parts of its range?
- What precision in inputs is needed to adequately quantify safety assessment results?

It is also stated whether the answers apply to all applicable conditions – or only to some.

Conceptual uncertainties

The next section, according to the protocol, explores conceptual uncertainty affecting the data by addressing the following questions:

- Are there conceptual uncertainties related to the model in which the parameter is used?
- Are there conceptual uncertainties related to models used for deriving the parameter value?
- What alternative conceptual models could be reasonably conceivable?
- In light of the previous point, can the conceptual (model) uncertainty be expressed/illustrated through parameter uncertainty in the given model, e.g. by making a bounding assumption or considering the range of different conceptual models that may apply?

Data uncertainty, spatial and temporal variation

The next section, according to the protocol, concerns spatial and temporal variations and data uncertainties. Data uncertainty may both concern uncertainties in parameter values and uncertainties in the geometry of site structures and domains. The following questions are addressed:

- What is known about the spatial variation of the parameter? Is there any information about the uncertainty in the spatial variability? How is this considered in the parameter value and uncertainty estimates?
- What is known about the temporal variability of the parameter? How is this considered in the parameter value and uncertainty estimates?
- If the parameter value and its uncertainty are drawn from a database, is this site-specific or "generic"? In the latter case, how have the lack of site-specific data influenced the uncertainty?
- Are parameter values and uncertainty estimates based on analyses of field/laboratory data? Are there any measurement errors etc and how are they considered in the uncertainty estimates? Are there biases in, or poor representativity of, the data and how is this accounted for?
- If data for estimating the parameter have been produced using a model, what uncertainties does this introduce?

Correlations

A correct treatment of the probabilistic problem requires that any existing correlations between input data are identified. The extensive work with the FEP databases and the process reports implies that most functional dependencies between parameters are identified – and the important ones implemented in the safety assessment models. Also, the assessment of impacts from various conditions should cover most potential correlations. Still, other statistical correlations may exist. The following questions are addressed, according to the protocol:

- If the data vary in space or time – is anything known about their autocorrelation structure?
- Is there any other reason (apart from already cited functional relations etc) to suspect correlation between parameters considered as input to SR-Can?

Quantification of uncertainty

Finally, according to the protocol, the various sources of information are combined into quantified data values and uncertainty estimates. Based on their previous assessment, i.e. also considering conceptual uncertainty etc, justified uncertainty estimates of the applicable data are provided by the experts. Depending on possibilities and assessed importance, the uncertainty estimates are given either as a distribution function, subjective percentiles or as a range.

The preferable option is to describe the uncertainty as a distribution function, but the distribution has to be justified. For example, for a spatially varying function, well described by a given stochastic process, e.g. through a variogram or as realised in a discrete fracture network (DFN) description, a potential distribution function may be to state that all realisations of this spatially varying function are equally probable.

Another option is to only provide subjective percentiles ai in the distribution function: $P(x<a_i)=p_i$, i.e. a_i is the parameter value at which the subjective probability that the parameter will take a value less than a_i is p_i. If sensitivity analyses show that only part of the range has an impact on the function, less effort may be given to quantification of the probability distribution of parameter values outside this range.

If distribution functions or subjective percentiles cannot be supplied, the uncertainty may instead be described as a range. However, the meaning of the range must then be provided, e.g. does it represent all possible values, all "realistically possible" values or just the more likely values?

The uncertainty estimates should also provide information on correlations. For spatially/temporal varying functions this includes information on autocorrelation.

Final judgement

Finally the SR-Can team judges whether the expert input can be supported. In particular, the expert input on uncertainties and correlations may need to be interpreted into more closed form mathematical expressions (such as distribution functions), such that it can be used for the assessment calculations. For instance, if a most likely value and an upper and a lower bound have been given, a triangular distribution may be selected by the assessment team.

However, such judgemental selections of the distributional shape can only be motivated if the final risk calculations are insensitive to the details of the distribution. If there is doubt on this matter, calculations are undertaken to demonstrate this insensitivity.

9 Analysis of a reference evolution for repositories at the Forsmark and Laxemar sites

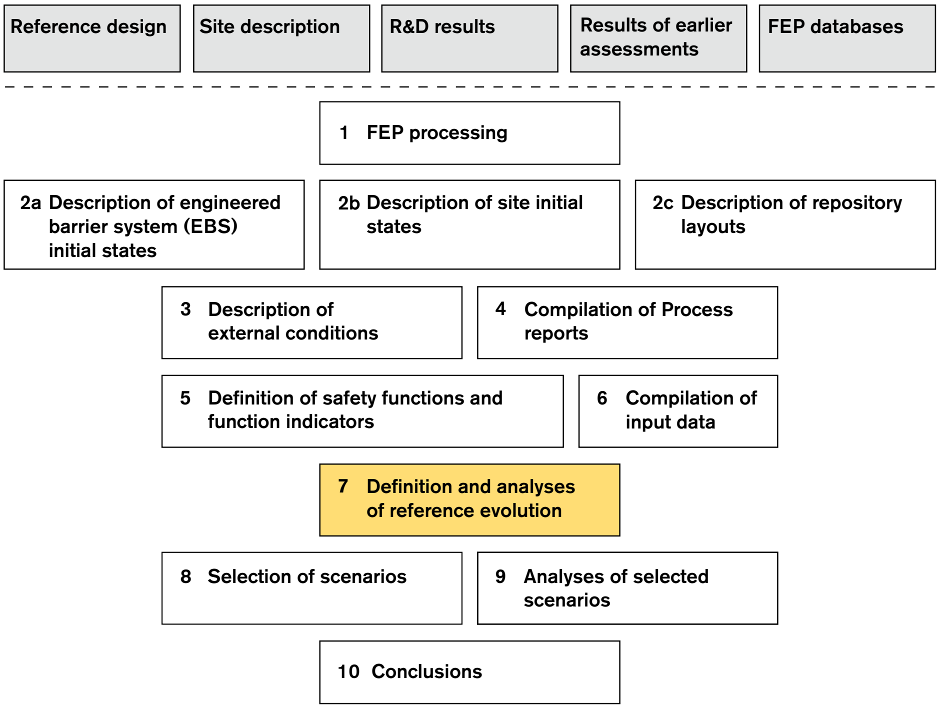


Figure 9-1. *The SR-Can methodology in ten steps (section 2.2), with the present step highlighted. This chapter deals with the definition of the reference evolution and with the analysis of the isolation potential. Retardation is treated in chapter 10.*

9.1 Introduction

This chapter describes a reference evolution of potential KBS-3 repositories at the Forsmark and Laxemar sites over the entire one million year assessment period. The purpose is to gain an understanding of the overall evolution of the system, for the scenario selection and scenario analyses that follow in chapters 11 and 12, respectively. The ambition is to describe a reasonable evolution of the repository system over time. The reasonable evolution is an important basis for the definition of a main scenario, see chapter 11 and, for details, section 12.2.1.

Focus is on the isolation capacity; consequences in terms of radionuclide releases are not analysed. Chapter 10 describes radionuclide transport and dose consequences for canister failure modes identified in the analysis of the general evolution below. In chapter 10, retention properties of the system are analysed for barrier conditions given by the general evolution in the present chapter.

Two variants of the reference evolution are analysed.

- A base variant in which the external conditions during the first 120,000 year glacial cycle are assumed to be similar to those experienced during the most recent cycle, the Weichselian. Thereafter, seven repetitions of that cycle are assumed to cover the entire 1,000,000 year assessment period. The base variant is analysed in sections 9.2 through 9.5.
- A greenhouse variant in which the future climate and hence external conditions is assumed to be substantially influenced by anthropogenic greenhouse gas emissions. This analysis is related to that of the base variant and is presented in section 9.6.

For both variants, the reference initial state described in chapter 4 is assumed and all internal processes are handled according to the specification given in the process report, as summarised in chapter 6.

9.1.1 Detailed prerequisites

Initial state of engineered barriers

The initial state encompasses the entire repository with all 6,000 deposition holes and the initial state relates to the conditions expected in the entire ensemble of deposition holes. This means that if the target value for the saturated buffer density is 2,000 kg/m^3, but, as the case is, the specified tolerance in the reference initial state is 2,000 ± 50 kg/m^3, the latter interval of buffer density needs to be considered in all analyses of the evolution.

The reference conditions for the engineered barrier system given in section 4.2 have, to the extent possible, been derived to meet this requirement. For example, the reference condition of the canister includes welding defects and the tolerances of the buffer density have been defined taking imperfections in deposition hole geometry, variations in raw material composition and imperfections in the manufacturing process into account. This initial state is therefore assumed in analysis of the reference evolution below.

At this stage of the repository programme, it cannot, however, be strictly shown that the reference conditions cover every possible mishap or design deviation with a high likelihood of occurrence. Possible deviations from the reference initial state are further handled in the selection of scenarios in chapter 11.

Geosphere and biosphere initial state

The initial state for the geosphere and the biosphere is that given by the site descriptive models version 1.2 of the two sites, including uncertainties and possible variants as described in section 4.3 and quantified for the purposes of SR-Can in the **Data report**. The site-specific layouts are those described in section 4.4.

Process system

The set of processes governing repository evolution is handled according to the information given in the **Process reports** for the fuel/canister, the buffer/backfill, the geosphere and the biosphere. Uncertainties in process understanding and/or model representation are handled according to the procedures established in these reports.

It should be noted that *all* identified processes are *considered* in the evolution. If, after consideration, a process is excluded, this exclusion is justified in the process report. The handling is summarised in Table 6-2 through Table 6-6 in chapter 6. Data uncertainty as identified in the **Data report** is also considered.

External conditions – base variant

As mentioned in section 5.2, it is not possible to predict future climate evolution in a long-term perspective. Neither is it possible to describe an evolution that can be said to be the most likely. It is very likely though that the potential repository sites in the long-term will experience periods of all the identified climate (see section 5.2.3) domains and all the associated transitions. The reference evolution should, therefore, include periods of temperate conditions including shore-level displacement, both regression and transgression, at different rates, as well as permafrost and glaciation of different extent and also the possible transitions between the domains. A relatively well known evolution including all the mentioned components is the one covered by the Weichselian glacial and the Holocene interglacial, i.e. the evolution from the end of the Eemian (Marine Isotope Stage 5e, see Figure 9-64) at about 120,000 years ago to the present time. In this assessment, this last glacial cycle has been chosen to constitute a reference evolution of climate-related conditions at the potential sites.

The selected external conditions are regarded as one example of a credible evolution during a glacial cycle. The description is neither an attempt to predict a probable future development, nor a “best estimate” of the Weichselian evolution, but a scientifically defensible starting point for the analysis of climate impact on repository safety. It is only necessary to capture the major aspects of the Weichselian at a regional scale, since even if the ice sheet development were to be constructed in more detail for the sites, the impact of any future glaciation will differ at such a detailed level. Instead, the exemplified glacial cycle is complemented by additional scenarios that describe more extreme conditions, with for example larger and smaller ice sheets.

The analysis of the evolution is initiated by a 1,000 year long period within which the development is based on extrapolation of current evolution and trends. Thereafter, the analysis is based on a model reconstruction of the Weichselian glacial cycle as it evolved from 120,000 years ago until the present day. At 120,000 years ago, the climate-related conditions are considered to have been similar to those existing at the present. For the remainder of the assessment period, this 120,000 years long glacial cycle is assumed to be repeated.

The reason for choosing the Weichselian as the reference evolution is twofold. Firstly, it is the best known of the past glacial cycles and the evolution and variability of climate-related conditions can be investigated by reference to associated geological information. Secondly, the available geological information makes it possible to test or constrain the supporting analysis and modelling efforts aiming at process understanding and the studies of the, often complex, coupled processes related to climate changes.

External conditions – greenhouse variant

An additional factor related to future climate evolution is introduced by the impact and duration of human influence on climate due to emissions of greenhouse gases. Recent studies envisage a very long period of relatively warm climate conditions /e.g. IPCC 2001b, BIOCLIM 2003/.

Therefore, as a variant of the evolution based on the repetition of the last glacial cycle, a greenhouse variant comprising a 50,000 year long period of temperate domain, followed by the first, relatively mild, 70,000 years of the base variant is analysed (section 9.6). The climate and climate-related conditions during the long period of temperate domain are based on results from SWECLIM /Rummukainen 2003, Tjernström et al. 2003, BIOCLIM 2003/, and on the shore-line migration resulting from melting of the Greenland ice sheet, corresponding to a sea-level rise of 7 m /**Climate report**, section 4.3/. For further details on the chosen approach regarding the greenhouse variant, see the /**Climate report**, section 4.3/.

The analyses of this variant is based on the analysis of the conditions within the relevant climate domains from the reference evolution.

The perturbation of the natural climate variations is assumed to remain until the emitted greenhouse gases, primarily carbon dioxide, have been lost from the climate system. Carbon dioxide is the most important and most persistent of these gases and is eventually lost by incorporation into sediments. The timescale for this process to occur has been estimated at 200,000 years /Archer et al. 1997/.

Under general global warming conditions, there is a possibility of regional cooling in Scandinavia caused by changes in ocean circulation /e.g. Rahmstorf and Ganopolski 1999/. Implications of external conditions more extreme than in the reference evolution are analysed in chapter 12, essentially by investigating the most severe conditions in terms of repository safety that could occur within the permafrost and glacial domains. External conditions related to future human actions other than human-induced climate change are excluded from the analysis of the reference evolution. Such future human actions are treated in section 12.10.

9.1.2 Structure of the analysis

The presentation of the analysis of the base variant of the reference evolution is divided into four time frames:

- The excavation/operational period, section 9.2.
- The first 1,000 years after closure and the initial period of temperate domain from the reference glacial cycle, section 9.3.
- The remaining part of the glacial cycle, section 9.4, and
- Subsequent glacial cycles up to one million years after closure, section 9.5.

In section 9.6, the greenhouse variant is analysed over an entire glacial cycle.

For each time frame, issues are presented in the following order:

- climate issues,
- biosphere issues,
- thermal, mechanical, hydraulic and chemical issues in the geosphere, and

- thermal, mechanical, hydraulic and chemical issues for the engineered barrier system (canister, buffer and backfill).

The commentary on each time frame concludes with a discussion of the expected status of the safety function indicators defined in chapter 7 during and at the end of the time frame.

A considerable part of the material presented is results from simulation studies. An overview of these studies is given in the assessment model flow chart, AMF, for the excavation/operation period, the first 1,000 years after closure and a continued warm period, section 6.5 and Figure 6-3. Table 6-7 explains how the modelling activities in the AMF are documented and the processes that are handled by each model. An AMF for permafrost and glacial conditions is given in Figure 6-4, with the associated Table 6-8.

Figure 9-2 shows the safety functions of the repository system and the safety function indicators used to evaluate whether the safety functions are maintained, as defined in chapter 7. The safety functions in Figure 9-2 are referred to in the following sections, to explain the safety-related purposes of the analyses undertaken in the evaluation of the reference evolution.

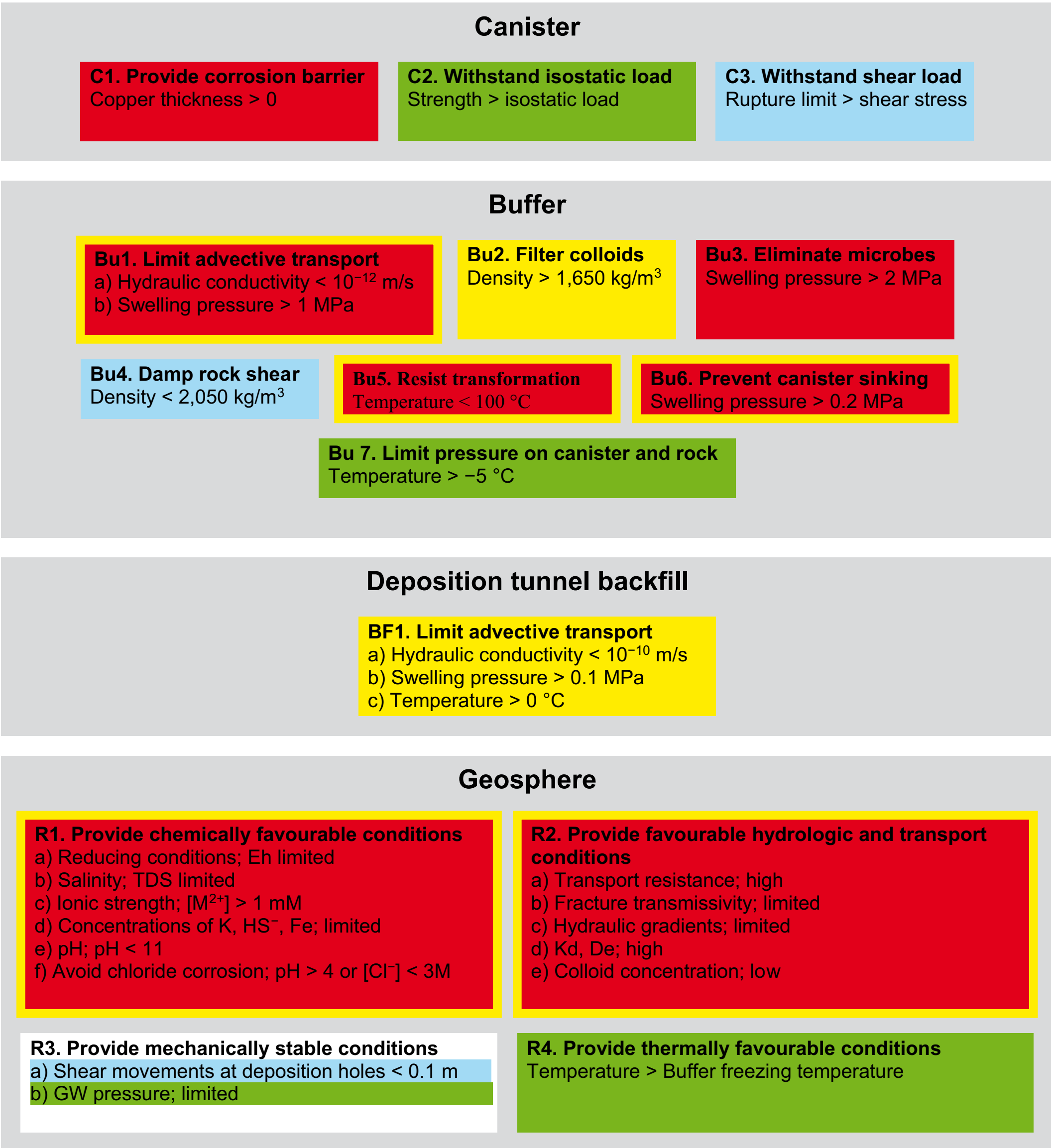


Figure 9-2. Safety functions (bold), safety function indicators and safety function indicator criteria. When quantitative criteria cannot be given, terms like "high", "low" and "limited" are used to indicate favourable values of the safety function indicators. The colour coding shows how the functions contribute to the canister safety functions C1 (red), C2 (green), C3 (blue) or to retardation (yellow). Many functions contribute to both C1 and retardation (red box with yellow board).

9.2 The excavation and operation phases

The analyses for the excavation and operation phases of the repository have mainly focused on disturbances of the mechanical, hydrological and chemical conditions induced by the excavation/operational activities.

The duration of this stage can be assumed to be several tens up to a hundred years, depending on the progress of the excavation/operational activities and the total number of canisters to be disposed.

9.2.1 Thermal evolution of the near field

The undisturbed rock temperature at repository depth is around 11°C and 14°C at the Forsmark and Laxemar sites, respectively /**Data report**, section 6.2/. As the rock is excavated, this temperature will be slightly affected by ventilation of the excavate volumes. This effect is small and of negligible significance compared with the thermal impact of the residual radioactivity of the gradually deposited spent nuclear fuel. This will alter the rock temperature for thousands of years and is, therefore, handled in more detail in section 9.3.4, which is part of the description of repository evolution during the initial period of temperate climate after closure.

Since the repository is gradually excavated and operated, the impact of the residual radioactivity will occur also during the excavation/operational phase. The safety relevant issue is, however, the peak temperatures over time and, for the determination of these, it is sufficient to assume that all waste is emplaced simultaneously. This is further discussed in the **Geosphere process report**, section 2.1.

9.2.2 Mechanical evolution of near field rock due to excavation

The rock mass at repository depth is under a pre-stressed condition, namely the in situ rock stress. Repository excavation, i.e. removal of rock, implies a major, but essentially local, rock mechanics impact. This raises several issues of concern for the construction work, such as the risk of breakouts into excavated volumes, spalling or key block instability. These engineering-related rock mechanics issues are evaluated within the framework of the repository design work and reported by /Brantberger et al. 2006/ for Forsmark and /Janson et al. 2006/ for Laxemar. However, since most of these impacts concern phenomena that occur during construction, i.e. long before waste emplacement, they do not directly impact long-term safety. The properties of the excavation-peripheral rock may, however, after excavation differ from the properties inferred from the SDM based on pre-excavation site data. From a safety point of view, the issue is whether the excavation phase would affect the safety functions of the rock mass.

The following mechanical processes related to the excavation and the open phase could have potential safety implications (the safety functions refer to Figure 9-2):

- Development of an Excavation Damaged Zone (EDZ) and other impacts on rock permeability (safety function R2a).
- Spalling, (safety function R2a and also safety functions of the buffer that either directly or indirectly depend on buffer density).
- Reactivation of fractures (safety function R3a).
- Induced seismicity (safety function R3a).

These issues are assessed in the following subsections.

Development of an EDZ and other impacts on rock permeability

The possibility that the damage done to the rock during excavation will result in zones of increased axial permeability has long been considered. The EDZ is defined as "the part of the rock mass closest to the underground opening that has suffered irreversible deformation where shearing of existing fractures as well as propagation or development of new fractures has occurred" /Bäckblom et al. 2004/. Clearly, there may also be reversible effects that, together with pure hydrodynamical changes, may impact on the inflow to open tunnels. However, these "skin effects" are of limited importance for the long term safety functions.

The EDZ has been addressed in topical overviews, e.g. /Winberg 1991, Tsang et al. 2005/ and in various conceptual studies /Pusch 1990, Pusch and Stanfors 1992/. The ZEDEX experiment conducted at the Äspö HRL was specifically designed to compare drill and blast damage with damage found in a nearby and parallel tunnel excavated with a tunnel boring machine /Emsley et al. 1997/. For the safety analysis, the issue is to estimate the width of the EDZ and assign it the relevant hydraulic properties. More recently, SKB has conducted EDZ studies in connection to the excavation of the TASQ tunnel at the Äspö HRL /Olsson et al. 2004/.

The ZEDEX experiment was conducted particularly to examine the integrated effects of disturbances caused by stress redistribution and direct excavation damage, whereas the currently used EDZ definition relates only to direct damage. Two nearby and parallel tunnels were used for the study. One of the tunnels was excavated with different drill and blast techniques (D&B), whereas the other was excavated mechanically with a tunnel boring machine (TBM). As expected, the depth of damage was found to be much less in the TBM tunnel (about 0.03 m) than in the D&B tunnel (0.3 m to 0.8 m) /Emsley et al. 1997/. Also the nature of the damage was different in the two tunnels. In the TBM tunnel, there was modest induced micro-fracturing, whereas there was evidence of induced macro-cracks in the D&B tunnel.

The evaluation of the ZEDEX experiment did not include direct measurements of the axial conductivity of the damaged zone, meaning that there is still a lack of knowledge regarding relevant permeability values to be supplied to hydrogeological models to be used in the safety analysis. Analyses of core samples suggested some local permeability increases, but these could not be shown to represent values relevant along a continuous zone of connected fractures /Emsley et al. 1997/.

The TASQ tunnel at ÄSPÖ HRL was excavated specifically to accommodate the Äspö Pillar Stability Experiment. This experiment required well-defined conditions in the floor region with a minimum of excavation damage. The D&B technique used for the excavation included a number of procedures to limit the extent of the EDZ /Olsson et al. 2004/. Usually, there is a thicker damaged zone below the floor caused by the heavier explosive charges used close to the floor in conventional drill and blast excavation, but it is possible to excavate the floor sections using "smooth blasting" techniques, which result in a damaged zone similar as in the walls and roof of the tunnel, see e.g. /Autio et al. 2004/. Excavation of top and bench separately, for instance, meant that smaller specific charges could be used for the floor contour holes. The extent of the EDZ was studied by sawing several slots in the tunnel wall, see Figure 9-3.

Several conclusions were drawn including the following:

- To excavate the deposition tunnel in two steps, first excavating a top heading and then the bottom bench, gives significantly less damage in the floor compared with ZEDEX experience; even less than in the roof and walls.
- For "typical" tunnel construction, based on current Swedish practice, the observed excavation damage is similar to that observed in the ZEDEX D&B tunnel.

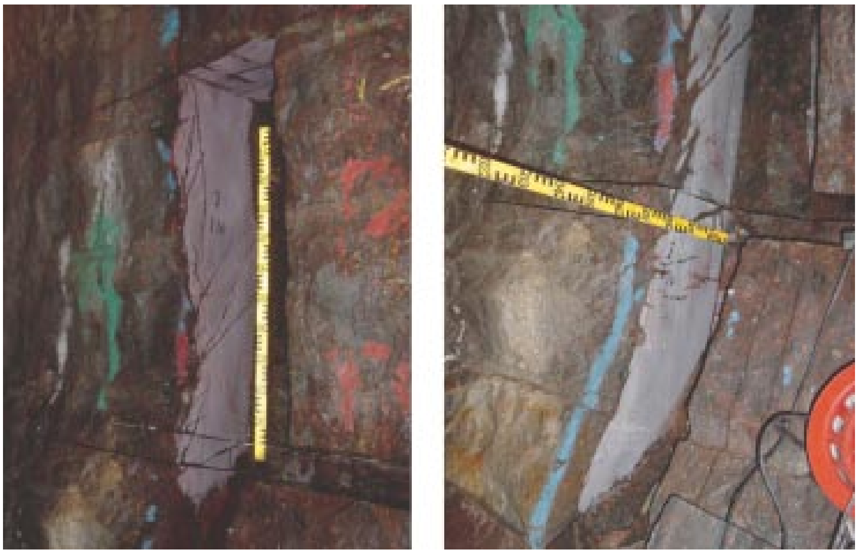


Figure 9-3. *Example of EDZ as observed by sawing a slot in the tunnel wall after excavating the TASQ tunnel at the Äspö HRL.*

- The blasting boreholes are slightly oriented out from the mean tunnel periphery, i.e. the blasting boreholes are not exactly parallell to the tunnel wall, and the specific charge distribution is not uniform along the blasting holes. These factors result in a discontinuous EDZ along the tunnel. It is, therefore, concluded that the impact of the EDZ on hydraulic conductivity along the tunnel is very small, because it is manageable through D&B design and QA control during excavation.
- The reasons for local significantly larger extension of the EDZ are well understood. They are most likely manageable in a systematic QA program during excavation. To implement appropriate quality plans and ensure their application in the execution of a tunnelling project may require special care and training.

In conclusion, it is reasonable to assume that in general, provided that proper excavation techniques and QA control are applied, the EDZ, if it develops at all, will be limited to a narrow zone (a few tens of cm) close to the tunnel and that it will not form a continuous hydraulically conductive path. Possibilities for more extensive fracturing would only occur as a consequence of poor engineering and inadequate QA practices, including the possibility that the tunnel is excavated sub-parallel to a joint set so that the EDZ fractures link to the joint set.

It is likely that conditions leading to more extensive fracturing could be avoided, although the importance of the EDZ need also be related to other potential design constraints for the deposition tunnel. Furthermore, it may also be possible to take some engineering actions, like the installation of plugs, to interrupt the EDZ at some intervals in the tunnel and eliminate enhanced hydraulic connectivity if it is found to arise despite the precautions taken during construction. However, for the purposes of SR-Can it is of interest to explore the potential importance of the EDZ and the necessity for controlling its impact. For this reason two different cases have been studied, as listed below.

1. The expected conditions are that the tunnel excavation work is performed with the intent of limiting the EDZ and with application of the necessary QA. In this case, the EDZ is likely to be be limited in spatial extent and discontinuous. Based on the observations made at the TASQ tunnel at the Äspö HRL, it is assumed that the rock permeability parallel to the axis of the tunnel will be increased by about half an order of magnitude over a thickness of 0.3 m, but due to the drill and blast techniques used the EDZ will occur in 5 m sections with 0.5 m breaks of undamaged rock between. However, in the flow modelling, see e.g. section 9.3.6, the EDZ is cautiously assumed to be continuous, but of low permeability.
2. A limiting case is to assume conventional and drill-and-blast of the tunnel, without applying any special QA procedures for controlling the EDZ. This may possibly create a continuous damaged zone, primarily in the tunnel bottom. This case is assessed by increasing the hydraulic conductivity of the EDZ in the flow model, but keeping the size, by two orders of magnitude. This increase is selected rather arbitrarily, but is judged typical, in order to assess the importance, if any of a significant EDZ. The EDZ would in this case anyway be much more permeable than the surrounding rock mass.

The **Data report** provides more detail and the actual values used in the analyses of these cases.

Spalling

If the initial, pre-excavation, stresses are sufficiently high, spalling may occur during the operational phase in response to the stress redistribution caused by excavation, in particular if the deposition tunnels are oriented normal to the major initial stress (see e.g. **Geosphere process report**, section 4.4.). In cases where the initial rock stresses are not sufficient to produce spalling, there is still the possibility that spalling may occur later because of the thermal load from the emplaced spent nuclear fuel. The potential occurrence of spalling is thus site and repository design specific, as it depends on the in situ stress, the intact rock uniaxial compressive strength (UCS), the ratio between the spalling strength and the UCS and, for the heated phase, on the repository layout. Experiences also suggest that it requires a very small confining pressure (≈ 150 kPa) to supress the spalling.

The likelihood, extent and characteristics of spalling in full-scale KBS-3 deposition holes are being examined experimentally within the APSE experiment in the Äspö HRL /Andersson and Eng 2005/. The APSE experiment is also aimed at improving the understanding of the details of the process, for instance the importance of small support pressures for suppressing initiation of spalling and, for unsupported walls, values of the spalling strength. The present view is that the spalling strength of the APSE rock is about 55% of the laboratory-determined UCS.

Estimates of the likelihood and extent spalling in deposition holes, are made using results obtained from 3DEC near-field models /Hökmark et al. 2006/, and by use of observations from the isothermal phase of the APSE experiment. These analyses are complemented by analytical analyses by /Martin 2005/.

- For Forsmark, /Hökmark et al. 2006/ concluded that the spalling threshold was not exceeded anywhere after completed excavation. However, the result is sensitive to uncertainty and variability of the in situ stress, the ratio between the spalling strength and the uniaxial compressive strength (UCS) of the rock and to the uncertainty and variability of the UCS. For example, had the limiting stress/strength ratio been 40% rather than the assumed 55%, then the rock would have been at the limit of failure already during the operational phase. These findings are in general agreement with the results of /Martin 2005/. He concluded that at a depth of 650 m the probability of spalling in deposition holes is less than one percent. However, it should be noted that below a depth of 500 m there is less confidence in the in situ stress magnitudes used in the analyses and the analyses also makes some simplifying assumptions. Nevertheless, it is judged that very few deposition holes will experience spalling during the operational phase.
- At Laxemar spalling in the deposition holes, during and after excavation, is estimated to be significant and increase with depth below a repository depth of 450 m. At 550 m depth, the probability of spalling is approximately 20% whereas at a repository depth of 650 m the probability of spalling increases to approximately 60%, but the analyses also show that the corresponding depth of spalling is limited. This means that there will be some likelihood of spalling in deposition holes at 500 m, even if the volume change may be so small that, possibly, few, if any, deposition holes would need to be discarded for this reason, but the results are sensitive to the uncertainties in stress and rock mechanics properties. Furthermore, criteria for accepting deposition holes with volume changes remain to be firmly specified.

Spalling that takes place during the operational phase, in open deposition holes, does not have to be important for performance and safety. Detached rock fragments can be removed and cavities can be filled with, for instance, pieces of bentonite or with bentonite pellets before or during installation of the bentonite buffer. For the few instances in which this is not possible, the holes will be discarded for deposition, with no safety consequence. However, procedures for handling deposition holes with initial spalling need to be established as part of the engineering work, see section 13.6.4.

In conclusion, there are no safety related impacts of the few cases of spalling prior to canister emplacement expected for Forsmark or Laxemar.

Reactivation of fractures

The stress redistribution resulting from the tunnel excavation may, in principle, reactivate existing near-field fractures. The process has been modelled in a set of numerical analyses /Hökmark et al. 2006/, using the 3DEC code to determine stress redistribution effects in fractured near-field rock. The results have also been used to estimate possible permeability changes caused by shear and normal fracture movements.

/Hökmark et al. 2006/ analysed the near field of a KBS-3 repository at both Forsmark and Laxemar. The design and layout were in accordance with the rules laid down by SKB /SKB 2004b/ and implemented in the proposed designs for Forsmark /Brantberger et al. 2006/ and Laxemar /Janson et al. 2006/. The canister spacing, for instance, was set with respect to the predicted mean thermal conductivity. In contrast, the fracture system was specified a few specified fractures representing the different fracture orientations at the sites. A small number of fractures intersecting the near field at different angles and at different positions in relation to the central part of the model were defined, thereby allowing general conclusions to be drawn about the mechanical and hydro-mechanical response of differently located and orientated fractures. Figure 9-4 shows the geometry of the Forsmark model. The geometry of the Laxemar model is basically the same, but with a different canister separation. For further details of the models, description of boundary conditions etc, see /Hökmark et al. 2006/.

The numerical analysis covers a series of events ranging from excavation of tunnel to the mechanical effects of glacial load with boundary stresses obtained from preliminary results from on-going simulations of mechanical ice/crust/mantle interactions. The model results are repeatedly referred to in this chapter, as concerns near-field mechanical analyses.

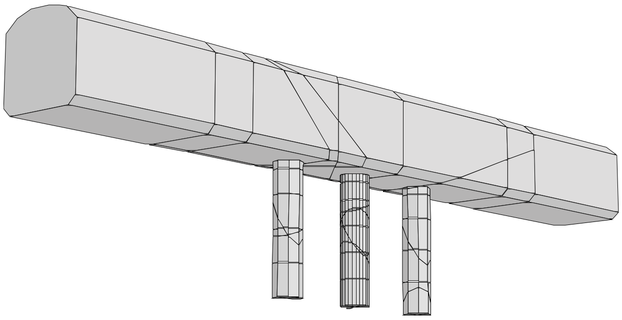


Figure 9-4. *3DEC near field models: excavated volumes.*

The results of 3DEC models were used, together with different stress/transmissivity models and experimentally obtained displacement-transmissivity relations, to explore the effects of fracture movements on the hydraulic conditions in the near-field, see e.g. Figure 9-5.

For the rock mass response to the excavation of tunnels and deposition holes, /Hökmark et al. 2006/ made the following observations:

- The joint normal stress possibly relaxes in some of the fractures. However, because of the non-linear relations assumed to apply for single fractures, it takes substantial relaxations to increase the transmissivity in any significant way. Before canister emplacement and heat loading, the maximum relative transmissivity increases are in the range of 10 to 20% for fractures that intersect deposition holes at depths larger than about 1.5 m below the tunnel floor. For fractures that are parallel to the tunnel walls or the tunnel floor and located within about 1.5 m, the normal stress reductions are considerable and the transmissivity increase may locally amount to between one and two orders of magnitude.
- Shear displacements are generally less than 1 mm, before the effects of the subsequent heat load are taken into account. Experimental data used to develop an empirical relation between fracture shear movement and transmissivity determined by /Olsson 1998/, clearly suggest that this is too small to cause any significant impact on fracture transmissivity.

In conclusion, the reactivation of fractures caused by the stress redistribution, other than the potential damage as assessed in the EDZ, only results in insignificant increases of transmissivity in near-field fractures.

Induced seismicity

The excavation activities may, in theory, induce seismicity through the generation of new fractures or reactivation of pre-existing fractures. However, as argued in the **Geosphere process report,** none of these possibilities need further consideration in SR-Can, for the reasons briefly discussed below.

Data from deep South African mines show that excavation in rocks deficient in faults, having low fracture intensities *and* high stresses might generate fracturing in pristine rock /Bäckblom and Munier 2002/. However, according to /Ortlepp 1997/, such fracturing has only been positively demonstrated in South African mines. Elsewhere, such seismic events typically have magnitudes that are less than 3.5 and require in situ stresses above 50% of the unconfined intact rock strength /Martin et al. 2001/. To produce seismic events more severe than minor slabbing, the major in situ stress must be about 40% or more of the unconfined compressive intact rock strength, i.e. typically 70–85 MPa.

The repository will be located in fractured bedrock at intermediate depth where stresses are moderate. The major principal stress, at repository depth, is at Forsmark typically about 20% of the strength of the dominating rock types and less than 20% at Laxemar.

Therefore, the possibility of excavation-induced seismic fracturing need not be considered in SR-Can.

The excavation activities may also trigger seismic events by reactivating existing faults /**Geosphere process report/**. There is, however, no evidence that present-day deviatoric stresses in Swedish bedrock are sufficient to power seismic events of a magnitude that can jeopardise canister integrity. The rate of excavation will be fairly low which is an additional factor that counteracts induced seismicity /e.g. Ortlepp 1992a/.

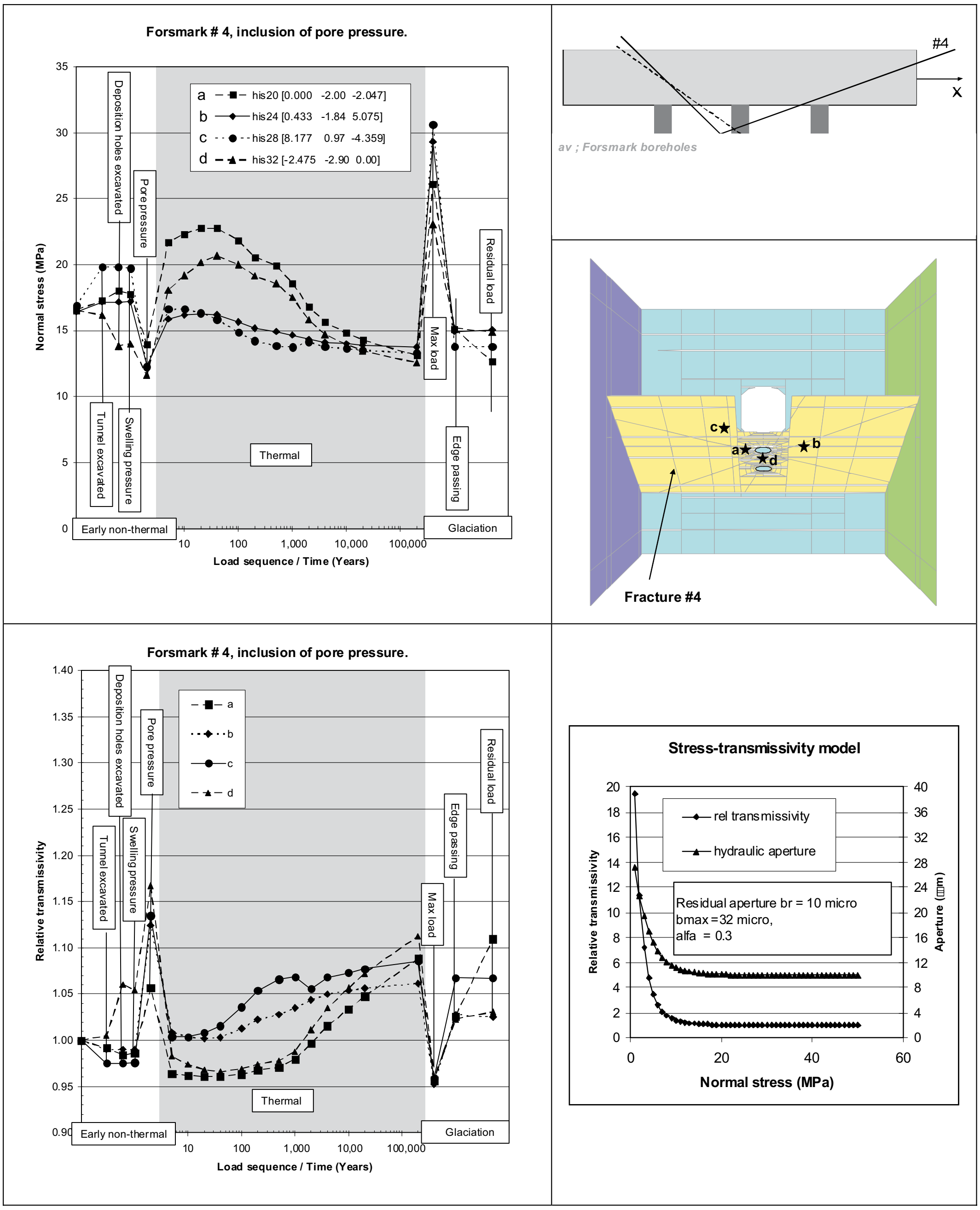


Figure 9-5. Change in normal stress (upper left) and relative transmissivity (lower left) on some points on fracture #4. The relation used to calculate the relative transmissivity is shown in the lower right part.

Unlike earthquakes triggered by the construction of dams /Scholz 1990/, mining-induced earthquakes rarely exceed magnitude 5. The largest mining induced earthquake recorded in the South African gold fields occurred in 1977 in the Klerksdorp mining district and was assigned a magnitude of 5.2 McGarr quoting Fernandez and van der Heever 1984 in /Lee et al. 2002/. In fact, most classification systems /e.g. Ortlepp 1992b/ are restricted to smaller events. A survey of mining-induced seismicity in Sweden /Larsson 2004/ was not able to positively demonstrate any magnitudes exceeding 4. This conclusion is also supported by data included in the seismic catalogue of the Swedish Seismological Network /Bödvarsson 2002, Bödvarsson 2005/.

To jeopardise the integrity of the canister, the earthquake must be larger than magnitude 6 /Munier and Hökmark 2004, Fälth and Hökmark 2006/. Though there is a possibility that a fracture across a deposition hole can be triggered to slip due to stress changes, a fracture able to host a slip exceeding the canister failure criterion (10 cm) must have a considerable area and would, by itself, correspond to a magnitude 4–5 event. Such fractures will be detected during tunnel mapping (see also section 4.4.1) and the associated deposition holes will not be used.

It is, therefore, concluded that the possibility of excavation-induced fault slip need not be considered in SR-Can.

9.2.3 Hydraulic evolution in the geosphere

Repository excavation and operation imply a major impact on groundwater flow, since the excavated tunnels will be at atmospheric pressure resulting in inflow of water. The inflow will result in a re-direction of flow and in changes of the groundwater flow pattern, potentially resulting in draw-down of the water table, infiltration of near-surface waters into the deeper parts of the bedrock, and in upconing of saline water from depth. The actual impacts primarily depend on the permeability distribution of the rock, the repository layout and on the tightness of the underground construction, which in turn depends on the grouting efficiency. In order to assess the magnitude of these impacts, groundwater flow simulations, based on the hydraulic models developed as part of the SDMs of Formark and Laxemar, have been performed. The overall objective has been to assess the effects of an open repository on site hydrogeological and hydrogeochemical conditions, i.e. safety functions R1 and R2 in Figure 9-2.

The expected effects with relevance for long-term safety are mainly related to changes in groundwater chemistry that may persist long after closure of the repository. Inflows during the operational phase are mainly relevant for construction issues, whereas near-surface effects such as lowering of the ground-water table are of primary interest for the environmental impact assessment.

Effects of an open repository on deep rock conditions

An open repository may affect the hydrogeological system and flow conditions on a regional scale. However, there is also an interest in assessing inflow into individual tunnels and deposition holes of the repository. This calls for a modelling methodology that can resolve the geometry of the repository with high enough detail while still capturing the regional scale, albeit with lower resolution. Modelling of groundwater flow, with emphasis on deep-rock conditions, has been performed using the code DarcyTools /Svensson et al. 2004/ and is reported in /Svensson 2005/ for the Forsmark site and in /Svensson 2006a/ for the Laxemar site. The multiple scales are dealt with using an unstructured grid enabling flexible meshing.

Forsmark

In the **Data report** (section 6.5), the main alternative model concepts for describing the bedrock are presented. These are a multi component Continuum Porous Medium (CPM) model based on multi-component homogenous properties derived for the site, an Equivalent Continuum Porous Medium (ECPM) model with heterogeneous properties based on the use of an underlying discrete fracture network (DFN) concept, and a pure DFN-representation in model volumes close to the repository, sur-rounded either by a CPM or ECPM representation further out. In the assessment of the open repository, the CPM concept is chosen. The reason is twofold; first, groundwater flow, rather than solute transport, is of main interest (and thus averaged conductivity values suffice), and second, a fully coupled density driven flow solution is needed since salinity effects are important. For a pure DFN application, density driven flow may only be accounted for in a more approximate manner, see further section 9.3.6.

The extent of the model is 15 km (northeast) by 11 km (northwest) with a depth of 2.1 km. This is identical to the regional model provided by the Forsmark 1.2 SDM /SKB 2005c/. Also, the structural and hydraulic properties of the model are consistent with the Forsmark 1.2 hydrogeological SDM as expressed in the CPM interpretation. The main deformation zones and CPM blocks are presented in Figure 9-6. It is noted that block CPM3, where the repository is located, has a very low hydraulic conductivity value of $K = 10^{-11}$ m/s. It is also noted that the deformation zones are treated explicitly and are not incorporated in the CPM blocks.

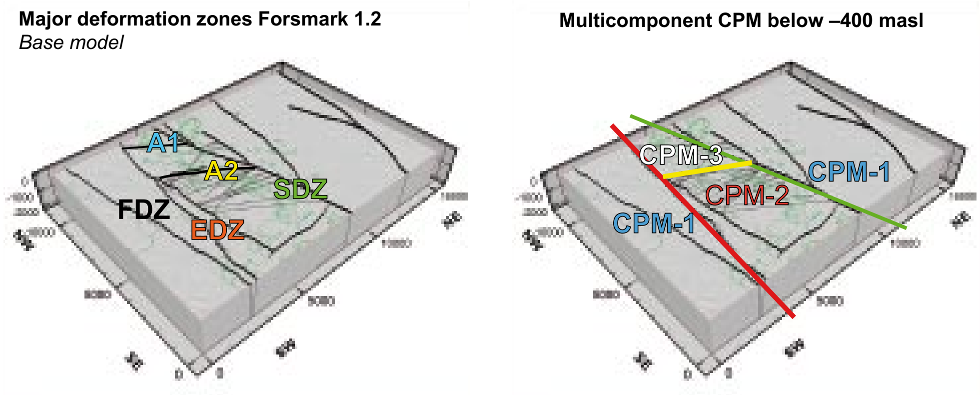


Figure 9-6. *Deformation zones (left) and rock blocks between the zones (right) /Follin et al. 2005/.*

Boundary conditions and other aspects of model specification are presented in detail in /Svensson 2005/. No formal calibration was performed in order to try to match surface hydrogeological features such as flow rates in streams or recharge/discharge patterns on the surface. However, without the repository present, the model reproduces known conditions in a general sense. For the open repository application, the tunnels are set to atmospheric pressure.

In Figure 9-7 the permeability field around the repository is shown. It is clearly seen that only a few high permeability zones cross the southern part of the repository and that no zones are located in the northern part. The deformation zones crossing the repository have a transmissivity of 10^{-7} m^2/s or lower. It is clear from this illustration that the total inflow to the repository will be small and that deposition tunnels in general are located in low permeability rock; i.e. the repository design avoids deposition hole locations in the larger hydraulic features.

Very low inflows to the tunnels are predicted with the model, cf Table 9-1. Even without any grouting, the total inflow to all tunnels is only 4 l/s. With grouting, such that the highest allowed conductivity of the rock surrounding the tunnels is $1\cdot10^{-9}$ m/s with a grouted thickness of 4 m, the inflow is reduced to roughly 2 l/s. These results indicate that the influence of the repository on the flow system is modest. Since inflows are small, also the upconing effects and salinity changes at repository depth are small. However, pressure effects are observed at repository depth. If no grouting is applied, the pressure is close to atmospheric and nearly uniform in the repository area, whereas the background pressure dominates when grouting is significant. Pressure effects can hence be large at repository level. Conversely, closer to the surface at a depth of 50 m below sea level, only small differences (head differences of 1 to 2 m) are observed when undisturbed conditions are compared with the case with an inflow of 4 l/s. It is finally observed that the grouting levels of 10^{-9} and 10^{-11} m/s are somewhat hypothetical; levels of 10^{-9} are rarely achieved using cement grout, whereas levels of 10^{-11} m/s are never obtained in practice.

It is observed that the hydraulic effects of an initially open repository in combination with the effects of subsequent decay heat from the emplaced canisters in the back-filled repository are not considered here. Such analyses have been performed elsewhere by e.g. /Löfman 2005/ and indicate that up-coning is influenced by the combined effects of pumping followed by heat generation. In SR-Can, thermal effects are analysed in the context of the back-filled repository, see section 9.3.6. However, in SR-Site the case with pumping followed by heat generation will be addressed.

An additional analysis of inflow into individual deposition holes /Svensson 2006b/ using the same model as described above indicates that 99.9% of all deposition holes in the Forsmark repository will have an inflow smaller than 0.01 l/min when no grouting is applied.

Table 9-1. Total inflow for different grouting criteria.

Maximum allowed conductivity [m/s]	Inflow [l/s]
Infinite	4.0
10^{-7}	4.0
10^{-9}	1.9
10^{-11}	0.05

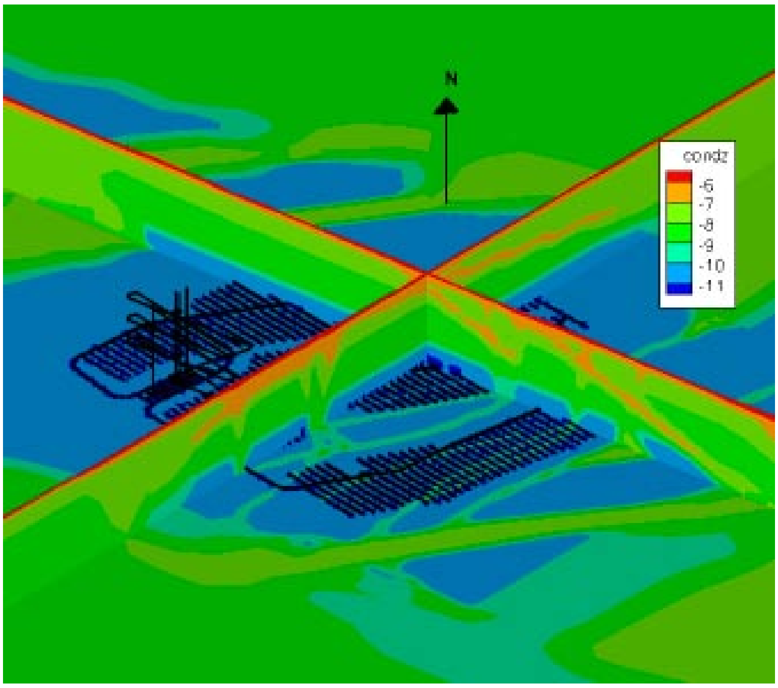


***Figure 9-7.** The log_{10} vertical hydraulic conductivity [m/s] in a horizontal plane (at 415 m below sea level) around the repository.*

Laxemar

In the **Data report** (section 6.5), the model concept for describing the bedrock on a regional scale at Laxemar is presented. The adopted model is an Equivalent Continuum Porous Medium (ECPM) model with heterogeneous properties based on the use of an underlying discrete fracture network (DFN) concept. It is noted that the confidence in the SDM is lower at Laxemar than at Forsmark; see discussion at the end of section 4.3.3 and section 6.5 of the **Data report**.

The extent of the model is approximately 20 km (east-west) by 15 km (north-south) with a depth of 2.1 km and follows regional surface water divides. This is identical to the regional model provided by the Laxemar 1.2 SDM /SKB 2006b/. Also the structural and hydraulic properties of the model are consistent with the Laxemar 1.2 hydrogeological SDM; however, two main differences are noted. First, the model used for the open repository simulations applies the characteristics of hydraulic rock domain A to the whole model, whereas, in reality, the system comprises several domains. Most notably the so-called domain DEM, in which part of the repository is located, has assumed properties of the more permeable domain A in the present application. The reason is a current limitation in the code DarcyTools in which only one up-scaled DFN domain can be used. For reasons of conservativeness, domain A was chosen. Second, low-confidence deformation zones, see Figure 4-37 in section 4.3.3, were not included in the model, since they were not considered by Engineering Design when producing the repository layout.

The methodology is consistent with the one used for Forsmark, and is presented in detail in /Svensson 2006a/. One difference is observed; for the Laxemar case, the model explicitly treats the different time periods when different parts of the repository are open. The different parts are illustrated in Figure 9-8 below.

The resulting inflows for the two grouting efficiencies 10^{-9} and 10^{-7} m/s are shown in Table 9-2 and Table 9-3, respectively. Without grouting, the model predicts a drawdown approaching repository depth, i.e. a condition the code cannot handle. In the tables, it is seen that a two order of magnitude decrease in grouting efficiency roughly doubles the total inflow. The sum of the inflows to the individual sections is slightly larger than the inflow for the case with all sections open at the same time.

The model predicts influence areas, defined as drawdown greater than e.g.1 m, of several km^2 for both grouting efficiencies. Locally above the repository, drawdowns of greater than 50 m are observed for the lower grouting efficiency, see Figure 9-9.

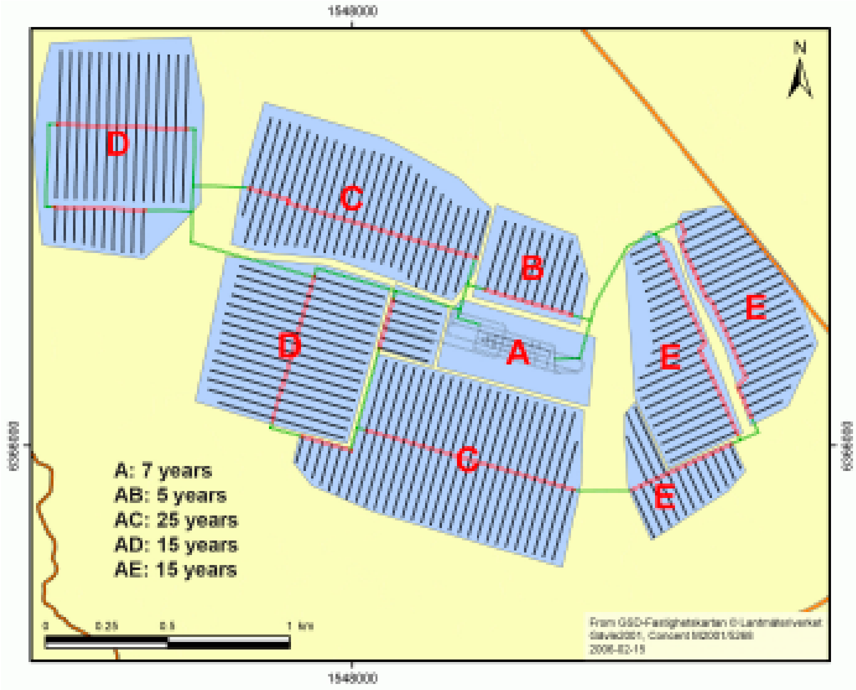


Figure 9-8. *Illustration of different parts of the repository.*

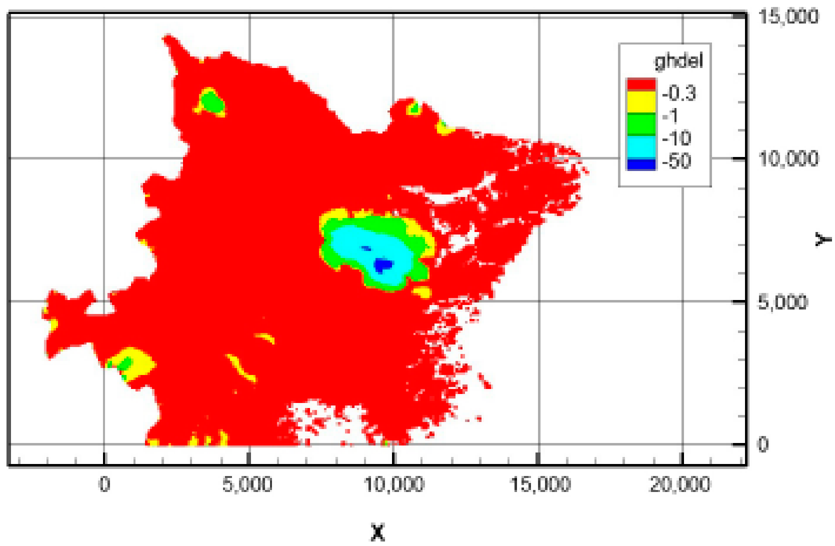


Figure 9-9. *Drawdown at ground level for the case with the whole repository open and a grouting efficiency of 10^{-7} m/s.*

Table 9-2. Inflow (in l/s) to different tunnel sections as a function of time. The opening times in years are given in brackets. Grouting to a resulting maximum conductivity of 10^{-9} m/s.

Tunnel section	Open section A (7)	AB (5)	AC (25)	AD (15)	AE (15)	All (5)
A	4.4	4.2	3.7	4.2	4.5	3.2
B		2.2				1.8
C			15.2			12.9
D				9.5		8.2
E					7.2	6.6
Total inflow	4.4	6.4	18.9	13.7	11.7	32.7

Table 9-3. Inflow (in l/s) to different tunnel sections as a function of time. The opening times in years are given in brackets. Grouting to a resulting maximum conductivity of 10^{-7} m/s.

Tunnel section	Open section					
	A (7)	AB (5)	AC (25)	AD (15)	AE (15)	All (5)
A	14.0	13.1	9.6	16.3	18.3	7.8
B		4.1				2.9
C			27.6			21.8
D				15.3		12.2
E					12.7	10.7
Total inflow	14.0	17.2	37.2	31.6	31.0	55.4

Very limited up-coning is predicted by the model. The reasons may be due to the fact that the repository essentially is located in a fresh water region and the response stays above the salinity interface. Also the assumed depth dependency in hydraulic conductivity may limit the up-coning. Finally, the vertical conductive deformation zones acting as a "water curtain" may limit the drawdown and thus also the up-coning.

The additional study of inflows into deposition holes /Svensson 2006b/ indicates that for ungrouted conditions less than 2% of all deposition holes will have an inflow larger than 1.0 l/min. This will increase to about 20% if the inflow limit is put to 0.1 l/min. The study also reveals a strong correlation between flows in deposition holes during open and saturated, back-filled conditions. This indicates that deposition holes with possibly poor performance due to high flows during saturated conditions can be identified during the open repository phase.

All results reported for Laxemar need to be considered provisional given the uncertainty in the SDM and also in how the SDM has been represented in the current model. Furthermore, the current layout did not really address the proper design and location of the access and ventilation ramps and shafts, see section 4.4.1.

Effects of an open repository on near-surface conditions

Even if the analysis of the deep-rock conditions indicates modest influences of the open repository on groundwater flow conditions, it is of interest to address near-surface conditions in more detail. Specifically, the lowering of the groundwater table and possible seasonal effects are of interest. The lowering of the groundwater table and possible seasonal variations in this effect have important implications within the Environmental Impact Assessment, and it is of general interest to compare seasonal effects with the time-invariant analyses performed for the deep rock system. However, these issues are not of primary concern when assessing long-term safety.

The code MIKE SHE is used for assessing the near-surface hydrogeological conditions /Bosson and Berglund 2006, Bosson 2006/. MIKE SHE is a process-based modelling tool, which considers the full hydrological cycle from rainfall to groundwater and to river flow /DHI Software 2004a/. The code MOUSE-SHE is used to implement the ramp down which wastes are transported and to describe the flow in the engineered structures /DHI Software 2004b/.

Forsmark

The model, also based on the Forsmark 1.2 SDM /SKB 2005c/, has an area of roughly 38 km^2 and a vertical extent of 135 m. Thus only the upper part of the ramp and shafts are included in the model. A transient top boundary condition based on meteorological data gathered in the Forsmark area between years 2003 and 2004 has been used. Bottom boundary conditions were taken from the DarcyTools simulation described above. It is noted that only fresh water is treated in the model.

Results indicate that the near-surface drawdown and the inflow of water to the ramp are highly dependent on the grouting efficiency. In the case with no grouting, the inflow to the ramp is 5 l/s. The groundwater table is lowered by approximately 25 m, but the effects are very local and concentrated in close proximity to the tunnel area, see Figure 9-10. Even if groundwater levels drop 25 m locally, there are no visible effects on surface water levels in lakes. Furthermore, discharge in water

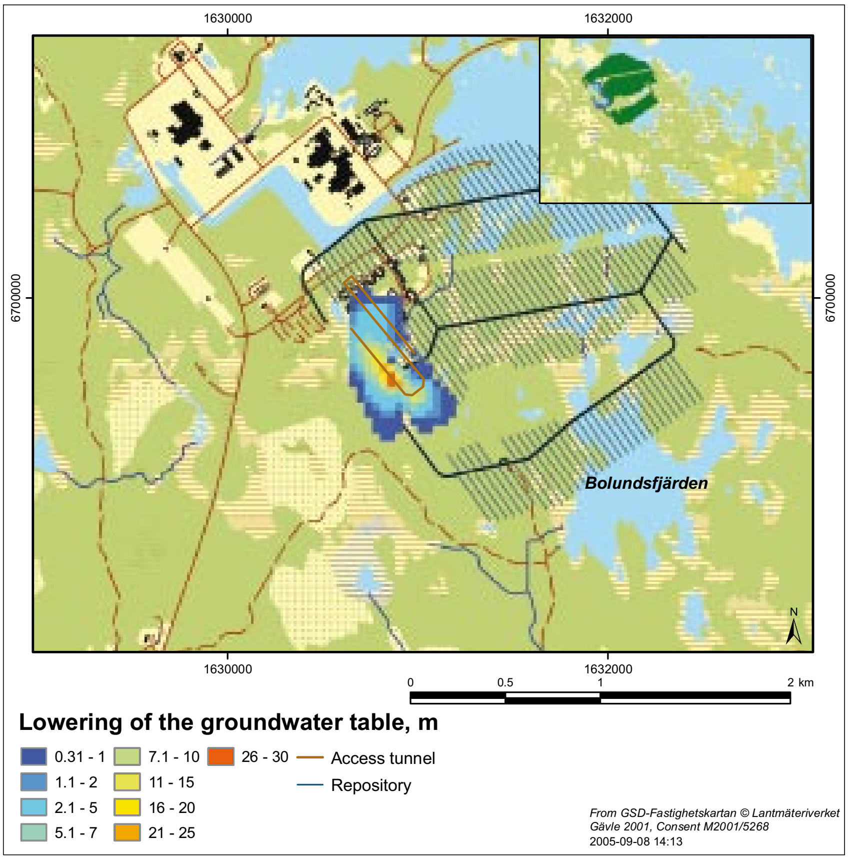


***Figure 9-10.** Lowering of the groundwater table in the case where no grouting is applied. The different tunnel constructions are marked in the figure.*

courses and run-off from the area are not influenced by the ramp and shafts. The influence area, defined as the area where the hydraulic head has been lowered by more than 0.3 m, is approximately 0.3 km^2. The main inflow to the ramp occurs in the upper most 50 m; at larger depths the low hydraulic conductivity limits the inflow. The inflow of water to the shafts is insignificant compared with the inflow to the ramp. Seasonal effects were found to be insignificant.

When the highest grouting efficiency was applied, there were almost no effects at all from the repository on near-surface hydrology.

The main differences observed between the deep rock and near-surface assessments concern groundwater levels in the upper 100 m of the rock. A greater impact is found in the near-surface analysis. This is due to the ramp and shafts not being represented at levels higher than 100 m below sea level in DarcyTools.

Laxemar

The model is based on the Laxemar 1.2 SDM /SKB 2006b/ and has an area of roughly 19 km^2 and a vertical extent reaching to 150 m below sea level. Thus, only the upper part of the ramp and shafts are included in the model. A transient top boundary condition based on meteorological data from Äspö during 2004 was used. The surface water divides were assumed to coincide with the groundwater divides, thus no-flow boundary conditions were used for the horizontal boundaries. The bottom boundary condition was a steady-state head taken from the DarcyTools model /Svensson 2006a/ described above.

The head drawdown and the size of the influence area are very dependent on the grouting efficiency. For numerical reasons, no results are presented for the case with no grouting. When the highest grouting efficiency was applied to the repository walls ($K = 10^{-9}$ m/s), the calculated influence area is roughly 9 km^2. The inflows to the tunnel are in the same range for all degrees of grouting efficiency and vary between 4 and 6 l/s. The calculated inflows to the repository in DarcyTools /Svensson 2006a/

are in the same range as the sum of water leaving the MIKE SHE model through the tunnel (ramp) and over the bottom boundary. The agreement is better for the cases with higher grouting efficiency. It is also shown that the assumed properties of the interface between the bedrock and Quaternary deposits have a large impact on the results. For example, an interface layer with low hydraulic conductivity ($K = 10^{-8}$ m/s) significantly decreases the size of the influence area and reduces the lowering of the water table.

In conclusion, the indication of the studies presented above is that the operational phase of a repository at Forsmark only has limited effects on near-surface conditions. Moreover, the total inflow to the tunnels is of a magnitude that easily can be dealt with. With a likely small amount of grouting, the inflows and near-surface effects can be reduced to insignificant levels. For Laxemar, the effects on the near-surface conditions are greater and much larger influence areas are obtained. If a grouting efficiency with a resulting hydraulic conductivity of $K = 10^{-9}$ m/s can be obtained, the resulting inflows are readily manageable.

9.2.4 Piping/erosion of buffer and backfill

An additional hydraulic issue during the operational phase concerns piping and associated erosion effects in the buffer and backfill. Water inflow into the deposition holes and tunnels will take place mainly through fractures and will contribute to the wetting of the buffer and the backfill. If the inflow is localized to fractures that carry more water than the swelling bentonite can adsorb, there will be a water pressure in the fracture acting on the buffer. Since the swelling bentonite is initially a gel, with increasing density over time as water goes deeper into the bentonite, the gel may be too soft to stop the water inflow. The result may be piping in the bentonite, formation of a channel and a continuing water flow and erosion of soft bentonite gel. There will be a competition between the swelling rate of the bentonite and the flow through, and erosion rate of, the buffer.

Piping

Piping will take place if the following two conditions are fulfilled:

1. For conditions when most of the water flow is not absorbed to the bentonite, the water pressure in the fracture, p_{wf}, must be higher than the sum of the counteracting total pressure from the clay and the shear resistance of the clay.
2. The hydraulic conductivity of the clay must be sufficiently low that water flow into the clay is prevented to the extent that the water pressure is kept at p_{wf}.

The piping may appear not only in a channel but in a newly created fracture in the bentonite that widens when water penetrates. This process is usually called *hydraulic fracturing*.

Erosion

Erosion will take place if the drag forces on the clay particles from the water movement are higher than the sum of the friction and attraction forces between the particles and the clay structure.

Piping or hydraulic fracturing probably only occurs before complete water saturation and homogenisation of the buffer since the swelling pressure of the buffer material is very high as opposed to the situation in the backfill where the swelling pressure is much lower. Erosion can occur in channels caused by piping or hydraulic fracturing. Piping/hydraulic fracturing and erosion are thus two different processes, but in order for this type of erosion to take place there must be an open channel caused by piping or hydraulic fracturing.

Sealing

If piping has occurred, it is essential for the long-term function of the buffer and backfill that the channels or fractures are closed through swelling. The ability of the buffer and backfill to seal the channel requires the following:

1. The mass transport rate of the swelling of the bentonite into the channel must be larger than the mass transport rate of the erosion.
2. When the channel has been sealed, piping must not occur again (see above).

This description concerns both the buffer material and the backfill. In the case of a 30/70 mixture of bentonite and crushed rock, the swelling pressure of the backfill will never be sufficiently high to resist the 5 MPa difference in water pressure between the groundwater in the rock and the open repository. Instead, the water inflow may not be stopped until a water tight plug is placed at the end of the tunnel and full water saturation is reached in the backfill.

Quantitative treatment of piping/erosion in buffer

Most deposition holes are not expected to have inflows large enough to induce piping. To further elucidate under what conditions piping could be a problem, the following rough estimate can be made.

- Initial dry mass of bentonite: Around 20,000 kg/deposition hole.
- Typical flow in a "wet" deposition hole: 0.1 litres/minute. This can be described as an above average inflow at Äspö and a high inflow at Forsmark.
- Observed concentration of bentonite in pipe water: 10 grams/litre. This is an upper value observed in the very early stage of piping experiments. Long term rates and field experiments have shown concentrations of ~ 1 g/l, see the **Buffer and backfill process report**, section 2.3.4. This is therefore a pessimistic maximum value.
- Rough estimate of duration: 100 days (higher flows means shorter time and vice versa). Six to eight weeks to backfill tunnel after deposition, plus time to fill system with water to regain water pressure. The time calculated here is the time it takes to restore the hydrostatic pressure in the tunnel section.
- Thus the total loss for these deposition holes can be estimated at 1.5 kg/day or a total of 150 kg, i.e. around 0.75% of initially deposited mass. However, the loss will occur locally close to the point of water inflow. Due to friction, this mass loss will not be evened out within the total buffer mass. There will be a local increase of hydraulic conductivity and a decrease in swelling pressure, see further section 9.3.8.
- Variations:
  - At an inflow of 0.01 litre/min, the mass loss would be 15 kg. Hence, it is very likely that piping would not occur at this flow, since the buffer would have time to develop a sufficiently high swelling pressure to counteract the piping.
  - An inflow of 1 litre/min would yield a mass loss of 1,500 kg, which is not tolerable. However, it is possible that the pipe would close much earlier in such a case.
- From the point of view of preventing piping, grouting to achieve water flows of less than 0.1 l/min is required for long-term safety.

As described in section 9.3.6, for the Laxemar repository it is found by simulations that less than 2% of all deposition holes will have an inflow larger than 1.0 l/min and about 20% will have an inflow of more 0.1 l/min. For the Forsmark repository it is found that 99.9% of all deposition holes will have an inflow smaller than 0.01 l/min. These figures are based on ungrouted conditions. It is also noted that imposition of the deposition hole acceptance criteria discussed in sections 4.4.1 and 9.3.6 was not taken credit for in these simulations.

Treatment of piping/erosion in deposition tunnel backfill

Erosion and subsequent loss of the *deposition tunnel backfill* material may take place under different circumstances.

1. Before the tunnel is sealed with a tight tunnel plug, erosion and transport of backfill with flowing water may take place preferentially towards the tunnel opening, since the resistance to piping is very low at the rock interface when large water pressure gradients are still present.
2. After the tunnel is sealed with a tunnel plug, the same process may cause erosion before full saturation of the backfill is reached due to internal water redistribution.
3. After sealing and full saturation of the backfill, water may still leave the tunnel through fractures in either the rock or at the plug. If the fracture is large enough there may be erosion and transport of backfill through the fracture.

Piping is more likely to occur in the backfill, since it is more likely to be intersected by fractures with a sufficiently high water flow. The consequences of backfill piping can be calculated in a similar manner as in the case of the buffer:

- Initial dry mass of clay in backfill: 300,000 and 100,000 kg for Friedland and a 30/70 mixture, respectively, per deposition tunnel length corresponding to a deposition hole, i.e. 6–8 m.
- "Typical flow" in a wet deposition tunnel section corresponding to one deposition hole: 1 litre/minute.
- Observed concentration of bentonite in pipe water: 10 grams/litre (see above).
- Rough estimate of duration: 100 days (higher flows means shorter time and vice versa).
- Thus total loss of backfill for one deposition hole section can be estimated at 10 kg/day or a total of 1,000 kg, i.e. around 0.3 and 1% of initially deposited mass for Friedland clay and a 30/70 mixture, respectively. The material will most likely deposit somewhere else in the tunnel.

Piping in the deposition tunnel backfill will have lower consequences than piping in the buffer, since the cross section of the former is much larger. It will also only affect a rather restricted area of the backfill. Unless the piping occurs at the top of the deposition hole, this process will have a very limited effect on the buffer density.

It is still unclear if a mixed material, like 30/70, will be able to re-seal after a period of erosion. If not, this could leave the tunnel with a conductive transport path. For Friedland clay this should not be a problem since it is a homogenous material having a rather high swelling pressure.

/Börgesson and Sandén 2006/ have studied the erosion and piping phenomena in backfill materials and bentonite pellets. Their conclusions were that:

- piping together with erosion is likely to occur unless the local inflow of water is very low,
- the phenomena are dependent on the inflow rate and the water salinity, but not on the length of the pipe,
- erosion rates can initially be very high (with water concentrations of solids > 60 g/l), but will decrease to a value of ~ 10 g/l after a rather short time – this value is rather independent on the conditions,
- pellets and blocks behave rather similarly in respect of erosion,
- the 30/70 mixture has a very limited self-sealing ability.

Erosion of backfill material during the operational phase could lead to a local loss of backfill density at the top of a deposition hole. This is further addressed in section 9.3.9.

Conclusions

Based on the calculated inflow of water to the entire repository at Forsmark (section 9.2.3), the inflow of water to a typical deposition hole would be ~ 0.01 l/min. At this value, piping will not be an issue. If the positions of the deposition holes are selected with some care and the major water-bearing fractures are avoided, it should be possible to avoid the piping phenomenon in the buffer entirely at the Forsmark site. It is noted that at the Laxemar site, the inflows to deposition holes are expected to be considerably higher. Nevertheless, as only 20% of the positions are assessed to have an inflow above 0.1 l/min, it should be possible to avoid piping in almost every position either by grouting or rejection of a few deposition holes.

The average inflow to a deposition tunnel could be in the range of 2–4 l/min at Forsmark and about an order of magnitude higher at Laxemar. If this flow is localised to a few points, piping and erosion cannot be excluded. However, the loss of mass will be limited and the properties of the backfill will most likely be maintained. However, it is uncertain whether a mixed material like the 30/70 mixture backfill will be able to self seal after a severe piping/erosion episode.

The discussion in this section further indicates that grouting of deposition holes to inflows below 0.1 l/min is required, if these holes are to be used for deposition.

9.2.5 Chemical evolution in and around the repository

Introduction

During the excavation and relatively long operational period, hydraulic conditions will change as described in section 9.2.3. The changed hydraulic conditions may alter the groundwater composition around the repository. Some of these changes will be induced by the presence of the repository, but also shore-level displacements and climatic variations may cause more limited alterations. As a consequence, the salinity in some parts of the repository may decrease due to an increased infiltration of diluted waters of meteoric origin, whereas in other regions the corresponding up-coning might instead induce an increase in salinity. This involves the safety function indicators R1b and R1c in Figure 9-2, and in extreme cases it might affect the swelling of the backfill, see section 4.2.8, or enhance colloidal erosion of the buffer during deposition, see section 9.2.4.

In addition to the groundwater changes caused by hydrological processes, other chemical aspects need to be considered during this period. It is to be expected that the excavation will be accompanied by grouting, and the chemical influence of the grout on groundwater must be considered. In general, cementitious grouts will increase the pH of the water, involving the safety function indicator R1e. During the operational phase, the role of stray materials must be assessed, as well as that of any other process that could possibly change the chemical conditions in the repository, such as the precipitation of minerals as waters emerge in the tunnels. These processes might, for example, affect the safety function indicators R2d and R2e in Figure 9-2, that is, the generation of colloids and the sorption properties of minerals.

When deposition tunnels are backfilled and plugged, air will be trapped in the porous buffer and backfill, and processes consuming oxygen must be evaluated. Air will also cause some initial corrosion of the copper canisters until anoxic conditions are reached. All these chemical processes are related to the safety indicators C1 (copper canister thickness) and R1a (reducing conditions) in Figure 9-2.

Other chemical processes taking place in the buffer and backfill occur on longer time scales than the relatively short operational phase, and they are discussed in section 9.3.10.

Natural groundwater conditions at the sites

The chemical characteristics of groundwater at Forsmark and Laxemar prior to the construction of the repository are set out in detail in their corresponding SDM 1.2 /SKB 2005e, 2006g/. A typical groundwater composition near repository depth is listed in Table 9-23, at the end of chapter 9. Additional details on the state of the repository are given in chapter 4.

Salinity (upconing effects)

Upconing may occur as a consequence of the groundwater inflow into open tunnel sections. This phenomenon has been observed for example in some boreholes at Äspö. In extreme cases, high salinities in the groundwaters might decrease the swelling pressure of the backfill, safety function indicator R1b in Figure 9-2. It is to be expected that groundwater conditions will return to normal after the repository has been backfilled and closed, and that saline groundwaters that had moved upwards will then sink due to their higher density. Diffusion into the rock matrix might retain a certain amount of salts at repository depth, but the excavation and operation phases are too short to allow a large diffusion.

The inflow to the tunnels will be reduced by injecting grout into the surrounding fractures. This prevents the depression of groundwater levels near the ground surface and the corresponding upconing of saline waters.

The effect of grouting has been modelled for both sites, see section 9.2.3. The results using the code DarcyTools indicate that for both Forsmark and Laxemar very little upconing of saline groundwaters is to be expected during construction and operation of a repository located at these sites. Further details are given in section 9.2.3 and references therein.

Redox conditions

Even with moderate inflows to the open tunnels, see section 9.2.3, large amounts of superficial waters are predicted to percolate when considering the whole period of repository operation. Infiltrating waters will initially be equilibrated with oxygen in the atmosphere, whether they are of marine, lake, stream or meteoric origin. It could be contended that the redox stability of the rock volume on top of the repository area might be challenged at the time of repository closure by the large amounts of infiltrating O_2-rich waters.

However, microbial oxygen consumption takes place already in the overburden and in the first metres of rock, and therefore infiltrating waters are free of dissolved O_2. Oxygen consumption in saturated soils is well documented, see for example /Drew 1983, Silver et al. 1999, Pedersen 2006/. The Äspö Redox Zone experiment /Banwart 1999, Molinero-Huguet et al. 2004/ also showed that microbial respiration in the upper metres of a fracture zone effectively consumes the oxygen in infiltrating waters. In addition groundwater samples from either Äspö or Stripa are always found to contain dissolved Fe(II) /Nordstrom et al. 1989, Wikberg et al. 1988/ indicating that groundwaters remain reducing even after prolonged periods of inflow into the tunnels.

In conclusion, the reducing capacity of transmissive fracture zones is not affected during the excavation and operation periods, because consumption of oxygen in infiltrating waters takes place already in soils, sediments as well as in the upper metres of fractures by microbial processes.

Effects of grout, shotcrete and concrete on pH

As mentioned in the previous subsection, injection of grout into fractures surrounding the repository tunnels might be necessary to avoid inflow of groundwater. Traditionally, cement-based grout is used when excavating tunnels. Standard Portland cement paste has porewater which is highly alkaline ($pH \approx 12.5$). In order to avoid detrimental effects from porewater diffusing out of the cement matrix, cement recipes with porewaters having $pH \leq 11$ are assumed to be used in the repository. Such materials are being developed. Although the effects of these porewaters are much smaller, they must be evaluated, because it is possible that relatively large quantities of cement will be used. As mentioned in the previous subsection, limited amounts of grouting will likely be needed at Forsmark, whereas for Laxemar, substantial amounts will probablly be required /**Initial state report**/.

The distribution of shotcrete and concrete in the repository will be spatially limited and their potential impact during the excavation and operational phases will be restricted. Most of the leaking porewaters from these materials will be mixed with groundwater infiltrating into the tunnel and pumped away. A small part of the cement materials will be in contact with the buffer and the backfill, and cement porewaters will migrate to invade the bentonite. As long as low-pH cement materials are used, the consequences on the properties of the buffer and backfill may be neglected.

On the other hand, grout could have a large impact on the geosphere conditions, as it is widely and diffusely distributed in the fracture system. Grouting is, however, necessary to avoid a large groundwater drawdown (increased meteoric water influx) and the corresponding up-coning of saline waters. Grouting is also needed for construction purposes; the ingress of water needs to be limited for the engineering installation and for worker safety. Two types of grout are envisaged for the final repository /**Initial state report**/: low-pH cement based grouts and suspensions of nano-sized silica particles (Silica Sol). The solidified Silica Sol grout is similar in its properties to the silica present in large quantities in the rock and fracture fillings, and may, therefore, be ignored in a long-term safety context. Cement-based grouts on the other hand have chemical properties quite different from the surrounding rock, and their effects have to be studied.

Boreholes crossing grouted fractures at the Olkiluoto site in Finland have yielded waters with high pH values since sampling started. The more limited experience from Äspö shows that a pulse of alkaline solutions may be detected in the immediate vicinity of the grouted fractures. This pulse of alkaline waters is believed to be due to two factors: pore water released while the liquid grout solidifies; and erosion and dilution of grout by flowing groundwater in the outer edge of the grouted volume. These effects in the non-grouted fractures at Äspö were transitory, and after a few days the chemical composition of the groundwater returned to its original state. The pH values were sufficiently low as to indicate that substantial dilution had occurred. The data from Olkiluoto indicates that the intensity of this short alkaline pulse will be decreased by the use of "low-pH" cement. Because of its short duration and its low intensity, its effects are negligible.

After this short period grout will start to react with circulating groundwater, and a slightly alkaline plume will develop downstream in the grouted fractures /Luna et al. 2006/. This process is, however, relatively slow and it is, therefore, discussed in section 9.3.7 in connection with the evolution of the repository during the initial temperate period after closure.

Precipitation/dissolution of minerals

During the operational phase, inflow of groundwater into the tunnel and mixing of groundwaters of different origin within rock fractures will probably result in precipitation or dissolution of minerals. These processes could only indirectly affect the safety function indicators listed in Figure 9-2. This process may be observed at the Äspö HRL, and it is believed to cause the observed decrease in the overall water inflow at Äspö by ≈ 4% each year. Numerical simulations have been performed to confirm that they do not influence the performance of the repository negatively /Domènech et al. 2006/. The results show that calcite and iron(III)oxy-hydroxide are expected to precipitate at the tunnel/backfill boundary. The conclusions of that study are that, as expected, the precipitation of these minerals has no significant chemical effect on the performance of the repository, and that the precipitation of secondary minerals during the operational stage of the repository does not significantly affect the porosity of the area surrounding the tunnels.

Effects of organic materials and microbial processes

Organic materials (including microbial biofilms, tobacco, plastics, cellulose, hydraulic oil, surfactants and cement additives) may be decomposed through microbiologically mediated reactions, and because of this they increase the reducing capacity of the near-field of the repository. However, these materials might also be detrimental during later periods in enhancing the potential for radionuclide transport in groundwater after repository closure, for example by the formation of organic colloids (safety function indicator R2e in Figure 9-2).

An inventory of organic materials and an assessment of their impact on microbial processes has been prepared /Hallbeck et al. 2006/. This study concluded that it is to be expected that microbial degradation of organic materials will contribute to: a) quickly consume any oxygen left in the repository; and b) by a combination of processes, involving anaerobic degradation and sulphate reduction, sulphide can be produced in the vicinity of the deposition holes. Some of the sulphide could diffuse to the canister where corrosion would take place. The maximum amount of sulphide that can be generated microbially is ~ 10 moles for each deposition hole /Hallbeck et al. 2006/, which, if it was able to react completely with the canister, would be equivalent to a corrosion of less than 10 μm if distributed evenly. It is, however, to be expected that most of the sulphide produced will either react with iron(II) in the groundwater or diffuse away from the canister, and, therefore, the sulphide thus produced will have a negligible impact on the copper coverage of the canisters.

Oxygen consumption in backfill

Air will be trapped in the porous buffer and backfill when deposition tunnels are plugged. Most of the oxygen in this air will be in the backfill because of its larger volume. This oxygen can diffuse to the canister surface and cause some initial corrosion until anoxic conditions are reached, and, therefore, it is valuable to estimate the reducing capacity of the backfill. Both chemical processes and microbial activities are expected to consume oxygen.

Numerical calculations /Grandia et al. 2006/ coupling chemical processes consuming oxygen with the hydrodynamic saturation of the backfill have been used to estimate the time scale for reaching anoxic conditions in the tunnels of the repository. The study shows that several inorganic O_2 consumption processes may take place with the accessory minerals present in the bentonite in the buffer and in the backfill (bentonite compositions are listed in Table 4-3). These reactions are, in order of decreasing rate, the dissolution of Fe(II)-containing carbonates, the oxidation of pyrite, and the oxidation of Fe(II)-bearing silicates such as mica and montmorillonite. The calculated oxygen consumption times are highly dependent on the postulated value for the surface area of the reacting minerals. Nevertheless, the study concludes that anoxic conditions are likely to be reached after a period of the order of one month after the backfill becomes water saturated.

The calculations do not include the possible effects from microbial respiration, although the density of the backfill is low enough to allow microbial activities. The effect of microbes would be to shorten the time to reach anoxic conditions in the backfill.

In the Prototype Repository Project at the Äspö Hard Rock Laboratory, a programme is in progress for sampling and analysing gases at different locations in the buffer and backfill. One of the specific aims is to monitor the consumption of oxygen /Pedersen et al. 2004/. The two sections of the Prototype Repository were sealed in September 2001 and September 2003, respectively. Preliminary, yet unpublished, results were obtained during the first samplings concluded in the fall of 2004. The resulting oxygen content ranged from almost zero to full air atmosphere. The backfill was, however, not fully water saturated in all parts. These data, therefore, provides further indications that the oxygen consumption will be rapid.

In conclusion, inorganic reactions will quickly consume O_2 in the air trapped in the backfill, which has the largest pore volume in the deposition tunnels. The majority of the oxygen in the backfill will react before it can diffuse into the buffer and reach the surface of a canister.

Colloid formation

During the excavation and operation phases, substantial amounts of colloids may be formed due to microbial activities, bentonite erosion by diluted meteoric waters, precipitation of amorphous Fe(III) hydroxides, etc. These colloids are expected to be short-lived, mainly because colloids will aggregate and sediment in moderately saline waters, see for example /Degueldre et al. 1996/.

Other processes contributing to the elimination of colloids are microbial decomposition of organics, and the re-crystallization and sedimentation of amorphous materials.

In conclusion, an increased formation of colloids during the excavation and operational phases is not expected to affect the performance of the repository in the long-term, because the colloid concentrations will quickly resume the natural values.

Canister corrosion

Expected deposition of salts on the canister in the early evolution of the repository and the implications for corrosion are addressed in section 9.3.12, since it is a consequence of the thermal evolution of the system (section 9.3.4).

After disposal, during the operating period the canister will subject to atmospheric corrosion at elevated temperatures and at relatively high humidity. Under these conditions, /King et al. 2001/ estimated the maximum corrosion rate to be 100 to 300 μm per year. In order to maintain this corrosion rate, the oxygen supply must be unlimited over time, which will not be the case. After backfilling the tunnels, the available trapped oxygen can be calculated to be 560 moles per canister corresponding to a corrosion depth of 840 μm if evenly distributed on the canister surface. Of the available amount of oxygen in the backfill and buffer, only a very small fraction, if any, will reach the deposition hole. The oxygen will most likely be consumed by reactions with minerals (see above). The density of the tunnel backfill is low enough to allow microbial activity and this will also limit the amount of oxygen available for corrosion. A realistic estimate would be that only a few percent of the oxygen will be consumed through corrosion reactions with copper, i.e. the corrosion depth would be 20–30 micrometres.

During the time period when the oxygen potential is sufficiently high, pitting corrosion is conceivable. Experimental data from studies of copper corrosion under repository conditions show, however, that pitting corrosion most probably can be ruled out and an uneven general corrosion is to be expected, see further the **Fuel and canister process report**, section 3.5.4.

In conclusion, the corrosion depths are expected to be tens of micrometres at the most, and will thus have a negligible impact on the minimum copper coverage of the canisters.

9.2.6 Effects of operational activities on completed parts of the repository

The rock mechanics analyses only suggest very local impacts from the excavation work. The open repository simulations suggest that resaturation starts very soon in the repository parts that are back-filled and sealed. Consequently, it seems clear that the continued operation and excavation of the repository would not imply any detrimental impacts on the completed part of the repository. However, this issue needs careful analysis both for safety assessment purposes and for establishing the appropriateness of working procedures at the underground construction and detailed characterisation stage.

9.2.7 Summary of the excavation/operation phase

Summary of system evolution

The state of the repository system at the start of the excavation/operational phase is the initial state described in chapter 4.

The evolution of the system during this phase is obviously dominated by the excavation/operational activities. The evolution is thus different in nature from that at later stages, since the latter are essentially driven by naturally occurring processes. In principle, this evolution also depends on how the repository excavation and emplacement proceeds, but this is not specified in the current phase of the repository layout and design work. Several conclusions can be drawn without this more detailed specification.

The duration of this stage can be assumed to be several tens up to a hundred years depending on the progress of the excavation/operational activities and the total number of canisters.

Radiologically, the radiation intensity will decrease during this period. This has a direct impact on the residual radioactive decay heat from the deposited canisters.

The thermal evolution will be dominated by the heat output from the canisters and some parts of the engineered barrier system will reach their peak temperatures during the excavation/operational phase as this occurs after typically a few tens of years. This evolution is treated in more detail in the next section, as it continues for thousands of years and as the local peak temperatures are insensitive to details of the operational sequence. See section 9.2.1.

The mechanical evolution is dominated by the excavation of the host rock. An obvious mechanical impact is the creation of rock cavities for the repository. According to section 9.2.2, the following conclusions regarding additional mechanical consequences can be drawn.

- It is reasonable to assume that, provided that proper excavation techniques and QA control are applied, an EDZ, if it develops at all, will be limited to a narrow zone (a few tens of cm wide) close to the tunnel wall and that it will not form a continuous hydrologically conductive path. Possibilities of more extensive fracturing would relate to poor engineering and inadequate QA practices, including the possibility that the tunnel is excavated sub-parallel to a joint set so that the EDZ fractures link to the joint set.
- The reactivation of fractures caused by the stress redistribution, other than the potential damage as assessed in the EDZ, only results in insignificant increase of transmissivity in the near-field fractures.
- The possibility of excavation-induced seismic fracturing or fault slip need not be considered in SR-Can.
- There are no long-term safety related impacts of the few cases of spalling prior to canister emplacement expected at both sites. (Special procedures would be needed during excavation to ensure protection of workers.)

Hydraulically, the evolution is dominated by upconing and drawdown effects of the repository excavation. The studies of the deep and near-surface hydrogeology presented in section 9.2.3 lead to the conclusion that the operational phase of a repository at Forsmark only has limited effects on near-surface conditions. Moreover, the total inflow to the tunnels is of a magnitude that can easily be dealt with. With a likely small amount of grouting, the inflows and near-surface effects can be reduced to an insignificant level.

An additional hydraulic issue during the operational phase concerns piping and associated erosion effects in the buffer and the deposition tunnel backfill, treated in section 9.2.4. Preliminary calculations show that the effects could be considerable. They are also closely related to the extent of grouting in deposition holes.

During the excavation/operation phase, the chemical evolution mainly arises from the disturbance to the natural conditions caused by the presence of the repository. According to the results presented in section 9.2.5:

- For both sites, the effects on salinity from upconing and groundwater draw-down are assessed to be negligible.
- A short alkaline pulse in the groundwater from low-pH cement, shotcrete and concrete is likely to form, but its effects will be negligible.
- An increased precipitation of calcite and iron(III)-oxyhydroxides will occur at the tunnel wall during operations, but this process is evaluated as being of no consequence for the performance of the repository.
- Organic stray materials will be consumed by microbes, with the main effects being an increased rate of oxygen consumption and possibly also of sulphate reduction; the latter may at most contribute to an average depth of canister corrosion of about 10 micrometres, whereas any O_2 consumption will be favourable.

- An increased formation of colloids during the excavation and operation phases will not affect the performance of the repository in the long-term, because the colloid concentrations will quickly resume the natural values.
- Oxygen left in the repository will be consumed by either chemical processes or microbes; the majority of the oxygen in the backfill, which has the largest pore volume in the deposition tunnels, will react and thus not diffuse into the buffer and reach the surface of the canister.
- Canister corrosion depths are evaluated to be tens of micrometres at most, and will thus have a negligible impact on the minimum copper coverage of the canisters.

Safety function indicators at the end of the excavation/operation phase

Due to both the gradual excavation of the repository and the spatial variability of rock conditions, the state of the system at the end of the excavation/operation phase will vary e.g. between deposition holes.

Also, several safety function indicators are defined only for a water saturated repository, meaning that several safety function indicators are not meaningful to discuss at this stage.

Therefore, the detailed discussion of safety functions and status of safety function indicators is postponed until the end of the account of the initial temperate period, see section 9.3.14. There, also the development during the excavation/operation phase is taken into account.

9.3 The initial period of temperate climate after closure

9.3.1 Introduction

The initial period of temperate climate can be expected to last several thousand years after repository closure. From a compliance point of view, the initial 1,000 years after closure are of particular interest, since SSI's regulations require a more detailed account of repository evolution for this period. Since many of the initial, transient phenomena in the repository system occur within a 1,000 year period, a more detailed account of this time period is automatically obtained as every phenomenon is studied on the timescale appropriate to its nature. Examples of such phenomena are the resaturation of the host rock, the saturation of the buffer and the backfill and the thermal transient with its induced mechanical effects. Biosphere development is explicitly divided into an initial 1,000 year period and a subsequent period of development extending to the end of the temperate domain.

9.3.2 External conditions

The development of external conditions over the first 1,000 years after closure is based on the current knowledge of the repository sites and extrapolation of known trends, e.g. of shore-level migration. The development of climate-related factors for the remaining part of the initial period of temperate domain is mainly based on a model reconstruction of the Weichselian glacial, from 120,000 years ago up to present (see further section 9.4.1). At Forsmark, the initial period of temperate domain in the reference glacial cycle is about 8,000 years long, whereas at Laxemar it is about 8,300 years. For the assessment period of 1 million years, several identical glacial cycles are envisaged to follow each other. In this process, the following *full* interglacial periods each contain a ~ 20,000 year long period with continuous temperate conditions /**Climate report**, section 4.2.4/.

In the base variant of the reference evolution, the long-term climate trend is assumed to only be affected by natural climate variations, and not by antropogenically enhanced greenhouse warming. Therefore, palaeoclimate data depicting natural climate variability and trends can be used to assess the base case climate during the initial 1,000 years of temperate climate after closure. Climate variability in Sweden during the past 1,000 years has been relatively small /Moberg et al. 2006/. Therefore, in the reference evolution it is assumed that the temperate climate variability, in terms of temperature and precipitation, during the first 1,000 years after closure is also small, and, in line with this basic assumption, that long-term trends during this period follow patterns of natural climate variations.

With the model approach taken, interpretations of palaeoclimate from the GRIP ice-core /e.g. Dansgaard et al. 1993/, together with regional Fennoscandian climatic- and topographical conditions, also determine the ~ 8,000 year *duration* of the initial temperate period, as well as the timing and durations of all following climate domains during the reference glacial cycle described in section 9.4.1. The GRIP temperature curve, obtained from central Greenland, is used in absence of a long-term climate proxy record from Fennoscandia. However, this is not a big drawback considering the general approach adopted; namely to first develop a reference climate evolution describing *one relevant example* of the climate over a glacial cycle, followed by other complementary scenarios covering a broader range of possibilities of future climate development.

The case of antropogenically increased greenhouse warming is described in section 9.6.

9.3.3 Biosphere

The initial 1,000 years after closure at Forsmark

The shore-level displacement, measured as relative sea-water level, is projected to be about 6 m during the next 1,000 years, based on an almost constant rate of 0.006 m/year from /Ekman 1996, Hedenström and Risberg 2003/. This means that the coast-line moves at least 1 km from the repository (cf Figure 9-12) during the next 1,000 years. Thus, a part of the former seafloor will become land. This induces a succession from a shore dominated by herbs and grasses to forest in sheltered places, whereas for exposed areas, usually dominated by rock outcrops and boulders, the rate of succession is expected to be less pronounced. Bays with thresholds are isolated from the Bothnian Sea and then transformed to lakes (e.g. Figure 9-12). The water turnover of the lakes is dependent on the hydrology of the drainage area, but soon after isolation from the marine environment is also driven by occasional flooding from the Bothnian Sea, Figure 9-11.

Due to natural infilling (sedimentation and vegetation growth) of the coastal basins and lakes, organic matter is expected to accumulate and eventually lakes are transformed to land. The rate of infilling is dependent on the depth of the lake /Brydsten 2004/.

Although Bolundsfjärden is expected to quite quickly be transformed to a mire due to its shallow basin, a small creek draining the Forsmark area will probably be maintained as an open stream though Bolundsfjärden and the Norra Bassängen to drain the area (estimated flow rate 2 Mm^3/y) /Vikström and Gustafsson 2006/. Lake Puttan will, however, almost immediately be transformed to a mire with no open stream drainage /SKB 2006h/.

The deep channel north of the repository will remain as a lake for a long time, if it is left unaltered after decommissioning of the nuclear power plants at Forsmark /SKB 2006h/.

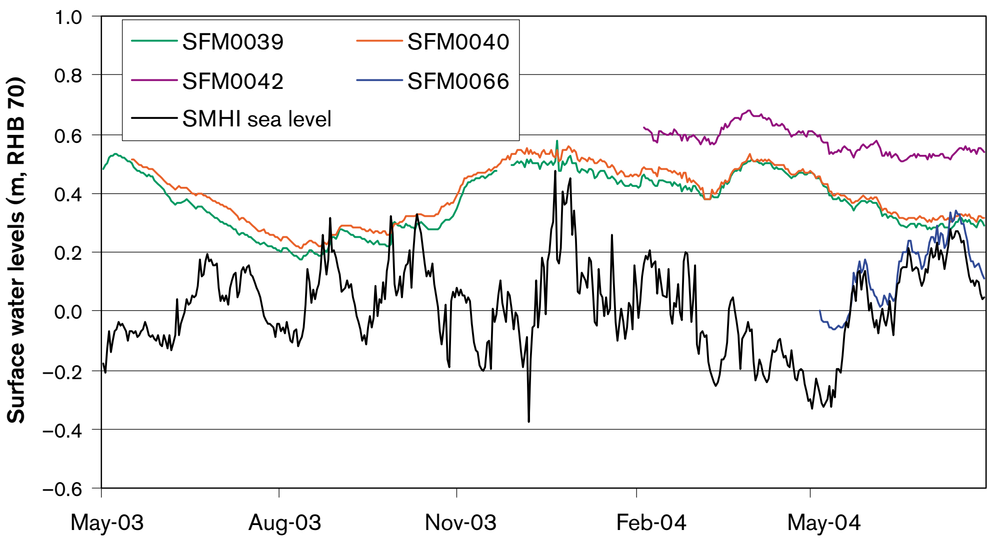


Figure 9-11. *Comparison of the water levels in the Baltic Sea, and the lakes Norra Bassängen (SFM0039), Bolundsfjärden (SFM0040), Fiskarfjärden (SFM0042) and Lillfjärden (SFM0066). Note the event in September 2003 in which sea level is higher than the levels in Bolundsfjärden and Norra Bassängen.*

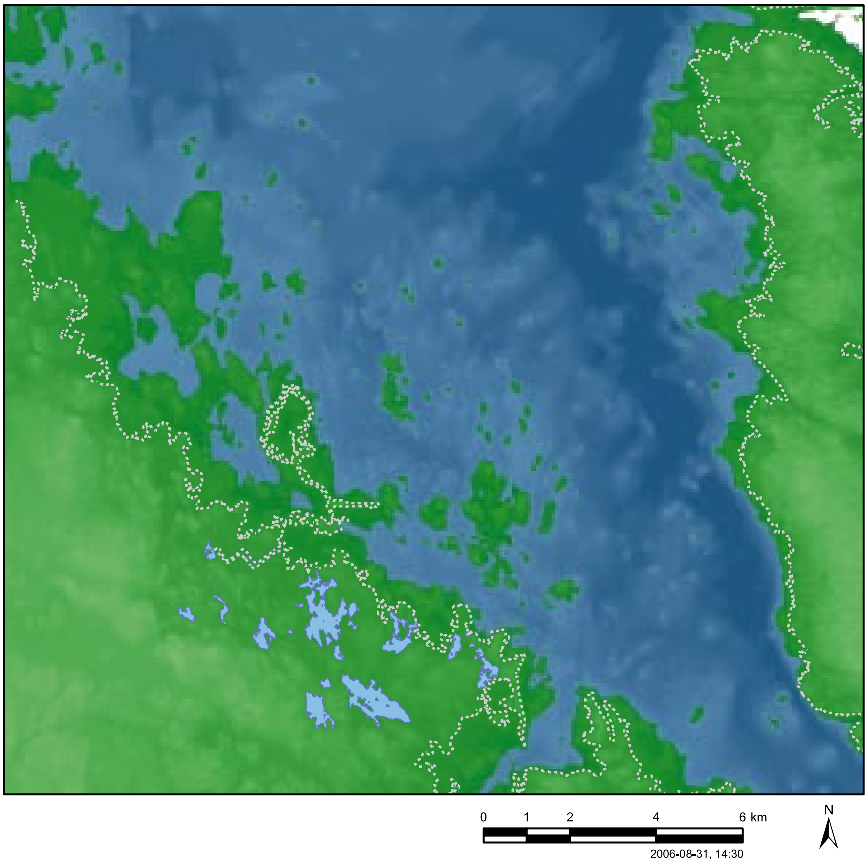


Figure 9-12. *The expected landscape of the Forsmark region in 1,000 years. Today's shoreline is marked as a grey dotted line. Lighter shades of green represent more elevated areas and darker shades of blue deeper sea.*

As the seafloor close to the coast gets shallower also erosion of the bottom will occur rather than sedimentation in unsheltered areas. The circulation in Öregrundsgrepen is expected to remain essentially as today /Engqvist and Andrejev 2000/. The salinity of the Bothnian Sea is expected to decrease slightly to 4.8 ppt during the initial 1,000 years assuming unaltered runoff to the Bothnian Sea /Gustafsson 2004a/.

The potential for sustainable human exploitation of food resources in the area over the coming 1,000 years is not expected to differ very much from the situation today, assuming that known methods are used. The newly formed land will likely not be developed as arable land due to the presence of boulder-rich sediments in the former sea and lake areas /Sohlenius et al. 2004/. Additionally, there will be new areas available for grazing of domesticated animals.

The total edible material production for the potentially contaminated zone in the drainage area close to the repository has been estimated to be about 10 kgC/y. This corresponds to the food intake for one month for an adult person /SKB 2006h/ (see further section 10.2.3).

The potential water supply for humans is expected to be fairly unaltered during this period. The freshwater bodies, today Bolundsfjärden and Puttan, contain bad-tasting water due to high occasional salinity and fringing mires. In the future, the stream through Bolundsfjärden might have a potential for use as a freshwater supply. The deep channel north of the repository has potential as a reservoir if the salinity decreases. New wells could be drilled in the area which is land today, whereas the new land will be too young for wells if current practises are sustained /Kautsky 2001/. However, the water quality of drilled wells is poor in this area and few wells are used for drinking water /Ludvigson 2002/. Any new wells drilled in the vicinity of the repository will have a large capacity, thus a large dilution, based on the hydraulic test performed at the Forsmark site /Gentschein et al. 2006/.

In summary, the biosphere at the site during the next 1,000 years is assumed to be quite similar to the present situation. The most important changes are the natural infilling of lakes and slight withdrawal of the sea with its effects on the coastal basins.

Biosphere development after 1,000 years until the end of the initial temperate period at Forsmark

The continued shore-line displacement will influence the local biosphere and eventually result in a situation where the site is located inland rather than at the coast, see Figure 9-13.

The shore-level displacement is assumed to continue, but at a gradually declining rate following the modelling by /Påsse 1997/, with parameters from the site /Hedenström and Risberg 2003/ (cf Figure 9-69). Applying this rate to the digital elevation model (DEM) from the site /Brydsten and Strömgren 2004/ gives that the coast line moves eastwards at a speed of approximately 1 km per 1,000 years. A semi-enclosed archipelago northeast of the repository is expected from approximately 3,000 to 5,000 AD. At 5,000 AD most straits in this archipelago are expected to become closed and lakes are isolated from the sea. In the period to 7,000 AD, the coast extends along the island of Gräsö, the coastline is about 7 km from the repository and the bay gradually shrinks to form two large and 20–30 m deep lakes.

Downstream, i.e. south-east from the repository, the bay has disappeared at 5,000 AD and leaves two shallow lakes. A small creek (flow $7.7 \cdot 10^6$ m^3/y) will drain the area above the repository. After 5,000 AD, this creek will converge with a large stream (flow $3.0 \cdot 10^8$ m^3/y) which consists of Forsmarksån and Olandsån, draining a large area of Northern Uppland ($1.3 \cdot 10^3$ km^2).

The strait at Öregrund is expected to be cut off about 3,000 AD which affects the circulation of water in Öregrundsgrepen and, due to the narrowing of the bay, the water turnover will be further restricted, but is not expected to be longer than a couple of days, except for basins near isolation /Engqvist and Andrejev 2000/.

The salinity of the sea is expected to decrease to 3–4 ppt at 6,000 AD due to the shallower sills between Ålands hav and the Baltic Proper /Gustafsson 2004b/. This means that an ecosystem similar

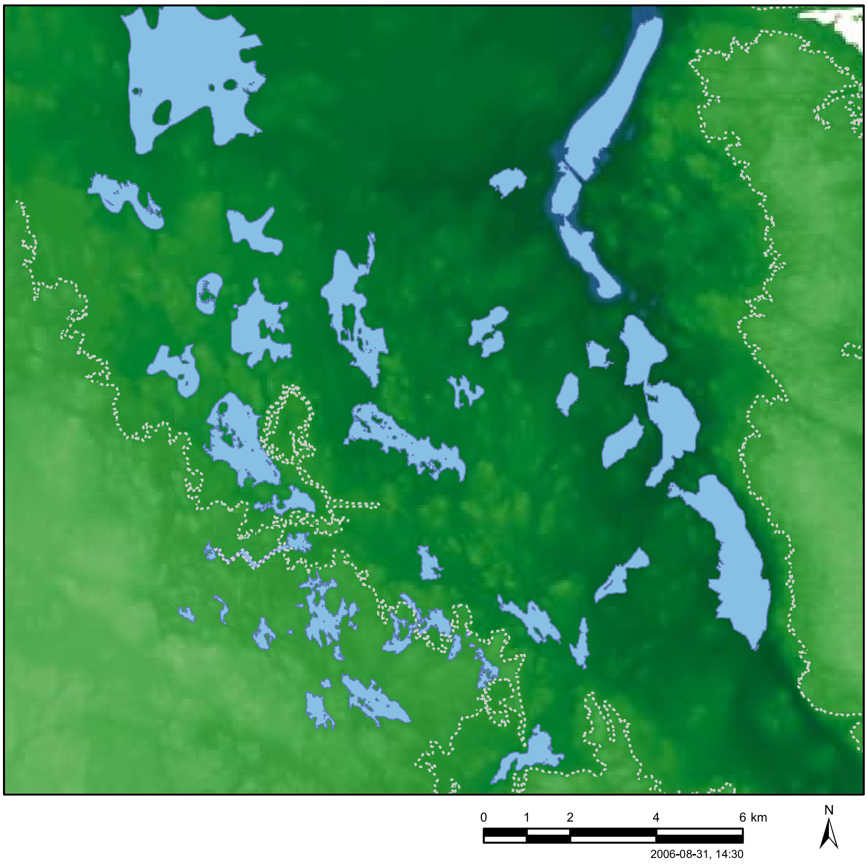


Figure 9-13. *The expected biosphere characteristics of the Forsmark region at 9,000 AD. The entire area is terrestrial and some large deep lakes are situated along the shoreline of the former island of Gräsö. Today's shoreline is marked as a grey dotted line. Lighter shades of green represent more elevated areas.*

to the Northern Quark, with a low abundance of marine species, will develop. Around 10,000 AD, freshwater is predicted for the entire Bothnian Sea. Öregrundgrepen will consist of freshwater anyhow due to the shore-level displacement.

The area of accumulation sediments is predicted to increase in Öregrundsgrepen, due to the increased shelter from islands and shallow areas restricting the erosion by waves /Brydsten 1999/. But close to the shoreline the force of the waves is sufficient to wash out fine material from the bottom, resuspend it and deposit it in deeper parts of the basins.

Most of the new lakes are expected to quite quickly be transformed into mires. Only a few deeper lakes are projected to exist for more than 1,000 years, Only the large lakes near Gräsö are expected to last for a period of around 10,000 years.

The area for fishery shrinks as the distance to the coastline increases. Few areas of the new land will be suitable for farming due to boulder- and stone-rich deposits /Elhammer and Sandkvist 2005/. Only one larger area in central Öregrundsgrepen seems to have fine-grained sediments today. However, the infilling process and mire development will give some further potential areas for future agricultural activities. Most of newly formed land is expected to be suitable for forestry, wild game, cattle, mushrooms and berries.

The food productivity of the area is expected to increase due to the larger extent of terrestrial environment. However, the total production in areas downstream from the repository will likely decrease, due to canalisation in the drainage areas.

The potential water supply for humans is expected to gradually increase with the decreasing extent of marine bodies. Both surface water and groundwater bodies will be available in the future area; most of these will be isolated from drainage from repository due to canalisation.

The climate variation within the defined limits (permafrost to greenhouse) will give longer drier and wetter periods which can affect the dominant vegetation and mire build-up. The main effect of temperature changes is on the vegetation period (due to modifications to snow cover and frost characteristics) through the altered duration of winters. This vegetation period varies regionally today between 170–210 days dependent on elevation, local topography, aspect direction and distance to the seashore. The assumption is that the uncertainty about the variations of climate will not exceed spatial variation and inter-annual variation at the site.

The initial 1,000 years after closure at Laxemar

The vertical shore-level displacement is projected to be 1m for the next 1,000 years, based on c 1 mm/year /Ekman 1996/. In contrast to Forsmark, this will move the coast-line marginally from today's coastline during the next 1,000 years (cf Figure 9-14). Mainly the bay Borholmsfjärden south of Äspö is estimated to have 40% of its former area and 30% of its volume, but is expected to remain a bay of the Baltic Sea. Some shallow straits between islands are expected to shrink.

Lake Frisksjön will be filled up with sediments and in-growing vegetation and is projected to become a mire at 3,000 AD. Otherwise, most ecosystems are expected to remain as today.

The potential food supply will thus also be maintained as today as well at the water supply from the streams and wells.

Thus, in summary, the landscape at Laxemar over the next 1,000 years is expected to be similar to the present landscape.

Biosphere development after 1,000 years until the end of the initial temperate period at Laxemar

At 4,000 AD, the bays north and south of Äspö are expected to become isolated from the sea and form large lakes. Accordingly, the coastal period ends and a terrestrial landscape dominate the surroundings of the repository. Most of the area close to the repository is assumed to be agricultural land. Thereafter, the remaining lakes are gradually infilled, a process which will take c 2,000 years for the shallow Borholmsfjärden. However, Granholmsfjärden, which is deeper and has relatively steep shores, will remain a lake even after 10,000 AD. Also, the coastline on the seaward side of the Simpevarp peninsula changes only slightly, see Figure 9-15.

The surface ecosystems around the proposed repository location stabilise quite early in the period as potential agricultural land, which is maintained through the rest of the interglacial period.

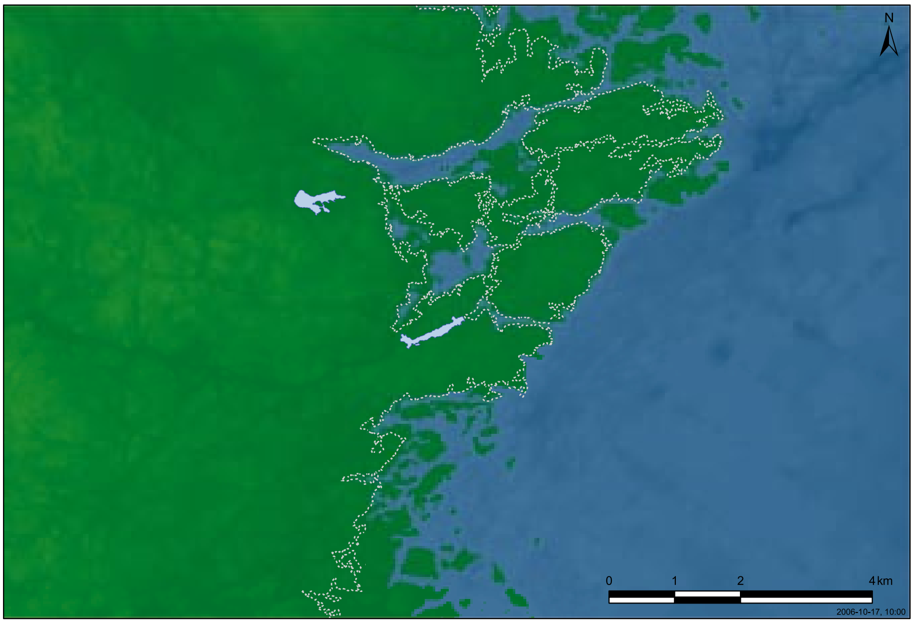


Figure 9-14. Laxemar at 3,000 AD. White line shows the shoreline of today. Light blue shows new lakes formed after 2,020 AD.

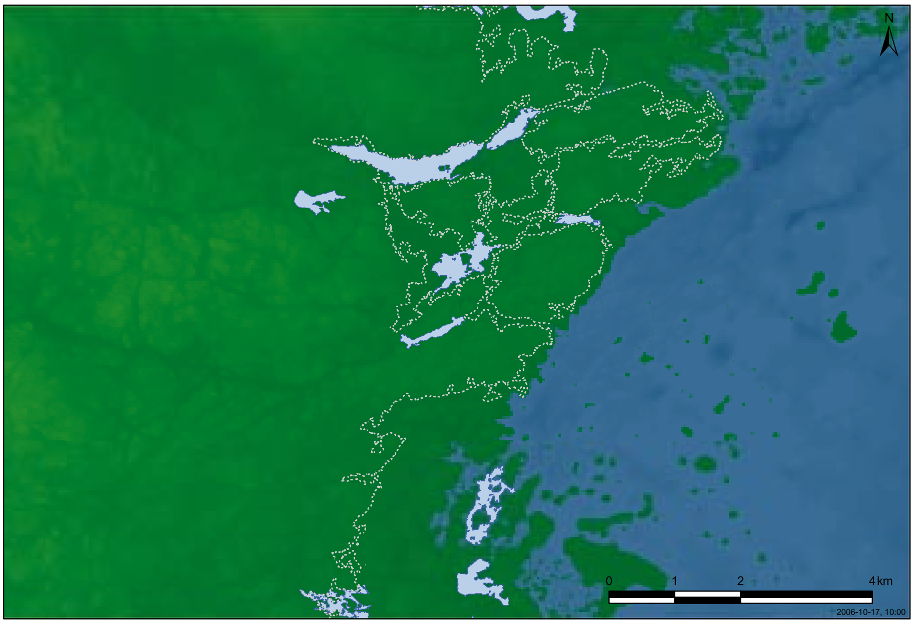


Figure 9-15. Laxemar at 10,000 AD. White line shows the shoreline of today. Light blue shows new lakes formed after 2,020 AD. The main part of the present bays around Äspö is terrestrial except the deepest parts of Borholmsfjärden.

9.3.4 Thermal evolution of the near field

Introduction

The thermal evolution of the near field is of importance as general input information to the mechanical, chemical and hydrological processes. The direct safety relevant thermal criterion concerns the buffer peak temperature, safety function indicator Bu5 in Figure 9-2, that requires that this temperature does not exceed 100°C, chosen pessimistically in order to avoid, with a margin of safety, mineral transformations of the buffer.

Peak temperature calculations

The peak temperatures as a function of time in the fuel, the cast iron insert, the copper canister, the buffer and the host rock were calculated using an analytic model /Hedin 2004b/. Similar treatments are presented for the host rock and buffer in /Hökmark and Fälth 2003/. Benchmarking against the results of /Hökmark and Fälth 2003/ and against numerical finite element calculations for buffer and rock yields discrepancies of peak canister temperature of less than one degree /Hedin 2004b/.

Primary rock thermal data for the calculations were obtained from the **Data report**, section 6.2. In order not to overestimate the heat conduction, the thermal conductivity values were assessed for 80°C. The recommended values of thermal properties for rock domain RFM029 (i.e. where the repository would be located) are shown in Table 9-4. The standard deviation of thermal conductivity reflects spatial variability on the canister scale (the relevant scale for peak canister and buffer temperature calculations) and measurement uncertainties. Geometric data for the near field used in the calculations are given in Figure 9-16.

Figure 9-17 shows the results of the thermal calculation for Forsmark as the thermal evolution at a number of points located on a radius extending horizontally from the canister mid-point along the deposition tunnel. The peak canister surface temperature at the canister mid-height is 90°C, for the input data as listed in Table 9-4, and decreases towards the end of the canister. The mean value of rock thermal conductivity was used. When the peak canister temperature occurs, the temperature drop across the 5 mm gap between canister and buffer is around 10.4°C meaning that the buffer inner temperature is 80°C. The corresponding drop across the 30 mm gap between buffer and rock wall is just over 4°C, from 65 to about 61°C.

It is noted that the theoretical calculation of temperature drops across these gaps assumes idealised geometries and other properties related to the absorption/reflection of heat radiation. Back-calculation of experimental data obtained from SKB's Prototype Repository at the Äspö laboratory suggests that the temperature drop between canister and buffer may correspond to an effective copper surface heat emissivity of 0.3, rather than the laboratory-determined value of 0.1 used in the calculation /Hökmark and Fälth 2003/. This would give a temperature drop of about 8.1°C rather than the 10.4°C calculated above.

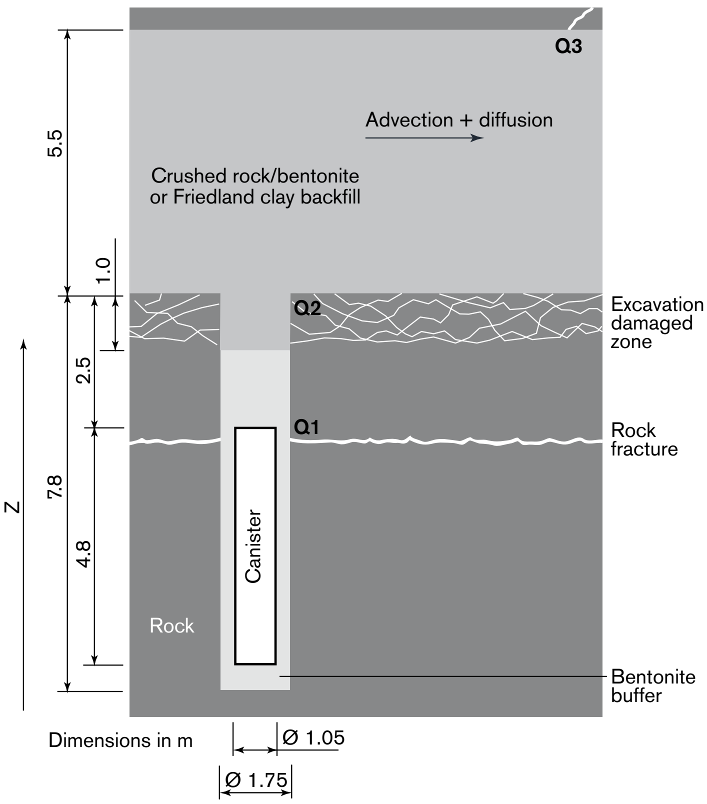


Figure 9-16. *Geometry of the near field. Note that the EDZ may be much less developed than indicated in this conceptual figure, see section 9.2.2.*

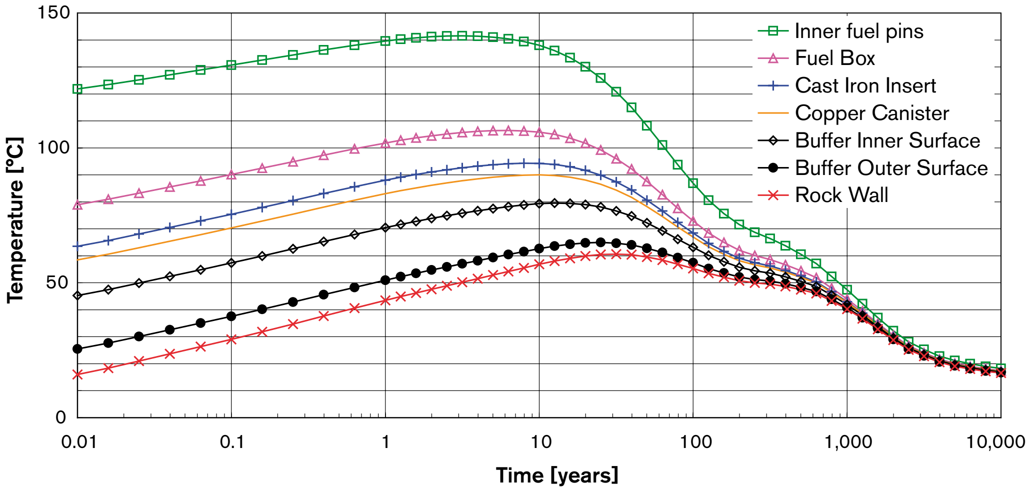


Figure 9-17. *The thermal evolution for a number of points at canister mid-height for data given in Table 9-4.*

It was cautiously assumed that no groundwater is taken up by the buffer, since this would lead to an increased thermal conductivity and eventually to a closure of the gaps at the buffer interfaces. The thermal conductivity of the buffer was set to 1.1 W/(m·K), which is representative of the originally deposited material before water uptake /**Data report**, section 5.1/. The gap between the buffer and the wall of the deposition hole is, in this calculation, assumed to be empty and to have a width of 0.03 m. This can be seen as representative also of a 0.05 m gap filled with bentonite pellets, a design that is currently being discussed to mitigate effects of potential spalling at the Forsmark site, see section 9.3.5. The treatment neglects the presence of the tunnel backfill above the deposition hole, but this has been demonstrated to influence the critical temperature only marginally /Hökmark and Fälth 2003/.

Table 9-4. Thermal sub-model data for the central case presented in Figure 9-17. Site-specific data are taken from the Data report. The canister is assumed to be filled with air. The rock is assumed homogeneous. Other geometry data required for the calculation are given in Figure 9-16.

	Forsmark	Laxemar
Repository depth	400 m	500 m
Canister spacing	6 m	7.2 m
Tunnel spacing	40 m	40 m
Canisters per tunnel (typical value)	160	160
Mean value of rock thermal conductivity at 80°C, RFM029/RSMA	3.34 W/(m·K)	2.77 W/(m·K)
Standard deviation of rock thermal conductivity, RFM029/RSMA	0.22 W/(m·K)	0.29 W/(m·K)
Rock heat capacity	2.17 MJ/(m^{3}K)	2.24 MJ/(m^{3}K)
Temperature at repository depth	11°C	13.8°C
Initial gap copper/buffer, assumed open	0.005 m	
Initial gap buffer/rock,	0.03 m	
Initial canister power, P_0	1,700 W	
Buffer thermal conductivity	1.1 W/(m·K)	
Emissivity of buffer inner surface	0.88	
Emissivity of copper outer surface	0.1	
Thermal conductivity in copper/buffer gap	0.03 W/(m·K)	
Emissivity of copper inner surface	0.03	
Emissivity of cast iron outer surface	0.24	
Emissivity of cast iron inner surface	0.3	
Emissivity of Zircalloy surfaces	0.4	

Sensitivity analyses

Figure 9-18 shows the distribution of canister and buffer peak temperatures for a probabilistic calculation with all data taken from Table 9-4 where a normal distribution of thermal conductivity with parameters as in the table was assumed /**Data report**, section 6.2/. This distribution essentially reflects the spatial variability of rock thermal conductivity at the canister scale for Forsmark. The figure shows the result of 5,000 realisations. The highest peak temperatures recorded were 100°C and 90°C for the canister and the buffer, respectively. This suggests that there is a large margin to the 100°C peak temperature criterion for the buffer, even when the spatial variability of the rock thermal properties is taken into account. It is further noted that the entire host rock is assumed to have a particular heat conductivity in each realisation, whereas the spatial variability occurs on a scale of typically ten metres. The spread in peak temperatures shown in the figure is, therefore, an overestimate of what would actually be the case with the measured rock thermal properties.

Figure 9-19 shows how the peak temperatures vary with the centre-to-centre spacing of the canisters. This distance is, however, determined in the layout and is thus not uncertain in the same sense as e.g. the rock thermal conductivity discussed above. It is important to carefully select an appropriate spacing, since this determines the overall requirements on space for the final repository.

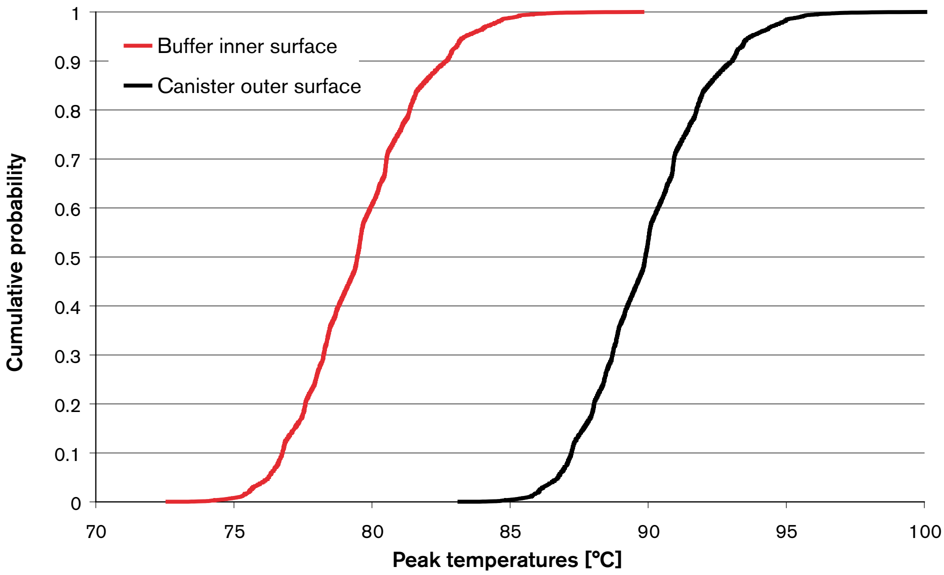


Figure 9-18. *Probabilistic evaluation of the effect on buffer and canister peak temperatures of variability in rock thermal conductivity. Other data as in Table 9-4.*

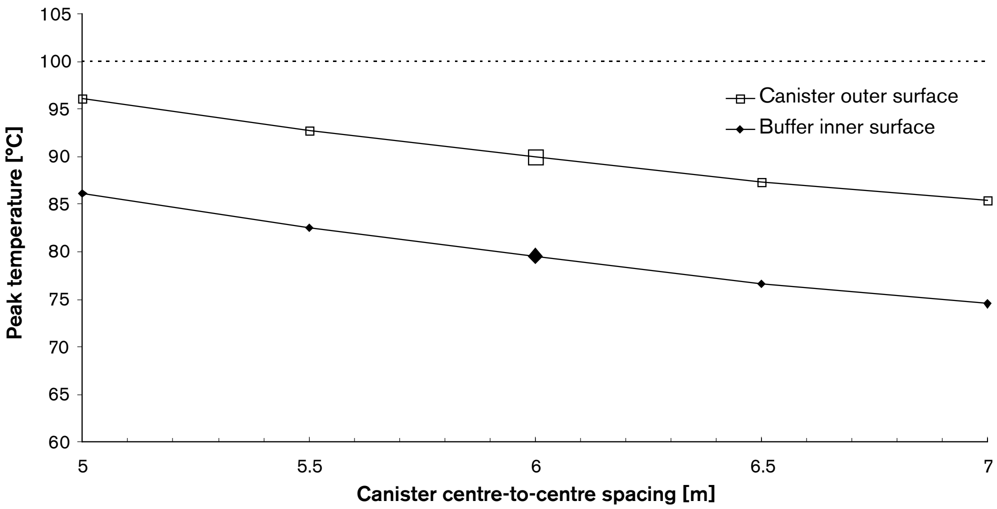


Figure 9-19. *Sensitivity of canister and buffer peak temperatures to the canister centre-to-centre spacing. Other data as in Table 9-4.*

Laxemar

Similar calculations have been carried out for the Laxemar site, with data from the **Data report** reproduced in Table 9-4. The results are presented in /SKB 2006a/ and show similar margins of the peak buffer temperature to the peak temperature criterion.

Conclusion

For both sites and suggested layout, the analyses presented above suggest that there is a large margin to the peak temperature criterion for the buffer, even when the spatial variability of the rock thermal properties is taken into account and with other data essential for computing the result chosen pessimistically.

9.3.5 Mechanical evolution of the rock

After deposition, backfilling and closure, the mechanical evolution is controlled by the heat generation from the spent fuel, by the swelling pressure of the bentonite buffer in the deposition holes, by the gradual restoration of the groundwater pressure, which will reduce the effective stress and the fracture shear strength, and by the time dependent decay of stress concentrations around the deposition tunnels and deposition holes. The timescale for the thermal effects can be predicted in detail as demonstrated in section 9.3.4 above and numerous other analyses of the thermal development of the repository. The time-scale for the development of the swelling pressure depends on the local permeability conditions around the individual deposition hole and on the general repository-scale restoration of the groundwater pressure.

Furthermore, as further explained in the **Geosphere process report** (section 4.1), the Baltic Shield is continuously subject to a horizontal compression or "ridge push" due to seafloor spreading from the Mid-Atlantic Ridge at the western tectonic plate boundary /Muir Wood 1993/. The compression is an important factor for the development of the state of stress currently prevailing in the Swedish bedrock (see chapter 4) where the maximum principal stress tends to be horizontal and oriented NW-SE, i.e. in the ridge-push direction.

The following mechanical processes related to the initial temperate period after repository closure, could have potential safety implications:

- Reactivation of fractures in the near field due to thermal load that could affect the mechanical stability (safety function R3a) and the fracture transmissivity in the near-field rock (safety function R2a).
- Reactivation of fractures in the far-field that could affect fracture transmissivity (safety function R2a).
- Reactivation due to increased ridge push that could affect the mechanical stability of the deposition holes (safety function R3a).
- Fracturing of the rock that could affect the deposition hole geometry (safety function Bu2) and migration between buffer and rock (related to safety function R2a).
- Potential for creep deformation that could affect deposition hole geometry (related to safety functions Bu2 and Bu4). Here the term creep is used also for cases in which the mechanical load is not constant over time, i.e. when the shear strain successively relaxes the stresses.

These issues are assessed in the following.

Reactivation due to thermal load

The stress redistribution resulting from the swelling pressure, the development or restoration of the fracture pore pressure and, more importantly, the heat load from the spent fuel will reactivate existing near-field fractures. The process is modelled in the 3DEC studies /Hökmark et al. 2006/ of stress redistribution effects in fractured near-field rock, as discussed in section 9.2.2. The numerical analysis covers a series of events ranging from excavation of the deposition tunnel to the mechanical effects of glacial load with boundary stresses obtained from preliminary results from on-going simulations of mechanical ice/crust/mantle interactions. The results are used to estimate possible permeability changes caused by shear and normal fracture movements, by using some empirical relations between deformation and permeability changes. Generally, there is a high uncertainty when applying these relations, but they are useful for judging whether there will be any hydraulic impact and to get an order of magnitude indication of the magnitude of any such impact.

/Hökmark et al. 2006/ make a set of observations concerning the reactivation caused by the swelling pressure, the pore pressure and the thermal load. Most results are valid for both Laxemar and Forsmark, whereas some are specific to one of the sites, as noted below.

- The joint normal stress relaxes in some fractures as a result of the excavation-induced stress redistribution (cf section 9.2.2). The combined effects of heating and development of swelling pressure and pore pressure is to increase the fracture normal stresses, at many places well above the initial pre-mining values, the net effect being that fracture transmissivities drop below the initial ones. At the end of the thermal period, stresses and transmissivities tend to approach those found after excavation swelling pressure development and pore pressure development. Locally, there will be some effects of inelastic, irreversible fracture deformations during the thermal pulse giving additional but small transmissivity increases.
- In the Forsmark model, there is potential for shearing along some of the fractures. Calculations show examples of fractures moving between 4 and 5 mm at some locations. Using empirical relations between fracture shear movement and transmissivity determined by /Olsson 1998/, this may mean that the local transmissivity increases by two orders of magnitude, but on most of the fracture plane, the displacements are much smaller. Increasing transmissivity due to shear deformations in fractures will not necessarily occur, but it is a pessimistic assumption in this case. In addition, the normal stress acting across the fracture was much larger than the maximum stress considered in the empirical relations. This means that transmissivity increases would be less.
- The proximity to the excavations controls the response of the fractures to the different loads. The tunnels are backfilled with material that does not produce any significant pressure on the peripheries. This creates a zone around the tunnel peripheries where normal stresses are low on planes that are parallel to the tunnel. That zone is particularly wide below the flat floor of horseshoe shaped tunnels. The cylindrical deposition holes are smaller in volume and do not have nearly as far-reaching effects on the stress field as the tunnel. The region below the tunnel floor is not only stress-relaxed in the vertical direction by the nearby low pressure tunnel floor boundary and subject to increased stress parallel to the floor – it is also the region of maximum thermal impact. Fractures located at some distance from the repository openings will be either in increased or insignificantly reduced compression through the entire load sequence and exhibit little displacement.

/Hökmark et al. 2006/ also attempt to summarize the above and the results of the 3DEC simulations schematically, cf Figure 9-20. Six fractures were considered with different orientations and with different positions in relation to the repository openings were explicitly modelled in the 3DEC analyses. The shear behaviour and the separation/closure behaviour of these fractures can be considered to represent the response of most near field fractures of potential importance.

In summary, there could be some significant, but very local effects on the fractures very close to the deposition holes, as suggested in Figure 9-20. The hydraulic importance of these effects is discussed in section 9.3.6. Otherwise the reactivation, which at most is a few mm, has little importance. It is certainly not sufficient to adversely affect canister integrity.

It should also be noted that in the 3DEC simulations, the 5 MPa pore pressure and the bentonite swelling pressure were established before the heating started. Both processes give slightly increased transmissivities in the near-field. In reality, the temperature will start to increase as soon as the canisters are deposited, while the pore pressure and the swelling will increase slowly after backfilling and closure at a rate that will depend on the time-scale for the overall restoration of the groundwater pressure and on the local permeability conditions. After the thermal pulse these pressure effects remain and will be responsible for part of the small net residual effects found locally at some of the modelled fractures.

Reactivation of fractures in the far-field

The combined thermal load from all canisters will also change the stress at the far-field scale. There will, for instance, be increased horizontal compressive stresses in the hottest region at repository depth and decreased compressive stresses above and below that region. Stress magnitudes and region

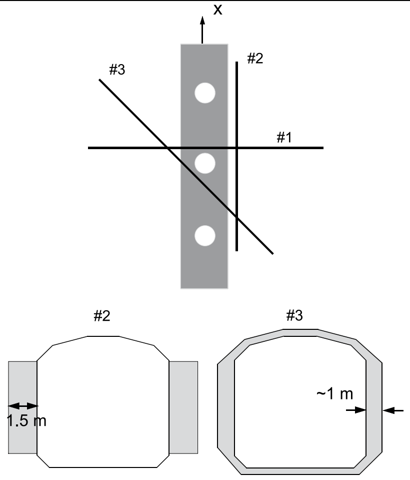
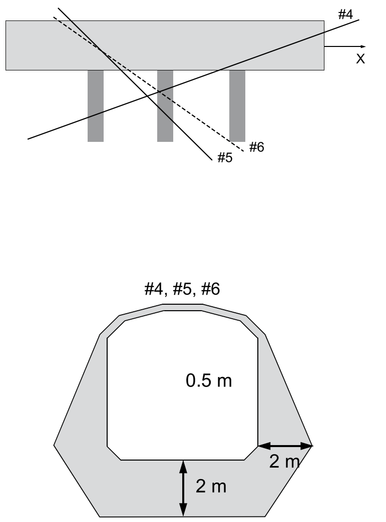
Fractures and regions	Nr	Transmissivity change	Dip range	Strike range
	#1	No change in transmissivity.	65-90	0±22.5, 180±22.5
	#2	Two orders of magnitude increase in 1.5 m wall regions because of extensive normal stress relaxation. No increase in roof and floor regions.	65-90	90±22.5, 270±22.5
	#3	Two orders of magnitude increase at up to 1 m distance from the tunnel periphery	65-90	45±22.5, 270±22.5
	#4	Two orders of magnitude increase in the grey-shaded region around the tunnel, no change elsewhere.	0 - 65	All strikes
	#5	Two orders of magnitude increase in the grey-shaded region around the tunnel, no change elsewhere.	0 - 65	All strikes
	#6	Two orders of magnitude increase in the grey-shaded region around the tunnel, no change elsewhere.	0 - 65	All strikes

Figure 9-20. *Schematic summary of how fractures of different orientations would have a transmissivity increase locally around the tunnel. These rules are based on results suggested by /Hökmark et al. 2006/.*

volumes will change over time. In order to examine this /Hökmark et al. 2006/ applied a far-field version of the 3DEC model already discussed. The large-scale Forsmark 3DEC thermo-mechanical model was used to examine the thermal stresses around the repository as a function of time.

The in situ stress-depth relations obtained from the Forsmark site-descriptive model /SKB 2005c/ were then used, together with the calculated thermal stresses, to find the resulting horizontal stress at different times as function of depth below the ground surface (Figure 9-21).

Regions where the resulting horizontal stresses are tensile, or rather where compression will approach zero, are found only at shallow depths. In the minor stress direction, stresses are compressive below 80 m depth at all times. At depths below about 300 m, compression increased at nearly all times, with only insignificant exceptions at early times. Qualitatively, the thermal stresses agree well with stresses calculated analytically by /Claesson and Probert 1996/ for a generic, square-shaped repository at 500 m depth.

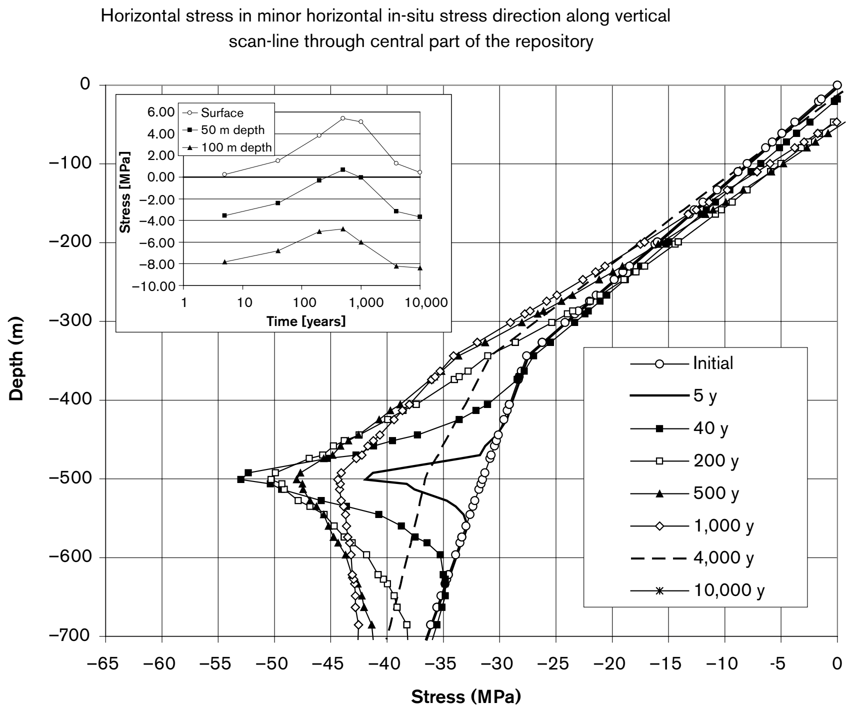


Figure 9-21. Simulated minor horizontal stress at different times along a vertical scanline at Forsmark. The insert shows stress as function of time at three shallow depths.

/Hökmark et al. 2006/ also calculated relative transmissivities using the stress-transmissivity relation suggested by /Dershowitz et al. 1991/ and an alternative based on work by /Liu et al. 2003/. The uppermost 100 m, where the compressive stresses may approach zero for some time, were ignored. The increase in transmissivity appears to be modest. Below a depth of 200 m the increase was at most 25% and 50%, respectively, for the two stress-transmissivity laws (after 200 years). Both laws gave unchanged or modestly reduced transmissivities at all depths below 300 m at all times. There can be increased fracture transmissivity above this level.

In conclusion, there will only be insignificant changes of fracture transmissivity below 200–300 m. There can be increased fracture transmissivities above this level.

Reactivation due to ridge push and/or glacio-isostatic adjustment

There are, basically, three considerations for the assessment of future seismicity in Sweden:

1. The role of tectonic loading processes.
2. the role of glacio-isostatic adjustment.
3. the extrapolation of current earthquake catalogues.

The tectonic conditions in the Baltic shield have been stable for the past 2 million years /Muir Wood 1995/. In addition to ridge push, the shield suffered shorter-term loading and unloading because of repeated glaciations and deglaciations.

Though the ridge push contribution to the stress state is essentially constant over time, there exists some uncertainties as to whether present-day seismicity in Sweden is predominantly tectonic in origin, due to mid-atlantic ridge push /Slunga 1991/ or whether the seismicity is predominantly the effect on-going glacio-isostatic recovery /Muir Wood 1993/. Consequently, the extrapolation of present-day seismicity into the future is uncertain. Additionally, regardless of the uncertainties related to the origin of present-day seismicity, the earthquake catalogue, covering the last century, contains both instrumental and historical records. The small number of earthquakes measured and their small magnitudes makes extrapolation of small-scale regression relations to large magnitude earthquakes quite uncertain, both for physical and mathematical reasons.

Earthquake frequencies are usually given in terms of a reference area and reference time over which the earthquakes are anticipated to occur. Both the time periods and areas differ between quoted references. It is, therefore, practical, for the purposes of SR-Can, to normalise the frequencies obtained from various sources to a common unit: number of earthquakes with $M \geq 6$ per km^2 and year.

An estimation of the future seismicity was made by /La Pointe et al. 1999, 2002/ based on a methodology /LaPointe et al. 1997/ originally developed for the safety report SR 97. Having adjusted for seismicity in the Lake Vänern region, /La Pointe et al. 1999 Table 4-5/ estimated a frequency of less than $8.69 \cdot 10^{-10}$ $year^{-1}km^{-2}$ in a SE Swedish province as defined by /Kijko et al. 1993/.

An expert elicitation project addressing the issue of glacially induced seismicity in Sweden /Hora and Jensen 2005/ proposed a frequency of $3.18 \cdot 10^{-9}$ $year^{-1}km^{-2}$ which is close to the frequency proposed by /La Pointe et al. 1999/.

Recent calculations by /Bödvarsson et al. 2006 Table 4-3/ propose a frequency of $4.77 \cdot 10^{-9}$ $year^{-1}km^{-2}$. This estimate focused only on the next 1,000 year period, whereas the estimates of both /Hora and Jensen 2005/ and /La Pointe et al. 1997/ addressed a period of 100,000 years, to include effects of a future glaciation.

The short term frequency estimate of Bödvarsson et al. is, still, very close to a long term estimate, $4 \cdot 10^{-9}$ $year^{-1}km^{-2}$, for stable cratonic cores proposed by /Fenton et al. 2006/.

In summary, published estimates of future earthquake frequency are within the range $8.69 \cdot 10^{-10}$–$4.77 \cdot 10^{-9}$ $year^{-1}km^{-2}$.

/Fälth and Hökmark 2006/ showed that magnitude 6 earthquakes will not induce secondary fracture shear displacements exceeding 25 mm on radius = 150 m fractures if these are located at distances larger than 500 m from the earthquake-generating fault. This is well below the 100 mm criterion adopted as a cautious threshold for canister damage, which means that 500 m can be regarded as a prudent, pessimistic measure of the effective influence range for magnitude 6 events. Beyond the effective influence range of 500 m, fractures must, according to /Fälth and Hökmark 2006/, have radii exceeding 500 m to be able to host slips exceeding 0.1 m. If the range of influence is approximated to scale with the fault rupture area, then, using regression relations given by e.g. /Wells and Coppersmith 1994/, a magnitude 7 earthquake would have a corresponding influence range of 5 km.

We choose to normalise the forecast earthquake frequencies to a circular area with a radius of 5 km. This has the advantage of being sufficiently large both to cover the site investigation areas (Figure 9-22) and, at the same time, sufficiently large to host epicentres along the deformation zones able to host the largest earthquakes. The normalised earthquake frequencies are given in Table 9-5.

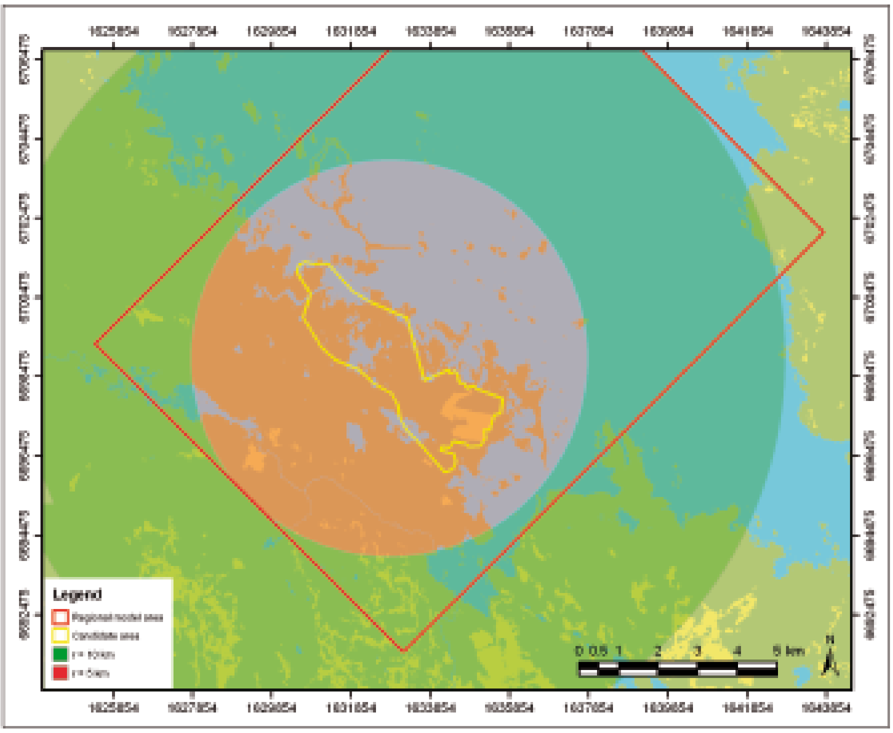
Fracturing of the rock

Even if the initial rock stresses are not sufficient to produce spalling, there is still the possibility that spalling may occur later due to the additional thermal load. The potential occurrence of spalling is site- and repository design specific, as it depends on the in situ stress, the intact rock mechanical strength and on the repository layout. This is the only fracturing mechanism identified as relevant during the initial temperate period.

Table 9-5. Yearly frequencies for magnitude 6 events or larger normalised to a circular area with radius 5 km.

Normalised frequency (y^{-1})	Reference
$3.75 \cdot 10^{-7}$	/Bödvarsson et al. 2006/
$6.83 \cdot 10^{-8}$	/La Pointe et al. 1999/ excluding Lake Vänern area Table 4-5
$2.50 \cdot 10^{-7}$	Expert Elicitation project /Hora and Jensen 2005/
$3.14 \cdot 10^{-7}$	/Fenton et al. 2006/

a)



b)

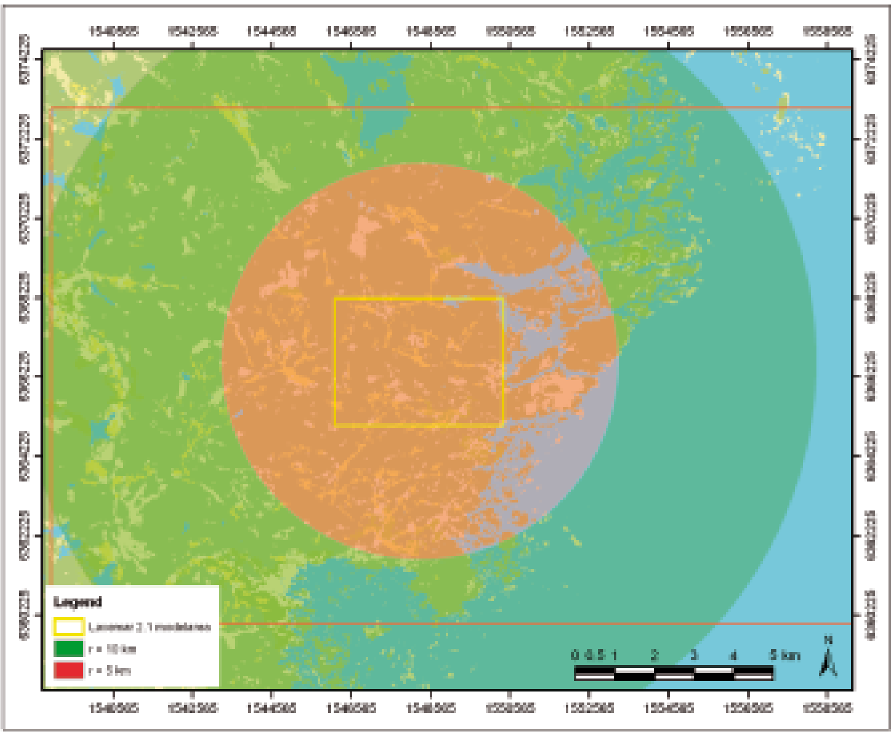


Figure 9-22. The location and size of the circular area (r = 5 km) over which earthquake frequencies in a) Forsmark, b) Laxemar are given in this report.

As discussed in section 9.2.2, estimates of the extent and characteristics of fracturing, e.g. spalling in deposition holes, have been made using results obtained from 3DEC near-field models /Hökmark et al. 2006/, and by use of observations from the isothermal phase of the APSE experiment.

The Forsmark models were analyzed assuming the rock type to be granite-to-granodiorite with a UCS of 225 MPa.

Figure 9-24 shows principal stresses in a horizontal section 4 m below the tunnel floor and in a vertical section along the deposition hole axis. Only rock within about 0.3 m distance from the walls is displayed. The arrows show the tunnel axis orientation and the dashed lines indicate the two sections. The three sets of stress plots represent the state after excavation, the state after 5 years and after 40 years, respectively. The stress tensor symbols scale with the projection of the principal stresses onto the viewing plane, whereas the colour code relates to the magnitude of the major principal stress. The contour lines indicate areas where the major stress reaches the spalling threshold, which is assumed here to be 120 MPa. This does not mean that spalling will occur everywhere within the contours.

/Hökmark et al. 2006/ drew the following conclusions.

- At both Forsmark and Laxemar, there will be spalling in the deposition holes because of the thermal load, unless there is some supporting bentonite swelling pressure. However, if the bentonite buffer has had time to take up water and begin to close the buffer-rock gap before the thermal stresses have reached levels that may cause spalling, then the bentonite support pressure will probably be sufficient to prevent spalling altogether, or to limit the growth of failed rock regions.
- An indication of the geometry of this spalled zone can be assessed from e.g. Figure 9-24. It indicates rock that is potentially at the failure limit according to the elastic analysis. The APSE experience indicates that the failure, once it has been initiated, redistributes the stresses continuously such that the rock eventually stabilizes outside a notch-shaped region of much smaller volume (see e.g. Figure 9-23). Similar observations have been made at the URL in Canada, cf /Martin 2005/.
- At present, there is no way of directly calculating the actual shape or depth of thermally induced failures. Experience indicates that the failures will be notch-shaped and that the notch will self-stabilize at some depth that depends on the stress that prevailed at the time of the failure. Once the notch is stable, subsequent increases in stress will not significantly increase the depth of the failure.
- It is anticipated that the notch will be 0.1 m deep and 0.14 m wide, i.e. it is likely that the notch forms and stabilizes much earlier, and at a lower tangential stress, than in the simulated results. However, the experience of brittle failures induced by continuously increasing thermal stresses is not extensive at present. When the full evaluation of the APSE experiment is at hand, it may be possible to make quantitative estimates.

Figure 9-23. *Example of spalling in a deposition hole wall as found in the APSE experiment.*

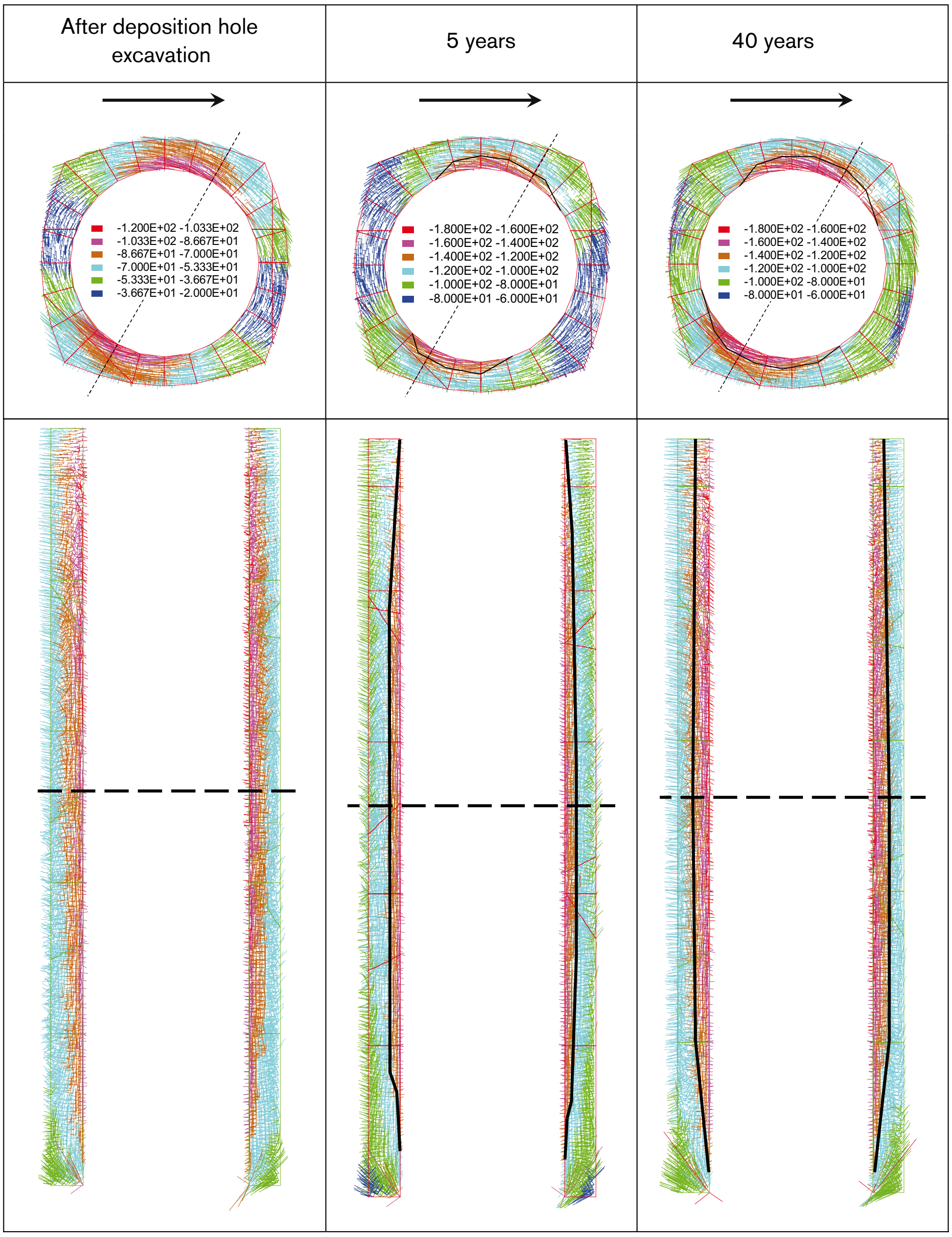


Figure 9-24. *Calculated principal stresses in a horizontal section 4 m below the tunnel floor and in a vertical section along the deposition hole axis. The contour lines indicate areas where the major stress exceeds the spalling threshold, which is assumed here to be 120 MPa. This does not mean that spalling will occur everywhere within the contours.*

These findings are considered in the SR-Can analysis. Overall conclusions from the analyses undertaken is summarised below.

- Given current understanding it must be considered that most deposition holes at Forsmark and Laxemar will exhibit some thermal spalling. The volume of the spalled zone could vary between very small cavities up to the sizes suggested above.
- With pellets in the buffer/rock gap, the impact on the buffer density is negligible. It is, therefore, concluded that the gap shoud be filled with pellets.
- Experiences from the APSE experiment suggest that thermal spalling could be completely avoided if a small resisting force (pressure) is exerted on the deposition hole wall. Possibly, pressures in the order of 150 to 200 kPa would be sufficient. However, the thermal load will act long before the bentonite swelling pressure acts on the wall (see sections 9.3.4 and 9.3.8, respectively, so other engineering solutions would be needed to create the pressure. This possibility is pessimistically neglected in SR-Can.

- The “spalled” rock may have high permeability and porosity. Furthermore, it cannot be simply assumed that the buffer will fill out the space between rock fragments and the extra volume created, although this may in reality be the case. This needs to be considered in transport calculations of radionuclides and canister corroding agents. The geometry of the spalled zone can be taken from the discussion above. Estimates of the effects on transport properties are discussed in section 9.3.6.

The impact of the spalling as regards the impact on the near-field transport are assessed in sections 9.3.6 and 10.5.

Potential for creep deformation

The concept of creep implies that a material has inherent time-dependent mechanical properties so that movements take place without additional loading, due to already active stresses. As further discussed in section 4.5 of the **Geosphere process report**, creep deformation of the rock mass may be neglected. If it is assumed that all significant movements take place along fractures, then the ultimate consequence of extensive creep movement over a long period of time is that, eventually, the shear stresses on the fractures will decrease to zero or at least to significantly lower levels than those recorded today. There is no evidence, anywhere in the world where deep mining is carried out in hard rocks that such a condition exists, i.e. substantial deviatoric stresses are recorded at all mine sites.

Creep deformation is, therefore, not further considered in SR-Can.

Mechanical impacts on rock permeability

The rock mechanics impacts on rock permeability (i.e. the mechanico-hydro (MH) and thermo-hydro-mechanical (THM) effects) during the first thermal phase are addressed in the subsections above. At the end of the thermal period, stresses and transmissivities tend to approach those found after excavation. The effects of the swelling pressure, developed toward the beginning of period of the thermal load also remain. These effects are, however, very small compared to the excavation effects.

9.3.6 Hydrogeological evolution

The hydrogeological evolution during the temperate period after repository closure involves two distinct time intervals. The first one is the time interval for resaturation of the repository once pumping of the open tunnels has stopped. The subsequent time interval deals with the evolution of the saturated repository up till the start of the next glacial period.

Resaturation of the repository

After repository closure, the tunnels will be back-filled and slowly become water saturated. The time for saturation of the repository is longer than the time given by the repository volume divided by the inflow as calculated for the open repository conditions. This is due to the complexities implied by the two-phase flow nature of the system, as the tunnels go from being air filled to water filled.

The analysis of the resaturation phase deals with effects of an initially open repository, i.e. a repository at atmospheric pressure, being water filled. The overall objective is to assess the implications of site hydrogeological and hydrogeochemical conditions on the repository saturation process, i.e. safety functions R1b and R2c in Figure 9-2.

The analysis of the resaturation is performed with the model presented in section 9.2.3; thus, details concerning the model are not repeated here. The analysis of the resaturation phase strictly calls for a two-phase flow analysis. However, a simpler alternative is evaluated in /Svensson 2005/ and /Svensson 2006a/. The analysis of the resaturation phase is based on modifying the hydraulic conductivity and storativity terms appropriately to mimic conditions of two-phase flow. The modification of parameters is done such that results of full two-phase flow simulations of the resaturation phase of a rock-backfill system /Börgesson et al. 2006/ are reproduced. The methodology used and results from the rock-backfill analysis are discussed in more detail in section 9.3.8 below. It is noted that the results presented in this section refer to the resaturation of the whole repository after closure, whereas the resaturation of the buffer and backfill components are discussed in section 9.3.8.

Applying the simplified analysis for Forsmark-like conditions indicates resaturation times between 15 and 50 years, and around six years for Laxemar conditions. For Forsmark, only 2D simulations were undertaken, whereas a full 3D analysis was made for Laxemar. The development of the resaturation modelling methodology is still on-going; in the SR-Site analysis, a possibly up-dated methodology will be used.

The saturated repository

After saturation of the repository, topography is the main driving force for groundwater flow, and changes in groundwater flow conditions will be caused by the shore-line displacement. The shore-line displacement results in both changed pressure conditions as areas previously under water emerge as dry land, and in changed water composition, as fresh water (rain) infiltrates over previously sea-water-covered areas. In addition, also salinity changes in the Baltic Sea imply changed conditions.

Several aspects of the repository evolution are of interest for assessing the long-term safety. Groundwater flow directions and magnitudes are of interest for studying transport of solutes potentially harmful to the repository, and for studying potential releases of radionuclides from defective canisters. Groundwater flow paths provide information on where in the bedrock transport would take place and where exfiltration to the biosphere occurs. Properties along flow paths provide information on transport and retention characteristics of potentially migrating radionuclides. The overall objective is to assess the implications of site hydrogeological and hydrogeochemical conditions on repository performance. Generally, this is assessed by simulating the groundwater flow, identifying migration paths and calculating travel time and transport resistance (F-factor) for these paths. Thus, the analysis is mainly related to the safety function R1b and R2a–c and f in Figure 9-2.

The Forsmark site-descriptive model (SDM) version 1.2 (abbreviated F1.2) /SKB 2005c/ provides the underlying conceptual model and data parametrisation of the site. In the **Data report** (section 6.5), the main alternative model concepts for describing the bedrock are presented. These are a multi component Continuum Porous Medium (CPM) model based on multi-component homogenous properties derived for the site, an Equivalent Continuum Porous Medium (ECPM) model with heterogeneous properties based on the use of an underlying discrete fracture network (DFN) concept, and a pure DFN-representation in model volumes close to the repository, surrounded by an ECPM representation further out. Thus, with current knowledge, both CPM and DFN representations may be realistic representations of the site, and are discussed in the following sub-sections. However, when consequences in terms of, e.g., radionuclide release and transport are considered, the DFN representation results in more severe consequences. Hence, more emphasis is put on the DFN representation in later chapters.

The Laxemar SDM version 1.2 (abbreviated L1.2) /SKB 2006b/ provides the underlying conceptual model and data parametrisation of the site. The conceptual model is based on a discrete fracture network representation of the site. The models are implemented either as up-scaled ECPM models or pure DFN models on the repository-local scale surrounded by an ECPM on the regional scale.

Regional scale groundwater flow – Forsmark

In order to assess how groundwater flow, and hydrogeochemical and transport conditions evolve over time, it is important to study the repository in a regional setting. In the current application, the code Connectflow is used /Hartley et al. 2006a/. The Forsmark 1.2 SDM application using Connectflow is reported in /Hartley et al. 2005a/; a consistent approach is applied here for the Temperate period simulations.

Both the CPM and ECPM representations of the rock have been used. However, a slight modification of the SDM description has been made. The so-called Alternative case geological model was chosen for reasons of conservatism; this model contains more deformation zones, though it should be recognised that many of the lineaments used for supporting their existence are of low confidence, see section 4.3.2. Also, the DFN statistics have been up-dated to reflect the low hydraulic conductivity conditions in the deep rock below zone ZFMNE00A2. This was achieved by reducing the transmissivity of the fractures at depths greater than 350 m and below ZFMNE00A2 by a factor of 10. With this modification, the block conductivity values at repository depth are around 10^{-11} m/s in the resulting ECPM model, and thus consistent with the CPM representation of the SDM.

Groundwater of variable salinity, where the salinity arises from a number of groundwater constituents, is treated in both the CPM and ECPM models. The transport equations are thus coupled with the overall mass conservation equation for groundwater. In addition, rock matrix diffusion is included in the transport of each groundwater constituent. The constituents may be expressed as selected reference waters which are then transported by the groundwater flow. The results of the reference water analysis are presented in section 9.3.7.

Transient boundary conditions in terms of shore-line displacement and salinity of the Baltic Sea are used. For rock matrix diffusion of salt, a flow-wetted surface value of 0.25 m^2/m^3 was used inside rock domain 29, consistent with the span given in the site-descriptive modelling /Hartley et al. 2005a/ and based on global estimates of fracture surface area (P_{32} values) in the model. The flowing fracture frequency (P10c) in the corresponding rock volume is 0.06 m^{-1}, implying a flow-wetted surface of 0.3 m^2/m^3 (flow-wetted surface = $2 \cdot \alpha \cdot P10c = 2 \cdot 2.5 \cdot 0.06 = 0.3$ where α is a function of the geometrical parameters of the DFN model). Thus, the used value 0.25 m^2/m^3 is consistent with the measured flowing fracture frequency. However, in the calculation of transport resistance (F-factor) in the ECPM model, up-scaled values from the underlying DFN model were used. On average, the resulting flow-wetted surface is 0.08 m^2/m^3 in the volume surrounding the repository. The lower flow-wetted surface value reflects the fact that a fracture size truncation of 10 m is used in the underlying DFN model which results in a smaller surface area of connected fractures relative to the global P_{32} estimate. It is noted that higher resolution estimates of the F-factor were used at the repository scale, as described in the next subsection.

The analysis was performed for a time period from the end of the last glaciation up till the beginning of assumed permafrost conditions, i.e. up till 9,000 years AD. The shore-line displacement results in groundwater discharge substantially moving in concert with the retreating sea. Performance measures in terms of Darcy velocity at repository depth, advective travel time, and F-factor were analysed for snapshots in time from present up till 9,000 AD. The "snapshots-in-time" methodology implies that particle tracking is done using the instantaneous groundwater velocity fields taken at different times from the transient flow simulation. Also salinity fields, obtained from the transient simulations, have been assessed at different discrete time intervals, see section 9.3.7.

The results show a clear and general trend that at around 3,000–4,000 AD the flow field around the repository area is subject to major changes. At this time, the shoreline moves away from the vicinity of the repository and the head gradients alter significantly. The flow pattern in the candidate area is quite complex due to the sharp changes in hydraulic properties between the very tight rock in the candidate area and the surrounding more conductive rock mass outside.

In Figure 9-25 below the Darcy velocity at repository depth, advective travel time and F-factor from repository depth to the top surface of the model are presented for three snapshots in time for the ECPM model. Here it can be seen that both travel times and F-factors are higher at 3,000 AD compared with values under today's conditions.

Corresponding results for groundwater salinity and individual groundwater constituents are discussed in section 9.3.7.

A number of variants have been tested on the regional scale. These include, in addition to testing model representation in terms of CPM versus up-scaled ECPM, tests of the geological model (deformation zone model), DFN representation in terms of properties below zone A2 (modified transmissivity or reduced fracture intensity), test of fracture length-transmissivity correlation in the DFN model (specifically, fully correlated or semi-correlated length-transmissivity relationships), change of fracture length distribution in the DFN model, multiple DFN realizations, and change of transport properties in both the deformation zones (kinematic porosity) and in the bedrock surrounding the deformation zones. The most important sensitivities are found to be related to the CPM versus ECPM representation, choice of geological model, DFN representation in terms of properties below zone A2, and fracture length-transmissivity relationship. Based on the outcome of the sensitivity studies, a limited set of variants were propagated to the repository scale models, see section below.

The regional model was also used to assess thermal effects of the deposited waste on the groundwater flow field. The heat will raise the temperature of the rock and groundwater in the vicinity of the repository. This leads to buoyancy forces that tend to create convection cells with flow up through the repository and down as the water cools at some distance from the repository. The modification of the flow alters the migration paths of radionuclides potentially migrating from the repository during the period when buoyancy forces are significant. Furthermore, the thermal-buoyancy-driven flow may lead to upconing of saline water beneath the repository, which might affect chemical conditions within the repository. Finally, the increased temperature in the vicinity of the repository will decrease the groundwater density and viscosity, thus also affecting the flow.

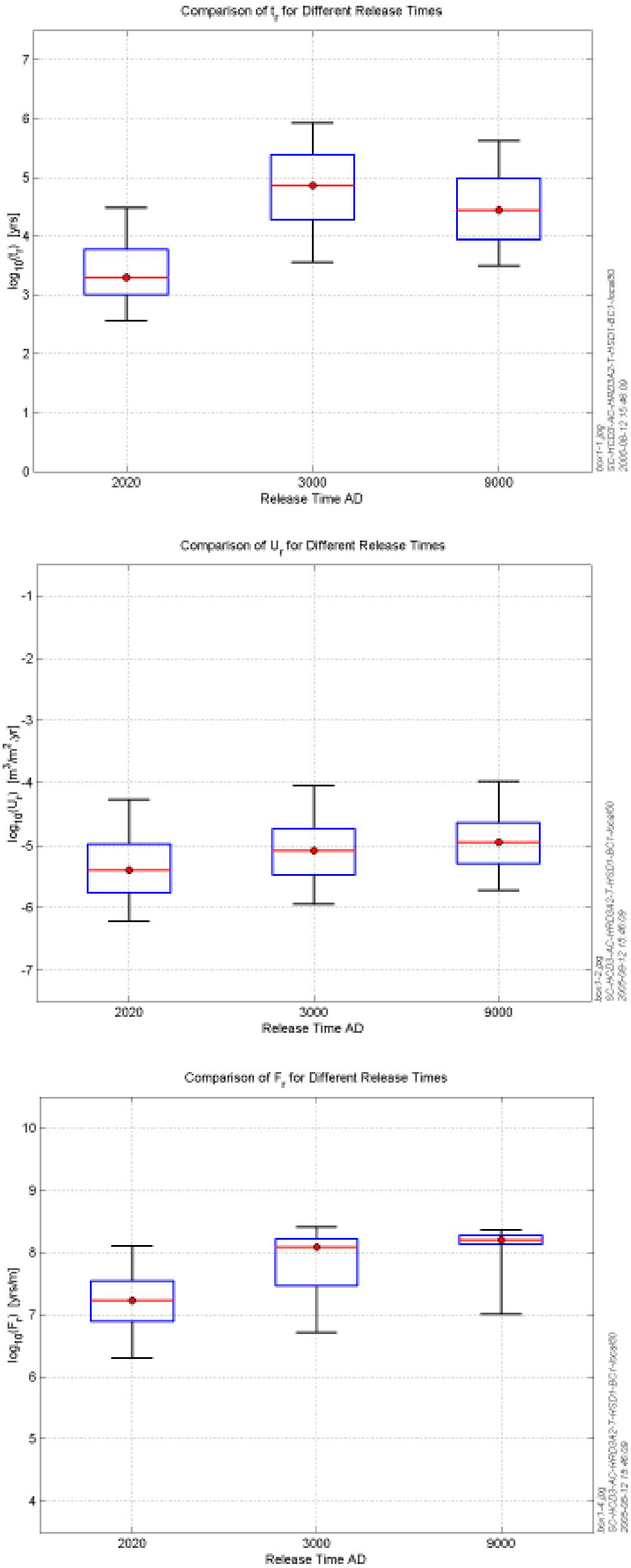


Figure 9-25. *Box-and-whisker plots for particles released at 2,020 AD, 3,000 AD and 9,000 AD. From top: travel time, Darcy velocity and transport resistance. The statistical measures are the median (red), 25th and 75th percentile (blue bar) and the 5th and 95th percentile (black "whiskers").*

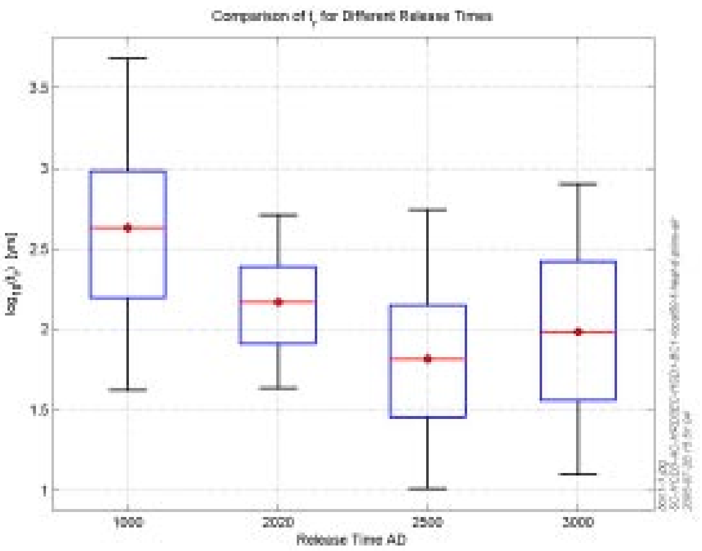


***Figure 9-26.** Box-and-whisker plots to compare distributions of travel time for different release times in the ECPM model. The three cases to the right are for transient particle-tracking calculations with thermal effects included.*

Results show that up-coning of saline water due to heating is minimal, but that flow paths from repository depth are affected. The effect on flow paths is mainly an increased velocity, hence resulting in shorter travel times, rather than changed exit point locations. An example of travel time reduction is shown in Figure 9-26. It is noted that the thermal effects are of short duration; within a period of 500 to 1,000 years the effects have essentially vanished. Thus, from a radionuclide transport perspective, the thermal effects are of little interest since canister failures are not anticipated over this period, see further chapter 10. Thermal effects on the resaturation phase have not been addressed within SR-Can.

Repository scale groundwater flow – Forsmark

In the site-descriptive model, flow simulations are only made on a regional scale, although the description of hydraulic properties is provided on multiple scales. In the assessment of repository performance, where flow in fractures down to a scale of individual fractures intersecting the canister deposition holes are of interest, a much higher resolution is needed. To achieve this resolution while still capturing the regional flow effects, a simulation method of nesting different scales is adopted. Specifically, when analyzing flow and transport in the repository scales, a continuum representation of tunnels and deposition holes is nested within repository scale models that are either DFN or CPM applications. The DFN representation is carried through as a pure DFN, i.e. not up-scaled to a representative ECPM. An example of such nesting is shown in Figure 9-27 and Figure 9-28. The models on the repository scale adopt boundary conditions from the corresponding regional scale models (i.e. regional scale CPM for repository scale CPM model, regional scale ECPM for repository scale DFN model). It is noted that density driven flow is handled with only minor simplifying assumptions in the pure DFN model; for details see /Hartley et al. 2006a/.

The hydraulic conductivity of the back-filled engineered structures is assumed to be 10^{-10} m/s. The hydraulic conductivity of the EDZ is elevated relative to the surrounding rock by half an order of magnitude (i.e. increased by a factor 3.16). The EDZ is assumed continuous, see section 9.2.2 and the **Data report** (section 6.5) for details.

For subsequent radionuclide transport calculations, three distinct transport paths are of interest. These are i) transport through a fracture intersecting the deposition hole (Q1 path), ii) transport in the EDZ (Q2 path), and iii) transport through a fracture intersecting the deposition tunnel (Q3 path), see Figure 9-16. The flow is sampled at all three points, and based on the flow values, equivalent flow rates, Q_{eq}-values, are calculated. The Q_{eq}-values serve as input both for canister corrosion calculations, see section 9.3.12, and for radionuclide transport calculations, see section 10.5.3. Particles are also released in all three transport paths in order to calculate advective travel times and the transport resistance (F-factor).

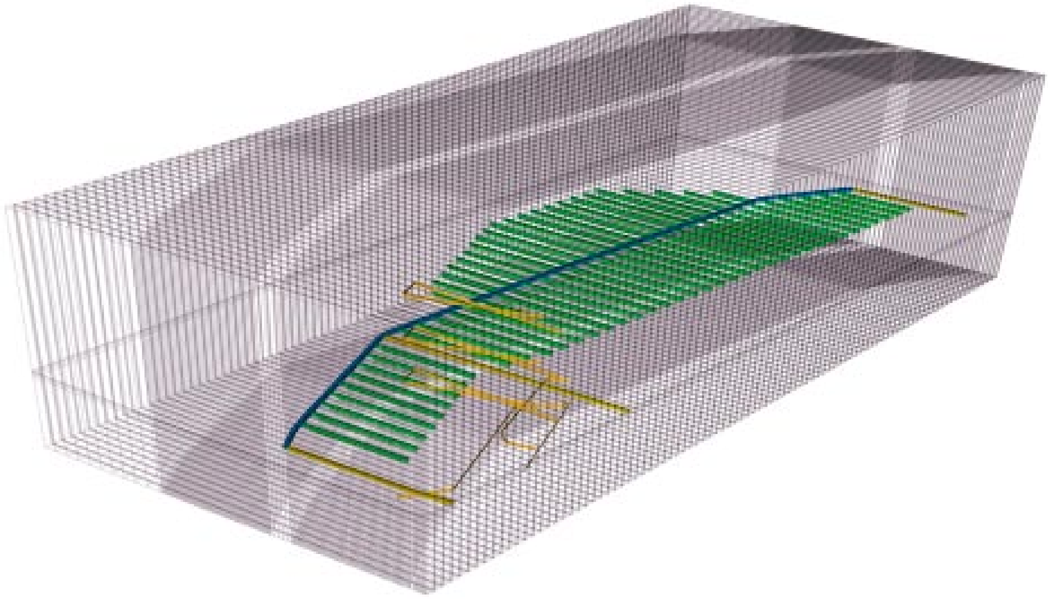


Figure 9-27. *Domain used for the nested DFN model of the Western repository block. The outer grid shows the domain for the DFN model. Inside of that, the repository structures are represented by a continuum sub-model (deposition tunnels are coloured light blue, access tunnels dark blue, and transport tunnels and ramp yellow).*

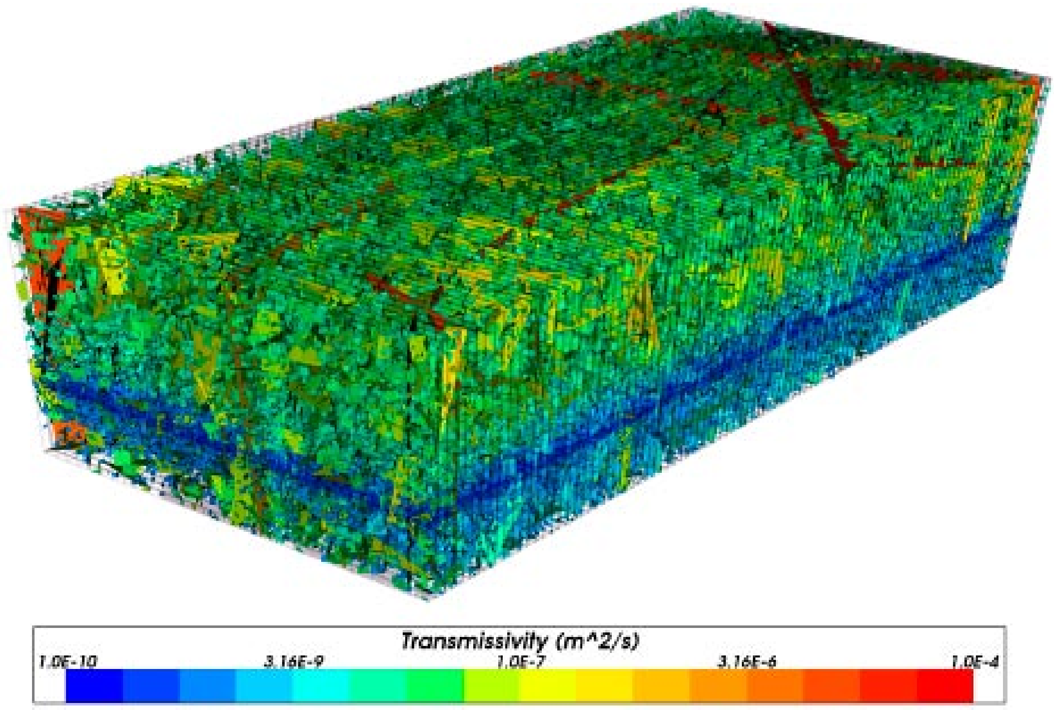


Figure 9-28. *DFN model of the Western repository block. Fractures are coloured by transmissivity. The larger fractures correspond to deterministic deformation zones from the geological model.*

The DFN model that surrounds the repository is shown in Figure 9-28. The fractures are derived from 3 sources: deterministic deformation zones imported from the geological model, stochastic fractures imported from the regional DFN model including fractures down to a radius of 7.0 m, and additional stochastic fractures in the radius range 1.1–7.0 m. The inclusion of smaller fractures implies that the flow-wetted surface area used for calculation of the transport resistance (F) is, on average, 0.2 m^2/m^3, which is consistent with the CPM value and the ECPM value used for rock matrix diffusion of salt on a regional scale.

Several variants are modelled on the repository scale. For both the CPM and DFN representations, variants are simulated with an increased hydraulic conductivity of the backfill (K increased by two orders of magnitude), and with an increased hydraulic conductivity of the EDZ (increased by one order of magnitude). These tunnel and EDZ variants are also combined with the most important variants identified in the regional simulations (i.e. fracture size-transmissivity correlation in DFN representation).

For a complete presentation and discussion of the results, the reader is referred to /Hartley et al. 2006a/; for a discussion on which cases to propagate to radionuclide transport calculations the reader is referred to the **Data report**, sections 6.5 and 6.6. Here, only a brief illustration of some of the key results is given.

A major issue in the calculation of flow-paths in the DFN model is the poor connectivity of the network. Many of the deposition holes are not intersected by fractures that connect to the main flowing network; furthermore, there are sections of tunnels with essentially stagnant flow where Darcy velocities are around 10^{-6} m/y or less. A sizeable proportion of holes, around 60%, are either not intersected by a connected fracture, or intersected by a cluster that is only connected to the tunnel system but not to the main connected network. Particles can also get stuck, due to numerical reasons, if particles start in fractures or sections of tunnels with very small flows. Also, if particles start in fracture connections that form closed loops, particles tend to get stuck. Concerning particle transport, it is noted that 40% of particles that start near a canister tend to become stuck very close to the start location, and that only about 40% of the canisters have Q1 paths leading to the surface. For the releases in the EDZ and the tunnel, Q2 and Q3, about 40% of the particles remain close to the repository due to nearly stagnant flow conditions. The reason that there are areas of nearly stagnant flow in the tunnel and EDZ is that each deposition tunnel is essentially a dead-end, so to get advection along or out of the tunnel there must be a head gradient along it, which requires that at least two moderate to large water-bearing fractures intersect the tunnel. Furthermore, the general head gradient tends to be orthogonal to the axis of the deposition tunnels, which also reduces advective velocities along tunnels.

For the particles that do migrate in the DFN model, it is very noticeable how particles congregate on a few large fractures. This clearly indicates that if a particle can enter the connected network, its pathway tends to focus rapidly on the larger fractures, most notably the deterministic deformation zones, but also the large stochastic fractures greater than about 50 m in length. Particles tend to move vertically upwards in large fractures since there are few long horizontal connections through the network, and this suggests markedly different transport pathways to the ones obtained in the continuum based regional models.

In Figure 9-29 the distribution of F-factor ($\log_{10}$) at 6,824 Q1-starting locations in the repository is shown for the 40% of particles that reach the surface of the DFN model. It is noted that particles that reach a vertical boundary in the DFN model are continued in the regional scale ECPM model. The blue colour indicates smaller values (F-factor about 10^4 y/m) and red indicates higher values (F-factor 10^9 y/m). All tunnels have some canister positions with a Q1 path. The smallest F-factors, around 10^4 y/m to 10^5 y/m, lie close to the deterministic deformation zones. It is likely that the deformation zones give rise to areas of locally enhanced fracture connectivity since the zones connect the fractures. This makes it easier for particles to find a route through the background fracture network to the deformation zone. For comparison, if one assumes a L = 400 m long planar zone with a transmissivity of $T = 10^{-6}$ m^2/s and a gradient of i = 1%, the resulting transport resistance would be $F = 2 \cdot L/(T \cdot i) \approx 2{,}500$ y/m which compares well with the lowest values obtained in the model.

Furthermore, the results suggest that the DFN model gives F-factors one or two orders of magnitude lower than the corresponding ECPM regional scale model. One of the main reasons is that flow-paths are shorter, predominantly vertically upwards rather than to the shoreline as in the ECPM model. Another factor is that paths tend to be more focussed towards channels through the larger fractures and deformation zones in the DFN model, whereas they are more diffusely distributed in the continuum model.

Travel times and F-factors in the rock are almost identical for each of the release points (Q1, Q2 and Q3) associated with an individual canister, suggesting that the flow path is the same for each release point and that flow does not diverge down different flow conduits around the repository. Only the initial velocities are moderately different for the three release points. All initial Darcy velocities have a median around 10^{-5} m/y, slightly higher in the fracture and tunnel, and slightly lower in the EDZ. The release time also has little effect, as transport is more strongly influenced by the presence

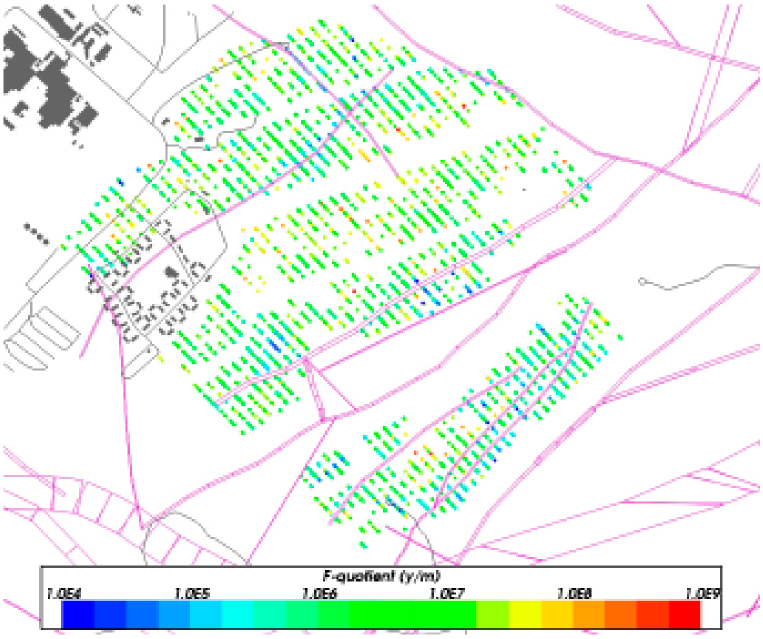


Figure 9-29. *Distribution of $log_{10}(F_r)$ for path Q1 at particle start locations at release time 2,020 AD. Also, the deformation zone model at z = –400 m (purple), roads and buildings (black are) are indicated.*

of structures, i.e. large stochastic or deterministic fractures, than variations in boundary conditions. For a release at 2,020 AD, travel times and F-factors are slightly lower and initial velocities slightly higher than for releases at later times. For details, the reader is referred to /Hartley et al. 2006a/.

When the continuum conceptualisation is studied on the repository scale, the repository is nested within a repository-scale CPM model. The properties of the repository scale CPM model are consistent with the regional-scale CPM model discussed above. Results indicate that performance measures calculated with the repository scale CPM model are consistent with the regional scale results. Specifically, path lines become longer as the shoreline retreats, and travel times and F-factors are higher than for the DFN model. Results for transport resistance and equivalent flow rates are presented in Figure 9-30 where a summary of results is made. The curves in the graphs are normalized with all deposition holes; the offset to the left represent deposition holes with zero flow. In the F-factor plot, the offset to the right indicate the fraction of flow paths which gets stuck in the geosphere. Thus, the curves represent the fraction of deposition holes which simultaneously have a flow greater than zero and have flow paths which exit the geosphere.

An important observation to be made in relation to Figure 9-30 is that the spread in values for the performance measures are much smaller for the CPM model than for the DFN model. This is a result of the homogenisation inherent in the continuum representation, where the details of discrete features on scales smaller than the deformation zones are lost. The higher transport resistance is primarily attributed to the lack of flow channelling which is typical in DFN models where flow tends to channelize within larger features. A second reason for higher transport resistance in the CPM model is the longer flow paths. The CPM model could be judged unrepresentative of bedrock conditions, since clearly only discrete fractures provide the transmissivity of the rock and flow measurements suggest these are sparsely distributed. However, the current hydrogeological DFN model may overestimate the connectivity of the fracture system. The CPM model is thus judged to be a fair representation of the spectrum of possible interpretations of current hydraulic data that indeed show very low – if any – transmissivity at depth.

The results from the nested continuum model also lend confidence to the nesting and modelling methodology. It is not the nesting as such of a continuum repository in a DFN repository scale model that results in vertical and short paths. Rather, it is the representation of the rock that determines the flow path configuration. In the SR-Can interim report /SKB 2004a/, similar vertical flow paths in a DFN model were possibly attributed to neglected density effects in the fracture network.

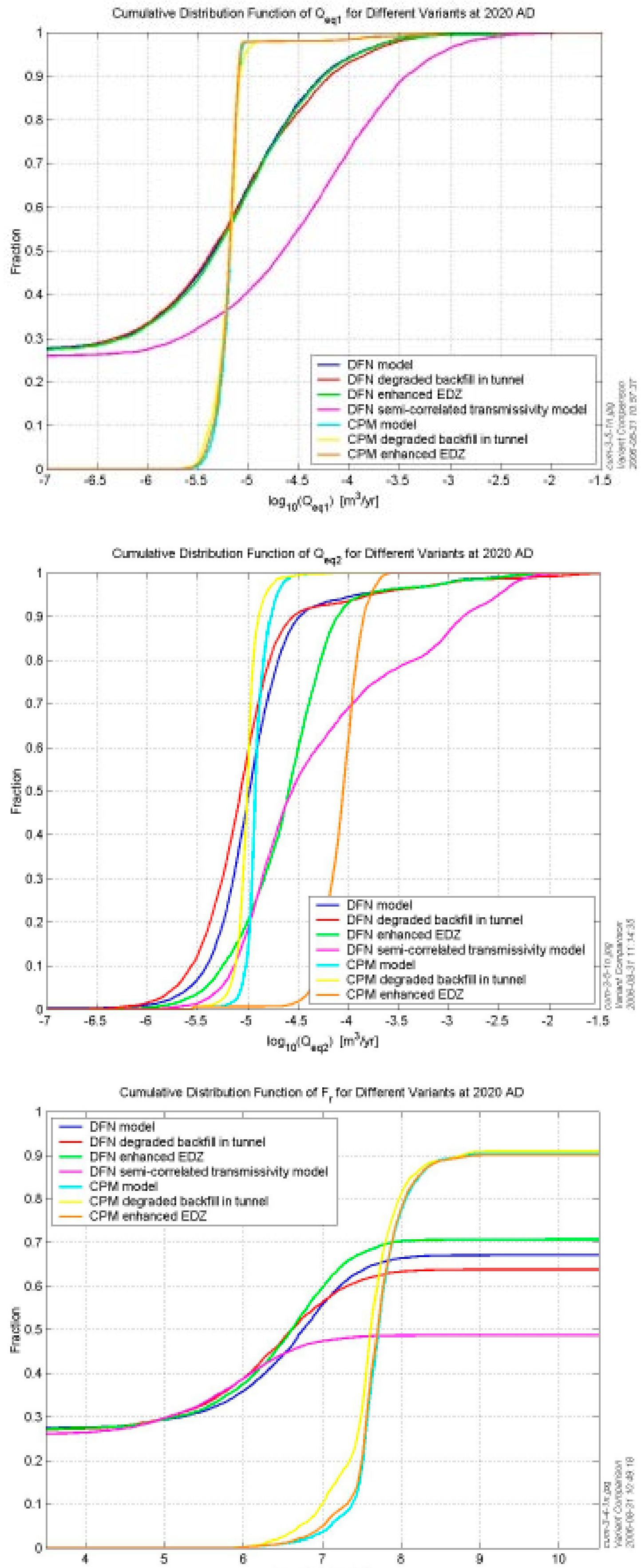


Figure 9-30. *Equivalent flow rates, Q_{eq}, for path Q1 and Q2, and transport resistance in rock (F-factor) for path Q1 at time 2,020 AD.*

A case with a degraded backfill is of interest as it shows whether the repository may become a significant conductor in the system if the expected low hydraulic conductivity of the backfill, is not achieved. For the degraded backfill case, a hydraulic conductivity of 10^{-8} m/s was assumed. Comparing with the central case in the DFN model, travel times decrease slightly by about 0.2 in $\log_{10}$-space for paths Q1 and Q2, and by about 0.35 for path Q3. Initial Darcy velocities increased significantly for the Q3 path by about one and a half orders of magnitude, as might be expected for an increase in backfill hydraulic conductivity of two orders of magnitude. The F-factor decreased slightly by 0.2–0.3 in $\log_{10}$-space for paths Q1 and Q2, and by about 0.5 for path Q3. The distance travelled in the tunnel increases to a range (5 and 95 percentiles) of between 4 and about 160 m with a median around 34 m for path Q3; the corresponding lengths for the central case are a range between 2 and 80 m with a median around 15 m. Qualitatively similar results are seen for the continuum representation.

A similar approach was used for the EDZ variants by choosing an EDZ hydraulic conductivity an order of magnitude higher than the central case. Changes in results were very slight for this case. The most notable change was an increase in the initial Darcy velocity for the Q2 path. In the DFN model, the increase in initial Darcy velocity was over half an order of magnitude, and the increase in the distance travelled in the EDZ was to a range of 1 to about 64 m with a median around 15 m. The corresponding lengths for the central case are a range between 1 and 36 m with a median around 8 m. Similar results are observed in the CPM model, where the initial Darcy velocity was increased by more than an order of magnitude. The sensitivity to the backfill and EDZ properties is not great, since the system of deposition tunnels is arranged orthogonal to the head gradients and overall flow direction. Results for transport resistance and equivalent flow rates are presented in Figure 9-30 below. It is clearly seen that the sensitivity to EDZ and backfill properties is negligible when the Q1 path is considered.

Concerning the length-transmissivity relationship used in the DFN model, results indicate a moderate sensitivity. A semi-correlated model may give moderately less favourable results than a fully correlated model in terms of inputs to radionuclide transport calculations (specifically Q_{eq} for Q1) in that the leading edge of the distribution lies somewhat higher than for a fully correlated model and thus corresponds to somewhat larger values of Q_{eq}. However, fewer particles escape to the surface for the semi-correlated model; see Figure 9-30.

In section 9.3.5, reactivation of faults as a result of thermal loading is discussed, and it is noted that an increase in hydraulic conductivity of up to two orders-of-magnitude is possible close to the tunnel and deposition holes. These effects are not directly implemented in the flow models discussed here. However, the effect of the locally increased hydraulic conductivity around the tunnel is likely to be small, since the flow system is already governed by a tunnel and EDZ with higher hydraulic conductivity than the surrounding rock. In the EDZ and tunnel variants implemented, it is shown that a one- and two-order-of-magnitude increase in EDZ hydraulic conductivity and tunnel backfill, respectively, does not change the flow to any great extent.

For all cases and pathways presented here, the advective travel time in the tunnel is very long, on the order of 10^4 to 10^5 years. In the continuum repository representation, the travel time difference between rock and tunnel is related to the used porosities. The high kinematic porosity of the tunnel (30%) implies by itself a lower advective velocity by almost two-orders of magnitude than in the rock. In the DFN representation, the volume of tunnels relative to the volume of the connected fracture network (in a unit volume) is large, again implying lower advective velocities in the tunnels than in the rock. However, not all particles travel through the tunnel system, and thus this feature of the system cannot be used alone as an argument for safety.

It is noted that the distributions presented above in Figure 9-30 are somewhat modified when used for radionuclide transport calculations in safety assessment applications. The specific modifications are summarised below.

- The F-factor distribution is corrected for channelling effects, since the underlying flow models do not incorporate an explicit description of internal aperture variability. In practice, it is assumed that only a small fraction of the fracture surface is available for flow, and the F-factor is reduced by a factor of 10. For details on the radionuclide transport calculations, see section 10.4.2. In the **Data report**, section 6.6.6, a more thorough discussion on the use of the channelling factor is given, and it is argued that it is a very conservative approach.
- The Q_{eq} values are corrected for spalling effects, see section 9.3.5 for a description of spalling, and further below in this section for implications for Q_{eq}. The reader is referred to the **Data report** for further information on the specific treatment for the radionuclide transport calculations.

- It is also noted that some canisters are located within deformation zones, since repository engineering based the layout on the deformation zone model without the additional low confidence zones contained in the alternative deformation zone model. The effects of these locations are clearly seen in the high tails of the Q_{eq1} results in the CPM models shown in Figure 9-30. These positions are excluded from consideration when radionuclide transport calculations are performed. An example of different deposition hole rejection criteria is given below in this section.
- As noted above, some deposition holes that have non-zero equivalent flow rates do not, for numerical reasons, have flow paths to the surface. These deposition holes will contribute to the release from the near-field, but not to the release from the far-field and thus not to the dose in the biosphere. The effect of the present numerical artefact needs to be kept in mind in the overall assessment. Clearly, this numerical particle tracking problem needs to be resolved within SR-Site.

The safety function R3 in Figure 9-2 relates to the properties of the rock and its potential to provide a hydrologically favourable environment. In the analysis presented in this section, it is shown that the conditions at the Forsmark site, as expressed in the Forsmark SDM version 1.2, are indeed very favourable properties in terms of performance measures. Specifically, the F-factor ranges between 10^4 and 10^8 y/m in the DFN representation. In the CPM representation, F-factors in the range 10^6 to 10^9 y/m are estimated.

The difference between the discrete fracture network and continuum representations concerning canisters with flow and associated transport to the surface is very noticeable. In the DFN representation, approximately 30% of canisters are not connected to any fracture in the network and have zero flow. Approximately 60–80% of canisters do not have a path to the surface, depending on transmissivity-length correlation assumed. Particles get stuck in the network if started in fractures or sections of tunnels with very small flows, or if started in fracture connections that form closed loops.

For the remaining canister positions in the DFN representation, connected flow paths exist. In contrast, the CPM representation results in a model with all deposition holes having connected flow paths with considerably higher F-factors. Thus, the DFN representation suggests that spatial variability on the canister scale results in a fraction of relatively low, although still favourable, values of the F-factor.

In addition, some flow paths will also have very long advective travel times in the tunnel system. Nevertheless, some flow paths still have short travel times and low F-factors (around 10^3 y/m), namely particles starting close to deformation zones with predominantly vertical flow paths to the surface.

The analysis also indicates that the results for the transport in the rock are not crucially sensitive to the properties of the tunnel backfill and EDZ. This result is due to the fact that the tunnel with its base case properties already constitutes a major conductor in the sparsely fractured rock. Thus, increasing the hydraulic conductivity of the tunnel and EDZ has only a minor influence on the flow conditions.

The analysis also shows that the thermal effects are minor, and related to the early times when transport from canisters is not expected. Furthermore, an assessment of possible gas effects shows that these are minor and not likely to influence groundwater flow and radionuclide transport conditions /Hartley et al. 2006a/.

It should also be noted that retention in deformation zones is underestimated since the internal structure is not resolved (i.e. the zones are modelled as two planar features). This is not considered a major limitation since most retention takes place in the smaller fractures in the rock adjacent to the canisters. Also, detailed information on deformation zone internal structures is missing, and so a more comprehensive, less pessimistic model cannot be justified.

Regional scale groundwater flow – Laxemar

Also for the Laxemar application, the code Connectflow is used /Hartley et al. 2006b/. The Laxemar 1.2 SDM application using Connectflow is reported in /Hartley et al. 2006c/; a consistent approach is applied here for the Temperate period simulations of Laxemar. The methodology applied is thus also consistent with the Forsmark simulations described above both in respect of nesting and included processes.

In the SDM analysis it was shown that the hydrogeochemical information used to calibrate the regional scale model resulted in changes to the derived hydrogeological DFN interpretation. Specifically, using the properties of the interpreted hydrogeological DFN and an assumed topographic head condition it was found that the model predicted too much flushing at repository depth and below. In consequence, a number of changes had to be made in the SDM hydrogeological models that included a lower water table, anisotropy between fracture sets and a slightly reduced hydraulic conductivity below –600 m elevation. The changes relating to the hydrogeological DFN are discussed in detail in the SDM report /SKB 2006b/ and in /Hartley et al. 2006c/.

The model is divided into several different hydraulic rock domains with different underlying DFN statistics. The repository is located in the two rock domains denoted HRD(A) and HRD(D,E,M). One of the outstanding uncertainties is the applicability of different rock domains for different rock volumes based on information from a single borehole in each volume.

An ECPM model has been run for a reference case from 8,000 BC to 20,000 AD, and for a number of variants from 8,000 BC to 9,000 AD. One group of variants was used to study the sensitivity to the geological model; specifically, variants with spatial variability within deformation zones and the exclusion of low confidence zones from consideration were studied. Another group of variants tested hydraulic and transport properties obtained from hydrogeological DFN models other than the reference case. In a third group of variants, the sensitivity of transport parameters on model results was tested. Finally, a more elaborate model for the hydraulic soil domain based on maps of the Quaternary deposits was studied.

Based on the studies of transient evolution, it was decided to propagate the following representative times for further analysis within the Repository scale analysis presented below: 6,000 BC – a time at the start of the Littorina period when there is a local maximum in the shore-level height and also when the first minimum occurs in travel times and F-factors; 2,000 BC – a time when a second minimum occurs in mean travel times and F-factors, and when the Littorina salinity is starting to decrease; 2,020 AD – present-day; and finally 6,000 AD – a time when the land rise above sea-level around Äspö and the performance measures both stabilize. In contrast to Forsmark, representative times prior to present are analyzed for radionuclide transport as well as future times. This is because these past times have lower values of the performance measures than the present. Because climate evolution is taken to be cyclic, as described in section 5.2.1, these conditions are expected to occur again in the future.

Given the large uncertainties in the underlying SDM model, the fairly similar results for the different variants, and most notably the fact that more recent data from the site indicates more favourable conditions than incorporated in the SDM L1.2 model, it was decided to only analyse the reference case further within SR-Can.

In Figure 9-31 below the exit locations for particles released at the location of the potential repository are shown on a GIS map. It is observed that all particles exit the model in fairly close proximity to the repository. Also, the flow paths do not get longer for future times; this is an indication that it is the major structures that govern the path geometry. In Figure 9-31 the particles are coloured according to the origin of starting location; i.e. whether a particle starts in hydraulic rock domain HRD(A) or HRD(D.E,M), or in a low confidence deformation zone (HCD). It is clearly seen that particles starting in rock domain HRD(A) tend to exit north of the repository, whereas particles starting in HRD(D,E,M) tend to exit south and east of the repository. This is consistent with the occurrence of the two rock domains at repository depth where the northern part of the repository lies in primarily rock domain HRD(A) and the southern part primarily in rock domain HRD(D,E,M). All performance measures are calculated for the different hydraulic units both separately and pooled together.

The initial Darcy velocity in HRD(A) is significantly higher than in HRD(D, E, M) and has less spread between the 25^{th} and 75^{th} percentiles. The median Darcy velocity over all canister locations is about $6 \cdot 10^{-4}$ m/y. Similarly the F-factor has a median about half an order of magnitude higher in HRD(D, E, M) than HRD(A). The overall median F-factor is about 10^6 y/m. Considering how performance measures vary between tunnel locations, the shortest travel times, about 10^2 years, occur in repository subareas 2 and 3, and the longest travel times, about 10^4–10^5 years, are in the southern part of subarea 1, and in subareas 5 and 7 (see section 4.3.3 for a description of the subareas).

Repository scale groundwater flow – Laxemar

The same methodology as applied in the Forsmark analysis on the repository scale is applied in the Laxemar analysis. Specifically, a repository scale DFN model with the repository tunnels implemented through a continuum representation is adopted.

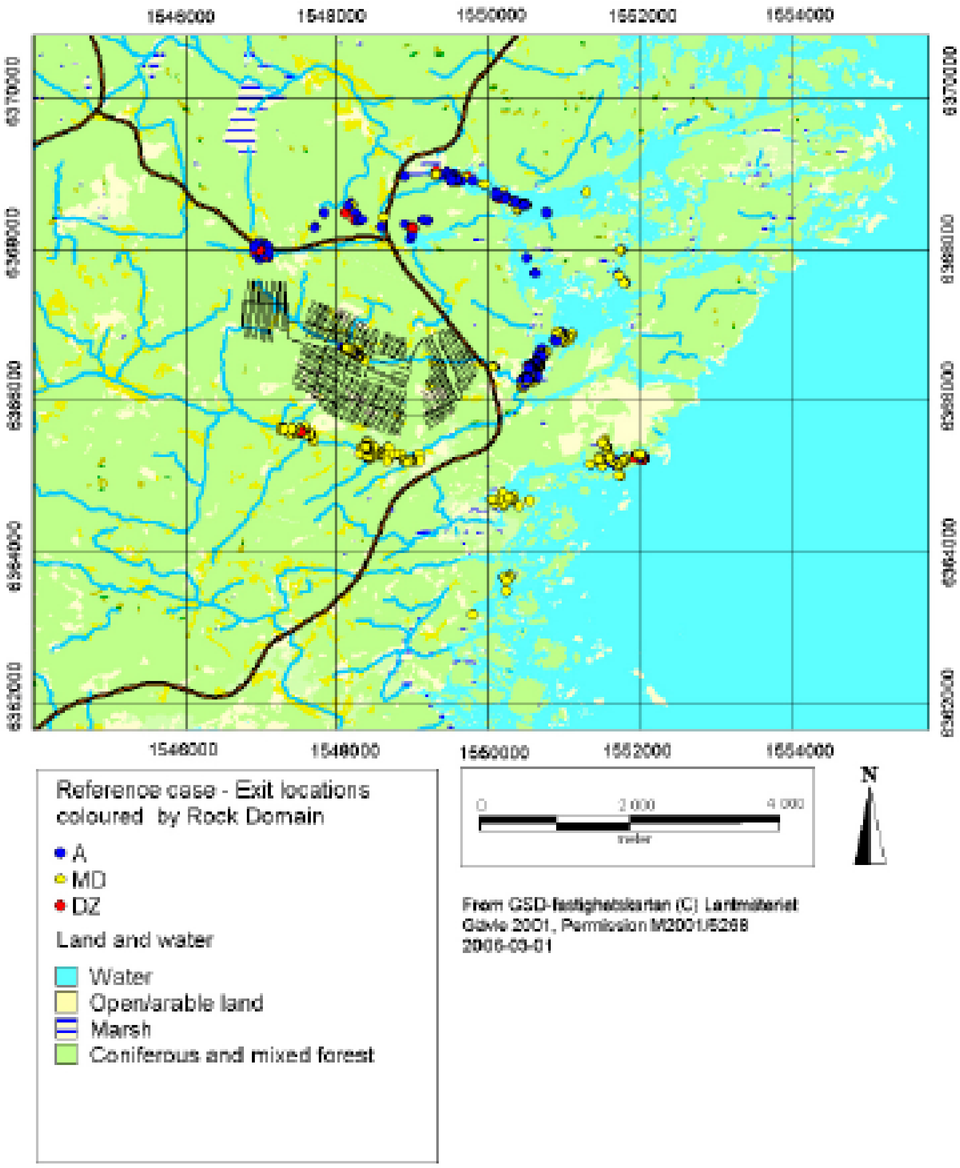


Figure 9-31. Particle exit locations coloured by the hydraulic domain that the particle release point lies within: Rock domain HRD(A) is denoted A, mixed rock domain HRD(D,E,M) is denoted MD, and HCD is denoted DZ. Particles are released at 2,020 AD in the reference case model. Repository tunnels are projected onto the ground surface.

For all canister locations, the three release positions Q1 (fracture intersecting a deposition hole), Q2 (transport in the engineered damaged zone, EDZ), and Q3 (fracture intersecting a deposition tunnel) are considered for transport. A snapshot-in-time procedure implying the use of the instantaneous velocity fields at representative times is adopted. Flow paths that exit the repository scale model are continued in the corresponding regional scale model. In this analysis, the regional scale model used for continuing the particle tracking used a site scale DFN model nested within an ECPM model so that the additional F-factor resulting from the continuation of the particle tracks would be largely derived from a DFN model. The fracture parameters used for the site-scale DFN model were consistent with those used to derive the properties of the surrounding ECPM model. The site-scale DFN model encompasses the entire repository footprint. It is noted that no pure CPM representation was used, in contrast to the approach adopted for Forsmark, but consistent with the conceptualisation in the Laxemar SDM model.

The reference case described above was analyzed both for expected properties of the repository as well as for variants assuming poorer EDZ (hydraulic conductivity increase by factor 10) and backfill (hydraulic conductivity increase by factor 100) properties. In addition, also a few variants identified in the regional scale analysis were studied, namely one with an increased transmissivity in one of the fracture sets of the DFN model, and one assuming a fully correlated transmissivity-length model rather than the semi-correlated model of the reference case. Finally, a case adopting the cubic law rather than the square (Doe) law of the reference case for relating fracture transmissivity and aperture was tested. The rationale for studying this final variant was to explore the sensitivity of the assumed aperture relationship on the equivalent flow rate for the Q1 release path.

Fractures are derived from 3 sources in the DFN sub-model that surrounds the repository in the repository scale model: deterministic deformation zones imported from the geological model, stochastic fractures imported from the regional DFN model including fractures down to a radius of 14 m, and additional stochastic fractures in the radius range 1–14 m; these smaller fractures were generated according to the same statistics as the regional DFN fractures.

In the Forsmark simulations /Hartley et al. 2006a/ described above, the poor connectivity of the fracture network was discussed along with the implications for transport of radionuclides. These issues are of less significance at Laxemar due to the greater connectivity, at least in rock domain HRD(A) where about 71% of deposition holes are projected to be intersected by a fracture that has an advective flow connection to the surface. However, the more sparsely fractured HRD(D,E,M) rock domain has only about 35% of deposition holes intersected by fractures with an advective flow connection to the surface.

In Figure 9-32 below the equivalent flow rates for the three release paths are presented. It is seen that more than 30% of the ensemble of canisters do not have a measurable flow intersecting the deposition hole, indicated by the offset of the Q1 curve on the left side of the graph (the offset represents the fraction of deposition holes with zero flow). Also for the EDZ path (Q2) there are locations with zero flow; this is due to the end of the deposition tunnels being essentially dead-ends for flow. It is also noted that the Q3 path presented in the figure contains an additional advective component representing release by the bulk tunnel flow. The derivation of the advective component of the equivalent flow rate for the Q3 path is given in section 6.6 of the **Data report**.

The transport resistance (F-factor) in the rock for the three release paths is presented in Figure 9-33 below. The locations with zero flow are not associated with flow paths; hence the same offset at the start of the curves as in Figure 9-32. It is clearly seen that the three release paths provide essentially identical F values along the associated flow paths, i.e. the three flow paths are likely almost identical through the geosphere. A fraction of the particles get stuck in the fracture network due primarily to stagnant flow conditions; this is indicated where the cumulative curves level off at the right side of the figure. Thus, the graph is normalized with all deposition holes, and the curves represent the fraction of deposition holes which simultaneously have a flow greater than zero and have flow paths which exit the geosphere. To the left, the fraction of deposition holes with zero flow is indicated, to the right the fraction which gets stuck in the fracture network.

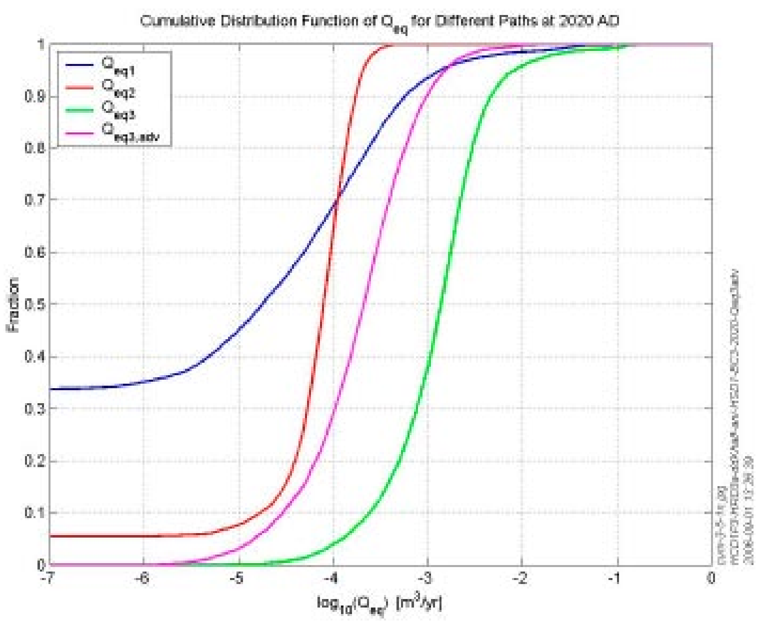


Figure 9-32. *Cumulative distribution plots of Q_{eq} for paths Q1, Q2, and Q3 in the combined repository- and regional scale models with 7,483 particles released at time 2,020 AD.*

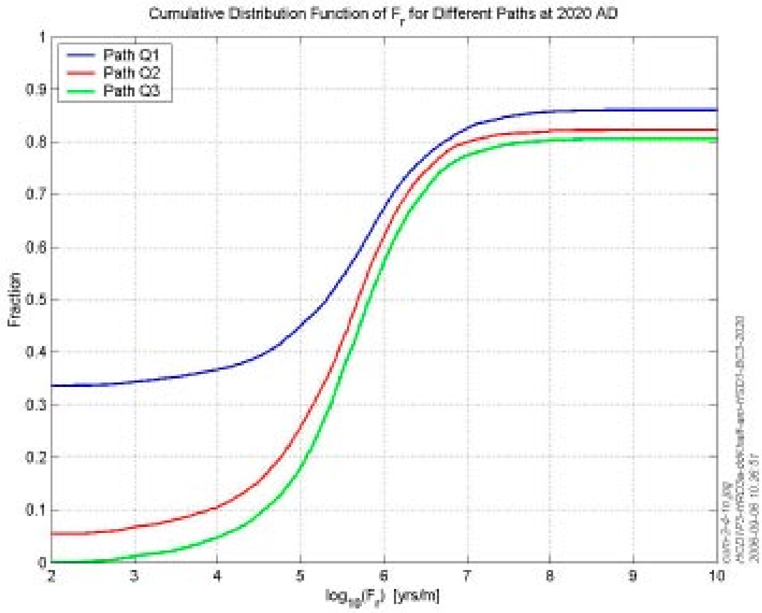


Figure 9-33. *Cumulative distribution plots of F_r for paths Q1, Q2, and Q3 in the combined repository- and regional scale models with 7,483 particles released at time 2,020 AD.*

Generally flow-paths tend to be focussed toward the deformation zones and the larger stochastic fractures since these are more connected, have higher transmissivities, and hence carry more flow. Typically, there are few long horizontal flow-paths that discharge away from the site area. This is due to the limited horizontal connectivity and geometry of the fracture network. One exception is the gently northward dipping and extensive zone ZSMEW007A that outcrops above the centre of the repository and provides a shallow but long horizontal flow-path running west to east. This is interesting, since it suggests major sub-horizontal deformation zones could have a significant positive impact on radionuclide transport making flow-paths longer, whereas sub-vertical deformation zones tend to have the negative impact of shortening flow-paths.

Considering the different variants, the cubic law transmissivity-aperture case, the case with increased transmissivity in one of the sub-vertical fracture sets, and the case with a fully correlated fracture length-transmissivity relationship, all have only a minor influence on the calculated performance measures. The cases with an increased hydraulic conductivity in the tunnel backfill or in the EDZ have somewhat larger, but still limited, influences on the performance measures. Even in these variants the 90th percentile for the distance in the EDZ or tunnel is only about 100 m; this suggests that flow tends to be limited by the fracture system and that paths leave the tunnel or EDZ after a relatively short distance to find a flow path to the surface through the fracture network. For a full compilation of performance measure results, the reader is referred to the appendices of /Hartley et al. 2006b/.

Deposition hole rejection criteria

In section 4.4.1, procedures for deposition hole screening are introduced. In short, the procedures are based on evaluating if fractures intersect the deposition tunnel, and evaluating the hydraulic conditions of a deposition hole. One of the intersection criteria is the Full Perimeter intersection Criterion (FPC) which checks if the anticipated extension of a fracture intersecting the full perimeter of the tunnel would also intersect a deposition hole, for details see /Munier 2006a/. In SR-Can, the hydraulic conditions are characterised using the transmissivity value of the fracture intersecting the deposition hole.

The results of applying the deposition hole rejection criteria are presented in Table 9-6 below in terms of remaining deposition hole positions. For practical reasons, it was not possible to try the impact of the Extended FPC, see section 9.4.5. It is likely that this criterion will be quite effective since it rejects canister positions being intersected by long, gently dipping fractures.

Table 9-6. Calculated percentage of remaining deposition positions using various rejection criteria. The number of deposition holes modelled at Forsmark and Laxemar are 6,824 and 7,483, respectively.

Rejection criterion	Remaining percentage of deposition holes after application of rejection criteria [%]							
	Excluding only deposition holes intersected by low confidence zones	FPC	T > 10^{-6} m²/s	T > 10^{-7} m²/s	T > 10^{-8} m²/s	FPC and T > 10^{-6} m²/s	FPC and T > 10^{-7} m²/s	FPC and T > 10^{-8} m²/s
Forsmark base case DFN (fully correlated)	99.8	94	99.8	99.4	97	94	94	93
Forsmark semi-correlated DFN	99.8	94	98.9	77	38	93	74	37
Laxemar base case DFN (semi-correlated)	99.8	90	96	78	46	88	74	45
Laxemar fully correlated DFN	99.8	90	97	91	62	89	86	61

In the table it is seen that the FPC criterion for both sites and correlation cases results in more deposition locations being removed than using only the hydraulic T > 10^{-6} m²/s criterion. A lower threshold of T > 10^{-7} m²/s results in comparable or more locations being removed than using the FPC alone. Furthermore, combining the FPC and T > 10^{-6} m²/s criterion has a minor effect relative to using the FPC criterion alone. If lower transmissivity thresholds are used, these dominate the screening and the FPC has a minor effect on the number of rejected deposition locations.

Applying the FPC criterion or combined FPC and T > 10^{-6} m²/s criterion results in somewhat shifted Q_{eq} and F-factor distributions for the Q1 path as shown for Laxemar conditions in Figure 9-34 and Figure 9-35. Specifically, the Q_{eq} distribution shows that the highest flow rates are removed from the distribution, whereas the F distribution shows a shift to higher values by slightly less than half a unit in log space. The difference between applying the FPC criterion alone or in combination with the T > 10^{-6} m²/s criterion has a minor effect as indicated already by Table 9-6.

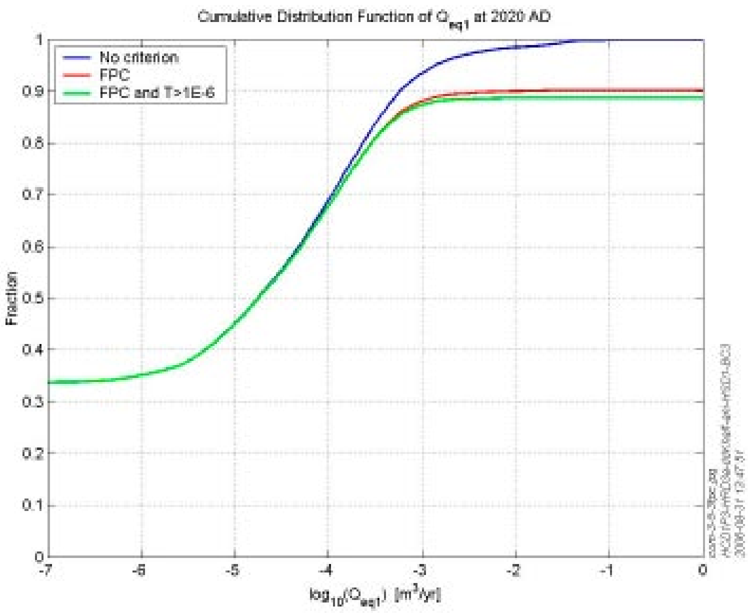


Figure 9-34. Cumulative distribution plots of Q_{eq} for path Q1 in the combined Laxemar repository and regional-scale models with 7,483 particles released at time 2,020 AD. Different deposition hole rejection criteria are considered.

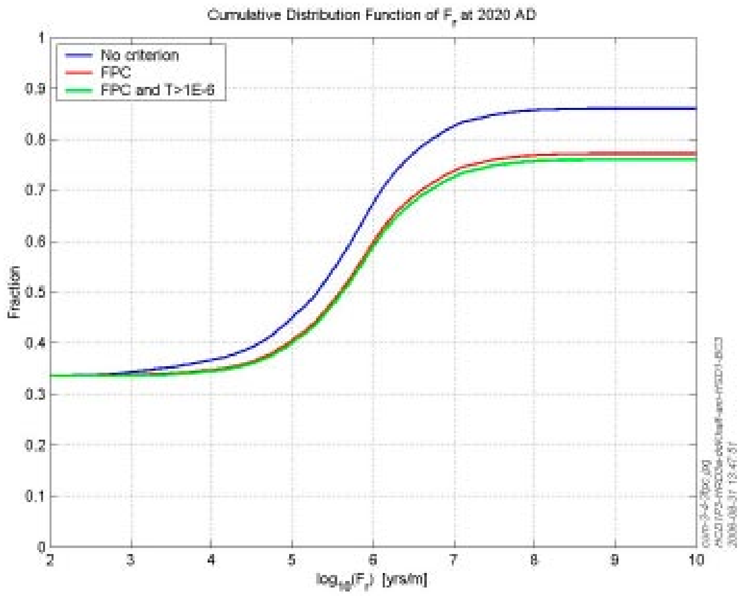


Figure 9-35. *Cumulative distribution plots of F for path Q1 in the combined Laxemar repository and regional-scale models with 7,483 particles released at time 2,020 AD. Different deposition hole rejection criteria are considered.*

Effects of spalling

In section 9.3.6 the mechanical effects of spalling in deposition holes induced by the waste heat are discussed. The spalling also results in changed conditions for mass exchange between the buffer and the fracture intersecting the deposition hole, in the form of an altered Q_{eq} for the Q1 path. In /Neretnieks 2006b/ an additional equivalent flow rate due to the damaged zone caused by spalling is derived, and in the **Data report** it is shown how the derived expression is implemented for use with results obtained from Connectflow. In short, an additional equivalent flow rate in the damaged zone, Q_{eqDZ}, is obtained as being proportional to the square root of the flow rate in the fractures around the deposition hole. That flow rate is estimated from the Connectflow results assuming values for the capture width of the damaged zone.

In Figure 9-36 and Figure 9-37 below, the effects of spalling are illustrated for both Forsmark and Laxemar. The results indicate that spalling may increase equivalent flow rates by more than an order of magnitude. It is noted that the handling of spalling in /Neretnieks 2006b/ is considered pessimistic. Additional research efforts, see section 13.8.5, may provide an improved insight into the spalling phenomenon and thus result in a less pessimistic treatment. A key issue is the increase in porosity of the damaged zone adjacent to the deposition hole.

9.3.7 Chemical evolution in and around the repository

Introduction

During the initial temperate period after closure, displacements of the Baltic shore line and changes in annual precipitation will influence the hydrology of the site as described above in section 9.3.6. These phenomena induce changes in the geochemical composition of groundwater around the repository.

One of the questions to be addressed for this period is whether the chemical environment will remain favourable after repository closure. The most important parameters are redox properties (safety function R1a in Figure 9-2) and salinity (safety function R1b and R1c). Other factors to consider are the groundwater content of potassium, sulphide and iron(II), as they might affect the chemical stability of the buffer and the canister (safety function R1d) and the effect of grouting in the geosphere and cement materials in the engineered barriers that could affect groundwater pH (safety function R1e).

Modelling

For the initial period of temperate climate after repository closure, groundwater compositions are modelled through advection, mixing and chemical reactions with fracture-filling minerals. The different

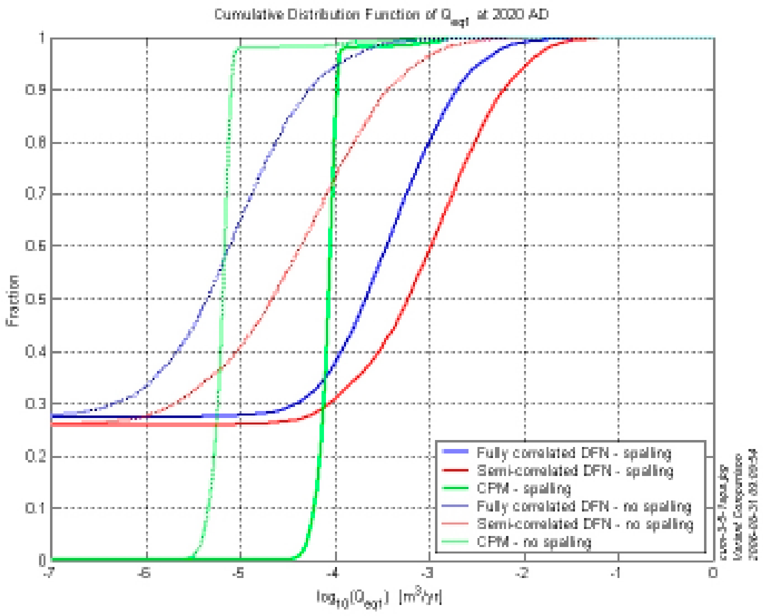


Figure 9-36. *Cumulative distribution plots of Q_{eq} for path Q1 in the combined repository and regional scale models at time 2,020 AD in Forsmark for conditions with and without spalling.*

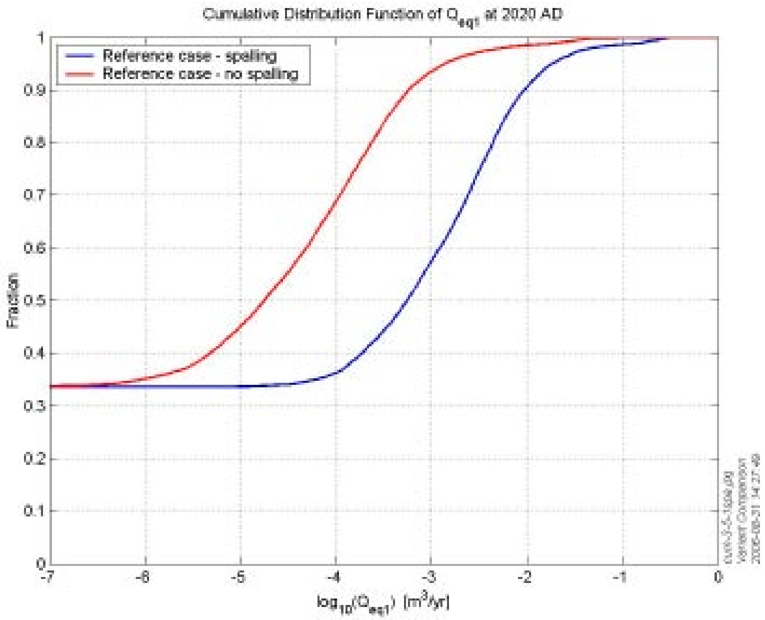


Figure 9-37. *Cumulative distribution plots of Q_{eq} for path Q1 in the combined repository and regional scale models at time 2,020 AD in Laxemar for conditions with and without spalling. Semi-correlated DFN model.*

components of the modelling are not fully coupled: the results of the regional-scale groundwater flow modelling are used as input for a geochemical mixing and reaction model. The aim has been to obtain equivalent groundwater models for hydrology and geochemistry. The loose coupling of the two models also allows a description of the geochemical heterogeneity, which otherwise would be hard to attain.

The groundwater flow modelling using Connectflow is reported in /Hartley et al. 2006ab/ and it is described above in section 9.3.6. One of the processes modelled is the transport of fractions of selected reference waters (rain, marine, glacial and brine). By this approach, the mixing proportions of these waters may be obtained at any time for the different parts of the studied rock volume, as illustrated in Figure 9-38.

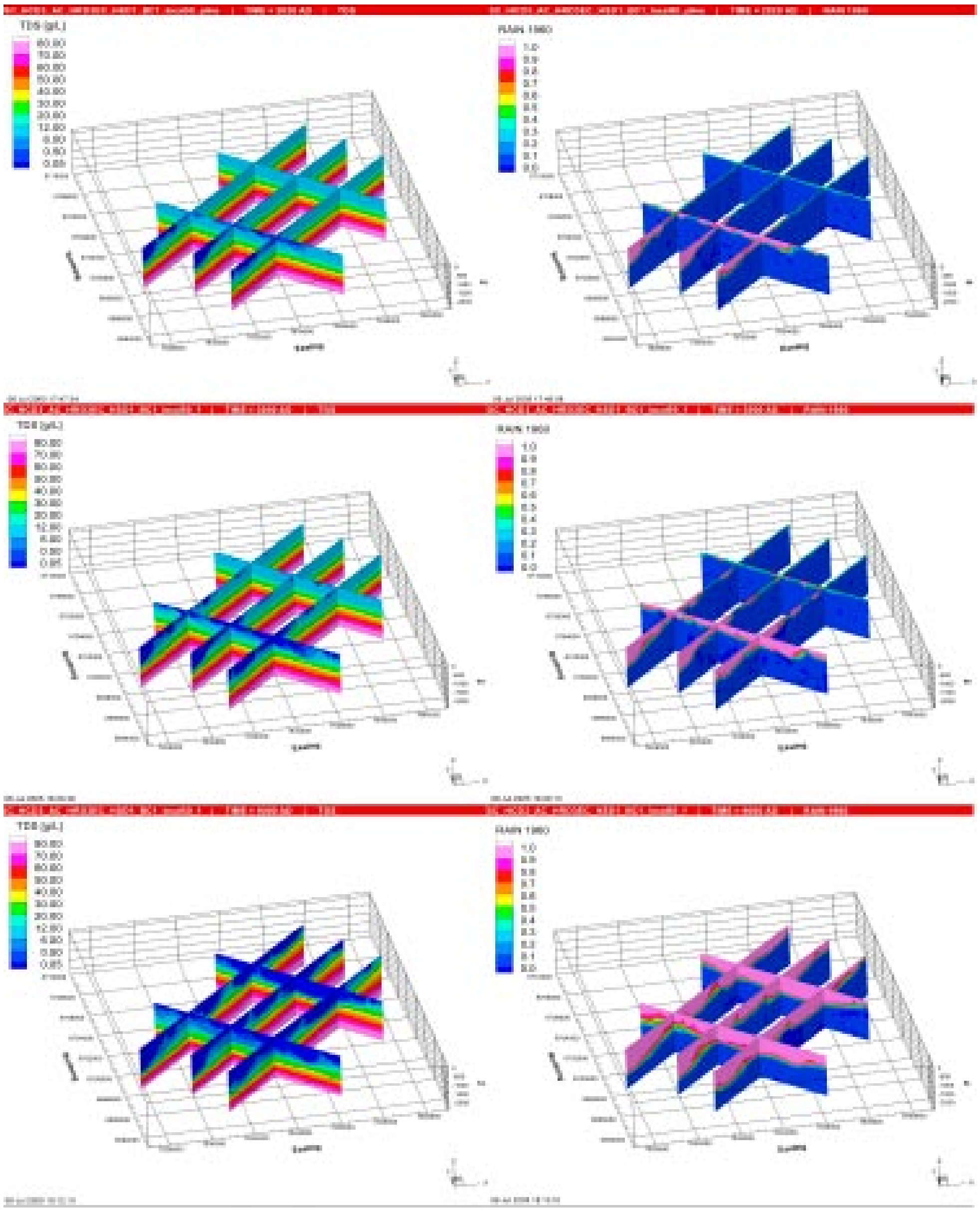


Figure 9-38. *Distribution of TDS (total dissolved solids, g/L, left) and Rain fraction (right) for Forsmark in vertical slices at times equal to (from top to bottom) 2,020 AD, 3,000 AD and 9,000 AD. From /Hartley et al. 2006a/. The figure shows the gradual inflow of rain water, and the corresponding decrease in TDS as the shore line is gradually displaced towards the upper-right corner of the modelled domain. The model and its uncertainties are discussed in section 9.3.6.*

From information on the composition of the reference waters, as well as their fractions as a function of space and time obtained from the hydrogeological modelling, calculations on the chemical consequences of groundwater mixing have been performed in combination with representation of chemical equilibrium reactions. Some groundwater components behave as "conservative", that is, they normally do not participate in chemical reactions, and are mostly affected by groundwater mixing. Examples are the water isotopes such as deuterium and ^{18}O, as well as chloride and sodium, and, to some degree, calcium. However, most of the groundwater chemical components are reactive, for example Fe(II) and Fe(III), H^+, and bicarbonate. Sulphate may be reduced to sulphide under hydrothermal conditions, that is, at high pressure and temperature. At lower temperatures, as are applicable in this context, sulphate can only be reduced to sulphide by microbially mediated reactions with organic matter.

Due to the factors mentioned above, the evolution of groundwater components can not be dealt with through calculations involving only groundwater mixing, and it has instead been modelled by using the results from the hydrogeological model as input to fully coupled chemical mixing and reaction calculations. The computer code Phreeqc /Parkhurst and Appelo 1999/ was used for that purpose. The results of this modelling are reported in the **Data report** (section 6.6) and in /Auqué et al. 2006/. The minerals calcite, chalcedony, kaolinite and a Fe(III) oxyhydroxide have been equilibrated with the mixtures at all points in space and time. The type of results that can be obtained using this procedure are illustrated in Figure 9-39, which shows a comparison between the calculated calcium concentrations for about 16,000 locations at repository depth (400 m) with the data obtained in the site investigation programme.

Several approximations have been used in this modelling strategy. The minerals chosen to be at equilibrium with the groundwater mixtures are reasonable in that they include relatively fast groundwater/rock interactions, as in the case of calcite, or characterize the silica levels observed in the groundwaters, as in the case of chalcenody. However, they are a limited subset of those likely to be present. Nevertheless, even if other solid phases could be stipulated, it would not be possible to justify their selection and the minerals selected effectively represent the chemical effects observed in the reactive components discussed here. For the upper part of the simulated domain, less than ≈ 100 m depth, the assumption of chemical equilibrium with the selected minerals is perhaps less well justified than at greater depths.

The waters of meteoric origin entering the modelled system are essentially rain, but due to their chemical reactivity these waters react quickly in the overlaying soil layers, if there are any, and with the bedrock minerals in the upper metres of their pathways. Microbial activities contribute substantially to these processes. As a result, meteoric waters quickly obtain small amounts of solutes which may be seen for example in groundwaters sampled both at Forsmark and Laxemar in the upper ≈ 100 m of rock. This has been reflected in the composition chosen for the reference water labelled "Rain" in the mixing calculations.

One of the uncertainties in the geochemical modelling strategy followed within SR-Can is that the composition of the marine reference water varies with time as the waters change from a Littorina sea composition at ≈ 8,000 BC to the present Baltic sea composition, which will be further diluted in the future. This has been properly taken into account in the hydrogeological model, but for the geochemical modelling the Littorina salinity has been assumed as the reference water used in mixing

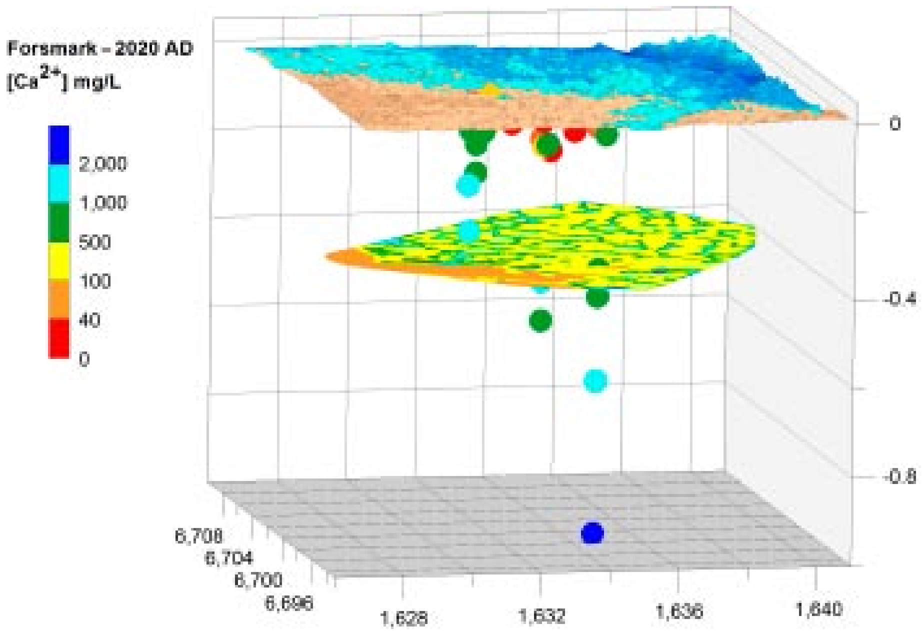


Figure 9-39. *The concentration of calcium in groundwaters sampled in boreholes at the Forsmark site compared with a contour plot at 400 m depth showing calculated values. The topography of the site is also shown at the top with blue colours indicating areas below sea level. The axes labels are given in km (RT90-RHB70 coordinates), and the vertical scale has been grossly exaggerated. The contour plot has been drawn using the proportions of reference waters obtained from the hydrogeological model as input for chemical mixing and reactions, including calcite dissolution and precipitation among others.*

calculations. This assumption is justified by the fact that less saline marine waters do not displace the Littorina component, which is denser, whereas meteoric waters displace the denser marine waters due to topographic effects.

A full propagation of uncertainties, from the hydrogeological modelling into the geochemical calculations, has not been performed. In addition, the natural variability and other uncertainties in the compositions of the reference waters used for mixing (rain, marine, glacial and brine) have not been propagated to the mineral reaction calculations. It is, therefore, possible that the real variability in the chemical compositions of groundwater components is somewhat larger than that presented here.

Evolution of salinity

As mentioned previously in sections 9.2.3 and 9.2.5, the salinity distribution may initially be affected during repository operation by perturbations in the hydraulic conditions, although in the case of Forsmark this perturbation is negligible. After repository closure, the backfilled tunnels will become water saturated. The modelling discussed briefly in section 9.3.6 above indicates resaturation times between 15 and 150 years for Forsmark. The effects of the open repository on groundwater salinities at Forsmark, which will be minor, are expected to disappear during the resaturation period.

As explained in the introduction to this subsection, during the remaining part of the initial temperate period after repository closure, groundwaters will be affected by increasing amounts of waters of meteoric origin, see Figure 9-38. On a regional scale this corresponds to a gradual decrease of the groundwater salinity, especially in the upper part of the modelled rock volume, which is 2 km deep overall. The salinity distribution for this time period has been calculated using the Connectflow model presented in section 9.3.6 /Hartley et al. 2006ab/, and the details are not repeated here. Figure 9-40 presents the calculated distribution of salinities at Forsmark at 400 m depth at three time steps. Towards the end of the modelled period over 70% of the groundwaters in the Forsmark region have less than 1 g/L of dissolved salts at repository depth, while less than 10% of the groundwaters had low salinities at the start of the simulation, that is, at repository closure.

In conclusion, the salinities during the first temperate period following repository closure will remain limited both at Forsmark and Laxemar, ensuring that the swelling properties of the buffer and backfill are not negatively affected, cf the safety function indicator R1b in Figure 9-2.

Evolution of concentrations of other natural groundwater components

The increasing proportions of groundwaters of meteoric origin will decrease the overall salt content of the groundwaters as discussed in the previous sub-section. However, the effects on the individual chemical constituents will depend on their reactivity. The evolution of the different chemical properties of groundwaters has been estimated by coupling the results from the hydrological calculations with a mixing and chemical reaction model, as described above in the introduction to this section. The final objective has been to check if, during its evolution, the chemical environment around the repository fulfils at all times the safety function indicator criteria R1a to R1e in Figure 9-2. In this sub-section, the results are discussed for divalent cations (safety function indicator R1c), potassium, sulphide and iron (R1d), and alkalinity and pH (R1e). The results for salinity (R1b) are discussed in the previous sub-section, whereas the results for redox conditions are presented below in the following sub-section.

Calcium

The concentration of divalent cations (safety function indicator R1c in Figure 9-2) is important in that their presence decreases the stability of colloids (see the discussion on colloids later in this section). In groundwaters that are too dilute, colloids might enhance the transport of radionuclides. In addition, as the buffer swells into fractures, montmorillonite colloids may be transported away by dilute groundwaters. The criterion for the safety function indicator R1c is $[M^{2+}] > 0.001$ mol/L, as available experimental data suggests that montmorillonite colloids are not stable at concentrations above this limit.

Calcium participates in water-rock interactions as carbonates and may be released from the weathering of feldspar. At Forsmark and Laxemar the deep saline groundwaters are quite rich in calcium, and examination of the groundwaters at depths larger than ≈ 100 m shows that the calcium concentrations may be simulated by mixing of reference waters and that the relative effects of chemical reactions are minor. The other major divalent cation is magnesium, which is normally regulated in granitic

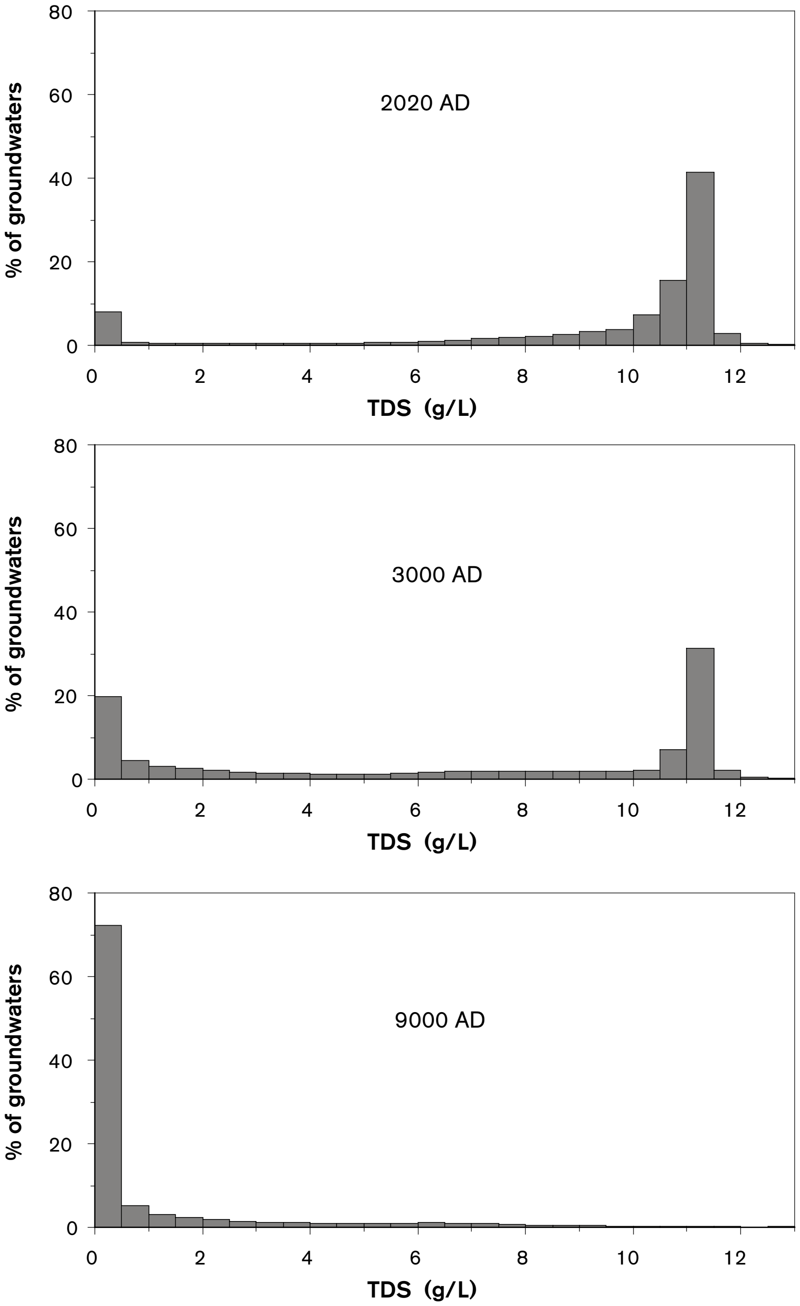


Figure 9-40. *Histograms of spatial distribution of groundwater TDS (total dissolved solids) at Forsmark at the projected repository depth of 400 m at times of (from top to bottom) 2,020 AD, 3,000 AD and 9,000 AD. Diagrams calculated using the model results in /Hartley et al. 2006a/. The figure shows the effect at repository depth of the gradual inflow of rain water.*

groundwaters by the precipitation and dissolution of chlorite, a mineral that may have a wide range of compositions. In general, magnesium concentrations in groundwaters are much lower than those of calcium, and because of the low solubility of chlorites and the uncertainty in the composition of this mineral, the modelling of Mg concentrations is much more uncertain than that of Ca. Magnesium ions, that have the same positive effect on safety as Ca ions are, therefore, pessimistically, disregarded in the evaluation of the divalent cation component of groundwater composition.

The calcium concentrations observed at present at Forsmark increase rapidly with depth in the top ≈ 100 m of the bedrock, see Figure 9-41. For Laxemar, the increase of Ca with depth is gradual, and most of the samples at depths ≤ 300 m have Ca concentrations close to or below 0.001 mol/L. The selected meteoric reference water for Forsmark in the mixing and reaction calculations corresponds to groundwaters sampled at 50 to 150 m depth, which have the composition expected for a rain water that

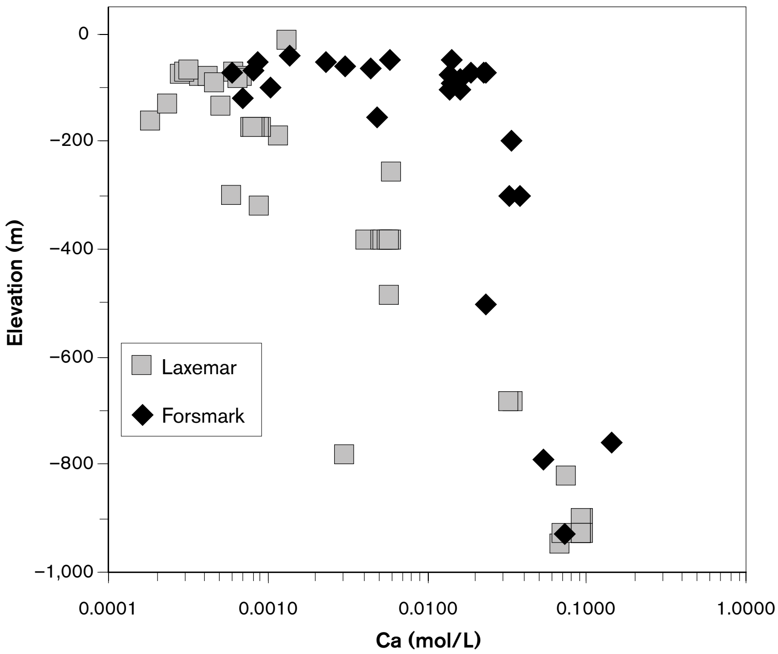


Figure 9-41. *Calcium concentrations in groundwaters sampled at Forsmark and Laxemar as a function of depth.*

has travelled a short distance in the fractures of the granite at Forsmark. In Figure 9-38, these superficial groundwaters correspond to the top few hundred metres in the South-West part of the modelled domain, and the hydrological calculations for 2,020 AD show that they are entirely "rain" water.

The results of coupling the hydrogeological model results with the mixing and reaction calculations, including equilibrium with calcite, are shown in Figure 9-42, which illustrates the gradual dilution of the groundwaters at repository depth due to the inflow of superficial waters of meteoric origin. Figure 9-43 shows the distribution of calcium concentrations for Forsmark at the end of the simulation (9,000 AD), at repository depth, when most of the groundwaters that were present at repository closure have been replaced by waters of meteoric origin. It should be noted that the Ca concentrations in groundwaters found at present in the upper 150 m vary between 0.2 and 24 mM, according to the data shown in Figure 9-41. This spread of the data is not included in the meteoric reference water used in the mixing calculations, and, therefore, the variability shown in Figure 9-42 and Figure 9-43 is probably underestimated. The corresponding results for Laxemar are presented in /Auqué et al. 2006/.

It may be concluded from these modelling results that for the whole temperate period following repository closure calcium concentrations at repository depth at Forsmark and Laxemar will, in general, remain close to 0.001 mol/L, that is, near to the limit where montmorillonite colloids start to become unstable. However, because the sharp cut-off in Figure 9-43 is a consequence of excluding the uncertainty in composition of meteoric water shown in Figure 9-41, it cannot be excluded that some of these groundwaters will have concentrations slightly lower than 0.001 mol/L and, if so, these waters would infringe the safety function indicator R1c in Figure 9-2 which might increase the stability of bentonite colloids. Two factors that have not been considered here which will contribute to increase $[M^{2+}]$ in the groundwaters are ion-exchange processes and magnesium ions.

Potassium, sulphide and iron

Potassium concentrations are generally low in the groundwaters sampled at both sites, as observed also in other Fennoscandian sites in granitic rocks. Solubility control by sericite has been proposed as a mechanism controlling the maximum concentrations of potassium /Nordstrom et al. 1989/, but ion-exchange processes can not be ruled out. Even if the exact mechanism is not known all available groundwater data indicates that the increased infiltration of waters of meteoric origin will not increase the potassium concentrations found at present. The reaction modelling performed within SR-Can is not well suited to constrain potassium concentrations because, as mentioned, there is not enough information available on the possible reactions that could control this element. The mixing calculations give maximum values of $[K^+]$ below 0.004 mol/L at any time for both Laxemar and Forsmark.

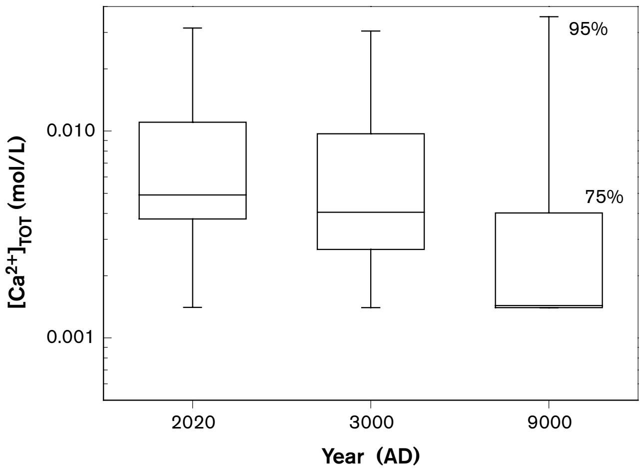


Figure 9-42. *Box-and-whisker plots showing the distribution of Ca concentrations at Forsmark at 400 m depth as a function of time. The statistical measures are the median and the 25th and 75th percentile (box) and the 5th and 95th percentile ("whiskers").*

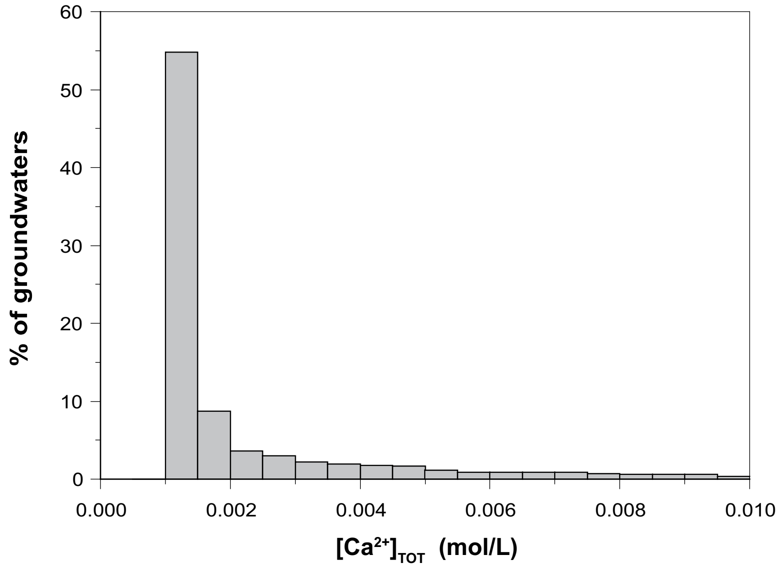


Figure 9-43. *Histogram showing the calculated distribution of Ca concentrations at Forsmark at 400 m depth at 9,000 AD.*

Sulphide concentrations have not been extensively modelled in the site characterisation models, mainly because the data are scarce: sulphide concentrations are usually below the detection limit. Under oxidising conditions, for example in superficial waters, sulphide is quickly oxidised to sulphate. Under reducing conditions, dissolved Fe(II) is normally present and the maximum sulphide concentrations are regulated by the precipitation of Fe(II) sulphide according to

$HS^- + Fe^{2+} = FeS(s) + H^+$

with $\log_{10}K = \log_{10} ([H^+] / ([Fe^{2+}] [HS^-])) \approx 3$. At pH between 7 to 8 one obtains $\log_{10}([Fe^{2+}][HS^-]) \approx -10$ to -11. In most groundwaters $\log_{10}[Fe^{2+}] \geq -6$ which sets the maximum $\log_{10}[HS^-]$ in the range -4 to -5.

This is confirmed by the data from groundwater analyses from the sites, see Figure 9-44. The maximum value for Forsmark is $\log_{10}[HS^-] = -5.1$ (0.26 mg/L) from KFM07A at 780 m depth. For Laxemar the highest value is $\log_{10}[HS^-] = -4.1$ (2.5 mg/L) in an old sample from KLX01 at 670 m depth. These are, however, exceptions and, for many of the groundwaters, sulphide is below the reporting limit of the analytical methods ($9 \cdot 10^{-7}$ M or 0.03 mg/L).

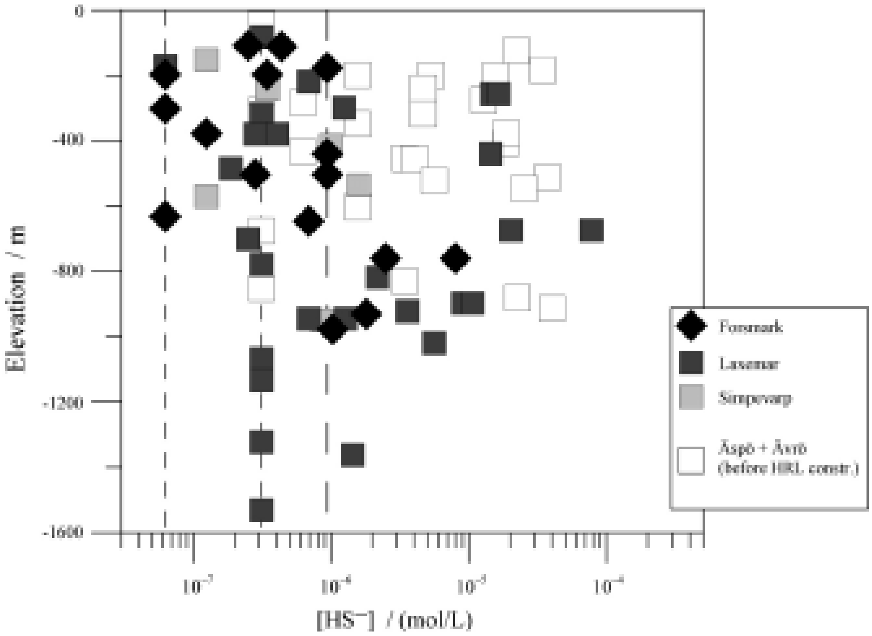


Figure 9-44. *Sulphide concentrations in contemporary groundwaters of the Forsmark and Simpevarp areas. Only one value has been selected for any given depth section of each borehole for cases where several analyses have been performed. The dashed lines correspond to 0.03, 0.01 and 0.002 mg/L, representing the reporting limit, and two detection limits for the analytical methods used when obtaining the data. Values plotted at such a limit indicate that sulphide concentrations were analysed and found to be below the limit.*

In the reaction modelling performed within SR-Can, apart from the "marine" and "brine" components, the reference waters used in the mixing calculation were assumed to contain no sulphide. However, marine waters infiltrating in the rock may be relatively rich in organic matter, and observations at Äspö have show that some sulphate reduction takes place in these groundwaters. Therefore, the "marine" component was assumed to be in equilibrium with solid Fe(II) sulphide.

The results of mixing the marine component with the other reference waters are shown Figure 9-45, illustrating the decrease in sulphide values as meteoric waters become increasingly dominant with time. In reality the concentrations of sulphide are not expected to decrease to the same degree as the figure shows because the calculations only reflect the effect of dilution with meteoric waters and does not include the possibility of pyrite dissolution.

The concentrations of methane and hydrogen are also of importance as nutrient sources for microbially mediated sulphate reduction to sulphide:

$SO_4^{2-} + CH_4 \rightarrow HS^- + HCO_3^- + H_2O$

$SO_4^{2-} + 4H_2 + H^+ \rightarrow HS^- + 4H_2O$

In Figure 9-46 it is seen that the maximum possible contribution to sulphate reduction from H_2 is modest. If all hydrogen was quantitatively used by microbes in sulphate reduction, at most the sulphide concentration would increase by $10^{-5.6}$ M. The figure also shows that methane concentrations are as a rule below 10^{-5} M. From this, from the data in Figure 9-44, and from the results of the hydrogeological and geochemical modelling described above, it may be concluded that sulphide concentrations, including the potential contribution from methane, averaged over the temperate period will be at the levels found at present at the sites or lower, that is, $\leq 10^{-5}$ M for any deposition hole. This is regarded as a cautious assumption: for any given deposition hole oscillations in sulphide levels will take place, but the time-averaged concentrations are expected to be $\leq 10^{-5}$ M.

The concentration of Fe(II) is regulated by a complicated set of reactions including the slow dissolution of Fe(II)-silicates, such as chlorite and biotite, the precipitation of Fe(II) sulphides and redox reactions. The concentrations of Fe(III) are in general negligible in granitic groundwaters, as the oxyhydroxides of Fe(III) are quite insoluble and they precipitate quickly. For the reaction modelling

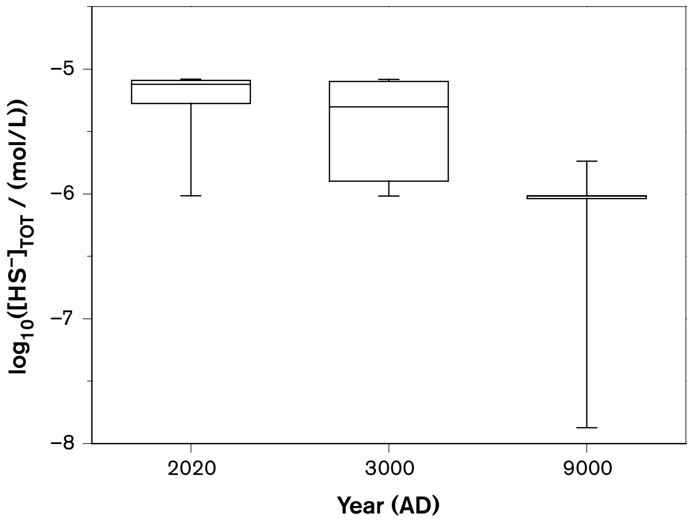


Figure 9-45. *Box-and-whisker plots showing the distribution of sulphide concentrations at Forsmark at 400 m depth as a function of time. The statistical measures are the median and the 25th and 75th percentile (box) and the 5th and 95th percentile ("whiskers").*

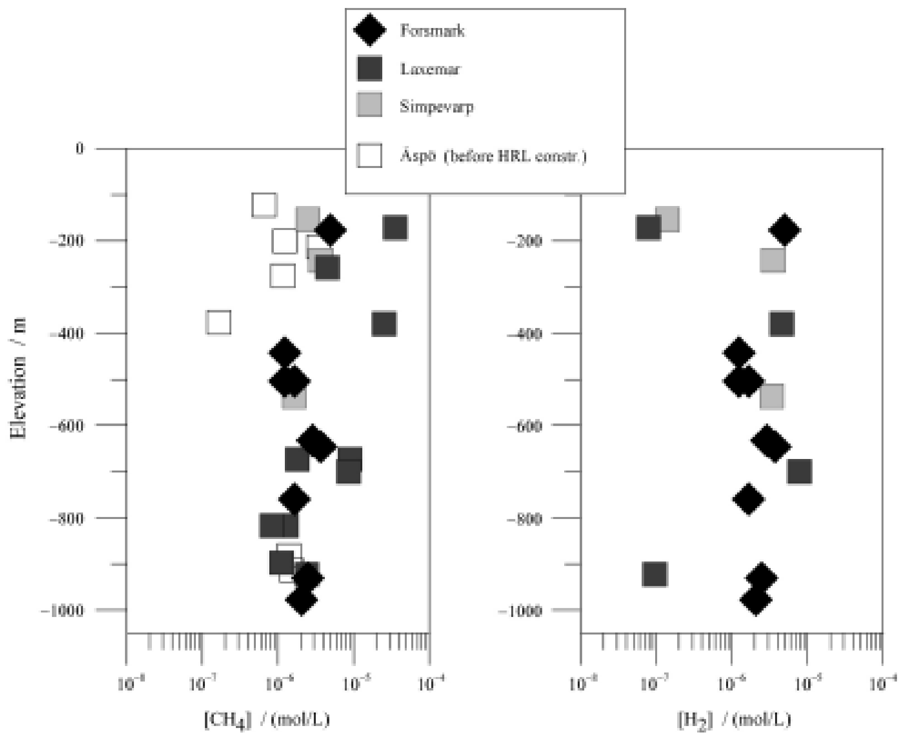


Figure 9-46. *Methane and hydrogen concentrations in contemporary groundwaters at the Forsmark and Simpevarp areas.*

in SR-Can, it has been assumed that Fe(III)-oxyhydroxide is at equilibrium, and this assumption has some effect both on redox potentials, discussed below, and on total iron concentrations. Figure 9-47 shows that the Fe concentrations of groundwaters at repository level tend to increase with time as waters of meteoric origin, assumed to have [Fe] ≈ 10^{-5} mol/L, become increasingly dominant.

In conclusion, during the initial temperate domain following repository closure at the two sites, the potassium concentrations are expected to remain ≤ 0.004 mol/L, sulphide concentrations are expected to be ≤ 10^{-5} mol/L for any deposition position averaged over the temperate period and iron concentrations are expected to gradually increase up to 10^{-5} mol/L.

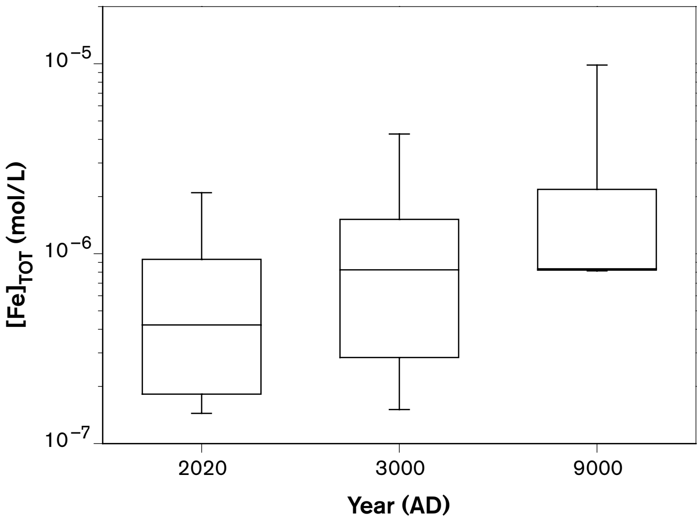


Figure 9-47. *Box-and-whisker plots showing the distribution of iron concentrations at Forsmark at 400 m depth as a function of time. The statistical measures are the median and the 25th and 75th percentile (box) and the 5th and 95th percentile ("whiskers").*

pH and bicarbonate

For pH and bicarbonate, the mixing and reaction calculations are dominated by the precipitation and dissolution of calcite. The results for both sites show that the pH values remain approximately in the range 7 to 8, and that bicarbonate values increase gradually with time up to about 0.004 mol/L. The results for Forsmark may be seen in Figure 9-48. It may be shown that the calculated partial pressures of dissolved carbon dioxide increase with time, as it is assumed in the modelling that the infiltrating meteoric waters have a higher CO_2 content than the other waters in the system. The conclusion is that the criterion for the safety function indicator R1e in Figure 9-2 (pH < 11) is fulfilled during the whole temperate period following repository closure.

Chloride and sulphate

Although chloride and sulphate are not listed in the safety function indicator criteria of Figure 9-2, chloride is used when selecting radionuclide transport properties (sorption coefficients) and sulphate is important when determining the solubility limits for radium. These two components behave almost conservatively, i.e. they rarely participate in chemical reactions, and they have been modelled by mixing calculations in SR-Can. Figure 9-49 shows that the groundwater concentrations of chloride and sulphate at repository level tend to decrease with time as waters of meteoric origin become increasingly dominant. Similar results are obtained for Laxemar /Auqué et al. 2006/.

Colloids

Colloids are partly stabilised by neutralising electric repulsions between charges in their surfaces. Some of these charges arise from the dissociation of acid-base groups, and are, therefore, pH dependent. The presence of ions in the water counteracts these charge effects, and, therefore, most colloids quickly sediment in waters containing more than either 1 mM of Ca^{2+} or 100 mM Na^{+}. The results from the modelling calculations show that colloids will not be especially stable during this period, because the pH values, salinities and calcium concentrations will be high enough to destabilise them. The conclusion is that colloid concentrations are expected to remain at the levels that have been measured during the site investigations, i.e. less than 100 µg/L /SKB 2005e, 2006g/.

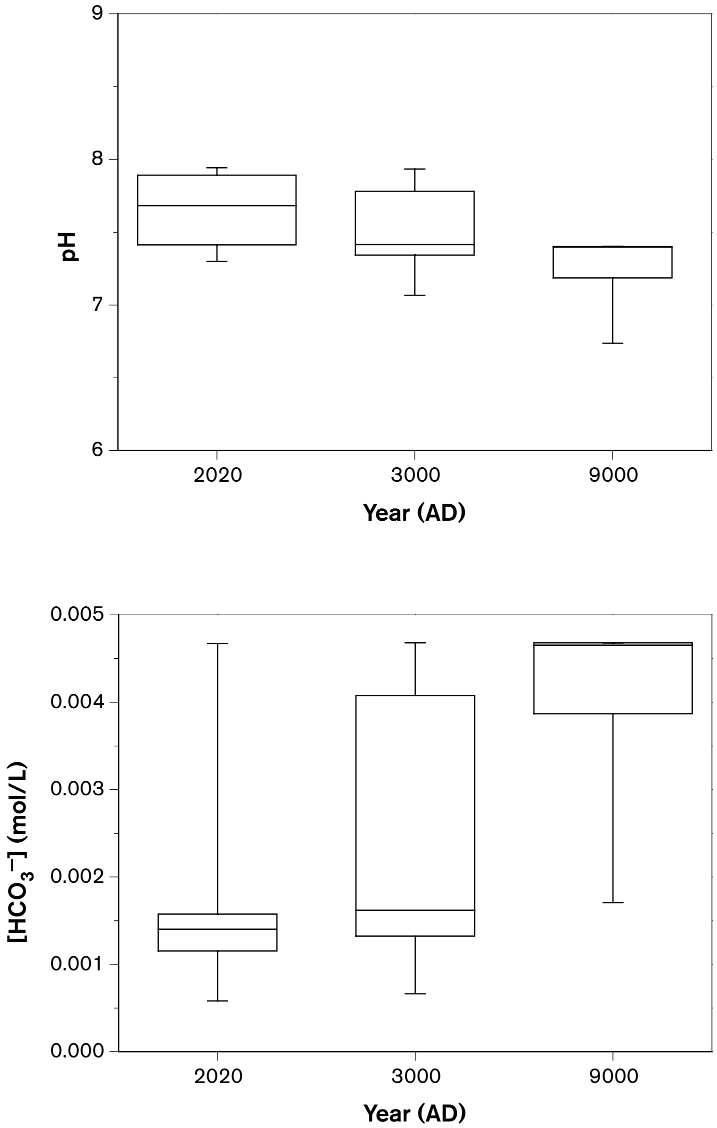


Figure 9-48. *Box-and-whisker plots showing the distribution of pH values (top) and of "free" bicarbonate concentrations (bottom) at Forsmark at 400 m depth as a function of time. The statistical measures are the median and the 25th and 75th percentile (box) and the 5th and 95th percentile ("whiskers").*

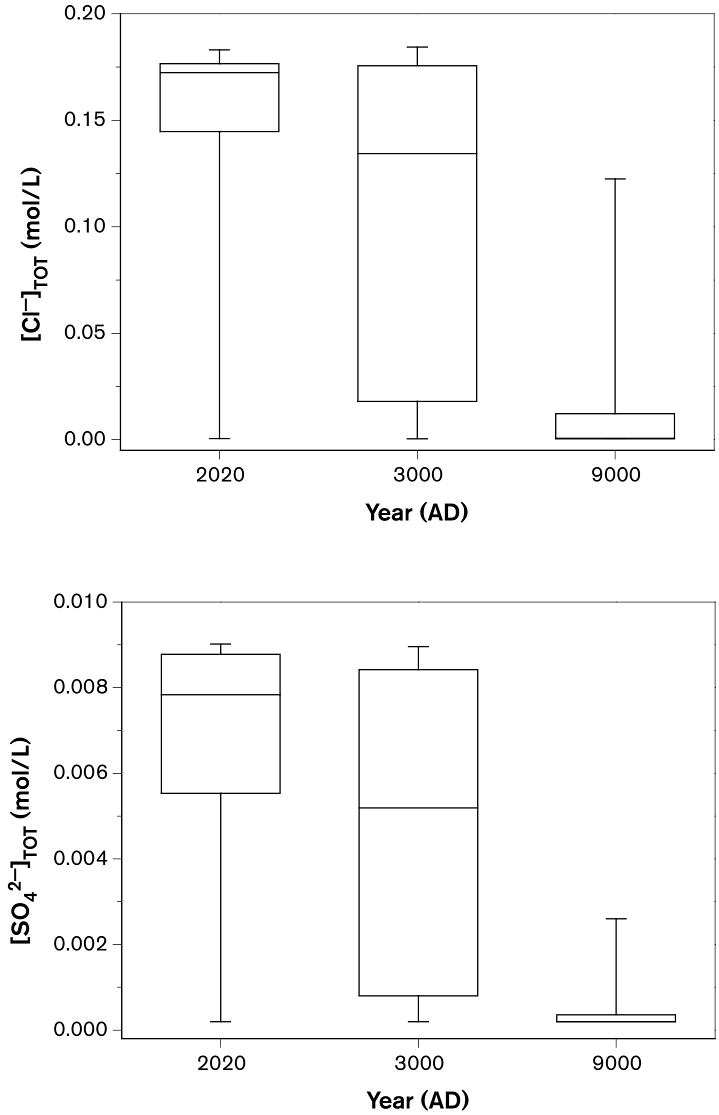


Figure 9-49. *Box-and-whisker plots showing the distribution of chloride concentrations (top) and of sulphate concentrations (bottom) in Forsmark at 400 m depth as a function of time. The statistical measures are the median and the 25th and 75th percentile (box) and the 5th and 95th percentile ("whiskers").*

Evolution of redox conditions

Evidence from the Äspö laboratory and other Swedish sites, shows that anoxic conditions prevail in the host rock even at a short distance from tunnel walls or from the ground surface. Air will be entrapped in the buffer and backfill, but anoxic conditions are expected to be established soon after the tunnels become resaturated, see section 9.2.5. Even if the buffer or backfill do not become fully saturated during this period (see also the discussion in section 9.3.8), oxygen consumption processes will take place in the partially saturated materials, as shown from the data obtained at the Febex and Prototype experiments /Jockwer and Wieczorek 2003, Pedersen et al. 2004/.

The hydrogeological modelling described in section 9.3.6 shows that the proportion of waters of meteoric origin at repository depth will increase with time, see Figure 9-38. This evolution is not expected to change the reducing characteristics of the groundwater, as infiltrating meteoric waters become depleted of oxygen by microbial processes in the soil layers of the site, if there are any, or after some tens of metres along fractures in the bedrock, as shown by the data collected within the Rex experiment /Puigdomenech et al. 2001a/ and from groundwaters sampled at 40 to 70 m depth during the "Redox Zone" experiment at Äspö /Banwart 1999, Banwart et al. 1999/.

The results from the hydrogeological model have been coupled with the mixing and reaction calculations, as described in the introduction of this section. The calculations included equilibrium with either an Fe(III) oxyhydroxide or with Fe(II) sulphide. The results are slightly dependent on the solid phase chosen. The calculations for Forsmark presented in Figure 9-50 show that the redox potentials increase slightly with time but remain well below −100 mV at the end of the simulation period.

It may, therefore, be concluded that for both sites the anoxic groundwater conditions now prevailing at repository depth will continue for the whole temperate period following the closure of the repository, in spite of the increasing proportion of meteoric waters with time. The chemical environment surrounding the repository will thus satisfy the criteria for the safety function indicator R1a in Figure 9-2.

Effects of grout, shotcrete and concrete on pH

The presence of cement materials in the repository is discussed in section 9.2.5. Cement recipes with porewaters having pH around or below 11 will be used in the repository in order to avoid detrimental effects from porewater diffusing out of the cement matrix. The effect of these porewaters is much smaller than that of Standard Portland Cement paste that contains porewater that is highly alkaline (pH ≈ 12.5).

At Forsmark, it is expected that only deformation zones will require grouting to avoid the inflow of groundwater into the tunnels during repository operation. These zones, however, may have a large role in model simulations of radionuclide transport. In deposition tunnels, the average amount of grout in rock fractures is expected to be less than 20 kg per metre of tunnel /**Initial state report**/, while shotcrete will only be used in transport tunnels and other cavities in which deposition does not occur. The values for Laxemar are more uncertain; they are estimated to be in the range 69 to 110 kg per metre of tunnel /**Initial state report**/. It must be noted that grouting will be concentrated to a few locations in each deposition tunnel and that therefore grout will be unevenly distributed.

After repository closure, grout and shotcrete will start reacting with circulating groundwater, and a slightly alkaline plume is expected to develop downstream in the grouted fractures. A generic model has been used to illustrate this process. The 2D model, 80×40 m in size, consists of a high transmissivity fracture intersecting a deposition tunnel backfilled with crushed rock and MX-80 bentonite in a 30/70 ratio /Luna et al. 2006/. The Phast computer code /Parkhurst et al. 2004/ was used for the simulations.

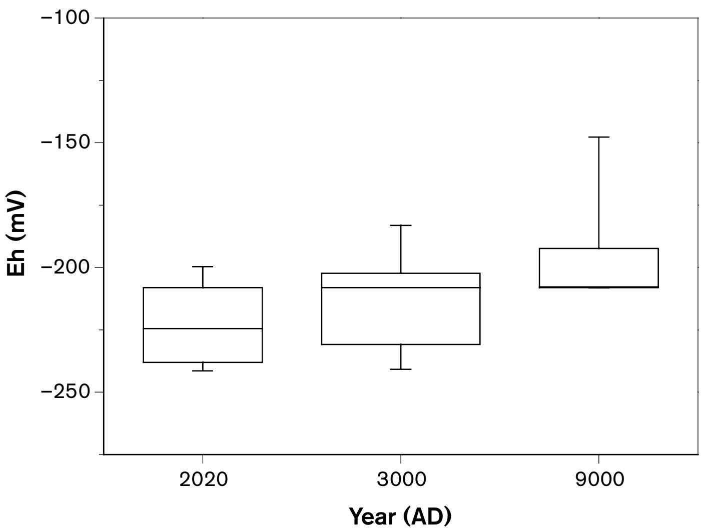


Figure 9-50. *Box-and-whisker plots showing the distribution of Eh values (redox potential) at Forsmark at 400 m depth as a function of time. The statistical measures are the median and the 25th and 75th percentile (box) and the 5th and 95th percentile ("whiskers").*

The results show that a moderately high pH plume (pH ≈ 9) can develop in grouted fractures intersected by the deposition tunnel and to a minor extent also in the backfill material, cf Figure 9-51. The leaching of grout material leads to the precipitation of CSH phases (calcium silicate hydrates) and calcite ($CaCO_3$) in the fracture, leading to the pH plume shown in Figure 9-51 and a corresponding decrease of the carbonate concentrations in the groundwater.

Several factors, such as the effect of the fracture characteristics, remain to be tested and will be addressed in the future. Although the numerical calculations are limited to 1,000 years, it is expected that the process will continue until all cement has reacted. Depending on the geometry and hydrologic properties of the grouted fracture and on the amount of grout, this process could continue for up to one hundred thousand years.

A consequence of this process is that transport pathways for potentially released radionuclides will include groundwaters that have circulated through a grouting zone and have been modified to higher pH (≈ 9) and lower carbonate (due to increased calcium concentrations and consequent calcite precipitation). This could affect the retention properties of the transport pathways. The model mentioned above does not take into account changes of porosity in the fracture as CSH phases and calcite are

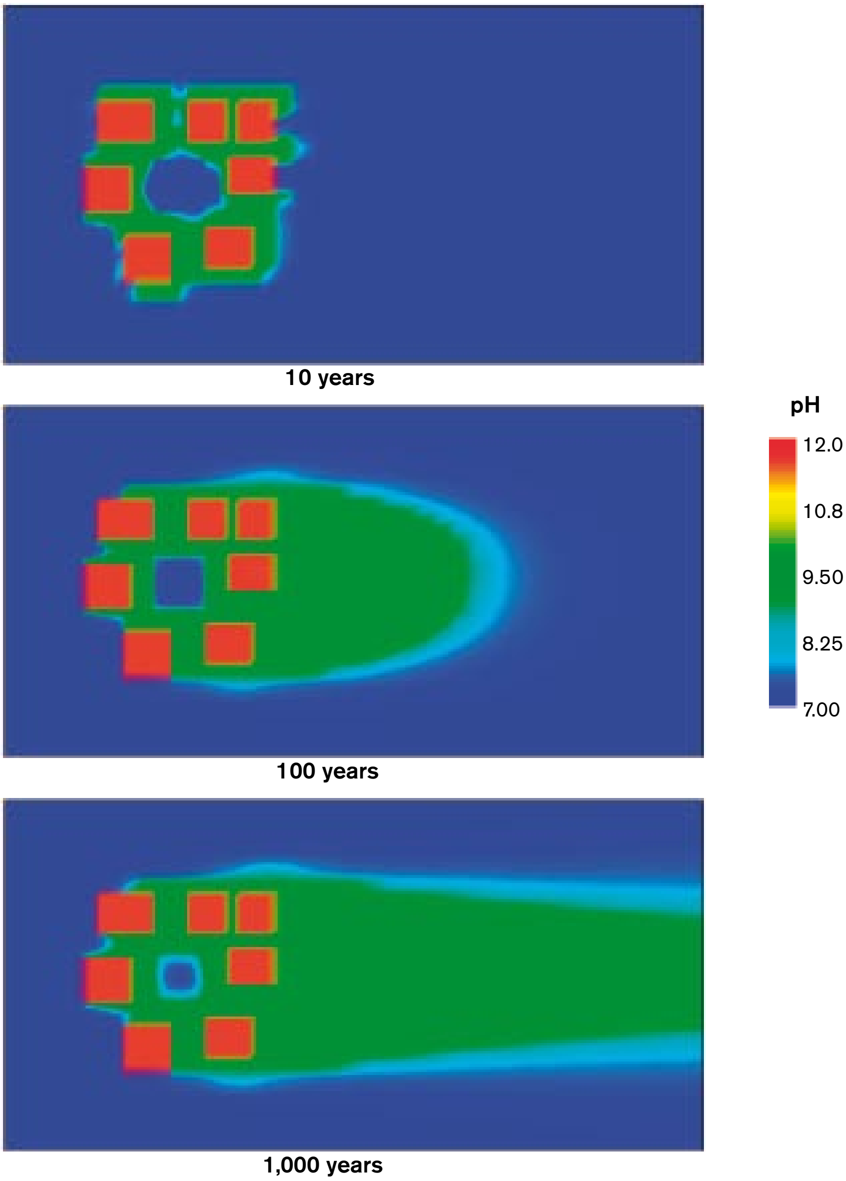


Figure 9-51. *Calculated evolution of pH inside a grouted fracture transecting a deposition tunnel /Luna et al. 2006/. Grouted areas in the fracture have pH ≈ 11 and in this modelling they have been crudely represented by square areas located around the backfilled deposition tunnel, a square area with lower pH surrounded by the grouted parts of the fracture (red squares).*

precipitated. Experience from the HPF experiment in Grimsel /Mäder et al. 2004/ shows that this could be an important factor in reducing the transport of high alkaline fluids, although the HPF experiment was conducted with solutions simulating standard cement (pH ≈ 12.5). The groundwater sampled in grouted fractures at Onkalo show high pH values /Ahokas et al. 2006/, but the time span for these measurements is too short (some months) for conclusions to be drawn relevant to the longer timescale addressed here. There is, therefore, no experimental evidence to indicate that the model results are pessimistic.

The conclusion is, therefore, that the effect of grout in fractures will be to increase the pH in deformation zones to values ≈ 9 for relatively long periods of time, probably lasting throughout the first glacial cycle (≈ 120,000 years). pH values ≈ 9 are, however, within the criterion for the safety function indicator R1e in Figure 9-2. Radionuclide sorption data /**Data report**, section 6.7/ have been selected for the pH range 7 to 9, and are therefore adequate as long as "low" pH materials are used for grouting.

Degradation of grout in grouting holes

In order to be able to penetrate small fractures, cement-based grout has to have a high porosity (high water/solid materials ratio). Preliminary, yet unpublished, modelling shows that because of this, cement-based grout in grouting boreholes is quickly degraded (less than about 100 years) by groundwater components. For SilicaSol the natural evolution is instead to slowly recrystallise into thermodynamically more stable forms of silica, and both grouted fractures and grouting holes where SilicaSol has been used will, therefore, remain sealed. The conclusion is, therefore, that for modelling purposes it may be assumed that cement-based grouting boreholes are filled with a material having a high porosity. Grouting holes are, however, not included as flow paths in the flow and transport modelling in SR-Can and it is expected that their connectivity to flow paths is limited. Small amounts of organic additives (superplasticizers) included in cement-based grouts will be gradually released during grout degradation and these substances will then be accessible for microbial processes. Their contribution to the concentration of organic carbon of groundwaters will, however, be negligible.

9.3.8 Saturation of buffer and backfill

General

The buffer will be emplaced with a dry density of 1,570 kg/m^3 as average density per deposition hole. This will give a saturated density of 2,000 kg/m^3. The acceptable variation on the saturated density is ± 50 kg/m^3. However, the expected variation based on experience from the Prototype Repository (section 4.3.5) is much less. This reference saturated density corresponds to a swelling pressure and hydraulic conductivity at full saturation of 7–8 MPa and 2–5·10^{-14} m/s, respectively (see section 4.2.8).

The Friedland backfill will be emplaced with a dry density of a least 1,780 kg/m^3. This value is based on the average of the blocks, the pellets and the voids in the tunnel. A higher backfill density is not disadvantageous and 1,780 kg/m^3 should be seen as a minimum value. This would lead to a hydraulic conductivity of around 10^{-12} m/s and a swelling pressure of roughly 3 MPa, see section 4.2.8.

During the early stage of the repository evolution, the deposited buffer and backfill blocks will take up water from the surrounding bedrock. The water will expand the mineral flakes and the buffer and backfill will start swelling. The swelling will be restricted by the rock wall and a swelling pressure will develop. After final saturation, the hydraulic conductivity of the buffer and backfill will be very low. This section describes the general modelling of the processes together with a discussion on how this is applied to the specific sites.

The buffer blocks will be deposited into the deposition holes with an initial water content of 17% (by weight). The groundwater in the bedrock will enter into the deposition holes and eventually saturate the buffer. This process is dependent on the properties of the buffer as well as on the local hydraulic conditions and the saturation state of the tunnel backfill.

The deposition tunnels will be backfilled in a similar manner. Pre-compacted blocks of either a 30/70 mixture of buffer bentonite and crushed rock or 100% natural clay will be deposited in the tunnels. The saturation of the backfill is mainly dependent on the material properties and the conditions in the surrounding rock.

The water saturation of the backfill and the buffer have been determined by modelling of coupled 3D THM-processes influenced by several properties of the buffer/backfill materials and the hydraulic conditions of the rock /Börgesson et al. 2006/. Two-phase flow conditions were also represented. The analysis was done in three steps:

- Investigation of the influence of the backfill properties and wetting conditions on the water saturation phase of the buffer as an update of the wetting calculations /Börgesson and Hernelind 1999/ for the SR 97 assessment.
- Investigation of the influence of the rock conditions on the wetting phase of the backfill in the deposition tunnels for three different backfill types.
- Investigation of the influence of entrapped air on the wetting phase of the backfill in the deposition tunnels.

The mechanical interaction between the buffer and the backfill, in particular due to the buffer swelling at the end of the saturation process has not been considered in this study. This aspect is discussed below in this section, and also in /Johannesson and Nilsson 2006/ and in /Börgesson and Hernelind 1999/.

Saturation of the buffer

The calculation of the saturation process for the buffer for a range of conditions is presented in /Börgesson et al. 2006/. The conclusions from the study are as listed below.

- A very low conductivity of the rock matrix will have a strong influence on the wetting rate of the buffer. It will take ~ 50 years to saturate the buffer with a hydraulic conductivity of the rock matrix $K_{rock} = 10^{-13}$ m/s, assuming no fractures in the deposition holes and no contribution from the EDZ or tunnel backfill. If $K_{rock} = 10^{-14}$ m/s, the buffer will not reach full saturation in a very long time.
- If the conductivity of the rock matrix is high ($K_{rock} \geq 10^{-12}$ m/s), the wetting rate will be determined by the properties of the buffer and the saturation time of the buffer will be in the range of 5–10 years. The exact figure depends on where the water feeding boundary is located. The referred calculation has a distance of about 12 m to the boundary.
- Conductive fractures in the deposition hole, a conductive EDZ or water pressure in the tunnel backfill will have a strong influence on the wetting rate of the buffer for the case with a dry rock. These cases give a saturation time of 10–20 years. The geometric interface between the water source and the buffer plays an important role in these cases.
- If the rock matrix were completely impervious, the buffer would saturate by taking up water from the initial water content of the backfill (drying the backfill). In such cases, the saturation time would be 500–2,000 years.

The calculations are based on an MX-80 buffer. A Deponit CA-N buffer is expected to behave similarly, since its swelling pressure and hydraulic conductivity are similar to those of MX-80 at buffer density.

At the end of the saturation process, the buffer will swell and exert a swelling pressure on the canister, rock wall and backfill, see below.

Saturation of the backfill

The backfill will play an important role for the saturation of the buffer if the hydraulic conductivity of the rock is low. /Börgesson et al. 2006/ also covered the saturation process of the tunnel backfill for a wide range of conditions. The main conclusions from that study were as listed below.

- The 30/70 mixture will saturate 2 to 5 times faster than the Friedland Clay. This is more or less independent of boundary conditions. The reason is the lower hydraulic conductivity of the latter.
- There is a strong effect of fracture intensity on the saturation time.
- The transmissivity of the water-bearing fractures is of minor importance for the saturation time, unless the transmissivity is less than about 10^{-11} m^2/s.
- The hydraulic conductivity of the rock mass is of minor importance for the saturation time. (This assumes that there will be fractures intersecting the tunnel).
- The tunnel backfill will generally become saturated faster than the buffer.

- Air initially entrapped in the backfill material will slow down the saturation rate if the water supply from the rock is high, but will have very limited effect in a dry rock. In that case, the air will escape faster than the water will enter.
- A conductive “skin” zone at the interface between the rock and backfill would speed up the saturation rate. This would correspond to the pellet-filled space between the backfill blocks and the rock wall. That would also be the location of piping events.

The time for saturation for the backfill varies between 0.5 to 200 years in the calculations.

The calculations for the 30/70 mixture were done for the MX-80 material. For the Deponit CA-N mixture, the difference in properties will mainly be a lower suction potential and a higher hydraulic conductivity. The time to saturation for the mixture with Deponit CA-N is expected to be shorter, since the wetting is mainly controlled by the hydraulic conductivity of the backfill.

Application to hydraulic conditions at the Forsmark site

According to the DFN description of the rock surrounding the repository (see section 9.3.6 above, and the **Data report** section 6.5 for a description of the hydraulic DFN model), the vertical fracture spacing is between 21 and 28 m if a fracture length truncation of 2 m is used /Hartley et al. 2005a/. Using the assumed transmissivity-length relationship, a 2 m long fracture has a transmissivity of $2 \cdot 10^{-9}$ m^2/s. The longest fractures included in the DFN model are 1,000 m; these have a transmissivity of $1 \cdot 10^{-6}$ m^2/s /Hartley et al. 2005a/. Deposition holes are predominantly intersected by short fractures.

This would give a saturation time for the backfill of about 6–8 years for the 30/70 mixture and 40–50 years for Friedland Clay. In Forsmark, it is likely that some deposition holes will be intersected by water conducting fractures whereas others will be dry. This means that the saturation time for the buffer in different holes will vary over a range from about 10 years to 50–100 years.

The rock stress situation in Forsmark together with the thermal pulse may cause spalling of the rock wall in the deposition holes, see section 9.3.5. This will lead to a more fractured part on one side of the hole. However, the extent of the area is expected to be relatively small and it will probably not be of importance for the saturation process (possibly a slight increase).

Application to hydraulic conditions at the Laxemar site

According to the DFN description of the rock surrounding the repository (see section 9.3.6 above, and the **Data report** section 6.5 for a description of the hydraulic DFN model), the vertical fracture spacing is between 5 and 10 m in rock domain A below 200 m depth based on model and field data on connected fracture frequency ($P10_c$ and $P10_{PFL}$, respectively) /Hartley et al. 2006b/. Using the assumed transmissivity-length relationship, a 1 m long fracture has a geometric mean transmissivity of $3.5 \cdot 10^{-10}$ to $3.5 \cdot 10^{-9}$ m^2/s depending on fracture set (a 1 m truncation has been found appropriate for modelling flow at canister scale). The longest fractures included in the DFN model are 1,000 m; these have geometric mean transmissivities between $3.5 \cdot 10^{-7}$ and $3.5 \cdot 10^{-6}$ m^2/s. Deposition holes are predominantly intersected by short fractures.

These values give a saturation time for the backfill of about 2–3 years for the 30/70 mixture and ~ 20 years for Friedland Clay. At Laxemar, it is likely that a large proportion of the deposition holes will be intersected by water-conducting fractures, which will give a saturation time for the buffer of about 10 years.

Spalling can not be ruled out at the Laxemar site either. The conclusions about the importance of this for the saturation process are the same as for the Forsmark site.

Summary

The calculations above show that the buffer will be saturated in a period of a few to of the order of one hundred years. The longest calculated saturation times are shorter than those for repositories in clay, e.g. /Nagra 2002/. The length of this period is expected to have no significant impact on the buffer performance.

A long saturation time means that no corrosion or radionuclide transport can take place for that period. However, the saturation time is still too short for this to have any significant positive impact on the overall performance of the repository. The temperature in the repository will be higher with a long saturation time, but no credit for water in the rock is taken in the calculation of the peak temperatures (that typically occur after 10 years), see section 9.3.4. The buffer properties are not expected to be affected by a long time of partial saturation. The bentonite has been exposed to partially saturated boundary conditions for millions of years /Smellie 2001/.

9.3.9 Swelling and swelling pressure

The primary purpose of the buffer is to ensure that transport of species from the rock to the canister and from the canister to the rock is dominated by diffusion. The swelling pressure in the bentonite is expected to seal all gaps and ensure that there is tight contact between the rock and the buffer. It is, therefore, important that the swelling pressure is maintained. The safety function indicator criterion for ensuring tightness in the buffer is a swelling pressure of 1 MPa (section 7.3.2), safety function indicator Bu1b in Figure 9-2. The required swelling pressure for eliminating microbes is 2 MPa, safety function indicator Bu3 and for preventing canister sinking is 0.2 MPa, safety function indicator Bu6. The densities needed to meet these values are discussed in section 4.2.8.

The two buffer materials MX-80 and Deponit CA-N have reference saturated density intervals 1,950–2,050 kg/m^3. The swelling pressure for the reference density will be 7.5–8 MPa for both materials, see section 4.2.8. With account taken for the allowed variations in density, the swelling pressure may vary between 4.5 and13 MPa (see section 3.2.5), provided that the buffer material is fully confined to the volume it occupies at deposition. The hydraulic conductivity will be well below 10^{-13} m/s. These values are valid for a rather large range of groundwater salinities. The present day groundwater at Forsmark has a salinity of ~ 0.9% or 0.15 M Cl^-.

For the two backfill materials with specified minimum dry densities of 1,930 kg/m^3 for the 30/70 mixture and 1,780 kg/m^3 for Friedland Clay, the swelling pressures after full water saturation for both materials would be slightly above 3 MPa, based on results from compressibility tests /Johannesson and Nilsson 2006/, in good agreement with extrapolated results from section 4.2.8. The tests were done for a water salinity of 3.5% (NaCl/$CaCl_2$). Under these conditions, both materials would have a hydraulic conductivity of $1.1–1.5 \cdot 10^{-12}$ m/s. For the Forsmark and Laxemar conditions, the swelling pressure is expected to be somewhat higher and the hydraulic conductivity somewhat lower.

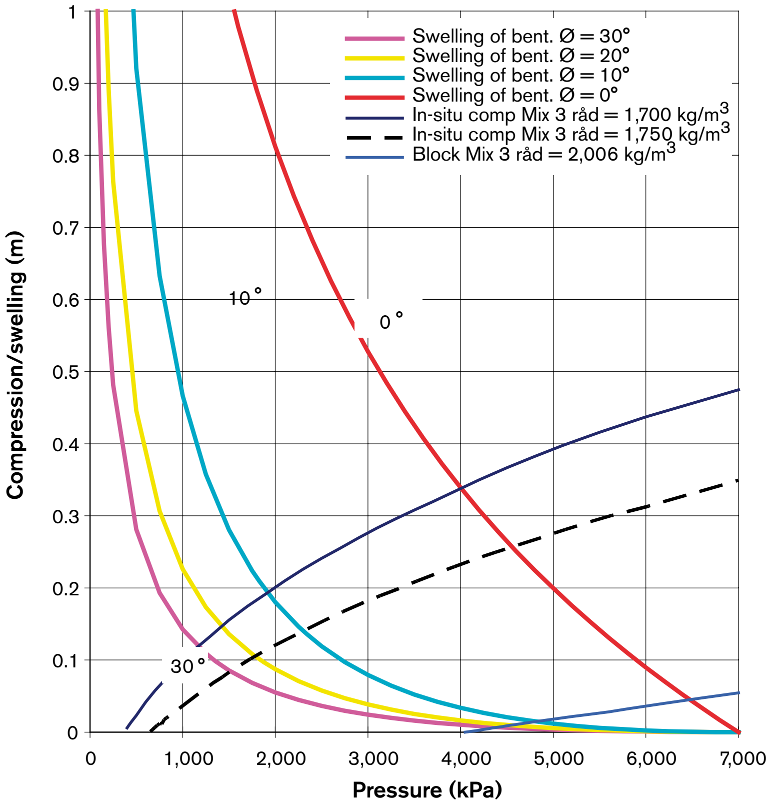
Buffer upward expansion

The swelling pressure from the buffer will compress the backfill to a certain extent. This will lead to an expansion of the buffer and a loss of swelling pressure and density in the top part, affecting the buffer safety function indicators Bu1, Bu2, Bu3 and Bu6 in Figure 9-2. One important function of the backfill is to limit this expansion.

/Johannesson and Nilsson 2006/ have calculated expansion of the buffer with an initial swelling pressure of 7 MPa into the backfill for the 30/70 mixture as well as for the Friedland clay, see Figure 9-52. For the specified density of the Friedland backfill (1,780 kg/m^3 dry density), the expansion of the buffer is a few cm for friction angles between buffer and rock of 10–30°. The displacement is less than 10 cm even with the assumption of no friction in the system. The calculations are based on a dilute water. The friction data are based on material properties from /Börgesson et al. 1995/. The internal friction angle in the bentonite is 10° and the friction between rock and buffer is expected to be at least as high as this. Data for these calculations are given in the **Data report** (section 5.2).

Table 9-7 and Table 9-8 show the calculated backfill displacement, the swelling pressure at the interface (Psa), the distance down the deposition hole where the buffer density is affected (z), and the buffer density at the top of the canister for a number of combinations of buffer and backfill dry densities. The values in the tables are only for an MX-80 buffer, but the swelling pressure of Deponit CA-N is almost identical (section 4.2.8) in the density range considered and no differences in the results are expected. A friction angle of 10° has been used in these calculations. A higher friction angle will give a smaller displacement, but the effect is small (Figure 9-52).

The results in Table 9-7 and Table 9-8 are based on material data for a groundwater salinity of 3.5%. It is expected that the buffer and backfill will be saturated with the groundwater from the site (Table 9-23, at the end of chapter 9). The present-day groundwaters at Forsmark (and Laxemar) are rather dilute (~ 0.9% in Forsmark). This would lead to a lower compressibility of the backfill



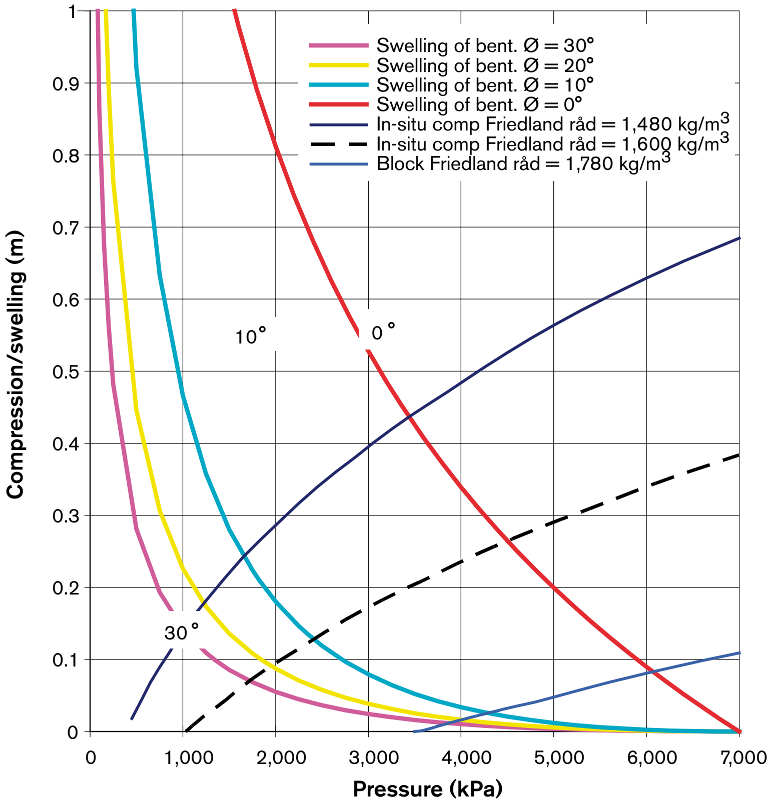


Figure 9-52. *The displacement of the interface between the compacted MX-80 bentonite and the overlying backfill. The calculations are made at different angles of friction between the buffer and the surface of the deposition hole and with different assumptions about the initial density of the backfill.*

Table 9-7. Mechanical interaction between buffer and backfill in the case of a MX-80 buffer and Friedland backfill.

Initial dry density Friedland backfill (kg/m^3)	Initial saturated density MX-80 buffer (kg/m^3)	Buffer/backfill interface displacement (m)	Swelling pressure at buffer/backfill interface (kPa)	Height of buffer affected (m)	Buffer density at top of canister (kg/m^3)
1,455	1,950	0.178	1,011	2.980	1,900
1,480	1,950	0.153	1,100	2.771	1,907
1,630	1,950	0.042	1,840	1.494	1,950
1,780	1,950	–	–	–	1,950
1,480	2,000	0.224	1,540	3.415	1,935
1,535	2,000	0.167	1,835	2.981	1,950
1,723	2,000	0.039	3,350	1.487	2,000
1,780	2,000	0.018	4,050	1.016	2,000
1,430	2,050	0.376	1,841	4.480	1,950
1,480	2,050	0.304	2,180	3.822	1,972
1,780	2,050	0.058	5,300	1.856	2,038
1,825	2,050	0.037	6,150	1.487	2,050

Table 9-8. Mechanical interaction between buffer and backfill in the case of an MX-80 buffer and a 30/70 backfill.

Initial dry density 30/70 backfill (kg/m^3)	Initial saturated density MX-80 buffer (kg/m^3)	Buffer/backfill interface displacement (m)	Swelling pressure at buffer/backfill interface (kPa)	Height of buffer affected (m)	Buffer density at top of canister (kg/m^3)
1,650	1,950	0.178	1,011	2.980	1,900
1,700	1,950	0.123	1,225	2.503	1,916
1,865	1,950	0.042	1,840	1.494	1,950
1,906	1,950	0.021	2,200	1.051	1,950
1,700	2,000	0.180	1,760	3.084	1,946
1,710	2,000	0.167	1,835	2.981	1,950
1,906	2,000	0.056	3,000	1.761	1,991
1,935	2,000	0.039	3,350	1.487	2,000
1,615	2,050	0.376	1,841	4.480	1,950
1,700	2,050	0.244	2,550	3.672	1,978
1,906	2,050	0.100	4,250	2.404	2,020
2,008	2,050	0.037	6,150	1.487	2,050

To get a minimum saturated buffer density of 1,950 kg/m^3 at the level of the top of the canister (1,900 kg/m^3 if the initial buffer density is 1,950 kg/m^3)

At expected density from in situ compaction (not considered in SR-Can)

To ensure that the buffer density is unchanged at the top of the canister

At expected density when backfilling with blocks (reference case in SR-Can)

materials, but a rather limited increase in swelling pressure for the buffer compared with the calculated results. The initial displacement and drop in swelling pressure at the sites is, therefore, expected be slightly less than the calculated values. In a longer time perspective, it is possible that more saline waters will enter the repository. This could then cause an additional expansion of the buffer into the backfill, but not more than is presented in the tables, unless salinity goes above 3.5%. It should be noted that neither the buffer materials nor the Friedland backfill are particularly sensitive to a change in salinity (section 4.2.8).

The results from the calculations of the expansion of the buffer into the backfill show that the drop in buffer density and swelling pressure around the canister will be small. The reference case with a buffer dry density of 1,570 kg/m^3 and a backfill density of 1,780 kg/m^3 will give a swelling pressure of around 4 MPa at the buffer/backfill interface. The swelling pressure does not drop below the safety function indicator criterion of 1 MPa for any calculated case. More important, the buffer density around the canister will remain within the tolerances (1,950–2,050 kg/m^3) for almost all the cases.

An additional, unlikely case would be that the buffer swells before the backfill. If the wetting of the deposition hole is faster than the wetting of the backfill, the upward swelling may be more complicated and difficult to calculate. In the case of in situ compacted backfill the difference is rather small, but if the backfill is made of blocks and pellets, there are both open slots and loose pellet fillings that may be compressed. In addition, the piles of blocks may be unstable and the blocks may be crushed or sheared to failure. /Börgesson and Johannesson 2006/ made a bounding calculation for the case where the buffer from a very wet deposition hole swells into a very dry pile of backfill.

With the simplified assumption that the backfill functions as a column with the same diameter as the deposition hole and without lateral support the total upwards displacement would be 18 cm. The staples would also be very close to failure with unknown consequences. However, these calculations were done with the assumption that there is no friction between the rock and the buffer that reduces the swelling pressure at the buffer/backfill interface. If a friction angle 10° is applied and the compression of the backfill is assumed to be proportional to the pressure from the buffer, the upwards displacement and the swelling pressure at the buffer backfill interface are reduced by more than a factor of two. The resulting upwards swelling is thus, according to this simplified calculation, estimated to be < 9 cm and the maximum deviatoric stress in the backfill column $(\sigma_1 – \sigma_3)$ < 4 MPa both of which are acceptable. However, the parameter values used are best estimates from present knowledge and need to be substantiated by large scale tests.

Overall conclusions regarding buffer expansion

Both backfill materials are well capable of maintaining the buffer density in the deposition hole at the required value if emplaced at reference density. The Friedland clay will be able to maintain a saturated buffer density at the canister top of 2,000 kg/m^3 (or actual buffer density if lower). With the 30/70 mixture, there will be a slight drop in buffer density at the canister top due to buffer expansion into the backfill. The Friedland Clay will perform well even if there is a rather large drop in the density, whereas the 30/70 mixture is more sensitive to variations in density.

Swelling of buffer after piping or due to initial mass deficit

Piping and associated erosion of the buffer was are discussed in section 9.2.4. A pessimistic estimate of the amount of eroded material indicated that 100 kg of buffer could be lost from a deposition hole.

/Börgesson and Hernelind 2006/ calculated the swelling pressure for two situations where the buffer mass is lower than intended. Situation 1 illustrates mass loss due to piping and situation 2 an initial mass deficit that can be used to illustrate the consequences of buffer mass loss that might occur for a number of reasons, see below.

Situation 1; piping

/Börgesson and Hernelind 2006/ based their erosion cases on a flow of 0.1 l/min into a deposition hole that erodes 2.5–10 g dry weight of bentonite per litre water. If it takes 12 weeks to restore the gradients this yields a total amount of flowing water of about 12 m^3 and a total mass of eroded bentonite of 30–120 kg.

This case illustrates erosion from an intersecting horizontal fracture that digs a hole in the form of a half donut around the buffer at its interface with the rock surface. It can also be interpreted as a 5 m long half pipe (a half pipe is a reasonably realistic geometry since the pipe most likely will be created next to the rock wall) running along an inclined or vertical fracture. The latter is a more realistic erosion development during the installation phase.

The geometry of the half pipe will at the buffer dry density 1,560 kg/m^3 yield a total empty volume of 0.019–0.077 m^3 at the inside of or along a deposition hole. If the dry mass loss is 60 kg, corresponding to 5 g dry weight erosion per litre of water, and the inner pipe radius is 0.067 m this condition is approximately fulfilled.

The results from the calculation of the swelling pressure in the piping case, Figure 9-53, show that the buffer will swell and reseal the pipe. Most of the original pipe will develop a swelling pressure of 2 MPa or higher. As shown below (Situation 2) a substantial swelling pressure will be restored even if a complete bentonite ring is lost. In this case, however, a large part of the buffer will have a swelling pressure lower than 1 MPa.

Also some of the backfill mass may be lost by erosion during the saturation phase, see section 9.2.4. If backfill density is lost by erosion, the expansion of the buffer will increase. However, the estimated losses in section 9.2.4 (0.3–1%) will not lead to unacceptable changes in the buffer density at canister level. According to Table 9-7 and Table 9-8, a Friedland backfill can lose 8% and a 30/70 mixture backfill can lose 2% of its mass with the buffer density being maintained at 1,950 kg/m^3 at the canister level if the loss is assumed to be evenly distributed in the entire backfill. In reality the loss will be local, most probably either as cavities or as tubes that are insufficiently homogenised due to the friction in the backfill. These situations have not been modelled but will in most cases probably lead to less severe expansion of the buffer unless the loss is located just above the deposition hole

Situation 2; initial mass deficit

These cases illustrate the development of void ratio and swelling pressure when one, two or three of the 50 cm bentonite rings surrounding the canister is omitted at installation. One ring corresponds to a dry mass of 1,200 kg. The purpose is to bound the effects of mishaps during emplacement, and to scope the effects of other causes for severe buffer mass loss. Figure 9-54 shows the development of the void ratio (i.e. the pore volume divided by the volume of solids, 75% corresponds to a dry density of 1,570 kg/m^3) and swelling pressure in the buffer for a case in which one of the bentonite rings is omitted.

As an illustration of the effects of a local loss of large amounts of bentonite /Börgesson and Hernelind 2006/ also calculated the swelling pressure (and void ratio) for cases where two and three entire bentonite rings surrounding the canister had been omitted. Figure 9-55 shows the resulting swelling pressure when two and three rings are removed. In the case with two omitted rings (~ 2,400 kg), there is still a swelling pressure of about 0.5 MPa in most of the outer part of the buffer. If three rings are omitted (~ 3,600 kg) all the swelling pressure is gone in a substantial part of the buffer. These results are somewhat sensitive to the assumptions on water chemistry and friction between the buffer and the rock. They are also based on the assumption that the mass is lost around the entire canister.

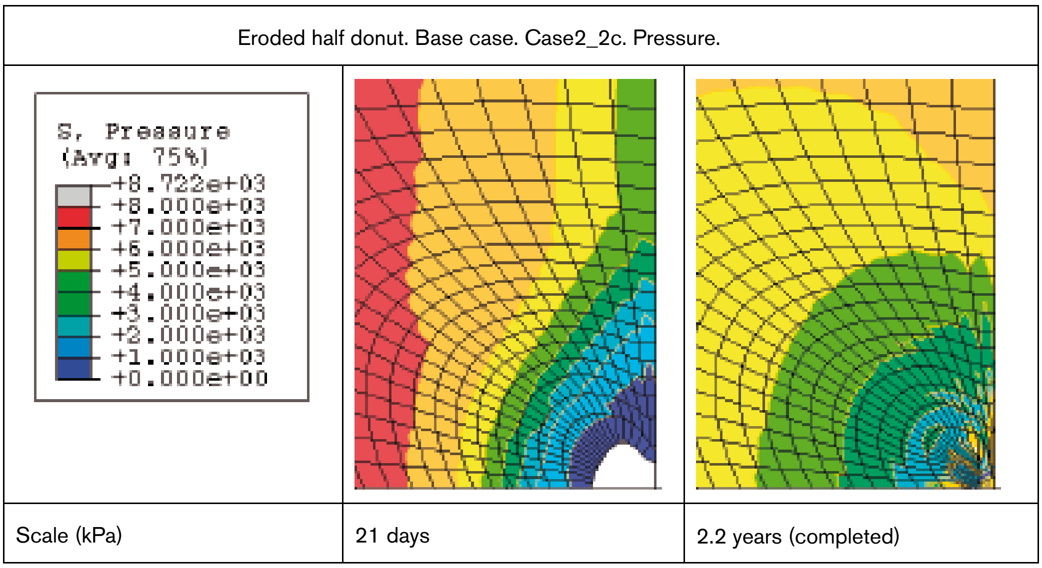


__Figure 9-53.__ Average swelling pressure plotted at different times for the erosion case. The erosion is assumed to have caused an open horizontal tunnel shaped space at the rock periphery (half a donut) in the centre of the deposition hole surrounding the entire buffer. The FE-model shows a vertical section through the opening. Axial symmetry around the canister axis and horizontal symmetry at the bottom.

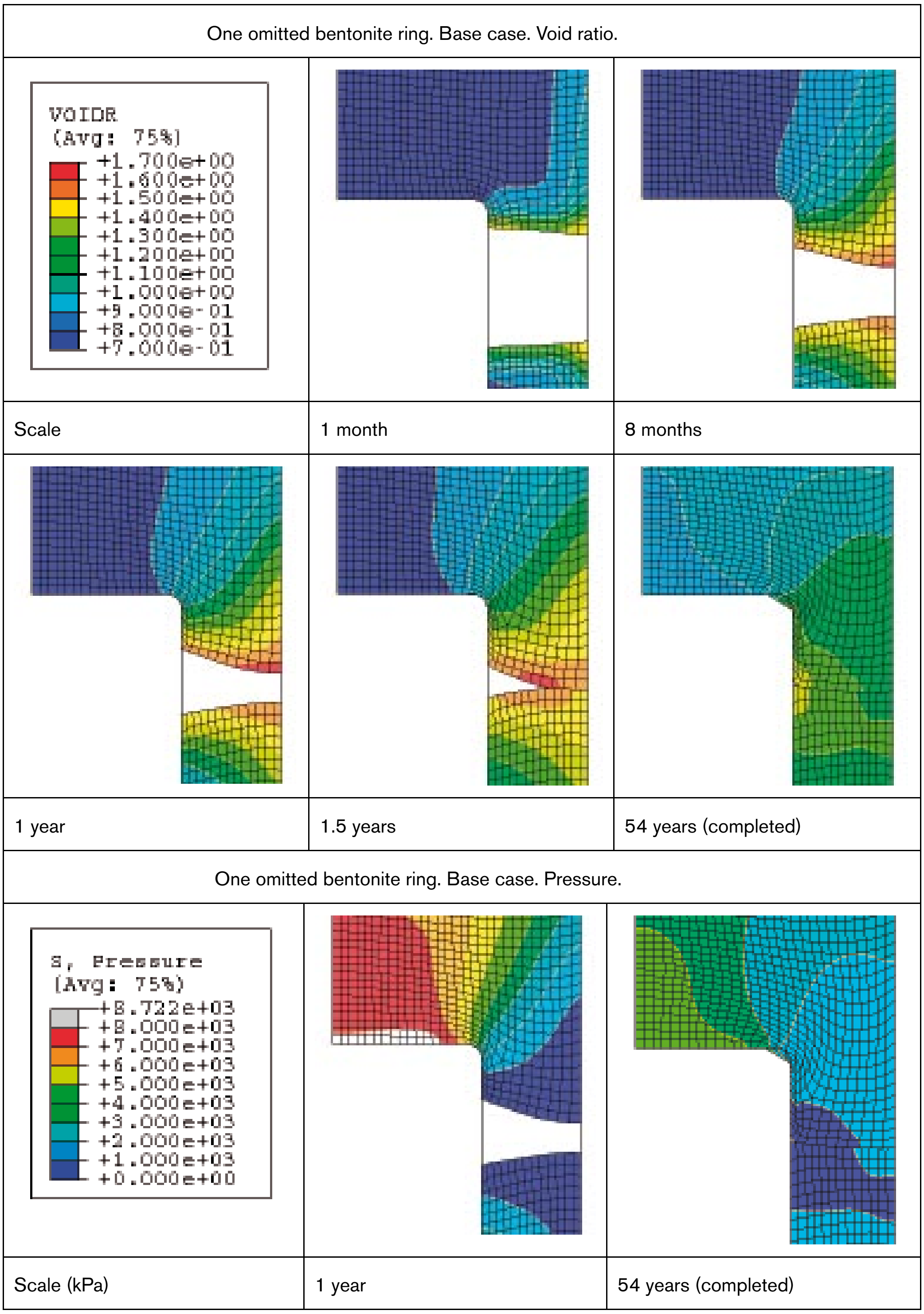


Figure 9-54. *Development of void ratio and swelling pressure in the case with one omitted bentonite ring.*

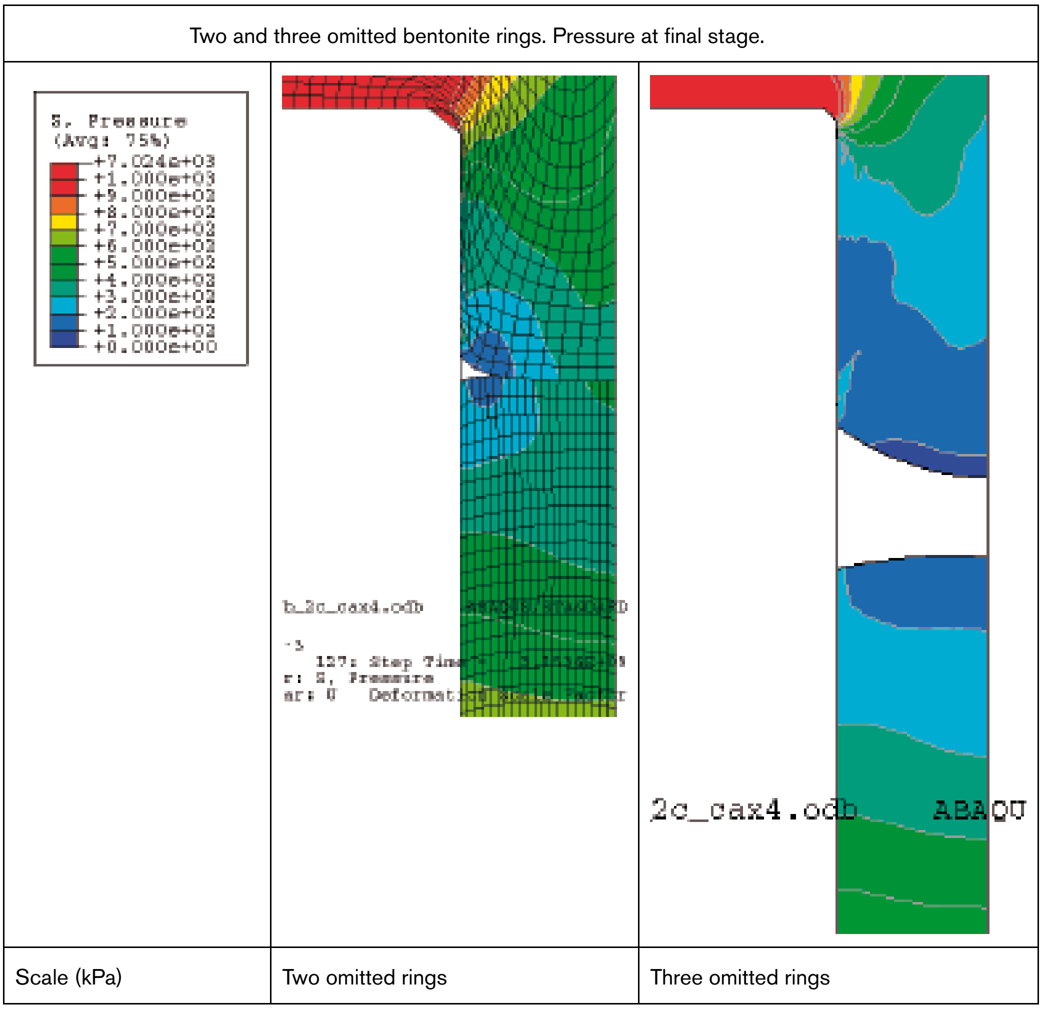


Figure 9-55. Resulting swelling pressure when two or three bentonite rings are omitted.

This means that for a buffer loss of more than 2,400 kg, based on loss around the entire canister, it must be concluded that several safety function indicators for the buffer are no longer fulfilled and that this needs to be considered when evaluating e.g. canister corrosion.

Possibility of advective conditions after piping or initial mass deficit

Advective conditions in the buffer can occur if the hydraulic conductivity is sufficiently high. The buffer function indicators (Figure 9-2) prescribe a hydraulic conductivity of 10^{-12} m/s and a swelling pressure of 1 MPa to rule out advection in the buffer. These values do, however, have some safety margins included in them. /Neretnieks 2006a/ calculated the conditions under which water is drawn into a deposition hole. He concluded that even for a rock fracture with a very high flow rate (transmissivity 10^{-6} m^2/s and hydraulic gradient 0.01), a buffer conductivity of around $3 \cdot 10^{-6}$ m/s suffices to prevent advection and causes the water in the fracture to flow around the buffer as if it were impervious. Such a conductivity corresponds to a dry density well below 500 kg/m^3 (Figure 4-8).

However, to ensure that the self-sealing ability is maintained and no channels or pipes will be formed, a certain swelling pressure is required. The minimum swelling pressure needed will be about 100 kPa. This is based on the same reasoning as for the function indicator for the backfill swelling pressure. To ensure this for all expected groundwater compositions a minimum dry density of 1,000 kg/m^3 is required (Figure 4-6, Figure 4-7). This corresponds to a void ratio of 1.75. As seen in Figure 9-55 this requirement is still met when two entire bentonite rings are omitted, corresponding to a dry mass loss of 2,400 kg. As the loss occurs locally in the buffer, it is more appropriate to consider the corresponding limit for losses over typically half the circumference, i.e. 1,200 kg. At higher mass losses, the swelling pressure cannot be guaranteed and advection in the buffer has to be considered. This is further elaborated for the case of buffer erosion in section 9.4.8.

Conclusions

- After a period of 10–100 years the buffer is expected to be fully saturated. The time is dependent on the availability of water in the individual deposition holes and the supply of water from the backfill.
- During saturation the buffer will swell and exert a swelling pressure on the canister, rock and backfill. The pressure is too low to have any effect on the canister and rock, but the backfill will deform to a certain extent. This will lead to a small loss of swelling pressure in the top of the deposition holes, but the buffer around the canister is expected to remain at initial values.
- The hydraulic gradients in the unsaturated repository may cause piping and erosion of the buffer and backfill. This may lead to a loss or redistribution of material. If the loss is in the range of 100 kg, the buffer is expected to reseal and a substantial swelling pressure is restored. Even if a mass corresponding to an entire bentonite ring was lost, this is not expected to lead to advective conditions in the buffer.

9.3.10 Buffer and backfill chemical evolution

Unsaturated phase

During the saturation process, the initial water in the buffer and backfill will be mixed with the incoming groundwater. The chemical reactions during the saturation process are not addressed in SR-Can, since the chemical reactions in a partly saturated buffer are not expected to differ from the fully saturated case. It is the saturated, final equilibrium that is of interest for the chemical conditions in the repository. The analysis of further chemical events is based on the assumption of a fully water saturated buffer with a well-mixed pore water.

/Arcos et al. 2006/ has calculated the initial chemical composition of the porewaters in the two reference buffer materials, see Table 9-9. These calculations have been done by equilibrating the Forsmark groundwater with bentonite of a porosity of 43%, including equilibrium with bentonite accessory minerals, treated as gypsum and quartz (equilibration with carbonate minerals has also been calculated when considering the Deponit CA-N bentonite), and exchange and surface reactions with the montmorillonite surface.

Period of elevated temperatures after saturation; general chemical evolution

The buffer material consists of montmorillonite and accessory minerals, as well as impurities, see section 4.2.5. In the repository environment, these can be dissolved and sometimes re-precipitated depending on the prevailing conditions.

During the phase of elevated temperatures in the near field, the temperature in the buffer will decrease from its inner to its outer parts. The maximum temperature in the buffer will be around 80°C next to the canister and the maximum temperature difference will be 25–35°C over the buffer thickness,

Table 9-9. Calculated initial chemical composition of bentonite pore water. Forsmark groundwater is also reported for comparison. All data are total concentrations in units of M/L, except for pH and pe.

	MX-80	Deponit CA-N	Forsmark
pH	7.08	7.09	7.20
pe	−2.19	−2.30	−2.42
HCO_3^-	$2.14 \cdot 10^{-3}$	$2.33 \cdot 10^{-3}$	$2.20 \cdot 10^{-3}$
Ca	$9.97 \cdot 10^{-3}$	$2.37 \cdot 10^{-2}$	$2.33 \cdot 10^{-2}$
Cl	$1.53 \cdot 10^{-1}$	$1.53 \cdot 10^{-1}$	$1.53 \cdot 10^{-1}$
Fe	$3.31 \cdot 10^{-5}$	$1.72 \cdot 10^{-4}$	$3.31 \cdot 10^{-5}$
K	$1.14 \cdot 10^{-3}$	$1.34 \cdot 10^{-3}$	$8.75 \cdot 10^{-4}$
Mg	$4.97 \cdot 10^{-3}$	$2.39 \cdot 10^{-2}$	$9.30 \cdot 10^{-3}$
Na	$1.69 \cdot 10^{-1}$	$7.11 \cdot 10^{-2}$	$8.88 \cdot 10^{-2}$
SO_4^{2-}	$2.94 \cdot 10^{-2}$	$1.32 \cdot 10^{-2}$	$6.80 \cdot 10^{-3}$
Si	$6.60 \cdot 10^{-5}$	$6.64 \cdot 10^{-5}$	$1.85 \cdot 10^{-4}$

see section 9.3.4. The solubilities of the minerals in the bentonite are temperature dependent. The solubility of calcite and calcium sulphates decreases with an increased temperature, whereas the solubility of most silica phases like quartz, cristobalite and the montmorillonite itself increases with temperature.

The extent of the transport of minerals in the buffer during the thermal period is modelled in /Arcos et al. 2006/. To model the thermal field, 14 concentric temperature zones were defined, with temperature increments of 5°C. At the canister – bentonite buffer boundary, a temperature of 80°C was assumed. At the buffer – granite host-rock (fracture) boundary, the temperature was set to 45°C. In the fracture zone, the temperature decreased from 45 to 15°C; this latter value is the temperature expected to be found at repository depths at Forsmark. Due to code limitations, no time-dependent warm-up followed by cooling of the domain was considered. A stationary thermal field was assumed during the entire 10,000 year period of simulation. In the simulation, the deposition hole was assumed to be intersected by a fracture with a flow of ~ 0.2 m/y. Together with the assumed fracture geometry this implied a Q_{eq} value of $5.44 \cdot 10^{-3}$ m^3/yr. The water in the fracture will supply calcium to the buffer; however, precipitation of calcite in the inner part is caused by the elevated temperature.

The predicted geochemical evolution of the system indicates an increase in pH in the fracture surrounding the bentonite buffer, reaching a maximum value of 7.33 after 100 years, but only close to the outflow part of the buffer. After this increase in pH in the fracture pore water, the model predicts a decrease in pH in the entire buffer, with a minimum pH of 6.5 after 10,000 years. This pH evolution in the bentonite is a consequence of the precipitation of calcite. The precipitation of calcite is, in turn, due to the diffusion of calcium from groundwater into the bentonite and, in particular, the solubility decrease of calcite with increasing temperature. The extent of the calcite precipitation is, nevertheless, very limited. The amount will be around 0.015 mole/l(porewater) close to the canister after 1,000 years.

The decrease in pH associated with the thermal effect and the diffusive transport through the bentonite is not necessarily associated with an acidification of the system. This is because the dissociation of water increases with temperature, thus for the temperature range in the bentonite, the neutral pH of water decreases from 7.0 at 25°C to 6.7 and 6.3 at 45 and 80°C, respectively. Thus, the resulting pH predicted during the simulation is still neutral or even slightly alkaline. There is a general dissolution of quartz in the bentonite, which is more pronounced close to the canister (the warmest part). The initial content is 3.07 moles/L, and after 10,000 years there is an accumulated dissolution of 0.03 and 0.01 moles/L in the warmer and cooler part of the bentonite, respectively. However, the aqueous silica concentration in the system did not change during the simulation, being from the beginning $4.71 \cdot 10^{-4}$ and $2.09 \cdot 10^{-4}$ moles/L in the warmer and cooler part of the bentonite, respectively. Other changes associated with the thermal stage are the replacement of anhydrite by gypsum in the bentonite, although it also dissolves relatively fast during the simulation (in less than 200 years), and the precipitation of gypsum in the fracture, which is associated with the dissolution of anhydrite in the buffer. However, gypsum precipitated in the fracture also dissolves once anhydrite from the bentonite is totally dissolved.

The modelling of the buffer evolution during the thermal stage has only been done for the MX-80 type bentonite.

A small enrichment of calcium carbonates next to the canister cannot be totally excluded. However, the calculated amount of calcite precipitated is very low (less than 0.05 wt% of calcite), and, therefore, this precipitation is not expected to affect the behaviour of the bentonite buffer. The amount of silica compounds that can be transported during the period with a thermal gradient is, on the other hand, negligible.

The 35°C temperature difference for 10,000 years assumed in the study is considerably more than will occur in the repository. According to Figure 9-17 such a difference can be expected for a few tens of years. After 100 years, the difference (at canister mid-height where it is largest) is about 10°C and after 200 years it is very small. Also, the expected absolute value of the temperature is lower than in the study. It is, therefore, concluded that the minor effects on chemical conditions in the buffer modelled above represent an over-estimate of what can actually be expected.

The temperature increase and the thermal gradients in the backfill are very small. These are not expected to have any significant effect on the chemical composition.

Mineral transformation

The advantageous physical properties of the buffer, e.g. swelling pressure and low hydraulic conductivity, are determined by the interaction between water and the montmorillonite mineral in the bentonite. Other minerals with the same principal structure but different layer charge occur in nature. If the layer charge is near zero (pyrophyllite), there is virtually no interaction with water, which results in radically different properties than for montmorillonite. Minerals with higher layer charge and thereby more balancing cations may lead to greater interaction with water. However, the cations can be bound to the mineral surfaces if the layer charge is sufficiently high, and the interaction with water again ceases.

In nature, the layer charge generally increases under conditions similar to those that persist in a repository, mainly due to a decrease in silica content. Potassium is fixed at lower charge than other possible cations, and this is consequently the first transformation to expect if potassium is available. The process is termed illitization and is well documented in several different geological formations, and has been reproduced under laboratory conditions. However, illite is not a well-defined material, and may be seen as a transition material from montmorillonite to mica minerals. All intermediate stages from swelling to non-swelling material may be found (mixed layer smectite-illite) and several models have been suggested in order to describe the reaction. The conversion always involves a charge increase, mainly due to a decrease in silica content and an uptake of charge-compensating potassium ions.

The overall kinetics of the smectite-to-illite reaction can be described by a kinetic expression /Karnland and Birgersson 2006/. With this equation /Huang et al. 1993/, the smectite content at a particular time can be calculated if the temperature and potassium concentration in the pore water are known. According to the model, practically no clay conversion is possible in a KBS-3-type repository under the conditions shown in Figure 9-56.

The transformation of smectite to illite is well-documented for a large number of geological formations. This is discussed in the **Buffer and backfill process repor**t, section 2.5.9.

The uncertainties in the model and data are related to the validity of the expression itself, the correctness of the constants, and the extrapolation from laboratory to repository conditions. The Huang expression is determined from laboratory results and validated on natural sediments, whereas other proposed expressions have used natural sediments only for the construction of the expressions. The uncertainties in the involved constant$_s$ are supposed to be rather insignificant for the test conditions, but they were determined in batch experiments with higher water to solid ratio than is present in the repository. The correctness in extrapolation from high temperature laboratory conditions to the significantly lower temperature in the repository is not self-evident, since the exact transformation reaction is not clear. In fact there may be evidences that recrystallisation reactions that occur at high temperaturee are replaced by dissolution/precipitation alteration reactions at lower temperatur However, the kinetics of quartz precipitation indicates that the degree of transformation will be overestimated by the extrapolation. Another bound on the magnitude of the transformation, independent of the above model,

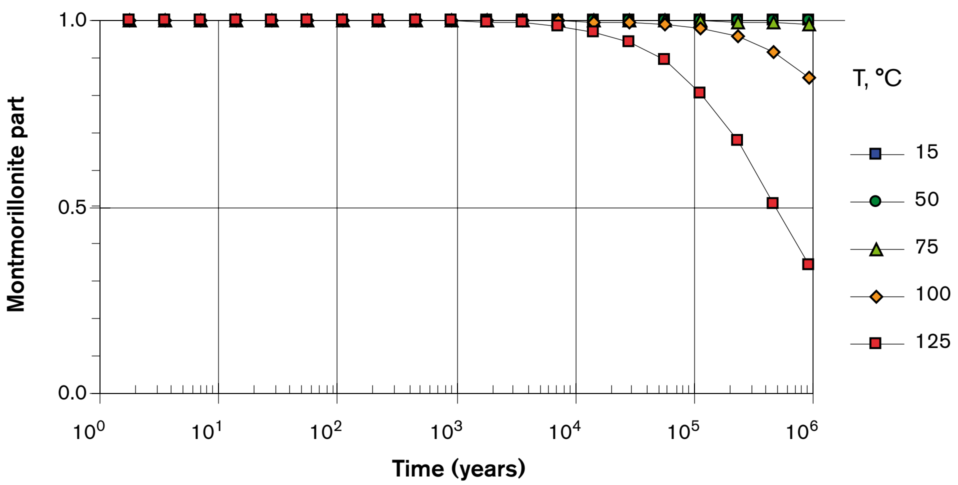


Figure 9-56. *Remaining smectite for different temperatures [°C] in a hydrothermal system with [K$^+$] = 0.002 mole/litre (80 ppm) according to the /Huang et al. 1993/ kinetic model and laboratory determined constants /Karnland and Birgersson 2006/.*

constants or extrapolation, is given by the access to K^+. With a groundwater K^+ concentration of 2 mM and a Q_{eq} of 1 l/yr the amount of illite formed would be less than 20% of the montmorillonite in one million years.

The montmorillonite could also be affected by a high pH in the groundwater. The solubility of silica minerals increases several orders of magnitude in typical cement porewater compared with typical groundwaters, which consequently leads to dissolution of tetrahedral silica in montmorillonite and a parallel dissolution of other silica minerals. In SR-Can it is assumed that no materials that could cause an increase the pH (to values higher than pH 11, where the silica solubility is increased by a factor of 10) will be present in the repository.

In the case of a defective canister, the buffer could come into contact with metallic iron. This could possibly cause a change in the oxidation state of the iron present in the bentonite or a transformation of the montmorillonite to other minerals. The octahedral layer in montmorillonite frequently contains a significant amount of iron which may change oxidation state /Stucki et al. 1984/. Normally, the iron is in a maximum oxidized condition in commercial material due to exposure to air during mining and handling. In the presence of metallic iron this may oxidize and thereby reduce the structural Fe (III) in the octahedral layer to Fe(II). This would lead to an increase of the total layer charge, and a potential fixation of interlayer cations if the charge change is sufficient. The effect of such octahedral layer change is expected to be less than a similar charge change in the tetrahedral layer /Sposito 1999/. The SR-Can reference bentonites contain 0.37 Fe (MX-80) and 0.45 Fe (Deponit CA-N) per $O_{20}(OH)_4$ unit, and the corresponding maximum layer charge increases are significant, but not sufficient for fixation of potassium /Karnland and Birgersson 2006/. Dissolution of montmorillonite and precipitation of other iron-rich minerals like berthierine is thermodynamically possible, if the partial pressure of oxygen exceeds magnetite-hematite equilibrium. These transformations would have similar consequences for the buffer as a transformation to illite. On the other hand, if the oxygen pressure is significantly lower than magnetite-hematite equilibrium, then the formation of Fe-saponites is expected. Both types of mineral formation have been experimentally verified, but only at high temperature (250°C) in long-term experiments, which indicate that kinetics strongly limit this process /Wilson et al. 2005/.

Osmosis

The salinity of the groundwater influences the vapour pressure relation and thereby the water saturation process. For the groundwaters at the sites, the effects in both the buffer and the backfill are small, see section 4.2.8.

Effects of shotcrete on the buffer and backfill

The effect of shotcreting on the backfill has been estimated numerically using a 2D reactive-transport model /Luna et al. 2006/. The results show the development of alkalinity plumes in conductive fractures transecting the tunnel. The released alkalinity leads to the precipitation of CSH phases and calcite both in the backfill and in the transecting fracture. The precipitation of these minerals can reduce the initial porosity by less than 1%, i.e. the presence of concrete has no major effects on the backfill performance.

Conclusions

The chemical evolution in the buffer during the thermal stage is not expected to have any significant effect on the buffer properties. Specific conclusions are listed below.

- The pore water composition will be affected by reactions with montmorillonite surfaces and impurities in the buffer. The resulting composition will still be similar to the groundwater composition from the sites.
- Calcite will precipitate in the warmer part of the buffer. The amount is very limited and is not expected to affect the hydraulic properties.
- The relatively low maximum temperature in the buffer and the short duration of the thermal pulse, mean that thermal effects are not expected to cause any transformation of the montmorillonite. The swelling pressure and the low hydraulic conductivity are thus expected to be maintained.
- Based on the current understanding, it can be assumed that metallic iron in the repository will not have a significant effect on the properties of the buffer.

- The groundwaters at the sites have rather low salinities and this is not expected to have any negative effect on the swelling pressure and the hydraulic conductivity of the buffer and backfill materials.

9.3.11 Evolution of the buffer and backfill after the thermal period

General chemical evolution

The barriers in the repository are designed to retard the intrusion of groundwater to the canisters and, in case of canister failure, to retard radionuclides on their way to the geosphere. Groundwater interaction with the components of the barriers will modify the composition of the groundwater that will eventually reach the canister. Knowledge of such a composition, especially of the master variables, pH and Eh, is important since it will affect:

- The solubility of radionuclides in case of isolation failure.
- The hydraulic and mechanical behaviour of the buffer.
- The chemical stability of the buffer.
- The corrosion of the canister.
- The sorption of radionuclides in case of isolation failure.

/Arcos et al. 2006/, described the chemical evolution in the repository for a range of conditions and assumptions. The modelling was based on an initial equilibrium between the Forsmark groundwater and the minerals in the bentonite see Table 9-9. The evolution of the chemistry was then calculated for a case where a fracture intersects the deposition hole (Figure 9-57). In these calculations, the flow of water in the fracture was set to a value which corresponds to an equivalent flow rate (Q_{eq}, see section 9.3.6) of $5.4 \cdot 10^{-3}$ m^3/yr. This would lead to a total exchange of the porewater in around 1,600 years. In the hydrogeological modelling of the Forsmark repository, 0.2% of the canister positions have higher flow rates (section 9.3.6). Thus, the modelling by /Arcos et al. 2006/ represents a canister position intersected by a rather high water flow. In most canister positions, the chemical evolution will be slower.

The following conclusions can be drawn for the MX-80 bentonite.

- As shown in Table 9-9, the calcium concentration in MX-80 bentonite pore water is half of that in the Forsmark groundwater. This generates a calcium concentration gradient between the fracture and the bentonite producing a diffusion of calcium into the bentonite. Figure 9-58 shows the increase of Ca in the buffer porewater.

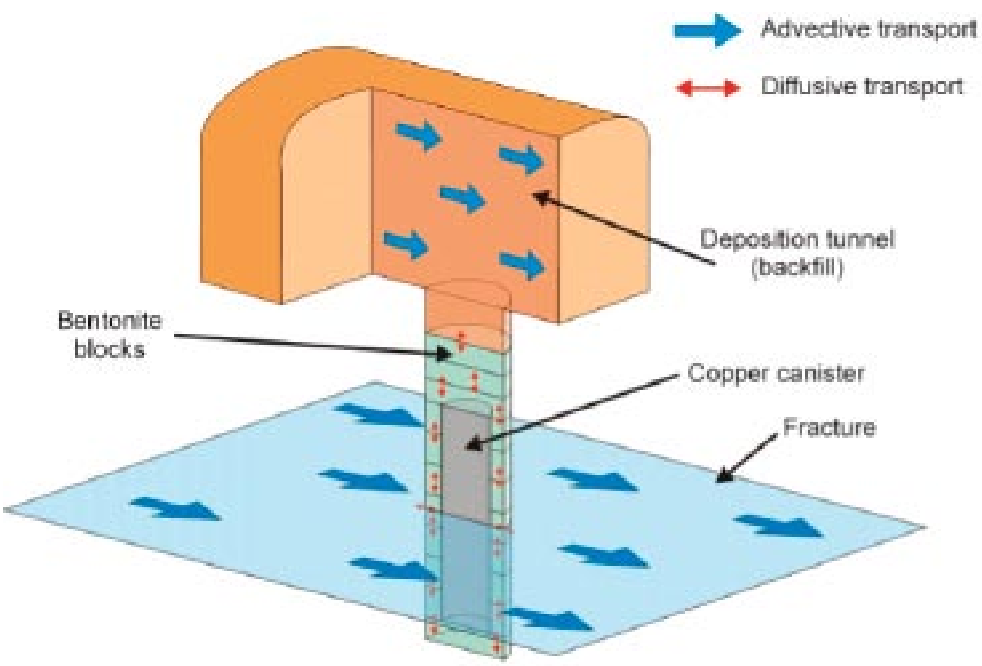


Figure 9-57. *Schematic view of the near field of a KBS-3 repository showing the transport mechanisms in the different parts of the system.*

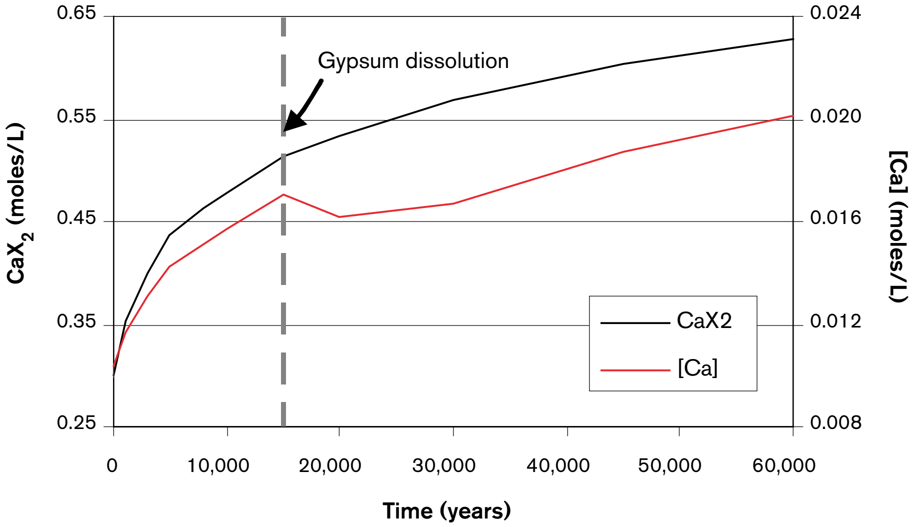


Figure 9-58. *Predicted evolution of calcium occupancy in the exchange sites and calcium concentration of bentonite pore water in the bentonite close to the fracture as shown in Figure 9-57. The time at which gypsum is totally dissolved is also shown.*

- The increase of calcium concentration in the bentonite, due to diffusion from the fracture and gypsum dissolution from the bentonite, results in the replacement of sodium by calcium in the cation exchange sites, see Figure 9-59.
- The modelling results show that pH undergoes small changes due to the interaction between the Forsmark groundwater and the buffer. The reason for the small changes in pH predicted by the model is linked to changes in the calcium concentration of pore water in the bentonite and groundwater in the fracture around the buffer. The surface acidity reactions and the composition of the Forsmark groundwater control the pH of the bentonite pore water, since there is no calcite in the MX-80 bentonite.

The evolution is slightly different for the Deponit CA-N bentonite, as described below.

- The pH is more or less stable during the simulation. The reason for this is the equilibrium with the calcite in the bentonite.
- The concentration of calcium and carbonate in the porewater is slightly higher than in the Forsmark groundwater causing a slow diffusion out from the buffer of these two components. To maintain calcite equilibrium in the porewater, calcium is supplied from ion-exchange and gypsum dissolution.
- The slightly higher concentration of sodium in the Forsmark groundwater than in the bentonite porewater leads to the replacement of Ca^{2+} by Na^{+} in the exchange sites, see Figure 9-60.

Canister sinking

During this period, the buffer will not be affected by any processes that may alter its swelling properties in a way that the swelling pressure would sink below the value needed to retain the canister in position (P > 0.2 MPa, see section 7.3.2).

Colloid release

Two possible types of erosion have been identified for the bentonite buffer. The first is mechanical erosion where a shear stress from the flowing water in a fracture can remove clay particles from the buffer. The second is colloid release where the clay particles are dispersed into the groundwater. The physical and chemical (here defined as the stability of the aggregates of clay particles in the buffer) stability of the buffer has been investigated in /Liu and Neretnieks 2006 /.

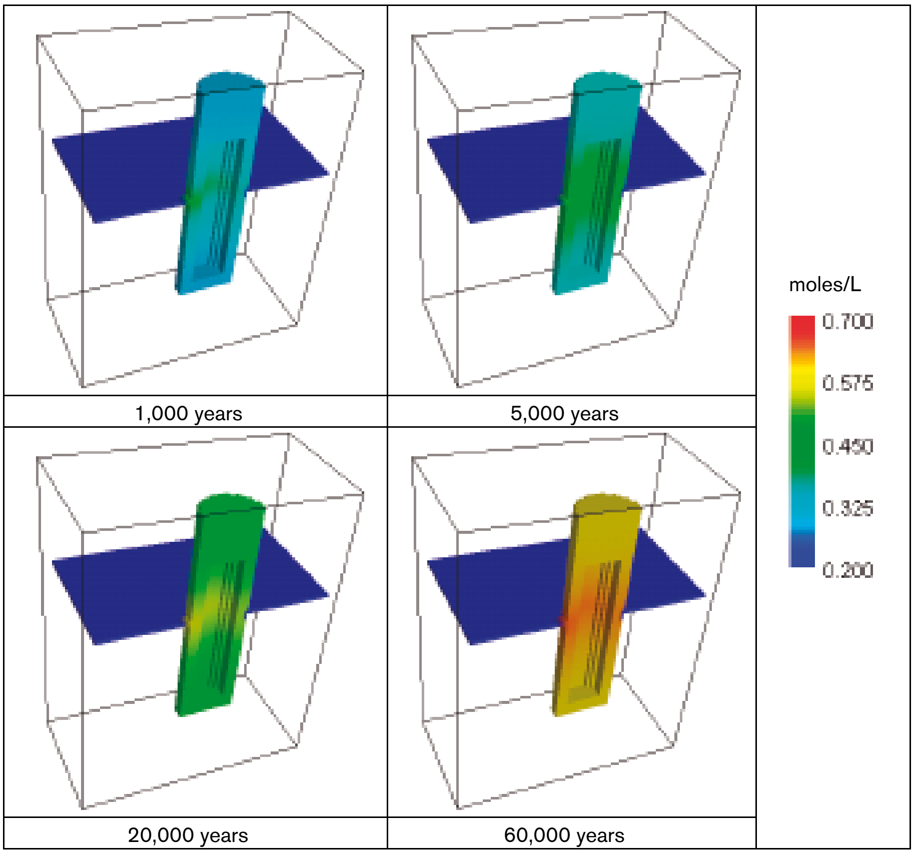


Figure 9-59. *Predicted evolution of Ca occupancy in the cation exchange sies of the MX-80 bentonite.*

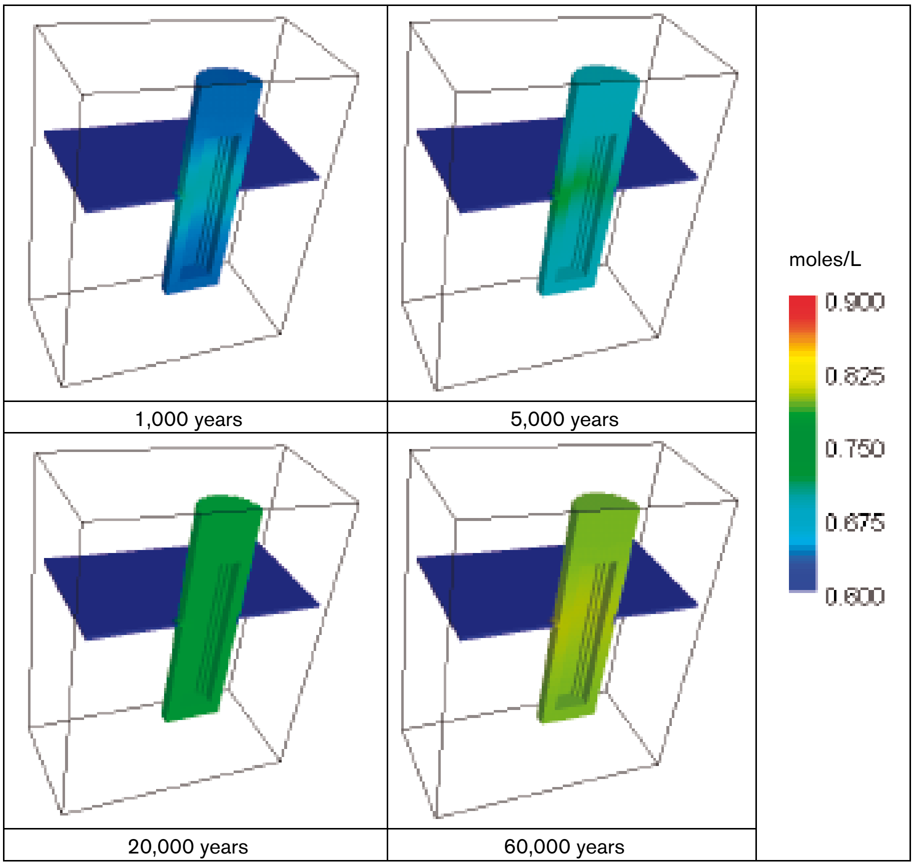


Figure 9-60. *Predicted evolution of Na occupancy in the cation exchange sites of the Deponit CA-N bentonite.*

From a mechanical point of view, the shear stress exerted by the flowing groundwater is much less than the typical Bingham yield stress (1.0 Pa) of the gel front. It can thus be concluded that the bentonite buffer is physically stable with respect to the tearing off by the shear force exerted by the flowing groundwater on the gel front provided that the pore water does not have a very low ionic strength, see below.

When the montmorillonite in the bentonite buffer is in contact with water, a clay gel may form. If the ionic strength of the water is lower than the critical coagulation concentration (CCC) of the montmorillonite, the gel may disperse into a colloid sol in the water. The relatively abundant divalent cations, especially Ca^{2+}, are of great importance since the CCC is inversely proportional to the square of the valence number. For montmorillonite in a pure N-form, the clay will disperse readily in waters having concentrations lower than the CCC. When accessory minerals containing cations important for upholding CCC are present, dissolution of these minerals may buffer the concentration of the cations in the pore water of the clay higher than the CCC, and the dispersion of the clay to form colloid sols will then be determined by the mass transfer processes of the cations out of the pore water of the bentonite. Calcium-containing minerals (mainly calcite) will act as a buffer of the calcium concentration in the pore water of the bentonite buffer. See also the **Buffer and Backfill process report**, section 2.5.10.

According to section 9.3.7, the groundwater concentration of Ca^{2+} is in general expected to exceed 1mM during the initial temperate period after closure at both Forsmark and Laxemar. Since the CCC has been determined to be 1 mM (on a pessimistic basis), this would be sufficient to prevent colloid release from the buffer. Even though the groundwater concentrations thousands of years into the future are uncertain, it is expected that the concentrations of Ca^{2+} will remain above CCC for both the selected sites.

If, for any reason, the Ca^{2+} concentration should drop below the CCC value, the loss of buffer from colloid release and erosion can be estimated according to the description for the glacial period (section 9.4.8).

The overall conclusion is that colloid release is not expected to cause any losses of buffer during the initial temperate period. The groundwater concentration of Ca^{2+} is expected to exceed also the pessimistically chosen CCC.

Osmotic effects on buffer and backfill

According to section 9.3.7, the changes in salinity in the Forsmark groundwater will be small during this period (from the present day value of 0.9%). According to the buffer material properties discussed in section 4.2.8, this is not expected to affect the hydraulic conductivity and the swelling pressure of the buffer and backfill in any appreciable way.

Effects of concrete plate

The concrete plate at the bottom of the deposition holes may affect the buffer chemically.

Montmorillonite mineral transformations have been modelled for bentonite in contact with standard Portland cement within the Ecoclay II project /Gaucher et al. 2004/. These results show complete bentonite alteration within a distance of about 20 cm from the cement surface after a period of 100,000 years. Laboratory experiments show that the dissolution of montmorillonite is orders of magnitude slower at lower concentrations of hydroxide ions /Karnland and Birgersson 2006/. Therefore, the rate of bentonite alteration in contact with "low-pH" cement with porewaters of pH < 11 ($[OH^-]$ = 1 mM) is expected to be much slower that if it were in contact with standard Portland cement porewater, that has pH 12.5 ($[OH^-]$ = 32 mM).

Concrete recipes with porewaters that prevent substantial alteration of the buffer are being developed for the concrete plates.

9.3.12 Canister evolution

Thermal evolution

The thermal evolution of the canister is analysed in section 9.3.4 above.

Expected deposits

At the time of disposal, the canister surface will be covered by a thin oxide layer through atmospheric corrosion. The heat generation in the fuel will result in increased canister surface temperature. The actual temperature will, among other things, depend on the heat transfer to the surrounding bentonite, but the maximum temperature in the bentonite is not allowed to exceed 100°C. A consequence of the higher canister surface temperature is the possible redistribution and enrichment of salts from the bentonite onto the canister surface. The extent to which this may occur will depend on the salt content in the groundwater as well as in the bentonite. The salts that may be of concern are chlorides and sulphates from the groundwater and sulphates and carbonates from the impurities in the bentonite.

In the LOT experiment /Karnland et al. 2000/, copper heaters are buried in compacted bentonite. Two of these packages have been retrieved and analysed. These had surface temperatures of 90°C and 130°C, respectively. Examination of the heater surfaces revealed that, in both cases, the copper surfaces were covered with a thin layer of calcium sulphate/calcium carbonate. No chloride enrichments were apparent, even though the groundwater had a chloride content of over 8,000 mg/L. Precipitation of calcium sulphate was also observed in a heater experiment performed in Stripa /Pusch et al. 1993/.

It is at this time not established whether or not the precipitation of the sulphates and the carbonates were caused by evaporation of water or by the lower solubility of the calcium salts at elevated temperatures. In the latter case, they are likely to redissolve as the temperature decreases again. Alternatively, the deposits can be redissolved when contacted with water undersaturated with respect to calcium carbonate and calcium sulphate. Even if this surface cover remains over longer periods of time, it is unlikely that any credit can be taken for it having protective properties. The deposits are not electrically conductive, so they are not expected to increase the risk of pitting corrosion, see e.g. /Adeloju and Duan 1994/. Also, an increase in the chloride concentration would lower the susceptibility of copper for pitting corrosion, since it would favour general corrosion /King et al. 2001/. A high chloride concentration will, however, not lead to increased general corrosion, since the near field pH is always expected to be slightly alkaline and, consequently, the extent of the corrosion will be determined by the amount of available oxygen.

In conclusion, the deposits that may be expected on the canister surface are considered not to be a cause of long-term detrimental effects on the canister.

Mechanical impact of buffer swelling

After emplacement of the canister and the buffer, water will enter the deposition holes via the water conductive fractures that intersect the holes. This leads to wetting and swelling of the buffer. After some time, the buffer will stop the water inflow through the fractures and the groundwater pressure will start to build up, which may lead to flow paths opening around the deposition holes in the superficial excavation-disturbed zone, where the flow resistance is expected to be lowest. This will tend towards a more uniform wetting of the bentonite and a more uniform pressure build-up. The size of this effect is, however, uncertain. It is, therefore, reasonable to assume that there will be inhomogeneities in the pressure build-up.

Furthermore, if the canister is slightly tilted or inclined in the emplacement hole, or if the rock is uneven, permanent pressure disequilibrium can exist in the bentonite even after water saturation. This can also occur due to swelling of the buffer at the top of the hole.

A number of pessimistic cases for transient and permanent uneven loads on the canister have been investigated by /Werme 1998/. In none of the cases could any threat to the integrity of the canister be shown. In the case of permanent load, the maximum bending stress was far below the yield point of the cast iron in the insert. This conclusion relates to the safety function indicators C2 and C3 in Figure 9-2.

Corrosion during the initial 1,000 years

One of the main safety functions of the canister is to provide a corrosion barrier, safety function C1 in Figure 9-2.

A range of studies over several decades, see e.g. /King et al. 2001/ for a review, have identified the following substances as capable of corroding the copper canister material under repository conditions, after the operating period:

- oxygen brought in from the buffer or from the groundwater via the buffer,
- nitric acid formed by gamma radiolysis of nitrogen compounds in moist air in the gap between canister and buffer,
- sulphide brought in from the buffer or from the groundwater via the buffer.

The corrosion processes are marginally affected by the changes in temperature expected in the final repository. The results of corrosion are corrosion products and a change in the thickness of the copper shell.

Corrosion caused by oxygen initially present in the buffer and the backfill was shown to have negligible effects in section 9.2.5. The chemical conditions in the repository are then expected to be reducing for the period of temperate climate, see section 9.3.7, i.e. no further corrosion due to oxygen is expected.

During the unsaturated phase, nitric acid formed by gamma radiolysis of moist air will contribute to the corrosion attack during this period. It can be shown, however, that the amount of nitric acid formed corresponds to a corrosion depth of a few microns only /**Fuel and canister process report,** section 3.5.4/.

After all the oxygen has been consumed, sulphide dissolved from possible sulphide minerals in the buffer and dissolved sulphide in the groundwater will be the only corroding agent present in the repository. This will proceed with formation of copper sulphide and molecular hydrogen.

$4\ Cu + 2\ HS^- \rightarrow 2\ Cu_2S + H_2$

The source of the sulphides in the groundwater can be either dissolution of sulphide minerals or a result of microbial reduction of sulphates. At fully developed bentonite swelling pressure, no microbial activity in the bentonite buffer is expected /**Buffer and backfill process report**, section 2.5.13/ and the corrosion rate will be controlled by the dissolution and transport of sulphides present in the buffer.

If the near field is oxygen-free and full swelling pressure has not yet developed, microbial activity in the wetter parts of the buffer may be possible. Microbial activity is, however, unlikely on or very near the copper surface since at the time the interface between the buffer and the canister is wet, the full swelling pressure has developed. Studies by Masurat and Pedersen /Masurat 2006/ have shown that the maximum microbial sulphide production rate, expressed as Cu_xS will be less than 1.5 $pmol \cdot mm^{-2} \cdot day^{-1}$. This corresponds to a corrosion depth of 4 µm in 1,000 years. Lactate was added to the bentonite as a source of energy and organic carbon. The experimental conditions were, therefore, much more favourable for microbial activity than can be expected in the repository. The rates of production of sulphide for several experimental conditions and bentonite swelling pressures are shown in Figure 9-61.

The contribution to the corrosion from sulphides originating from pyrite in the bentonite buffer can be estimated to be 15 and 35 µm in 1,000 years for MX-80 and Deponit CA-N bentonite, respectively, using a simple transport expression involving the diffusivity and the concentration limit of sulphide in the buffer /Hedin 2004b/.

In conclusion, the total amount of copper corrosion during the excavation and operational phases and the first 1,000 year period can be estimated to be in the range of 55 to 85 µm, when taking into account the contributions from residual oxygen in the repository and possible microbial sulphate reduction using the stray organic material discussed in section 9.2.5 above, the contribution from sulphides in the bentonite and the microbial activity discussed above in this section.

Corrosion after the initial 1,000 years

In a longer time perspective, corrosion due to sulphide from pyrite initially present in the buffer can be bounded by a simple mass balance estimate. If all initially present pyrite in the buffer sections surrounding the canister side attacks the canister side as sulphide, corrosion of 0.1 mm and 0.7 mm copper is obtained for MX-80 and Deponit CA-N bentonite, respectively. The corresponding values for pyrite in the top part of the buffer attacking the canister lid are 0.5 and 3 mm, respectively. The results are summarised in Table 9-10.

The time required for a complete depletion of pyrite can be estimated with a simple transport expression involving the diffusivity and the concentration limit of sulphide in the buffer /Hedin 2004b/.

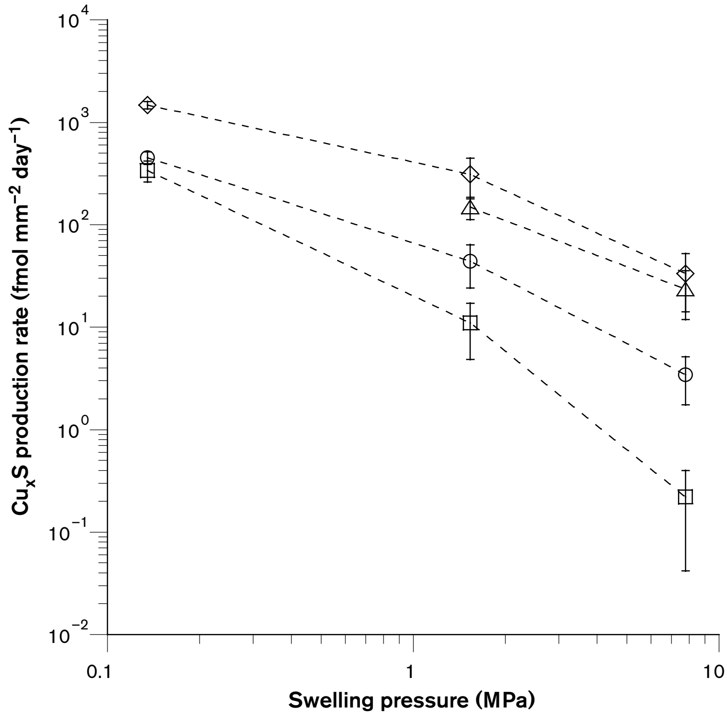


Figure 9-61. *Mean sulphide production rates at exposed plates at different swelling pressures. Error bars represent 95% confidence limits. The swelling pressures are valid for MX-80 Wyoming bentonite exposed to 0.1 M NaCl solution. The curves from the top down represent unfiltered groundwater, filtered groundwater, bentonite treated at 25°C and bentonite teated at 120°C.*

Table 9-10. Corrosion caused by pyrite initially present in the buffer.

	MX-80	Deponit CA-N
Pyrite (FeS_2) (weight %)	0.07 ± 0.05	0.5 ± 0.05
Cu thickness side (mm)	0.1	0.7
Cu thickness top (mm)	0.5	3

Both these quantities are uncertain. Using pessimistic values for both (10^{-3} m^2/y and $5 \cdot 10^{-5}$ kmoles/m^3, respectively) yields corrosion times of 160,000 and 3 million years for the side and top corrosion, respectively, in the Deponit CA-N case. The unevenness is estimated to be comparable to that expected for corrosion by oxygen, i.e. ± 50 micrometres /King et al. 2001, **Fuel and canister process report**, section 3.5.4/.

Conclusion: Even in a million year perspective, corrosion caused by initially present pyrite in the buffer has a negligible effect on the copper thickness. Should, for any reason, the estimated maximum corrosion thicknesses be considered as unacceptable, a lower pyrite content of the buffer material can readily be specified.

For temperate conditions, the only identified corroding agent in the groundwater is sulphide. According to section 9.3.7, sulphide concentrations in the Forsmark groundwater are not expected to exceed 10^{-5} kmoles/m^3. Combining this pessimistic upper bound with the equivalent flow rates for the ensemble of deposition holes at Forsmark, see section 9.3.6, yields copper corrosion rates according to Figure 9-62, i.e. less than one mm is corroded in 100,000 years even in the deposition holes with the most extreme flows for the most pessimistic hydrogeological model assumptions. Similar results are obtained for the Laxemar site.

It is also noted that, as long as there is pyrite present in the buffer upholding a concentration limit of sulphide, sulphide from the groundwater is prevented from entering the buffer and corrosion caused by groundwater sulphide will thus not occur until after the considerable times required for pyrite depletion of the buffer.

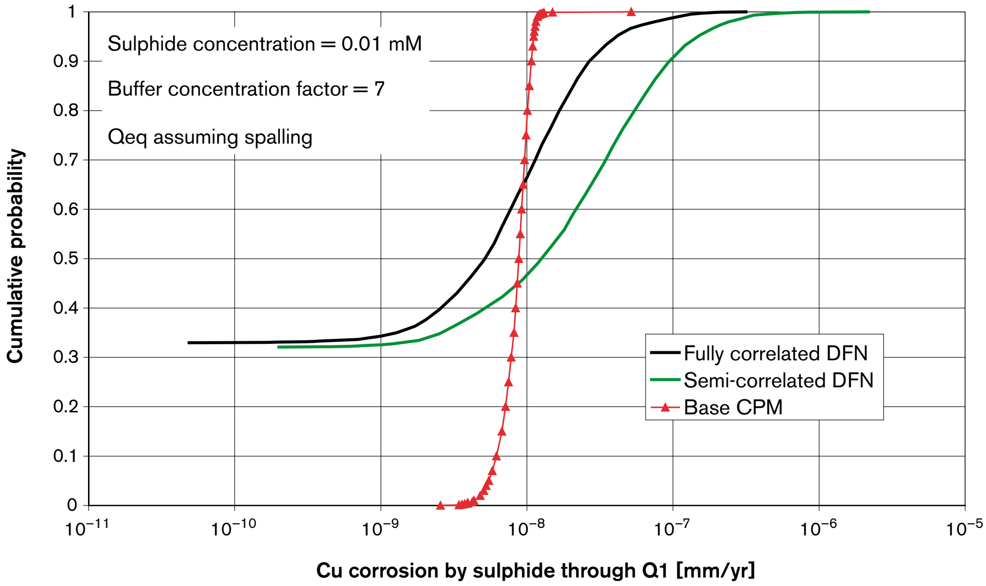


Figure 9-62. *Results of corrosion calculations for sulphide entering through intersecting fracture and attacking the canister side. A number of Q_{eq}-distributions from the hydrogeological modelling of the Forsmark site have been used in the calculation.*

The results were obtained using a simplified expression given in Appendix B.

The following points are also noted.

- The transport resistances offered e.g. by the buffer have not been included in the calculation, but this is readily implemented in the model used. This limitation is, however, insignificant for the highest equivalent flow rates, as the buffer transport resistance is small in comparison to that offered by the buffer/rock interface.
- If several fractures intersect the deposition hole, the equivalent flow rates for these have been added, which is pessimistic since a partition on several fractures would spread the corrosion attack over the canister area.
- All fractures are assumed to intersect the part of the deposition hole where the canister is located.
- It is important to critically assess all assumptions behind the Q_{eq} determinations in the hydrogeological calculations, since this quantity plays a decisive role in the quantification of copper corrosion. This is done in the **Data report**, section 6.6.

Conclusion: As in several earlier assessments, it is concluded that copper corrosion by contaminants in the buffer or groundwater do not pose a threat to canister integrity for the initial temperate period. Even during the one million year overall assessment period, expected corrosion of the canister for an assumed temperate climate would cause corrosion depths of the order of a few millimetres, even for the most unfavourable deposition positions at Forsmark.

9.3.13 Summary of the first 1,000 years after closure

For the Forsmark site and suggested layout, the analyses presented in section 9.3.4 suggest that there is a large margin to the peak temperature criterion for the buffer, even when the spatial variability of the rock thermal properties is taken into account and with other data essential for the result chosen pessimistically.

The mechanical evolution of the host rock is dominated by effects of the thermal load from the canisters and, to a minor extent, the developing swelling pressure from the buffer and the backfill. The long-term impact of the rock stress field need also to be taken into account. According to section 9.3.5, the following conclusions concerning the mechanical evolution can be drawn.

- Regarding thermally induced reactivation of fractures in the near field, there could be some significant, but very local, effects on the fractures very close to the deposition holes. This would result in a local increase in the transmissivity of some fractures, but the hydraulic importance of these effects is deemed to be insignificant. Furthermore, the reactivation, which at most is a few mm, has little importance for the other safety functions.
- Regarding reactivation of fractures in the far-field from the thermal load, there will only be insignificant changes of fracture transmissivity below 200–300 m depth. There can be increased fracture transmissivities at shallower depths.
- Reactivation of fractures due to ridge push is not an issue within the 1,000 year time frame.
- There will be spalling, e.g. new fracturing, in the deposition holes due to the thermal load, unless there is a significant supporting bentonite swelling pressure. Spalling is likely to develop within five years being a considerably shorter time than the saturation time for the buffer in most cases. The "spalled" rock may have high permeability and porosity, and this needs to be considered in transport calculations of radionuclides and canister corroding agents. The likelihood is difficult to assess and it is, therefore, pessimistically assumed that all deposition holes are affected by thermal spalling. According to preliminary evaluations, spalling could have a considerable effect on the equivalent flow rates around the deposition holes.
- Creep deformation of the rock is not an issue for long-term safety.

For Forsmark, two model representations of the hydraulic properties of the host rock have been used, as a result of an evaluation of uncertainties in available data from the site investigations and of the subsequent site descriptive modelling. One is a multi component Continuum porous medium (CPM) model and the other is a discrete fracture network (DFN) model. For Laxemar, only the DFN model was used.

Analyses of the hydraulic evolution of the system indicate that resaturation times for the host rock at the Forsmark site will be between 15 and 50 years, and around six years at the Laxemar site.

Detailed regional and repository scale groundwater flow analyses for the saturated host rock indicate that the Forsmark site has favourable properties in terms of performance measures related to groundwater flow and transport, using either of the models. Specifically, the transport resistance of the host rock, the so called F-factor, ranges between 10^4 and 10^8 y/m in the DFN model. With the CPM model, even larger F-factors are obtained. However, the CPM model clearly does not capture important flow and transport aspects such as channelling which tend to reduce the transport resistance, see section 9.3.6. Distributions of Darcy velocities and equivalent flow rates for use in subsequent analyses have also been obtained and show favourable properties. These types of results have also been obtained with DFN model for Laxemar. Here, the F-factor ranges between 10^3 and 10^8 y/m. The models also yield salinity distributions and handle mixing of different water types yielding concentrations of other relevant non-reacting components of the groundwater. All these results are propagated to subsequent analyses of engineered barrier performance and radionuclide transport.

The hydraulic conditions at the Forsmark site yield estimated saturation times of a Friedland clay backfill ranging between 40 and 50 years and for a 30/70 mixture of 6–8 years. The saturation time for the buffer will vary over a range from about 10 years to 50–100 years, depending on whether the deposition hole is intersected by a water conducting fracture or not. For Laxemar the saturation times for the backfill are estimated at about 2–3 years for the 30/70 mixture and ~ 20 years for Friedland Clay. At Laxemar, it is likely that a larger proportion of the deposition holes will be intersected by water-conducting fractures, yielding a saturation time for the buffer of about 10 years.

The saturation of the buffer will result in the establishment of a swelling pressure of typically 7–8 MPa. The pressure will be somewhat reduced in the upper part of the buffer, but the effect is calculated to be too small to jeopardise any of the buffer safety functions.

The analysis of the evolution of the geochemical conditions at the site has resulted in the following conclusions.

- For both sites, reducing conditions are expected to be re-established shortly after closure. This conclusion is based on several observations in similar systems and supported by the understanding of the underlying phenomena. Also, infiltrating meteoric water will be depleted of oxygen in the relatively thin soil layer of the site, or in the first few metres along fractures in the bedrock by microbial processes.

- At repository depth, the maximum salinity is expected during operation and immediately after closure, 12 g/L at Forsmark and lower at Laxemar. The salt content is expected to decrease slightly during the first 1,000 years due to the progressive inflow of waters of meteoric origin.
- Concentration of divalent cations: during the first 1,000 years calcium concentrations are expected to be around 50 mM at repository depth at both sites. A slight decrease will take place with time due to the progressive inflow of waters of meteoric origin.
- Concentrations of other natural groundwater components: for potassium the expected average concentration is no larger than 4 mM, and for iron ≈ 10^{-5} M, whereas sulphide, concentrations are expected to be ≤ 10^{-5} mol/L for any deposition position averaged over the temperate period
- Regarding effects of shotcrete and grout on groundwater composition, it is concluded that a plume of pH around 9 may develop in grouted fractures intersected by deposition tunnels and to a minor extent also in the backfill material. This plume may persist for up to one hundred thousand years. This could affect the retention properties of the transport pathways for radionuclides.

The buffer will experience chemical alterations, in particular during the phase of elevated temperatures when significant temperature gradients prevail in the buffer. Based on modelling results and the general understanding of these phenomena, these alterations are concluded to have no detrimental effects on the long-term properties of the buffer.

The mechanical load on the canisters from the swelling buffer and the groundwater pressure is far too low to jeopardise canister integrity.

Canister corrosion from initially present oxygen and sulphide, as well as from sulphide in ingressing groundwater, has been found to be negligible.

9.3.14 Safety functions for the initial temperate period after closure

The following is an account of the development of all safety functions in Figure 9-2 during the initial temperate period after repository closure. Also the development during the excavation/operation period is considered where relevant.

Rock safety functions

R1. Provide chemically favourable conditions

a) Reducing conditions; Eh limited

The analyses have lead to the conclusion that the chemical conditions will be reducing shortly after deposition in individual deposition holes and deposition tunnels and shortly after closure in the repository as a whole. This is of fundamental importance for the long-term safety of the repository and no process has been identified that challenges this conclusion during the initial temperate period after closure.

b) Salinity; TDS limited

The salinity at the Forsmark site has, through model studies, been demonstrated to be below 12 g/L, corresponding to 0.2 M [Cl^-], while lower salinities have been modelled for Laxemar. Upconing effects on salinity during the excavation/operation phase have also been studied and found to be negligible.

c) Ionic strength; [M^{2+}] > 1 mM

Calculations combining the mixing of reference waters with calcite equilibration show that, during the initial temperate period, calcium concentrations will be around 50 mM at repository depth for both sites.

d) Concentrations of K, HS^-, Fe; limited

The modelling mentioned under point c) above indicates that, at both sites, the potassium concentrations are expected to remain ≤ 0.004 mol/L, sulphide concentrations are expected to be ≤ 10^{-5} mol/L for any deposition position averaged over the temperate period and iron concentrations are expected to gradually increase up to 10^{-5} mol/L.

e) Alkalinity; pH < 11

The results of the geochemical analyses indicate that groundwater pH at the Forsmark site will be around 7 to 8. Similarly, the results for Laxemar indicate pH values between ≈ 6.5 and ≈ 8.5. In addition, leach water from grout, shotcrete and cement may exhibit pH-values of around 9 for extended periods of time. The use of low-pH formulations of these materials will limit pH in these situations. Such formulations are currently under development.

R2. Provide favourable hydrologic and transport conditions

a) Fracture frequency; limited

The natural fracture frequency at the sites is limited at repository depth and the analyses of the mechanical evolution for the initial temperate period have not led to any results that imply a change in this situation.

Provided that proper excavation techniques and QA control are applied, an excavation damaged zone, EDZ, if it develops at all, is expected to be limited to a narrow zone (a few tens of cm wide) close to the tunnel wall, and to not form a continuous hydrologically conductive path.

A safety relevant issue is however spalling in deposition holes. This can occur either as a direct result of the mechanical impact from the excavation, in which case it can be mitigated, or as a consequence of the thermal load from the spent fuel after deposition. For both the Forsmark and Laxemar sites, it has been concluded that thermally induced spalling must be pessimistically assumed to occur in every deposition hole. This has impact on transport conditions at the deposition holes and must be considered in all quantitative treatments of mass transfers between buffer and rock.

b) Fracture transmissivity; limited

The natural fracture transmissivities at the Forsmark site are limited, resulting in groundwater flows that are generally much lower than usually encountered in crystalline rock. The transmissivities at Laxemar are also limited, but higher than at Forsmark. For Laxemar, more representative data for the candidate repository volume is required. The analyses of the mechanical evolution for the initial temperate period have not led to any results that imply a change in these situations. There could be some significant, but very local, effects on the fractures very close to the deposition holes. The hydraulic importance of these effects is, however, concluded to be insignificant.

c) Hydraulic gradients; limited

The hydraulic gradients at the sites, as in Sweden in general, are controlled by the topography. Since the topography is relatively flat, the gradients are limited and this contributes to the favourable hydraulic properties at the sites.

d) K_d, D_e; high

Sorption coefficients and diffusivities in the rock have not been evaluated within the description of the reference evolution. These entities are assessed in the **Data report**, where the geochemical conditions found in the reference evolution are one of the bases for the evaluation.

e) Colloid concentration; low

After an initial increase of colloid concentrations during repository operation, such concentrations are expected to return to the levels found prior to excavation, i.e. ≤ 0.15 mg/L at both sites.

R3. Provide mechanically stable conditions

a) Shear movements at deposition holes < 0.1 m

The only identified cause for a shear movement of this size is an earthquake of magnitude 6 or larger in a major deformation zone in the vicinity of the repository. The likelihood of such an earthquake is estimated to < $3.75 \cdot 10^{-4}$ in 1,000 years (see Table 9-5, section 9.3.5). Such events are therefore disregarded for the initial temperate period.

b) GW pressure; limited

The groundwater pressure is determined by repository depth for temperate climate conditions. It is hence around 4 and 5 MPa at the suggested repository depths at the Forsmark and Laxemar sites, respectively, which, from the point of view of long-term safety, is not problematic.

R4. Provide thermally favourable conditions

For this safety function to be fulfilled, it is required that the rock temperature at repository depth exceeds the buffer freezing temperature, i.e. −5°C. Since a temperate climate similar to the current is assumed to prevail during the time period under consideration, there is no possibility that this criterion would not be fulfilled.

Buffer safety functions

Several of the buffer safety functions are related to the buffer density. The reference saturated density of 1,950–2,050 kg/m^3 may potentially alter during the initial temperate period due to erosion related to piping during the resaturation of the buffer and backfill, upward expansion of the buffer as a consequence of swelling and colloid release in the long-term.

For the majority of deposition holes, no losses due to piping are expected since the inflow of groundwater is expected to be too low to cause piping. Preliminary evaluations indicate that an inflow of 0.1 l/min to a deposition hole could result in a mass loss of around 100 kg. These and additional results will be used to formulate grouting requirements on deposition holes. Even without grouting, the hydraulic conditions at the Forsmark site however imply that very few deposition holes would be affected by piping. A preliminary evaluation /Svensson 2006b/ indicates that for Laxemar about 20% of the deposition holes have an inflow above 0.1 L/min, see section 9.2.3, but it should be possible to avoid piping by grouting or rejection of some deposition holes.

All deposition holes are expected to experience some loss of buffer mass due to swelling and upward expansion of the buffer. This phenomenon has been analysed through a number of calculations that demonstrate that buffer density at the canister top will remain within the reference interval of 1,950–2,050 kg/m^3 after buffer swelling and expansion.

For the initial temperate period, losses due to colloid release have been found to be negligible for all deposition holes.

It is, therefore, concluded that the saturated buffer density in deposition holes where piping does not occur will be in the reference interval 1,950–2,050 kg/m^3 around the canister.

If piping occurs, a preliminary calculation shows that the density may drop to around 1,900 kg/m^3 locally in the buffer.

Bu1. Limit advective transport

a) Hydraulic conductivity < 10^{-12} m/s

For deposition holes with reference buffer density, the hydraulic conductivity criterion is fulfilled with ample margin, also for groundwater salinities that can be expected during the initial temperate period.

b) Swelling pressure > 1 MPa

For deposition holes with reference buffer density, the swelling pressure criterion is fulfilled with ample margin, also for groundwater salinities that can be expected during the initial temperate period.

These conclusions hold also for deposition holes affected by piping.

Bu2. Filter colloids

For this safety function to be fulfilled, it is required that the saturated buffer density exceeds 1,650 kg/m^3 around a canister. For the initial temperate period, the analyses of possible loss of buffer mass have demonstrated that this is expected to be the case for all deposition holes.

Bu3. Eliminate microbes

For this safety function to be fulfilled it is required that the buffer swelling pressure exceeds 2 MPa around a canister. For the initial temperate period, the analyses of possible loss of buffer mass and groundwater salinities have demonstrated that this is expected to be the case for all deposition holes.

Bu4. Damp rock shear

For this safety function to be fulfilled it is required that the saturated buffer density is less than 2,050 kg/m^3. 2,050 kg/m^3 is the upper bound of the reference density and as no relevant processes that would increase the buffer density have been identified, it is concluded that this safety function is fulfilled for all deposition holes. It is also noted that canister failure due to rock shear has been demonstrated to be an insignificant issue during the initial temperate period.

Bu5. Resist transformation

For this safety function to be fulfilled, it is required that the buffer temperature is less than 100°C. This has been demonstrated to be the case through quantitative calculations with the canister centre-to-centre spacing suggested by the reference layout and otherwise pessimistic input data.

Bu6. Prevent canister sinking

For this safety function to be fulfilled, it is required that the buffer swelling pressure exceeds 0.2 MPa. This is less than the fulfilled criterion (> 1 MPa) for Bu1b above and the canister sinking criterion is thus fulfilled with ample margin.

Bu7. Limit pressure on canister and rock

For this safety function to be fulfilled it is required that the buffer temperature exceeds the buffer freezing temperature, i.e. −5°C. Since a temperate climate similar to the current is assumed to prevail during the time period under consideration, there is no possibility that this criterion would not be fulfilled.

Backfill safety functions

Piping followed by erosion is expected to occur in the tunnel backfill. The swelling pressure is too low to withstand the pressure gradients early in the repository evolution. The loss or redistribution of backfill will be limited since the period with pressure gradients will be relatively short and the amount of backfill material is large. The total expected loss is less than 1% of the swelling material in the backfill, which will result in negligible effects on the backfill properties. The main uncertainty associated with this is the self-sealing ability of the 30/70 mixture after a piping event.

BF1. Limit advective transport

a) Hydraulic conductivity < 10^{-10} m/s

For deposition tunnels with reference backfill density, the hydraulic conductivity criterion is fulfilled with ample margin, also for groundwater salinities that can be expected during the initial temperate period.

It cannot be totally excluded that a piping event in a 30/70 mixture would create channels (pipes) with a higher hydraulic conductivity locally. This would only affect a small part of the backfill.

b) Swelling pressure > 0.1 MPa

For deposition tunnels with reference backfill density, the swelling pressure criterion is fulfilled with ample margin, also for groundwater salinities that can be expected during the initial temperate period. If piping has occurred in a 30/70 mixture it cannot be concluded that the pipes will re-seal due to a local loss of swelling pressure (see above).

c) Temperature > 0°C

Since a temperate climate similar to the current is assumed to prevail during the time period under consideration, there is no possibility that this criterion would not be fulfilled.

Canister safety functions

C1. Provide corrosion barrier

For this safety function to be fulfilled, it is required that the minimum copper coverage exceeds zero. Given the initial, pessimistically estimated minimum copper thickness of between 40 and 50 mm for 99% of canisters and between 35 and 40 mm for the remaining one percent, the corrosion calculations for the initial temperate period indicate clearly that no canister failures will occur due to corrosion.

Quantitative bounds on the effects of corrosion caused by initially present oxygen in the repository, by microbial activities, possibly occurring before a full swelling pressure is developed and by sulphide, either derived from pyrite in the buffer or from the groundwater, show that these effects cause corrosion depths of the order of hundreds of micrometres at most.

C2. Withstand isostatic load

For this safety function to be fulfilled, it is required that the canister strength exceeds the isostatic loads to which it is subjected. During the initial temperate period, the isostatic loads consist of the groundwater pressure of 4–5 MPa and the swelling pressure of the buffer that is estimated at maximally 13 MPa for the reference buffer density interval. This is considerably less than the collapse load of the canisters which is more than 45 MPa for local collapse and more than 100 MPa for total collapse.

C3. Withstand loads from shear movements

For this safety function to be fulfilled, it is required that the canister rupture limit exceeds the shear stress to which it is subjected. During the initial temperate period, shear stresses occur from the possibly uneven swelling of the buffer. It has been demonstrated, by the formulation and analysis of a number of pessimistic cases, that these loads are considerably less than the canister rupture limit.

Status of buffer/backfill after the thermal and saturation phase

The buffer and, to a lesser extent, the backfill goes through a unique transient thermal and saturation phase in the first few hundred years after deposition. The status of these components after this transient phase is not expected to change much thereafter, meaning that the initial state, in combination with the alterations occurring during the transient phase, to a large degree determine the long-term properties of the buffer and the backfill. Therefore, a specific account of the expected status of the buffer and the backfill after the thermal and saturation phase is given here.

The buffer and the backfill will be deposited as blocks and the gaps between the blocks and the rock is assumed to be filled with bentonite. Water from the rock will enter into the pellets and come into contact with the blocks. The bentonite will take up water and swell. From the time of deposition, the residual heat from the waste will increase the temperature in the near field of the repository. Temperature differences of up to 20° will occur across the buffer for typically 100 years. Elevated temperatures in the near field are expected for about 1,000 years. During this period, the buffer and backfill are expected to evolve as described earlier in this section. The expected final state after the thermal and saturation phase is as set out below.

- After a period of 10–100 years the buffer is expected to be fully saturated. The time is dependent on the availability of water in the individual deposition holes and the supply of water from the backfill.
- During the period over which saturation is achieved, the buffer will swell and exert a swelling pressure on the canister, the rock and the backfill. The pressure is too low to have any effect on the canister and rock, but the backfill will deform to a certain extent. This will lead to a small loss of swelling pressure in the top of the deposition holes, but the pressure exerted by the buffer around the canister is expected to remain at initial values.
- The hydraulic gradients in the unsaturated repository may cause piping and erosion of the buffer and backfill. This may lead to a loss or redistribution of material.
- The increased temperature in, and the thermal gradient over, the buffer may lead to redistribution of minerals. $CaCO_3$ could be enriched close to the canister. The movement of compounds of silica is expected to be negligible.
- The maximum temperature increase and the maximum duration of increased temperature are well below the limits that might cause any significant transformation of the montmorillonite.

- Groundwater from the site will enter into the buffer and mix with the original porewater. This will yield a new composition for the buffer water. Both the composition of the original bentonite and the water from the site are well known and the new composition can be estimated.

In summary, for all identified processes occurring in the buffer and backfill during the saturation and thermal phase the consequences have been estimated. The conclusion is that none of these phenomena will jeopardize the long term performance of the buffer and backfill.

Conclusions for radionuclide transport

The following conclusions for radionuclide transport have been drawn.

- No canister failures are expected during this period.
- The EDZ developed during construction needs to be considered in the radionuclide transport analyses.
- The hydrogeological analyses have provided distributions of F, tw and Q_{eq} to be used in radionuclide transport calculations.
- The geochemical assessments have provided geochemical conditions for which retention properties in the host rock for radionuclide transport can be derived.
- The buffer assessments have provided buffer conditions for which retention properties in the buffer for radionuclide transport can be derived.
- Spalling may affect the equivalent flow rates, Q_{eq}, in deposition holes.
- The pH increase from cement leaching may affect geosphere retention in larger, grouted fractures.

9.4 Evolution for the remaining part of the reference glacial cycle

This section presents the evolution for the remaining part of the reference glacial cycle, essentially a repetition of the Weichselian. It is important to note that the model reconstruction of the Weichselian constituting the reference evolution should be regarded as an example of a credible evolution during a glacial cycle. The description is neither an attempt to predict a probable future evolution nor a "best estimate" of the Weichselian evolution, but a scientifically defensible starting point for the analysis of climate impact on repository safety. It cannot be described as a 'best estimate' for the Weichselian because it is a generalised abstraction of that glacial cycle, representing the major factors that would influence repository safety, but without attempting to infer a detailed picture of what occurred at the local scale.

Figure 6-4 in section 6.5 shows the assessment model flow chart, AMF, for permafrost and glacial conditions giving an overview of the modelling and other assessment studies for these periods.

9.4.1 Reference long-term evolution of climate related conditions

A model reconstruction of the last glacial cycle, the Weichselian, from 120,000 years ago to the present is chosen as reference evolution. The rationale for this is given in sections 5.2 and 11.3. The evolution of the repository is mainly affected by the evolution of climate-related conditions e.g. shore-level alteration and development of permafrost and ice sheets, whereas the climate as such, above the ground surface, is of less importance for the repository. On the basis of conditions and processes of importance for repository safety, three characteristic *climate domains* (see further section 5.2.3) that can be expected to occur in Sweden in a 100,000-year time perspective was identified:

- Temperate domain.
- Permafrost domain.
- Glacial domain.

In addition, periods when the ground above the repository is submerged, either by the sea or by a fresh water lake, can be expected. During submerged periods, the climate conditions can either be temperate or cold, the latter yielding permafrost development in areas not covered by the sea/lake. The evolution of climate-related conditions is described as time series of climate domains and submerged periods.

To generate the reference evolution, three models have been used; a dynamic ice sheet model /e.g. Fastook 1994, Payne et al. 2000/, a global isostatic adjustment (GIA) model /Milne 1998, Milne and Mitrovica 1998, Mitrovica and Milne 2003/, and a permafrost model /Hartikainen 2004/. The ice sheet, GIA, and permafrost models were developed at University of Maine, University of Durham, and Helsinki University, respectively. Further details and references on the models are found in the **Climate report**, chapter 3 and in the **Model summary report**. The basis for the reference evolution of climate-related conditions is a reconstruction of the evolution of the Fennoscandian ice sheet during the Weichselian, employing the ice-sheet model. The generated ice-sheet evolution has been used as input to the GIA model. The third main component in modelling the reference evolution is the permafrost model, yielding permafrost depths given the evolution of temperature, ice sheet extent and thickness, shore level and vegetation. The main data flows between the ice sheet, GIA and permafrost models are shown in Figure 9-63.

Ice sheet evolution and modelling

The dynamic ice-sheet model is capable of simulating realistic ice sheets that are typically not in balance with climate. Derived ice temperatures, together with density variations with depth, control ice viscosity and ice flow. The thermodynamic calculation accounts for vertical diffusion, vertical advection, and heating caused by internal shear. The model has been developed over an extended period /Fastook and Chapman 1989, Fastook 1994, Fastook and Holmlund 1994, Johnson 1994/ and model outputs agree with other major ice-sheet models /e.g. Payne et al. 2000/.

Inputs to the dynamic ice sheet model are:

- Topography.
- Geothermal heat flux.
- Global sea-level variations.
- Thermo-mechanical properties of the ice.
- Isostatic properties of the Earth's crust.
- Annual air temperature at sea level, and its variation over time.

When simulating a glacial cycle, the temperature pattern over the model domain is changed by reference to a palaeo-temperature curve, resulting in changes in the distributed precipitation and mass balance. In absence of a long-term paleo-temperature climate curve from Scandinavia, the simulation of the Weichselian ice sheet over Fennoscandia was controlled by the temperature curve from the GRIP ice core (Figure 9-64), obtained from central Greenland /e.g. Dansgaard et al. 1993/. This is a typical method used in ice-sheet modelling of the Weichselian glacial cycle.

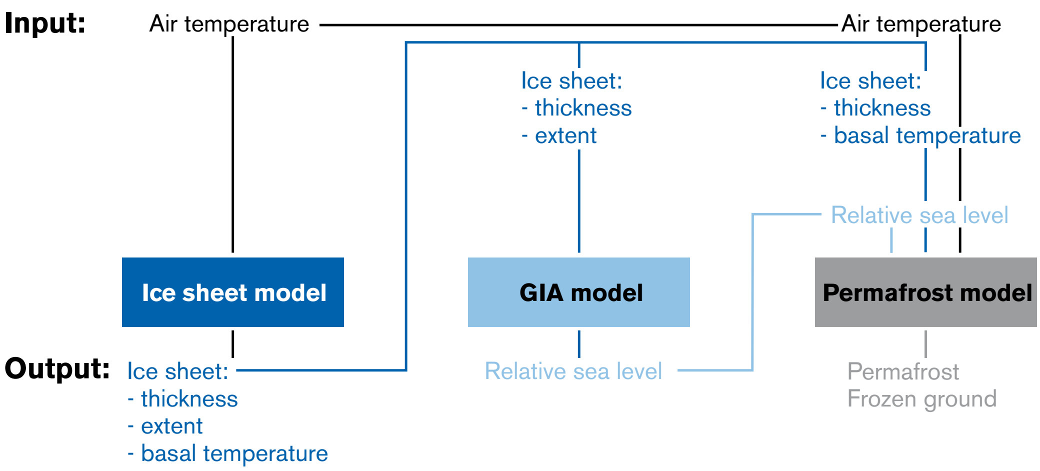


Figure 9-63. *Models used to provide data for analysis of the impact of climate-related changes on the repository. Only input and output data shared between the models used to generate the results are shown.*

The modelled ice sheet evolution starts at the end of the Eemian interglacial (MIS 5e), in a situation when ice sheet extent and shore level are assumed to be similar to the present. The geothermal heat flow and its spatial variation has been shown to be of importance for obtaining realistic modelled basal ice temperatures and basal melt rates /Waddington 1987, Näslund et al. 2005/. Basal temperatures and basal water yields are in turn important for the overall ice flow and ice dynamics. A detailed dataset of geothermal heat flux, based on national measurements of gamma emission in Sweden and Finland, has, therefore, been compiled /Näslund et al. 2005/ and used as input to the ice-sheet model.

The input of sea-level variation is derived from numerical ice-sheet modelling of all Northern Hemisphere ice sheets, using the same ice-sheet model as for the rest of the simulations. The volume of the Antarctic ice sheet was held constant at the present day value. The justification for doing this is that variations in Antarctic ice volume made only a minor contribution to sea-level changes over the last glacial cycle compared with the effects of variations in the volume of Northern Hemisphere ice sheets /Huybrechts 2002/. Modelled ice configurations were calibrated against geological information on the Weichselian glaciation history of Fennoscandia /Lokrantz and Sohlenius 2006/. For details on the ice sheet modelling, see the **Climate report**, section 3.1.

The resulting evolution of ice-covered area and ice volume during the past 120,000 years are shown in Figure 9-64, together with times at which geological information were used to constrain ice sheet evolution. The modelled ice configurations for these times are shown in Figure 9-65. During the glacial cycle, the ice sheet grows progressively larger in a number of distinct growth phases. Between these phases, the ice sheet has a more restricted ice coverage. The Last Glacial Maximum, as seen in peak ice volume, is reached around 18,000 years ago. The overall behaviour of the ice sheet can be characterised as being dynamic throughout the glacial cycle, in line with many of the studies described in /Lokrantz and Sohlenius 2006/. The reconstruction of the Weichselian is described in more detail in the **Climate report**, section 3.1.

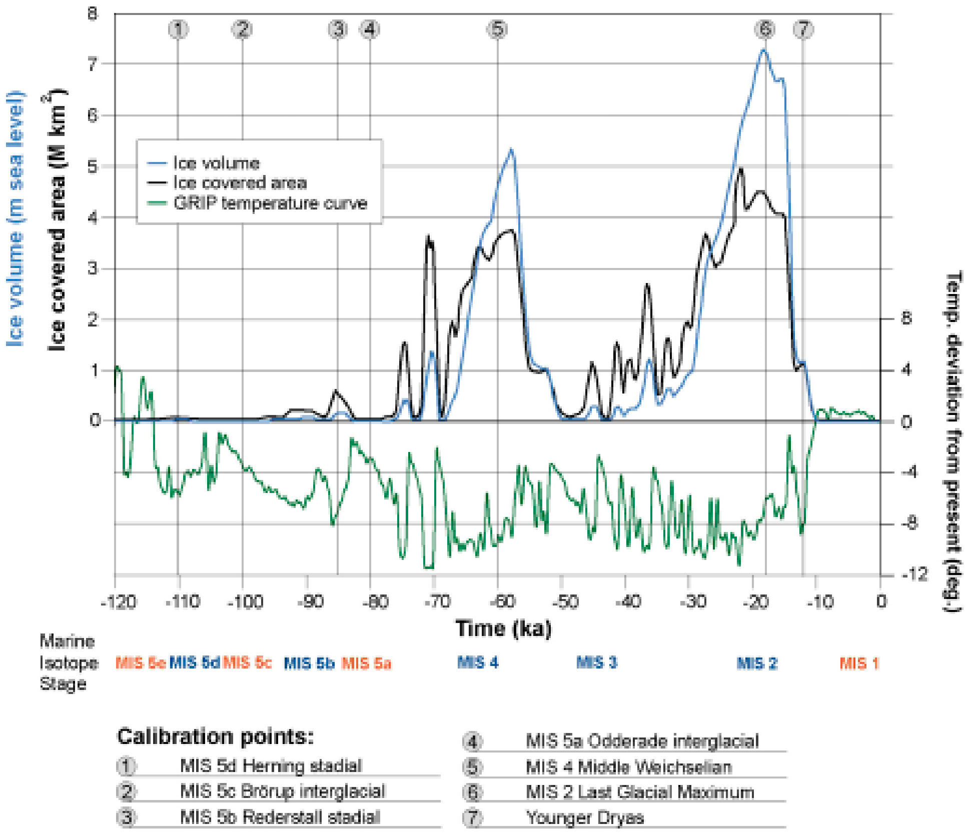


Figure 9-64. *GRIP proxy temperature curve, reconstructed ice-covered area and ice volume for the Weichselian reference model run. Times of model calibration are shown, as well as Marine Isotope Stages (warm stages in red and cold stages in blue).*

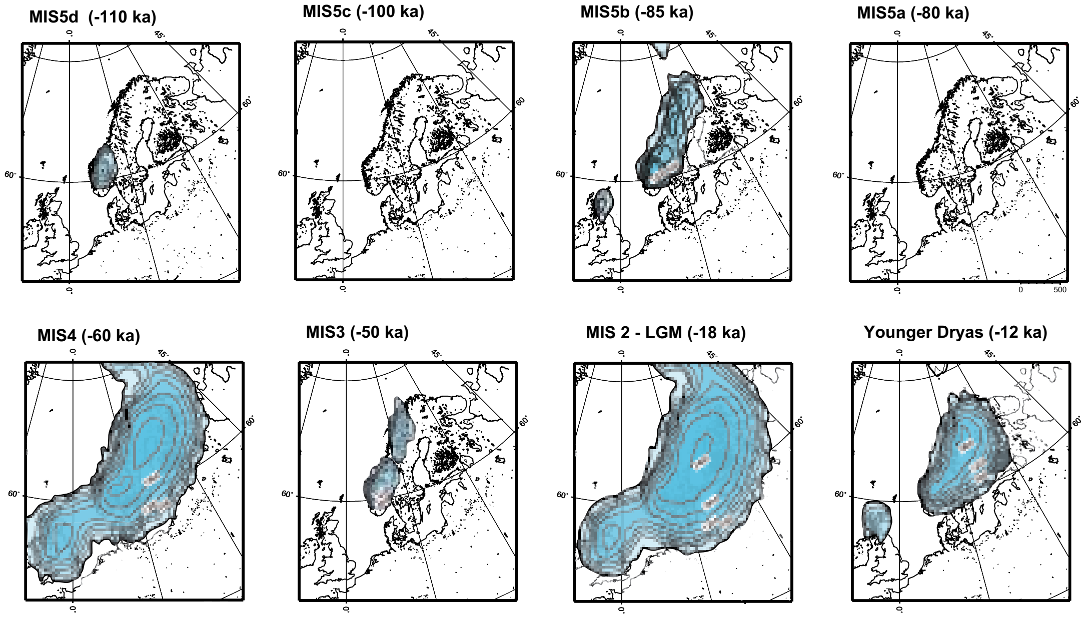


Figure 9-65. *Modelled ice-sheet configurations at major stadials and interstadials for the Weichselian reference evolution. Contour lines show ice-surface elevation with a 300 m contour interval. All maps show present day shore-line position.*

In the Weichselian reference evolution, the ice sheet over Forsmark and Laxemar was, as expected, at its thickest during the Last Glacial Maximum. The largest ice thicknesses at that time are ~ 2,900 m for the Forsmark region and ~ 2,400 m for Laxemar.

The groundwater pressure at repository depth is, for non-glacial conditions, determined by the repository depth and, for glacial conditions, by the repository depth as well as an additional pressure induced by the ice load. The ice-sheet thickness sets a limit for the maximum hydrostatic pressure that may occur at the ice sheet/bed interface. The additional hydrostatic pressure related to the maximum thickness in the Weichselian reference evolution is 26 MPa for Forsmark and 22 MPa for Laxemar. These values are listed in Table 12-2, section 12.8.4, together with other estimates of *maximum* expected ice loads and associated *maximum* hydrostatic pressures, discussed in section 12.8.4.

Shore-level and GIA modelling

Glacial Isostatic Adjustment (GIA)-induced sea-level changes depend on the following factors:

- the depth and extent of the oceans,
- the location and thickness of ice sheets,
- the structure and properties of the solid Earth and its response to surface loading.

In Sweden, the evolution of the Fennoscandian ice sheet is the principal factor governing changes in relative sea level. During a glacial cycle, the shore level of the water body which today is the Baltic is constrained by ice-sheet extent and by relative sea levels at its sills. During long periods of the Weichselian reference evolution, the Baltic is a lake with a surface level determined by the contemporary level of the shallowest sill, this being Darss sill located in the southern Baltic between Denmark and Germany.

The GIA-model used for generating the reference evolution was developed by Milne /Mitrovica and Milne 2003/. The global ice-loading function used in the study is modified from the ICE3G deglaciation history /Tushingham and Peltier 1991/, and has been calibrated using far-field (i.e. far from the margin of the ice sheet) relative sea-level data. An eustatic curve has been used to tune the mass of ice contained within far-field ice sheets. The Earth model is based on Maxwell rheology with a 1D radial three-layer structure. The lithosphere is represented by a 96 km thick layer with a very high viscosity and thus behaves as an elastic medium over GIA time scales, the density and elastic structure are from the preliminary reference Earth model (PREM) that has been determined to a high degree of accuracy by seismic methods /Dziewonski and Anderson 1981/. The upper and lower mantles are defined to be isoviscous, with viscosities of $0.5 \cdot 10^{21}$ Pa s and $1 \cdot 10^{23}$ Pa s, respectively. However, mantle viscosities are subject to considerable uncertainty, see further the **Climate report**, section 3.3.

During the first 1,000 years after closure and for the analysis of biosphere and hydrological evolution during the initial temperate domain, the shore-line evolution is extrapolated from shore-line data /Påsse 2001/. From about 8,000 years after closure to the end of the reference glacial cycle, the shore-line evolution is based on GIA-modelling.

During the initial phase of the glacial cycle, when climate is getting colder and ice sheet expand globally, sea levels fall. At the same time, the rate of isostatic rebound from the previous glaciation decreases. However, even if the rate is low, the amount of remaining uplift until the earth reaches a relaxed state is significant. In the central part of the former Weichselian ice sheet it has been estimated to be ~ 100 m, and in the distal parts to be ~ 25 m /**Climate report**, section 4.2.2/. In the reference evolution the Baltic is cut off from the Atlantic and is transformed into a lake after about 9,000 years. Due to the uncertainties in the GIA modelling relating to ice load input, 2D Earth structure, and Earth rheology, it is likely that this result underestimates the time at which isolation of the Baltic occurs in the reference evolution, see further the **Climate report**, section 4.2.2.

The Baltic constitutes a freshwater lake during a large part of the reference glacial cycle. In connection with the first major ice advance and the following retreat, after about 60,000 years (corresponding to Marine Isotope Stage 4), isostatic depression puts the candidate sites below water. The Baltic regains contact with the Atlantic after the final glacial advance to the equivalent of the Last Glacial Maximum. At this stage, large parts of southern Sweden again are submerged, this time by a saline Baltic sea. As the ice sheet retreats, the two candidate sites are submerged. At the end of the reference evolution, and as isostatic rebound proceeds, the Baltic is transformed to an enclosed brackish sea and the candidate sites re-emerge.

The most important factor affecting modelled shore level migration is the ice loading history, primarily the near-field history, and the characteristics of the earth model used in the GIA simulations. The relation between these two factors are further discussed in the **Climate report**, section 3.3.

The uncertainty in modelled shore-level mainly manifests itself in that reported relative sea-level values could be too high, resulting from a possible overestimation of isostatic depression. The size of the uncertainty varies over the modelled glacial cycle. Postulating that the ice sheet evolution is correct, the *mean* overestimation of relative sea-level, over the whole glacial cycle, may be up to 45 m for Forsmark and 27 m for Laxemar. For details on uncertainties in modelled relative shore-levels see the **Climate report**, section 3.3. Saline phases occur in the Baltic after major glacial advances, such as the ones occurring during Marine isotope stage 4 and 2. During such periods of maximum salinity in the Baltic, both candidate sites are submerged.

Permafrost development and modelling

Permafrost is defined as ground where the temperature remains continuously below 0°C for more than a year. The presence of permafrost does not necessarily mean that the ground is frozen, since, depending on the pressure and composition of groundwater, and on adsorptive and capillary properties of ground matter, water in ground freezes at temperatures below 0°C. Permafrost basically originates from the ground surface depending on a complex heat exchange across the atmosphere/ground boundary layers and on a rather time-invariant geothermal heat flow from the Earth's interior. In the reference evolution, permafrost occurs in the permafrost domain as well as beneath parts of the ice sheet in the glacial domain. Generally, the ice sheet will isolate the ground from the cold climate on the surface and the presence of an ice sheet will prevent the development of permafrost to great depth in cold climates.

The development of permafrost depends on:

- The climate conditions; mainly air temperature at the ground surface and its annual variation but also precipitation and wind.
- The topography; air temperature decreases with increasing altitude and, in northern latitudes, south slopes are more exposed to solar irradiation than north slopes.
- The presence of a soil cover and its porosity, saturation and thermal properties.
- The presence and kind of vegetation.
- The presence of water bodies of substantial extent.
- The presence of ice sheets and the basal ice temperature.

- The bedrock thermal, mechanical and hydraulic properties.
- The geothermal heat flow.

Depending on the climatic conditions, topography, and vegetation, permafrost can develop if mean annual air temperatures are lower than between −1 and −9°C /Washburn 1979, Williams and Smith 1989, French 1996, Yershov 1998/.

Permafrost growth is a progressive process, starting with sporadic permafrost at exposed areas and ending with continuous permafrost. Even in areas of continuous permafrost, a talik, i.e. an unfrozen layer, can exist beneath large water bodies such as lakes and rivers. The size of the water body required to retain a talik was investigated by permafrost modelling. For the results of these calculations, see the **Climate report**, section 3.4.4.

The calculations of permafrost development is based on 1-D model calculations, see further section 9.4.3 and the **Climate report**, section 3.4.4.

Reference evolution at Forsmark and Laxemar

Based on the reconstructions from the ice sheet, GIA and permafrost modelling, the evolution of climate-related conditions at Forsmark and Laxemar can be described in the reference evolution as a time series of climate domains and submerged periods, see Figure 9-66. The time scale thus changes from a "reconstruction time scale" with negative numbers denoting years before present, e.g. Figure 9-64, to a "reference evolution time scale" with positive numbers for ages, now expressed as years after repository closure, e.g. Figure 9-66. The time series and the identification of the main processes and conditions of importance for repository safety are the basis for identifying variations to the base variant of the reference climate evolution.

During the first 50,000 years of the reference evolution, and in the period between the two ice advances, the increasingly colder climate results in progressively longer periods of permafrost. The total duration of the permafrost domain is about 41,000 years at Forsmark and 46,000 years at Laxemar. In this reference evolution, the permafrost develops to quite great depths during the most severe permafrost periods; the maximum calculated permafrost depth is at that time ~ 250 m at Forsmark and ~ 160 m at Laxemar (Figure 9-67 and Figure 9-68). The rapid growth of permafrost at times is discussed in more detail in the **Climate report**, section 3.4.4. The calculation results are supported by analytical models that yield similar results, see Appendix B.

Forsmark and Laxemar are exposed to two major ice advances and retreats during the reference glacial cycle, the first after around 60,000 years and the second after about 90,000 years (Figure 9-67 and Figure 9-68). Prior to both of these glaciated periods, both Forsmark and Laxemar are situated above sea level with prevailing permafrost conditions when the ice sheet advances towards and over the sites.

A period of basal frozen conditions initiates the first major stadial of glacial domain at both sites. At Forsmark, the period of basal frozen conditions is ~ 4,000 years long and at Laxemar a few hundred years. During this period, the permafrost, which is now sub-glacial, reaches its maximum depth of about 250 m at Forsmark and 160 m at Laxemar. However, as the ice sheet continues to grow over the sites, it insulates the subsurface from the cold climate and in time induces basal melting conditions. The total length of periods of glacial domain in the reference glacial cycle is about 30,000 years at Forsmark and 19,000 years at Laxemar. During this time, ice sheet basal melting conditions dominate.

It is again emphasized that the reference evolution is not an expected or predicted climate evolution. It is *one example* of a climate evolution covering the climate-related conditions that could occur in a 100,000 year time perspective. The example is subsequently used in the process of identifying more extreme climate scenarios to analyse.

Climate-related factors of importance for safety

During periods of temperate domain, the main factor of importance for repository safety is shore-level migration and ground water salinity. When the sites are submerged, a reduced groundwater flow will be driven by prevailing differences in ground water density, and, when not submerged, the gradients for groundwater flow will be constrained by landscape topography. During periods of permafrost domain, the main factor of importance for repository safety is the development of permafrost and frozen ground. Frozen ground will affect groundwater flow and composition, and cause freezing of backfill material in the ramp and shaft. If, in extreme cases, temperatures below zero were to prevail at repository depth, the backfill in deposition tunnels and buffer might freeze.

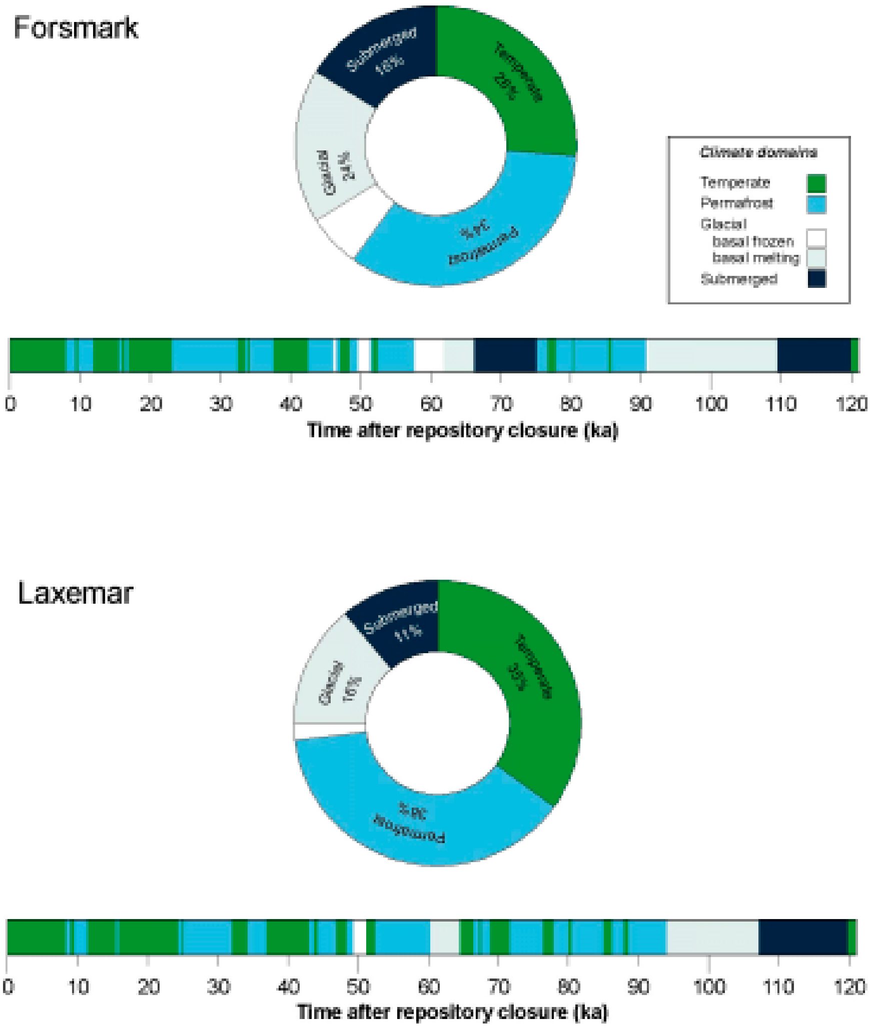


Figure 9-66. *Duration of climate domains at Forsmark and Laxemar, expressed as percentage of the total time of the base variant of the SR-Can reference evolution. The bars below the pie charts show the development of climate related conditions at each site for the base variant as a time series of climate domains and submerged periods. Periods of temperate domain occupy about 31,000 years of the reference evolution at Forsmark and 41,000 years at Laxemar. It occurs in the early phase of the reference evolution glacial cycle, during the interstadial between the two major ice advances, and during the interglacial period following the glacial maximum. The periods of temperate domain in the interglacial and early phases of the reference glacial cycle are generally warmer and longer than those occurring during interstadials in the later part of the glacial.*

The advance and retreat of an ice sheet over the repository site brings about the largest climate-related change the repository will experience during a glacial cycle. The main factors of importance for repository safety in the glacial domain are the maximum hydrostatic pressure, the penetration of oxygen rich and/or diluted glacial melt waters to great depth, the possible up-coning of saline waters from below the repository, the alteration of rock stresses, the occurrence of glacially induced faulting and the alteration of flow properties of the bedrock. Since the presence of liquid water is a prerequisite for occurrence of most of these effects, the basal conditions of the ice sheet are of major importance for its impact on the subsurface.

The evolution of climate-related conditions of importance for repository safety is illustrated by the succession of climate domains in Figure 9-66 and by the evolution of some important climate-related variables in Figure 9-67 and Figure 9-68. These figures also illustrate possible successions of climate domains at Forsmark and Laxemar. The temperate domain is always followed by the permafrost domain. The permafrost domain can either be followed by the temperate or glacial domain. Shorter periods of glacial domain with limited ice thickness at Forsmark can be followed by permafrost, but generally both sites are submerged after periods of major glaciation. The transition between sea/lake bottom and land can either occur during periods of temperate or of permafrost domain.

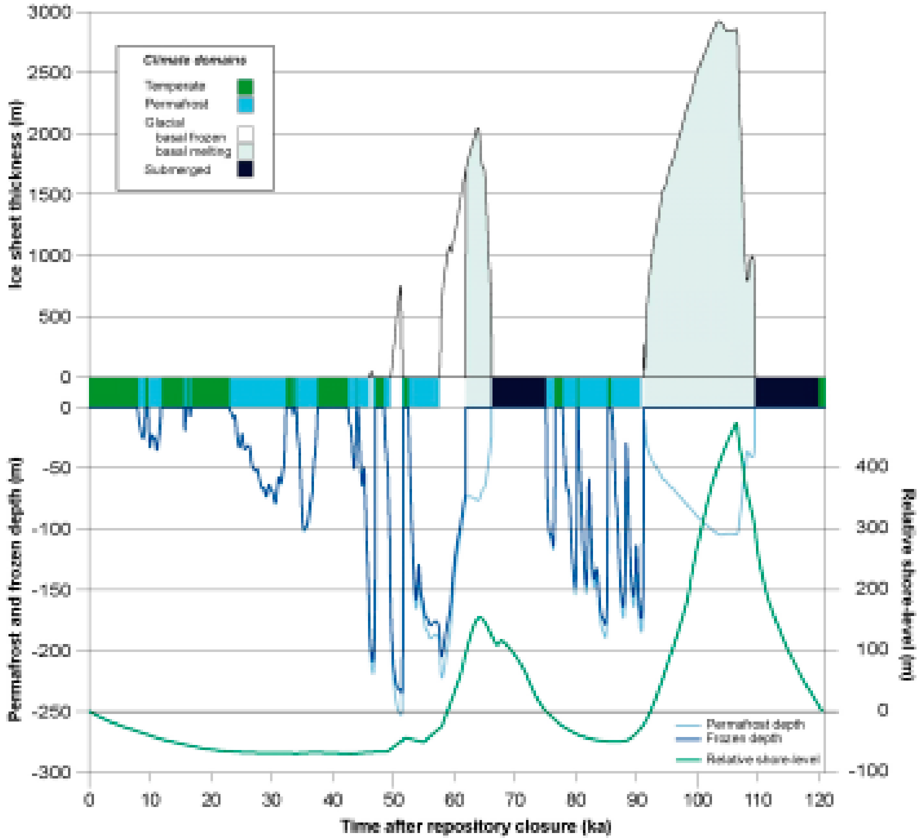


Figure 9-67. *Evolution of important climate-related variables at Forsmark in the base variant of the reference evolution.*

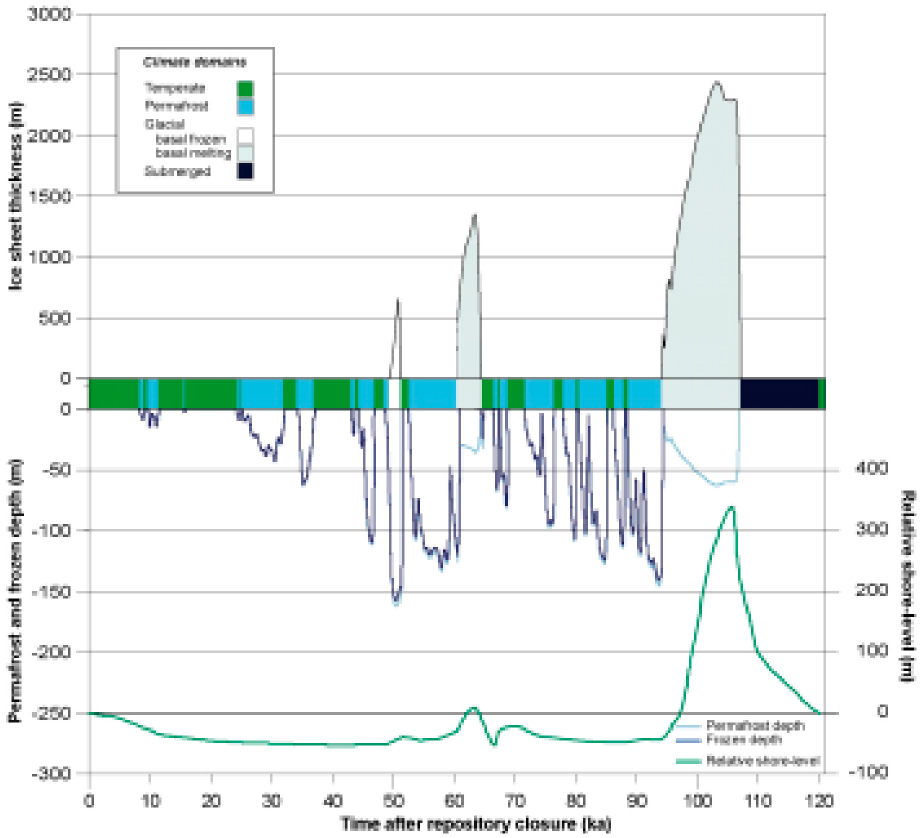


Figure 9-68. *Evolution of important climate-related variables at Laxemar in the base variant of the reference evolution.*

9.4.2 Biosphere

The development of the biosphere during permafrost and glacial periods is assumed to be similar for the sites, whereas that of the interglacial periods is expected to differ, primarily due to differences in topography.

Permafrost conditions

Periods of permafrost are characterised by tundra ecosystems. The precipitation is low, due to the limited amount of evaporation transporting water to the atmosphere. The low evaporation means that wet ground is prevalent and that surplus water is unable to seep into the ground because of the permafrost /French 1996/. This gives extensive swamps, but the amount of peat formed is negligible because plant productivity is low. Even if there is a snow cover of 50 cm during winter, raised parts are frequently blown free of snow where intensive erosion occurs by the blowing ice crystals. The tundra is devoid of forests. The vegetation consists of herbs and shrubs, at raised dryer places lichens, whereas, on wet ground, mosses dominate. The vegetation period is short and several species will have adapted to flower and set buds in different years. Most of the plants develop thick roots that serve as storage and some can live up to 200 years. No plants produce berries for their dispersal of seeds.

The major part of the vertebrate fauna of the tundra migrates south during winter. The birds that are abundant during summer migrate over long distances to subtropical areas. During the summer they thrive on the enormous amount of mosquitoes. Some rodents, e.g. lemmings, do not migrate and spend most of their life under the isolating snow-cover grazing, e.g. mosses.

Even on gentle slopes, the soil slips downhill with the peat cover on top, i.e. solifluction occurs. Other processes are upward migration of stones induced by freeze-thaw processes causing tundra-polygons. Thus, there are many processes disturbing the soil and also exposing it to erosion.

Taliks, i.e. unfrozen windows in the permafrost region under lakes or rivers, are potentially places near which animals and humans can settle. However, even if the taliks can be potential locations for settlement, the low productivity in the permafrost region requires utilisation of a large area to supply the resources needed by even a small community. Therefore, even if radionuclides are discharged in such areas, this does not necessarily imply that the average concentrations in the areas occupied by humans or in the foods consumed by them will be particularly high.

Glacial conditions

During glacial periods, contact between the biosphere and geosphere will occur only during the restricted periods when the ice sheet is thin over the site. At these times, elevated areas of land can protrude above the ice surface. There, lichens or occasional herbs may thrive. However, the productivity of these areas will be low and, due their position in the landscape, there will be no contact with contaminated water.

On the ice-surface, microbes, algae and some insects can exist. At the ice-margin, a productive aquatic community can also exist. This can sustain a fish population which can be exploited by the animals living on the ice (e.g birds, polar foxes, polar bears) and humans. The populations of vertebrates are likely to migrate over a large area to avoid the worst of the winter climate or to obtain sufficient amounts of food. In most cases, a human population will probably comprise occasional visitors, due to the hostile environment and the variable ice-situation. It is possible that a population could be present for longer periods close to the ice margin along the coast and live on fish. At such a coastal location, the water turn-over time is likely to be short to allow open water to be present and this will give a large degree of dilution. During the glacial domain, no long-term accumulation of radionuclides can occur in the regolith due to the short turn-over time of this potential reservoir. However, at ice-free sites, radionuclides can accumulate from underground sources, as for the permafrost environment.

Next interglacial period

During a glacial cycle, several interstadials can be expected to occur that may be climatically similar to our present interglacial period but usually of shorter duration.

Interstadials are distinguished from present-day environmental conditions mainly by the shore-line displacement. Longer interstadials are considered likely to exhibit a pattern of shore-line displacement with a similar temporal evolution to that which has occurred during the present interglacial period.

Thus, to obtain an idea of the development of a complete interglacial period, the development during Holocene at the sites is used as a representation of a future interglacial period. The main factor of interest is the subdivision between land and sea driven by the shore-level displacement and its consequences in terms of successions of lake-mire-agricultural land and of salinity of the sea.

Forsmark

From deductions of the history of Forsmark /SKB 2006h/ the closest shore-line is expected to be 80 km to the west of Forsmark directly after a deglaciation (comparable to 8,000 BC during the Holocene). The Forsmark area is initially expected to be covered by approximately 150 m of water.

The curve in Figure 9-69 shows that the shoreline in Forsmark has been continuously regressive since the last deglaciation. During the first c 1,000 years after that deglaciation, the regression rate at Forsmark was fast, of the order of 35 mm/year. Thereafter, for about 9,000 years, the regression rate was slower, at around 9 mm/year. After about 10,000 years, the rate was similar to the present land uplift rate at Forsmark, c 6 mm/year /Ekman 1996/. The corresponding succession of sea, lake and land can be followed in Figure 10-6.

The model by /Gustafsson 2004ab/ has, together with proxy records of salinity in the Baltic Proper, been used to make a rough estimate of the likely range of past salinity in the Bothnian Sea, i.e. the basin where the Forsmark area is situated, and thus a projection of future conditions over an interglacial period.

Recent work on sediment cores from Forsmark /Risberg 2005/ indicates that there was limited influence of saline water after the last deglaciation, i.e. during the Yoldia Sea period. Instead, a longer freshwater period, comparable to the Ancylus Lake period, seems to have occurred. Global eustatic sea level rise, in combination with a decreased isostatic rebound in the southern Baltic basin enabled marine water to enter the Baltic basin through the Danish straits about 1,000 years after deglaciation at Forsmark (comparable to the Litorina Sea *sensu lato*). This stage included an initial phase when the salinity was stable and low, the Mastogloia Sea, that lasted for approximately 1,000 years in Southern Uppland before the onset of a more brackish water phase (comparable to Litorina *sensu stricto* /Hedenström 2001/). The salinity was highest about 3,000 to 6,000 years after the deglaciation.

The model by /Gustafsson 2004ab/ uses the runoff to the Baltic Basin and the water exchange over the Danish straits and the Åland sill as driving variables for the salinity. The water exchange is affected by the geometry of the sill, which, in turn, is affected by the shore-level displacement. The difference in estimated salinity during the first 10,000 years between the Baltic Proper and the Bothnian Sea

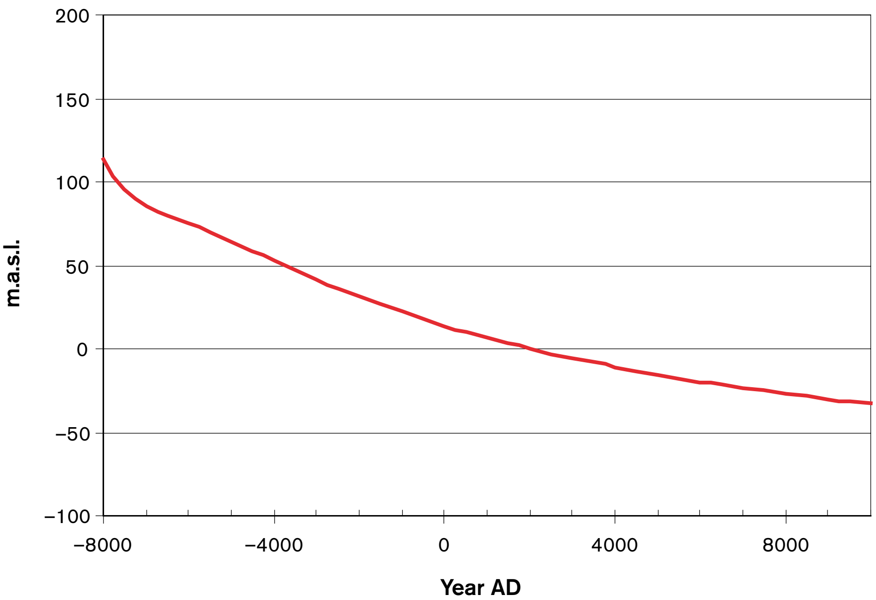


Figure 9-69. *Expected shore-level displacement (metres above present sea level) at Forsmark after deglaciation to the end of the interglacial period. Time scales refer to the Holocene period.*

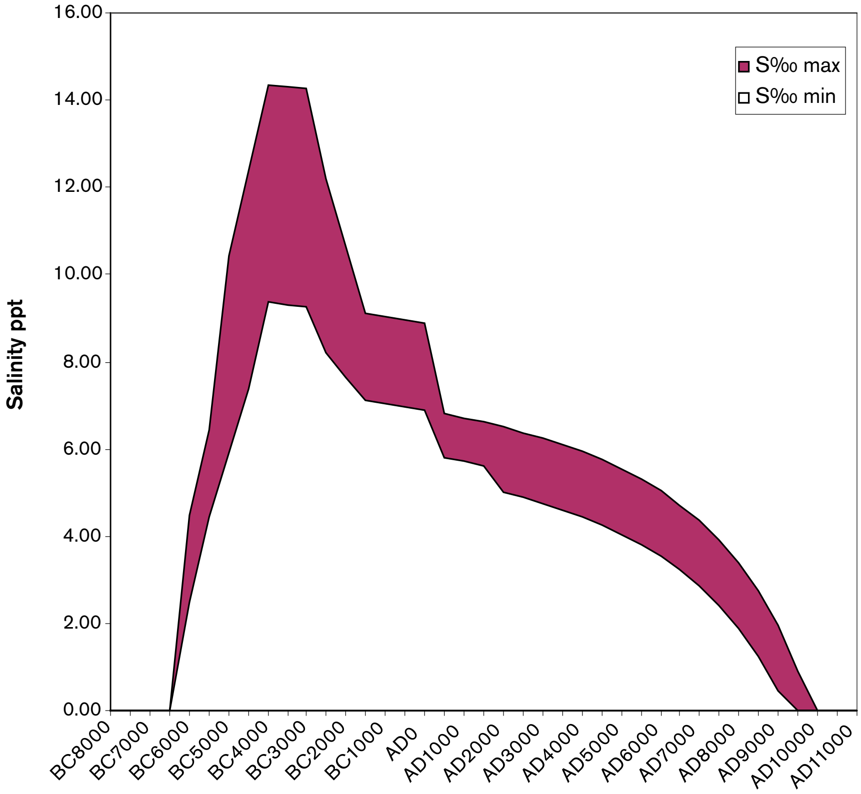


Figure 9-70. *The development of salinity in the Bothnian Sea at Forsmark for an interglacial period. Time scale refers to Holocene. The dark area shows the range of predicted salinity /SKB 2006h/.*

is generally low (< 1 ppt), due to the wide sill in the Åland sea. Due to the narrowing of this sill the difference increases and finally the Bothnian Sea consists of water that is almost fresh more than 17,000 years after deglaciation.

Laxemar

From deductions of the history of Laxemar /SKB 2006i/ the closest shoreline is expected to be 25 km to the west of Laxemar directly after a deglaciation (comparable to 11,000 BC during the Holocene). The Laxemar area is initially expected to be covered by approximately 90 m of water.

The past curve in Figure 9-71 shows that the shore-line in Laxemar has been mainly regressive since the last deglaciation., with some transgressions, e.g after c 3,000 years. After about 7,000 years, the rate was similar to the present land up-lift rate at Laxemar, c 1 mm/year /Ekman 1996/, and in projective modelling it slowly declines until 20,000 years after deglaciation (Figure 9-71). The corresponding succession of sea, lake and land can be followed in Figure 10-9.

The development of the salinity at Laxemar is similar to that at Forsmark, but without influence of the Åland sill. The geometry of the Danish straits is not expected to change sufficiently to affect the salinity of the Baltic Proper for the period beyond 10,000 years after deglaciation. Thus, a maintained salinity of between 6–8 ppt is expected.

Beyond 10,000 years after glaciation, the development of the environment is expected to continue as outlined in section 9.3.3 relating to the temperate climate domain.

9.4.3 Thermal evolution

Introduction

The main factors of importance for repository safety in the permafrost domain are the permafrost and frozen depths, the depth of the isotherm at which the clay buffer freezes, the duration of permafrost or frozen conditions and the possible freezing out of salt that may result in a zone with high salinity beneath the frozen front.

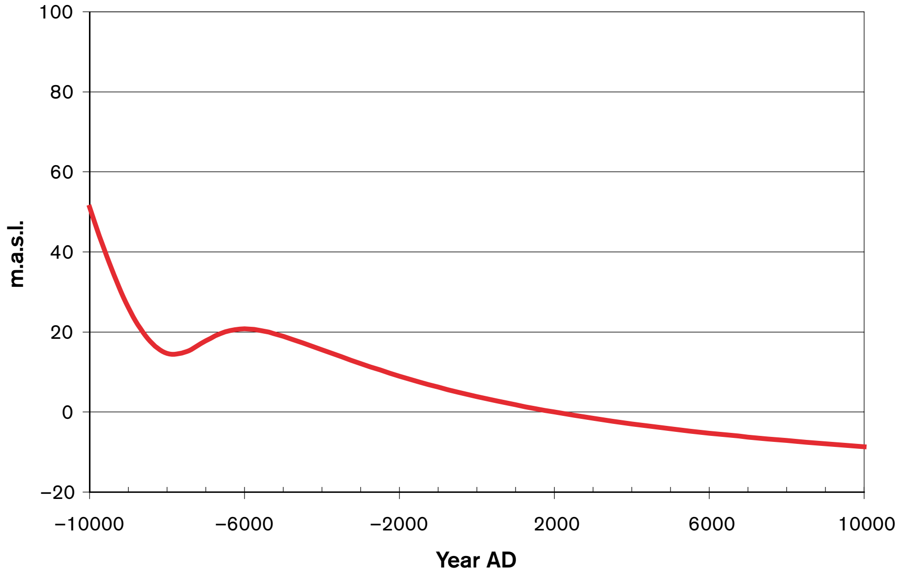


Figure 9-71. Expected shore-level displacement (metres above present sea level) at Laxemar after deglacition to the end of the interglacial period. Time scales refer to the Holocene period.

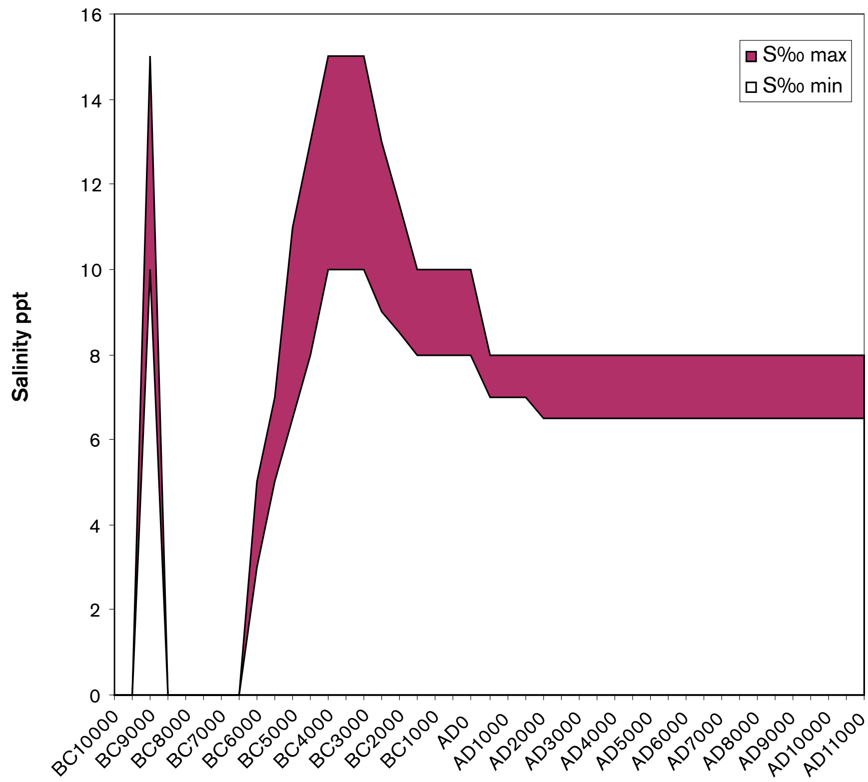


Figure 9-72. The development of salinity in the Baltic Proper at Laxemar for an interglacial period. Time scale refers to the Holocene period. The dark area shows the range of predicted salinity /SKB 2006i/.

Upper bounds on the temperatures at which the buffer and backfill freezes are −5°C and 0°C, respectively, see Figure 9-2. Both salinity (1.858°C/m) and additional hydrostatic pressure (0.075°C/MPa) lower the freezing point. The effect of freezing would be a mechanical pressure on the canister and surrounding rock. This effect can be estimated with Clausius-Clapeyron's equation, meaning that lower freezing temperatures result in a higher freezing-induced pressure, and vice versa.

It is thus of interest to determine the temporal development of the 0°C and −5°C isotherms in the rock during the reference glacial cycle. In addition, the −10°C isotherm is studied in order to illustrate sensitivities to assumptions regarding the safety indicator criterion for buffer freezing.

Permafrost development

The prevailing climate condition is the main factor determining the evolution of permafrost. Mean annual temperature well below 0°C for long periods is a prerequisite for the development of continuous permafrost to a substantial depth. Given climate conditions favourable for permafrost development, the thermal properties of the bedrock and the geothermal heat flow determine the maximum depth to which permafrost can develop.

Gradually colder periods of permafrost domain occur in the early phase of the reference evolution. During the long period of temperate domain that is predominant during the interglacial preceding the first periods of permafrost domain, vegetation including forests have established. It is plausible that this vegetation in part remains in spite of the transition to colder and dryer conditions. The vegetation acts to prevent the development of permafrost. During this initial phase, heat generated by the spent fuel also has a significant effect on the development of permafrost in the repository area /**Climate report**, section 3.4.4/.

Periods of permafrost domain also occur between the two major ice advances when the land has risen above sea level. During this period, vegetation is not established to the same extent as in the early phases of the glacial, and the heat from the residual power of the spent fuel has decreased.

Permafrost modelling

The evolution of permafrost and frozen ground has been investigated by means of numerical modelling. The permafrost model includes freezing and thawing of saturated soil and bedrock as well as the effect of saline groundwater. The bedrock is considered as an elastic porous medium and the groundwater as an ideal solution of water and ionic solvents. The model is based on the principles of continuum mechanics, macroscopic thermodynamics and the theory of mixtures and is capable of describing heat transfer, freezing of saline water, groundwater flow and deformation of the bedrock. The transport of solutes, however, is excluded from the model.

The continuum approach is adequate for modelling of permafrost and frozen ground development, since these processes are primarily governed by heat conduction and only secondarily by groundwater flow. For estimating the possible depth of permafrost and frozen ground, a 1-D approach is applied /Hartikainen 2004/. The 1-D modelling approach could, in certain situations, result in somewhat higher temperatures than would be calculated using a full 3-D approach. Lateral groundwater flow, cooling down the bedrock, is the most important factor that would need 3-D modelling instead of 1-D in the context of permafrost development. However, groundwater flow, as mentioned above, only has a minor role in permafrost development, compared to heat conduction. Furthermore, the anisotropy of thermal properties is not a problem in 1-D, since one can choose a combination of thermal properties that would give lowest temperatures, or at least very close to the lowest temperatures. Therefore, it is not likely that 3-D simulations would yield notably lower temperatures than the range obtained by the full series of 1-D sensitivity modelling simulations that have been performed, see the **Climate report**, section 3.4.4. A description of the permafrost model is found in /Hartikainen 2004/.

An example of temperature input used for calculations of permafrost depth and frozen ground is shown in Figure 9-73. For ice-free periods, it is a regional temperature evolution extracted from the ice-sheet modelling of the reference Weichselian case. For periods when the site is ice covered, basal ice temperatures from the same ice-sheet model simulation were used.

The influence of vegetation has been considered using an empirical relationship between air and ground temperatures for different kinds of vegetation /Lunardini 1978/. The influence of vegetation is further described in the **Climate report**, section 3.4.

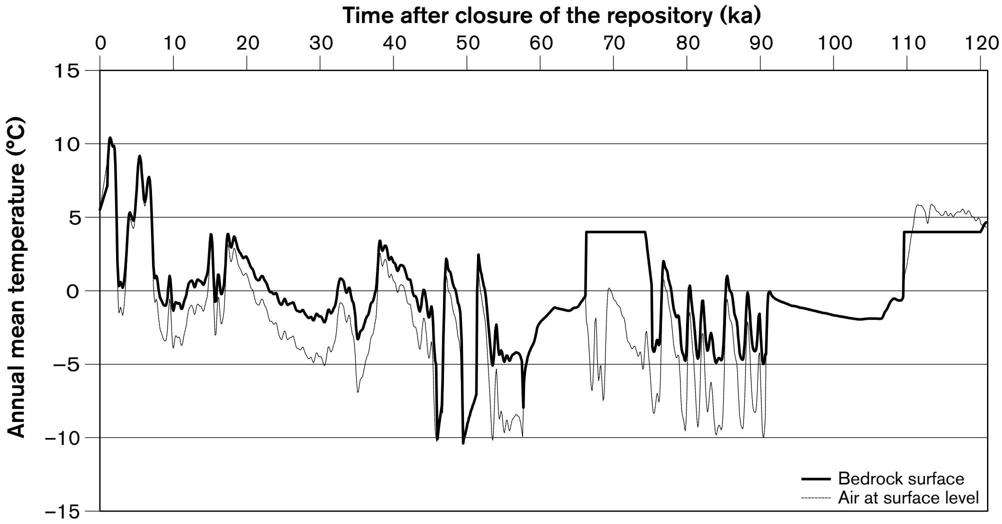


Figure 9-73. *Example of temperature evolution used for calculation of permafrost development. Data shown are for the Forsmark region. The temperature curve from the ice-sheet model has been adjusted for the presence of soil, vegetation, snow and water bodies. For ice-covered periods, the basal ice temperatures from the ice sheet model are used, whereas for the submerged period a constant temperature of +4°C was used, i.e. the temperature at which water is densest and, therefore, the lowest temperature likely to apply to bottom waters over extended periods of time.*

The soil depth (full depth of unconsolidated Quaternary deposits) and properties as well as the sub-surface properties and geothermal heat flow were obtained from the site descriptive models, mainly from Laxemar 1.2 /SKB 2006b/ and Forsmark 1.2 /SKB 2005c/. The results of the calculations of depth of permafrost (0°C isotherm by definition) and frozen ground are presented in Figure 9-74. Also the evolution of the −5°C and −10°C isotherms throughout the reference glacial are shown since these curves are more relevant for the state of the clay buffer.

The calculated maximum permafrost depth at Forsmark and Laxemar are around 250 m and around 160 m, respectively, see Figure 9-74. The −5°C isotherm reaches a depth of around 100 m at Forsmark and 60 m at Laxemar. Furthermore, in the reference evolution the −10°C isotherm reach a depth of 4 m at Forsmark, whereas no ground reaches a temperature as low as −10°C at Laxemar. The greater permafrost depths at Forsmark compared with Laxemar are mainly due to different thermal bedrock characteristics. In addition, the two sites have a different climate/ice sheet evolution caused by their difference in geographical location, which further affects permafrost development. The reconstruction of permafrost during the Weichselian is described in detail in the **Climate report**, section 3.4.4 and 4.2.3.

Conclusion

In conclusion, buffer and backfill freezing at the Forsmark and Laxemar sites is not considered in the reference evolution, based on the above results. Further evaluations of the uncertainties involved in this issue are given in a dedicated scenario, see section 12.4.

9.4.4 Rock mechanics

If the buffer or backfill were to freeze under permafrost conditions, this would imply a mechanical load on the surrounding rock. However, based on the analyses in section 9.4.3, freezing is not included in the reference evolution.

Glaciations will alter rock stresses compared with present-day conditions. The nature of glacially induced stresses depends not only on the ice-load, but also on the crust/mantle characteristics and interaction. Whereas estimating the added vertical stress component is relatively straightforward, it is more complex to assess the horizontal stress component, as this will depend on the evolution and properties of the ice sheet, the thickness and mechanical properties of the crust and the properties of the viscoelastic material that the crust is assumed to rest on.

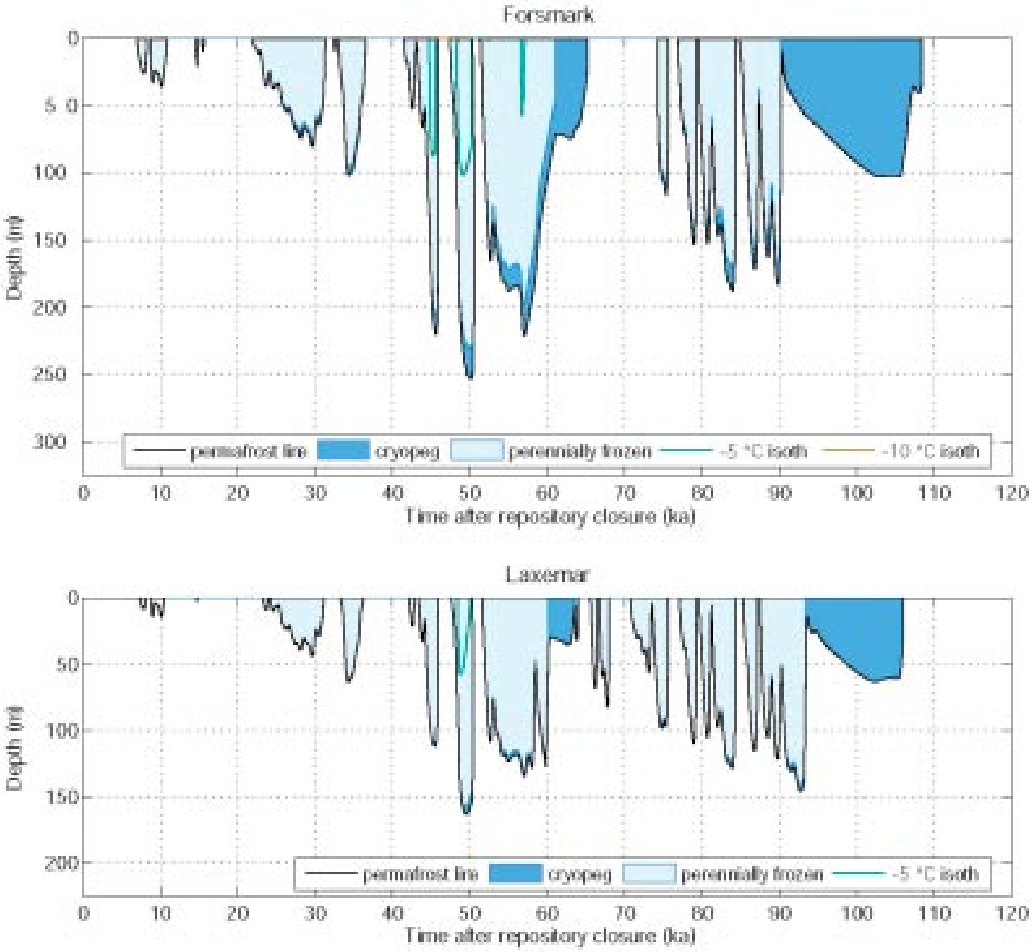


Figure 9-74. *Evolution of permafrost, perennially frozen subsurface, −5°C and −10°C isotherms at Forsmark and Laxemar for the reference glacial cycle. The calculations include heat produced by the spent fuel. The −10°C isotherm is barely seen in the results for Forsmark, whereas it is absent in the Laxemar results. The cryopeg is a volume of rock at sub-zero temperatures, but with unfrozen conditions due to high pressure.*

The load imposed by the ice sheet on the underlying bedrock leads, on the large scale, to downwarping under the ice sheet and upwarping on the margins of the depression (forebulge). This results in the development of bending stresses in the crust. On a small scale, the transient load of the ice sheet will cause an overall increase in total stresses, and an increased confinement. The combination of load from the ice sheet and increased pore pressures means that the effective stress is affected in two counteracting ways:

- An increase in total stress due to the mechanical loading of the ice sheet leads to an increase in effective stress, but
- An increase in pore pressure due to glaciation leads to a decrease in effective stress.

The resulting hydro-mechanical impacts will thus large depend upon how the load of the ice sheet is transmitted to the underlying rock.

The following processes related to the glaciation cycle could have potential safety implications:

- Reactivation of fractures that could affect fracture transmissivity in the far-field and in the near field (safety function R2b).
- Fracturing – potential for hydraulic jacking, that could affect fracture transmissivity (safety function R2b).
- Potential for creep deformation, that could affect the geometry of the deposition holes (safety function R3), which in turn indirectly could affect several of the buffer and canister safety functions.

- Seismicity and faulting, that could imply shear movement of fractures intersecting deposition holes (safety function R3a) and also increase the transmissivity of the sheared fracture (safety function R2b).

The safety implications of these processes except seismicity and faulting are assessed in the following sub-sections. Seismicity and faulting is treated in the dedicated section 9.4.5, including also an assessment of the effects on the buffer and canister.

Reactivation of fractures – hydraulic impacts

/Hökmark et al. 2006/ have examined the impact of the changes in vertical load generated by the last glaciation in Lambeck's ice model /Lund 2005/. When the site is covered by ice there is increased compression, and thus unaltered or reduced transmissivity of all fractures. However, during the melting phase, the analysis shows a 2–4 MPa decompression of steeply dipping fractures after the ice edge has passed. The largest normal load reduction found in their analysis is about 4 MPa. Figure 9-75 shows corresponding transmissivity effects on steeply dipping fractures that are aligned with the present day in situ horizontal principal stresses, using the Forsmark and Laxemar Stress Domain I stresses as examples. Results are shown for two of the stress-transmissivity models described in previous sections. The (worst case) 4 MPa stress reduction was applied in the major horizontal stress direction. In the minor horizontal stress direction the reduction was set to 2 MPa.

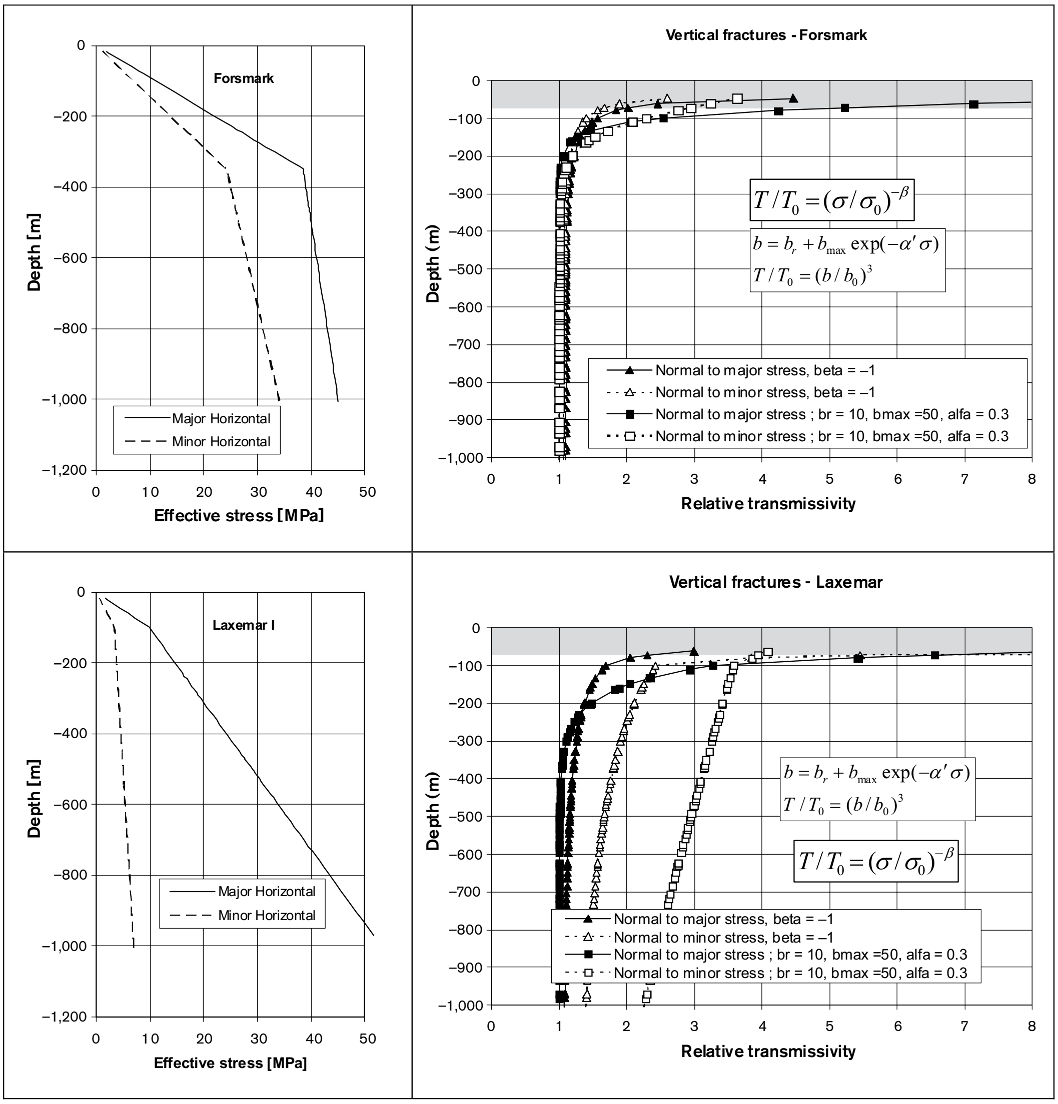


Figure 9-75. *Transmissivity effects of horizontal stress reduction on steeply dipping fractures at Forsmark and Laxemar. The left parts show present-day stress/depth relations derived from the site descriptions.*

The grey shaded bands indicate the depth region in which horizontal effective stresses approach zero and where transmissivity effects become uncertain. At 150 m depth, the transmissivity increased by, at most, a factor of 2 for Forsmark, and a factor of 3.5 for Laxemar. At 400 m depth the increase was negligible for Forsmark and a factor of 3 for Laxemar.

The above suggests that transmissivity changes induced by relaxation of fracture normal stresses during the glacial cycle will be very modest. There is, however, a possibility that there will be high pore pressures under the ice, approximately equal to the ice overburden pressure. Horizontal and subhorizontal fractures will experience only minor changes in effective stress and transmissivity. For steeply dipping fractures the horizontal stress additions will determine whether the effective stresses will increase or decrease. This could possibly imply significant transmissivity increases to rather great depths, but the result is sensitive to many of the assumptions made in the ice stress model. /Hökmark et al. 2006/ noted that preliminary results from new and improved models analyzed taking account of crustal compressibility and with realistic stiffness/depth relations /Lund 2006/ suggest that these issues may not be of significance. The horizontal stress additions under the ice seem to be similar to, or just marginally smaller than, the ice overburden pressure.

Possible changes in fracture transmissivities caused by shear displacements are more difficult to estimate, but /Hökmark et al. 2006/ concluded that the modest shear stress increase for a limited fraction of the fracture population seems to be too small to cause significant and systematic shear displacement. However, an elevated pore pressure may imply an enhanced potential for shearing, as discussed in the next paragraph.

/Hökmark et al. 2006/ discussed the potential for hydraulic shearing due to potentially elevated groundwater fluid pressures during the glaciation. Increasing the fluid pressure in a rock fracture reduces the effective normal stress and shearing is initiated if the pressure is sufficiently high. However, numerical simulations with an H-M model domain encompassing a volume approximately 25 km × 37 km × 4 km (deep), consisting of a sparsely fractured rock mass with a number of fracture zones with different orientations have been conducted within the international DECOVALEX III project /Chan et al. 2005/. These simulations did not indicate any induced hydraulic shearing at the points where stress histories were studied, but the orientations of fracture zones were not the most critical with respect to the stress directions. /Hökmark et al. 2006/ concluded that it is rather obvious, both from these model simulations and from analytical calculations, that some hydraulic shearing is likely to occur during the sequence of advance and retreat of a melting ice sheet. These small-scale shear displacements would, however, not have any significant impact on the overall hydraulic conditions. Since the effective normal stresses across the fractures are rather high, shear dilation is likely to be very small and with insignificant consequence on transmissivity.

Reactivation of fractures – potential hydraulic impacts in the near-field

The transmissivity impacts discussed in the previous section also apply to the near-field. However, to complement these analyses for the near-field scale, the 3DEC near-field rock mechanics analysis of /Hökmark et al. 2006/, see section 9.3.5, also explored the effects of the glacial load. Boundary stresses were obtained from the same simulations of mechanical ice/crust/mantle interactions /Lund 2005/ discussed in the previous section. However, this modelling only included effects of the loading history of the ice sheet, i.e. there are no subglacial water pressures giving rise to coupled H-M effects.

In general, it was found that the normal and shear displacements caused by these loads are of a similar magnitude to the displacements caused by the thermal load, i.e. only very local increases in transmissivity of some of the fractures might occur. However, in addition, the transmissivity of gently dipping fractures can be reduced significantly due to the increased normal load from the ice.

Current models of the crust do not fully reflect that the stiffness of the crust increases with depth. In reality, considering that the stress disturbances in the soft upper part of the crust will be significantly smaller than the schematically estimated stresses from the modelling used as input to the near-field analyses, the transmissivity effects will be less significant. The overall effects summarised by /Hökmark et al. 2006/ and in Figure 9-20 of section 9.3.5, would thus apply also for the glacial situation. Thus, these hydro-mechanical effects can be neglected, in relation to other uncertainties concerning conditions during a glaciation.

Fracturing – potential for hydraulic jacking

Hydraulic jacking of a fracture is initiated when the effective normal stress across the fracture becomes tensile, on condition that the fracture has no tensile strength. This is the same mechanism as hydraulic fracturing, which is a standard operation in the petroleum industry carried out in wells for improving oil or gas recovery from reservoir rocks and in rock stress measurement. Large-scale hydraulic stimulations are also carried out in geothermal energy projects where pressurised fluid is injected in fractured crystalline rock masses in order to create increased rock mass permeability.

When jacking occurs, the fracture surfaces separate from each other and the fracture aperture may be very large. Jacking can be expected to continue as long as there are tensile conditions in the fracture. Except for horizontal or sub-horizontal fractures close to the ground surface where the overlying rock can potentially be lifted, the maximum aperture resulting from the process is limited by the deformation potential of the rock mass surrounding the dilating fractures. According to /Hökmark et al. 2006/, it is generally assumed that the normal dilation resulting from jacking is a reversible process, as long as there is no associated shear component and no solid particles are introduced by the fluid. At the edge of an ice sheet, glaciofluvial sediments can be expected to be transported into the fractures that are jacked open.

As further discussed by /Hökmark et al. 2006/ evidence or at least strong indications for such glacial/postglacial hydraulic jacking events can be found at several sites in Sweden where drillhole records and excavations show subhorizontal fractures, filled with glaciofluvial material, down to some tens of metres in the crystalline bedrock. In the Forsmark area, such sediment-filled fractures have been observed down to a few tens of metres /SKB 2005c/.

/Hökmark et al. 2006/ discussed at what depth hydraulic jacking may occur. Numerical simulations carried out as a part of the international DECOVALEX III project /Chan et al. 2005/, investigated the potential occurrence of tensile failures in site-scale H-M models by studying the evolution of the minimum effective stress for selected points. There was a significant compressive effective vertical stress in the horizontal fracture during the entire glacial cycle, i.e. no hydraulic jacking occurred. Theoretically, hydraulic jacking can occur at great depth if specific conditions are fulfilled. The conditions promoting such a situation are:

- A steep slope of the icesheet front.
- High meltwater pressures at the ice-sheet bed.
- Conductive steeply dipping rock fractures beneath the part of the ice sheet that is melting.
- Horizontal or shallowly dipping high-permeable rock fractures leading towards a position beyond the ice margin.

From the hydrological perspective, the conditions that are most favourable to hydraulic jacking occur during deglaciation. However, a retreating ice sheet is expected to have a rather flat profile, compared with an advancing or steady-state ice sheet. For example, ice-sheet modelling carried out by /**Climate report**/ showed that an ice thickness of 200 m, which could be sufficient to give rise to water pressures high enough to induce hydraulic jacking beyond the ice front at 125 m depth, is during deglaciation not expected closer than some kilometres from the ice margin. This calculation cautiously presupposes that the basal water pressure head is equal to the ice thickness.

However, it cannot be completely ruled out that melting conditions giving rise to high sub-glacial water pressures can occur also during specific phases of the ice-sheet advance when the slope of the ice sheet is much steeper. This may theoretically lead to potential jacking at larger depths. A calculation of the shape of a steady state ice sheet /Patterson 1994/ gives a ice thickness of 350 m at a distance of 1,000 m from the margin. This thickness yields a critical depth where jacking can occur of about 220 m, with the same assumptions as above.

In order for the hydraulic pressure to be transmitted through the rock mass over such a distance, horizontal or sub-horizontal connective fractures of great length and width are required. Connecting permeable fractures in all directions, as well as friction losses, would in reality significantly reduce the fluid pressure. Neither Forsmark nor Laxemar has geological/hydrogeological conditions favouring the initiation of hydraulic jacking at depth.

If conditions for hydraulic jacking are fulfilled this is likely to occur at shallow depths in the first place. This will in turn act to reduce pressures so that jacking at larger depths becomes less likely.

As noted above, evidence of, or at least strong indications for, such glacial/postglacial hydraulic jacking events can be found down to some tens of metres in the crystalline bedrock at several sites in Sweden where drillhole records and excavations show subhorizontal fractures filled with glaciofluvial material. It is likely that the jacking effect will be preserved by the high density and viscosity of a meltwater/sediment slurry. The depths at which the observations have been made are in accordance with the discussion above.

In conclusion, studies of hydraulic jacking initiation at shallow depths, as well as the resulting transient effect in terms of enhanced fracture transmissivity, are of interest in order to create a increased understanding of glacial H-M effects. The effects are insignificant for the repository evolution.

Potential for creep deformation

As further discussed in section 4.5 of the **Geosphere process report** creep deformation of the rock mass may be neglected also for the mechanical loads that may occur during permafrost or glaciation. The process is neglected for the same reasons as for the temperate periods, see section 9.3.5. During the glaciation cycle, stresses will be higher /Hökmark et al. 2006, Lund 2005/ but not sufficiently to change the outcome of the estimates.

9.4.5 Canister failure due to shear movements

Introduction

One of three identified failure modes of the canister is that due to a rock shear movement across a deposition hole. The safety function C3 in Figure 9-2 relates to the ability of the canister to withstand such loads. The buffer is designed to damp rock shear, safety function requirement on the buffer in this context is that its saturated density should be below 2,050 kg/m^3. An integrated evaluation of the response of the buffer and canister to rock shear has lead to the criterion that the shear movement should not exceed 10 cm, safety function R3a.

The magnitudes of shear movements due to earthquakes is discussed in /Munier and Hökmark 2004/. The main conclusion is that if the canister is positioned beyond a respect distance from a deformation zone that could host a major earthquake, and the canister is not intersected by large fractures, earthquakes in the vicinity of the repository will not affect canister integrity. An essential aspect of seismic safety is thus to ensure that canisters will not be intersected by discriminating fractures, presently defined as fractures having radii exceeding 75 m using a 100 m respect distance and 150 m using a 200 m respect distance /Munier and Hökmark 2004, Fälth and Hökmark 2006/.

All these aspects of this failure mode are treated in more detail below, following a discussion of the likelihood of large earthquakes throughout a glacial cycle.

Occurrence

Glacially induced faulting, commonly referred to as “postglacial faulting” and commonly abbreviated “PGF”, occurs in glaciated regions in response to changes in the glacial load: either as a result of deglaciation (crustal unloading) or glacial advance (crustal loading). Glacially induced faulting has been reported from northwest Europe (Norway, Sweden, Finland, Russia, Eire, and Scotland) and North America (eastern Canada, New England, and possibly California and Montana). To date, all examples of glacially induced faulting have been recorded in regions of low to moderate seismicity, namely passive margin, failed rift, or intraplate/craton environments such as Sweden. With the notable exception of the 1989 M6.1 Ungawa surface rupture /Adams et al. 1991/, glacially induced faults are unique in that they occur in regions where there is no evidence of surface rupture during historical time. In addition, these regions have no historical record of seismicity that approaches the magnitude thresholds for generating surface faulting. To date, all examples of glacially induced faulting have involved reactivation of existing faults and fractures.

Glacially induced faulting was not reported in Europe until comparatively recently /Tanner 1930, Kujansuu 1964/. Subsequent to the work of /Lundquist and Lagerbäck 1976/ on the Pärvie 1976 fault several other, equally spectacular examples of postglacial faulting were discovered in northern Sweden /e.g. Lagerbäck 1979, Lagerbäck 1988/. Meanwhile, in Finnmark, northern Norway, the Stuoragurra fault was discovered and shown to be postglacial in age, using a combination of geophysical and geologic techniques /Olesen et al. 1989, 1992, Dehls et al. 2000/. The NEONOR project of NGU (Norges

Geologiske Undersøkelse) characterised a number of glacially induced faults that were summarised into a catalogue /Dehls et al. 2000/. In Finland, the Pasmajärvi and several other faults were the subject of intensive investigation /Paananen 1987, Vuorela et al. 1987, Kuivamäki et al. 1998/. SKB spurred further work on glacially induced faulting in Sweden using a wide variety of geological and geophysical techniques /e.g. Bäckblom and Stanfors 1989/. In particular, fault trenching and detailed age-dating investigations demonstrated that the exhumed faults (Figure 9-76) were displaced in a single event following deglaciation /Lagerbäck 1992/ which was later also argued for by /Arvidsson 1996/. This does, however, not rule out the possibility of multiple events, though we are not aware of any evidence in support of this possibility having been realized.

To date, the spectacular postglacial faults in northern Sweden are the most convincing examples of glacially induced faulting. Although there have been numerous claims of glacially induced faulting in southern Sweden /Mörner 1989, 2003/, many are questionable /Carlsten and Stråhle 2000, Wänstedt 2000/. /Muir Wood 1993/, evaluated claims for neotectonic activity throughout Fennoscandia. Only the postglacial faults of Lapland were considered unequivocally the result of neotectonic activity.

Within the framework of the SKB site investigations, a targeted investigation programme was initiated in 2002, aimed at tracing possible glacially induced fault movement. As no major distortions that could be associated with seismically induced liquefaction were identified, it was concluded that no major

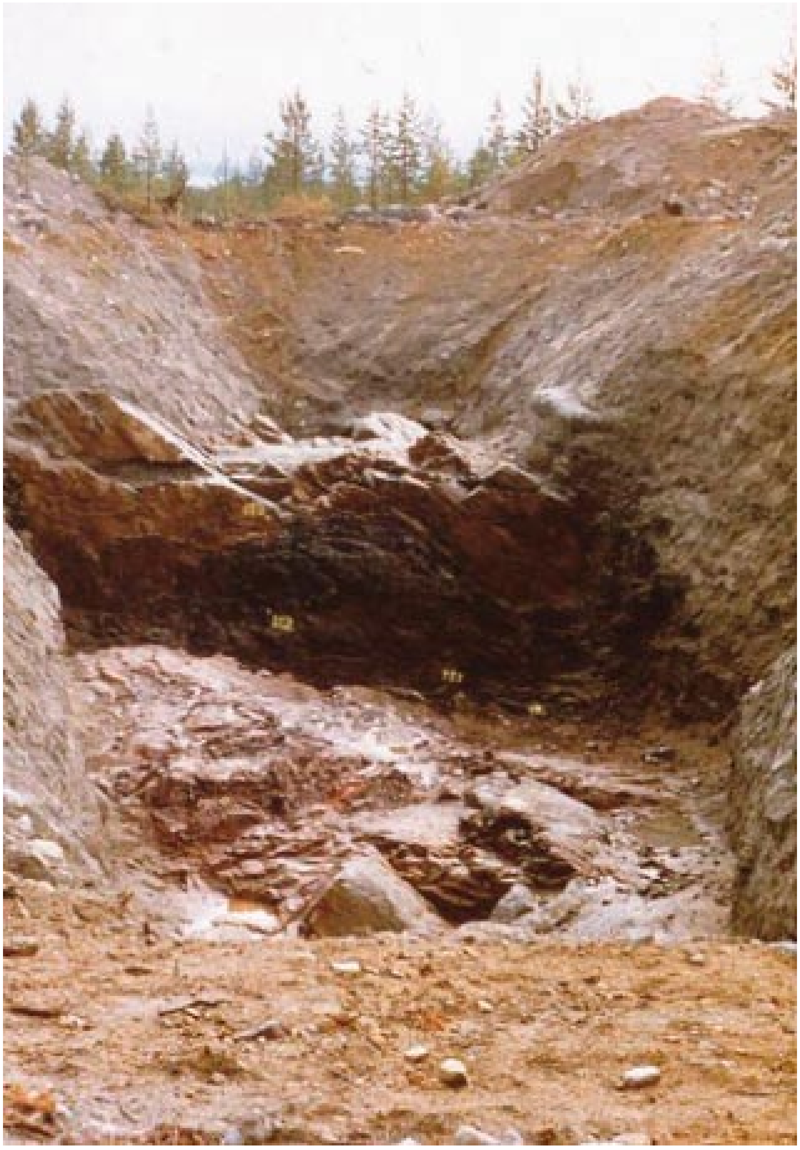


Figure 9-76. *View looking SE of one of three trenches excavated across the Molberget fault, near Lansjärv. The scarp height is about 5 m.*

(M > 7) earthquakes had occurred in the Forsmark area after the disappearance of the last ice sheet /Lagerbäck et al. 2004/. The summary report for the Oskarshamn region has not yet been completed, but ongoing investigations /Lagerbäck et al. 2005/ have not yet produced any information that would result in a different conclusion to that for the Forsmark region.

Additionally, ongoing analyses of fracture mineralisation at Forsmark indicate that, with the exception of the near-surface rock, no fracture reactivation can be demonstrated to have occurred later than Caledonian /Sandström et al. 2004/ (Tullborg pers. comm.).

The possibility of predicting future glacially induced faulting is associated with large uncertainties, which increase with increasing time span. Yet, as argued above, there is an abundance of relatively strong arguments for assuming that the probability of large earthquakes local to the sites is low or very low during a glacial cycle. An expert elicitation project conducted by SSI /Hora and Jensen 2005/, indicated that on average $3.0 \cdot 10^{-2}$ earthquakes of magnitude 6 or greater is estimated to occur within 5 km radius of any of the sites during a glacial cycle (see also section 9.3.5). The SSI project was aimed at testing the elicitation procedure rather than providing an answer on earthquake probability and the relatively limited resources given to the experts to respond to the question is noted. However, the remarkable similarity in the experts' opinions, despite disparate approaches to the problem, is seen as an indication that the estimated probability of occurrence is likely to be realistic.

Future earthquakes are anticipated to cluster along deformation zones. The probability of any zone to host an earthquake may be estimated by dividing the probability estimated for the circular area with the number of deformation zones within that area. Between $8.2 \cdot 10^{-3}$ /using La Pointe et al. 1999/ and $4.5 \cdot 10^{-2}$ /using Bödvarsson et al. 2006/ earthquakes of magnitude 6 or larger are anticipated during a 120,000 year glacial cycle (see section 9.3.5 and Table 9-5). If these events are distributed among the 19 high and medium confidence deformation zones within the Forsmark area (Figure 9-77, Table 9-11), the probability of any zone to reactivate within a 5 km radius from the centre of the Forsmark site, and within a glacial cycle, is between $4.3 \cdot 10^{-4}$ and $2.4 \cdot 10^{-3}$. Similarly, if these events are distributed among the 33 high and medium confidence deformation zones within the Laxemar area (Figure 9-78, Table 9-12), the probability of any zone to reactivate is between $2.5 \cdot 10^{-4}$ and $1.4 \cdot 10^{-3}$.

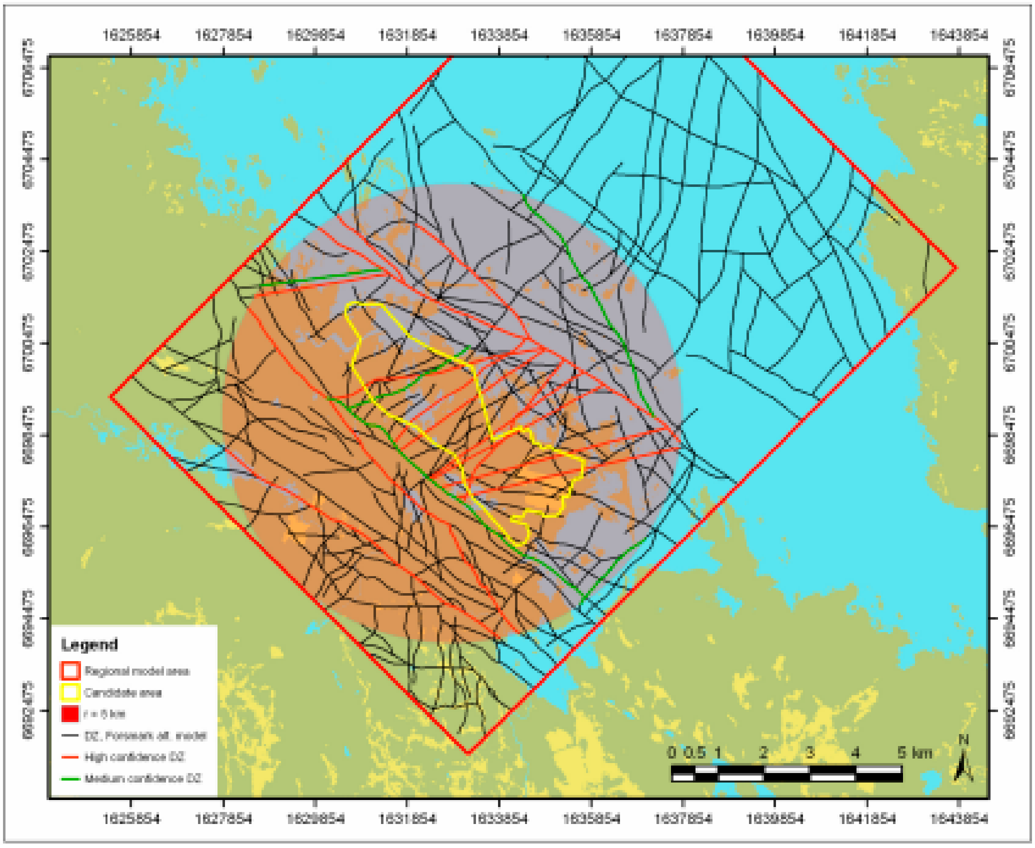


Figure 9-77. *High and medium confidence deformation zones within a circular area (radius = 5 km) centred at Forsmark. The deformation zones are listed in Table 9-11.*

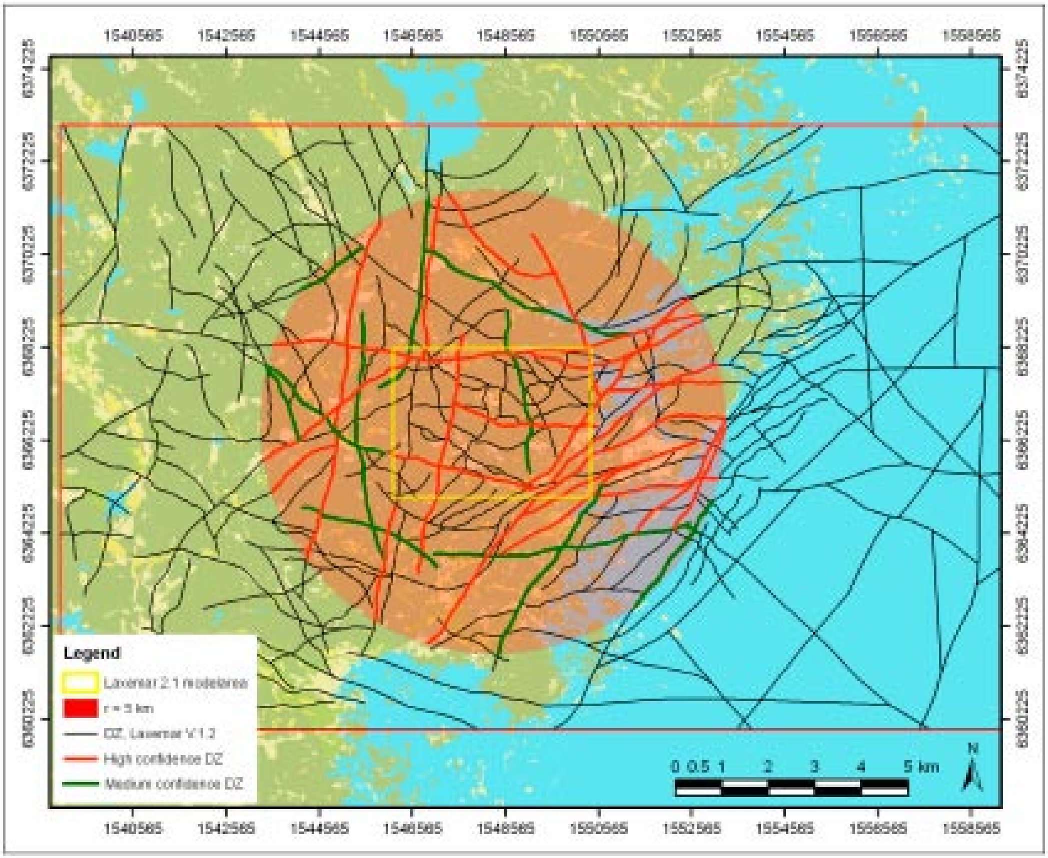


Figure 9-78. High and medium confidence deformation zones within a circular area (radius = 5 km) centred at Laxemar. The deformation zones are listed in Table 9-12.

Table 9-11. The 19 deformation zones entirely or partly within a circular area with a 5 km radius displayed in Figure 9-77.

Zone ID	Confidence	Zone ID	Confidence
ZFMNE00A1	Medium	ZFMNE1193	High
ZFMNE00A2	High	ZFMNW0001	High
ZFMNE00A3	High	ZFMNW0002	High
ZFMNE00A4	High	ZFMNW003A	High
ZFMNE00A5	High	ZFMNW004A	High
ZFMNE00A6	High	ZFMNW017A	Medium
ZFMNE00A7	High	ZFMNW0805	High
ZFMNE062A	High	ZFMNW0806	Medium
ZFMNE0065	High	ZFMNE0060	Medium
ZFMNE0828	Medium		

Table 9-12. The 33 deformation zone entirely or partly within a circular area with a 5 km radius displayed in Figure 9-78.

Zone ID	Confidence	Zone ID	Confidence
ZSMNE073A	Medium	ZSMEW023A	High
ZSMNW933A	High	ZSMNE313A	Medium
ZSMNS064A	Medium	ZSMNW042C	Medium
ZSMNS046A	Medium	ZSMNE011A	High
ZSMNS057A	Medium	ZSMNW075A	Medium
ZSMNS059A	High	ZSMEW013A	High
ZSMNW060A	Medium	ZSMNW042A	High
ZSMNS001D	High	ZSMNE021A	Medium
ZSMNS001A	High	ZSMNE024A	High
ZSMNW254A	Medium	ZSMEW038A	High
ZSMNS009A	High	ZSMEW007A	High
ZSMNE010A	High	ZSMNE012A	High
ZSMNE930A	High	ZSMEW002A	High
ZSMNW931A	High	ZSMNE004A	High
ZSMNE019A	High	ZSMNE031A	High
ZSMEW020A	Medium	ZSMNE005A	High
ZSMNW322A	Medium		

It is here assumed that all deformation zones have equal probability of reactivating, which, most certainly, is not the case. The prerequisites for reactivation are determined by the evolving stress field during a glacial cycle and the mechanical and geometrical properties of the deformation zones. It is possible that the prerequisites for triggering an earthquake will not be fulfilled for some, perhaps most, of the zones. Additionally, we have averaged over deformation zones regardless of their size whereas in fact each zone can only host a certain maximum magnitude event. this issue will be addressed in awaited results from ongoing simulation efforts /e.g. Lund 2005/, but, in the interim, the cautious assumption used here is judged adequate for the SR-Can assessment.

Canister failures due to postulated shear movements

The buffer material in a deposition hole acts as a cushion between the canister and the rock, which reduces the effect of a rock shear substantially. Lower density of the buffer yields softer material and reduced effect on the canister. However, at the high density that is suggested for a repository the stiffness of the buffer is rather high. The stiffness is also a function of the rate of shear, increasing with increased shear rate, which means that there may be a substantial damage on the canister at very high shear rates.

In order to investigate the stiffness and shear strength of the buffer material a number of laboratory test series has been performed with shearing of water saturated bentonite samples at different densities and shear rates. From those tests a material model of the buffer that takes into account the density and shear rate has been formulated. Shear rates up to 6 m/s have been tested /Börgesson et al. 2004/. The effects of faulting on buffer, copper shell and cast iron insert along a fracture intersecting a deposition hole was also subject to a first analysis, through simulations with a finite element model.

/Börgesson and Hernelind 2006/ have made new calculations using an improved finite element model. The finite element code ABAQUS was used for the calculations. Figure 9-79 shows the resulting deformation after 20 cm rock displacement of the entire model, which consists of three parts: bentonite buffer, copper canister and cast iron insert. The rock is not modelled but assumed to be rigid.

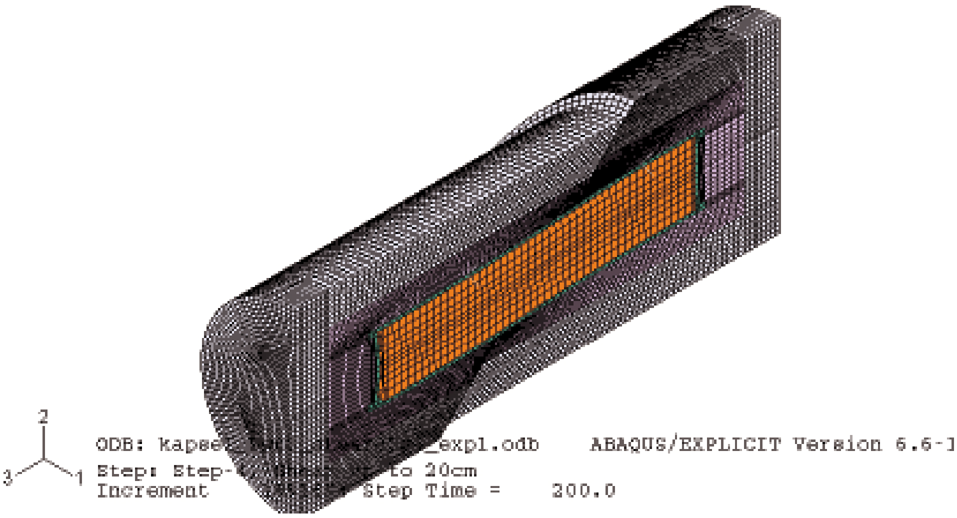


Figure 9-79. *Ca-bentonite;* ρ_m *= 2,050 kg/m*^{3}*; 45° tension shear. Results after 20 cm shear.*

The calculations include both sodium and calcium bentonite as buffer materials. The rock movements considered are shear movements at 90° angle to the length axis of the canister and either at the middle of the canister or at ¼ of the canister length. The calculations also include cases where the angle of the shear movement was 22.5° and 45° to the length axis of the canister and, for these cases, through the middle of the canister. This gives rise to two distinct cases for each shear angle. They are referred to as the compression and tension modes. In the compression mode, the shear movement will result in a reduction of the height of the deposition hole, while the tension mode will result in an increase of the height. The two shear modes are illustrated in the sketch in Figure 9-80. The shear plane was assumed to go through the centre point of the canister.

The analysis by /Börgesson and Hernelind 2006/ provides the stress and plastic strain of the copper shell, the insert and the buffer immediately after shearing. A summary of the results is given in Table 9-13A for the case of sodium bentonite and in Table 9-13B for the case of calcium bentonite. The tables show the maximum plastic strain in the copper tube (excluding the lid) and in the cast iron at two different slips (10 and 20 cm).

Table 9-13A. Calculated maximum plastic strain in the copper tube and in the cast iron insert at rock displacement of 10 and 20 cm (eccentric = shear at ¼ of the canister length and centric = shear at the middle of the canister). Sodium bentonite.

ρ_m (kg/m^3)	Shear angle (°)	Shear direction/ location	Maximum plastic strain (%)			
			After 10 cm shear		After 20 cm shear	
			Cu-tube	Fe-insert	Cu-tube	Fe-insert
2,000	22.5	compression	0.2	< 1	0.3	< 1
2,000	22.5	tension	2.5	< 1	3.3	< 1
2,050	22.5	compression	0.3	< 1	0.4	< 1
2,050	22.5	tension	3.5	< 1	4.6	< 1
2,000	45	compression	0.5	< 1	0.6	< 1
2,000	45	tension	3.5	< 1	5.0	< 1
2,050	45	compression	0.8	< 1	1.5	< 1
2,050	45	tension	5.5	< 1	8.0	< 1
2,000	90	centric	0.2	< 1	0.3	< 1
2,000	90	eccentric	1.2	< 1	2.0	1.7
2,050	90	centric	0.4	< 1	0.5	< 1
2,050	90	eccentric	1.2	1.3	2.5	3.6

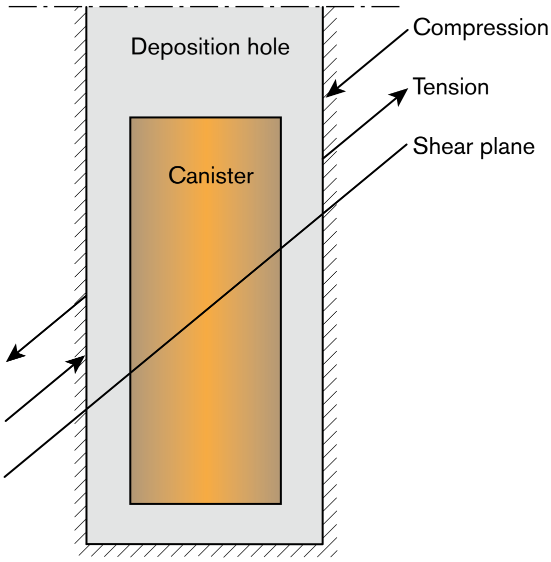


Figure 9-80. *Illustration of the compression and tension shear modes.*

Table 9-13B. Calculated maximum plastic strain in the copper tube and in the cast iron insert at rock displacement of 10 and 20 cm (eccentric = shear at ¼ of the canister length and centric = shear at the middle of the canister). Calcium bentonite. Red figures indicate violation of failure criterion.

ρ_m (kg/m^3)	Shear angle (°)	Shear direction/ location	Maximum plastic strain (%) After 10 cm shear Cu-tube	After 10 cm shear Fe-insert	After 20 cm shear Cu-tube	After 20 cm shear Fe-insert
2,000	22.5	compression	0.4	< 1.0	0.6	2.8
2,000	22.5	tension	4.4	< 1.0	6.0	< 1.0
2,050	22.5	compression	1.0	3.6	2.5	**11.0**
2,050	22.5	tension	6.4	< 1.0	10	1.5
2,000	45	compression	1.5	< 1.0	2.0	2.9
2,000	45	tension	7.5	< 1.0	11.0	1.4
2,050	45	compression	4.5	1.7	10.0	5.9
2,050	45	tension	10.0	< 1	19.0	4.0
2,000	90	centric	1.2	< 1	2.5	1.5
2,000	90	eccentric	2.5	2.3	6.5	4.9
2,050	90	centric	7.2	5.4	16.0	**13.0**
2,050	90	eccentric	5.5	2.4	13.5	**7.0**

Failure of the canister due to tensile strain

The current specifications for the copper canister state that the copper material must have a ductility of at least 30%. For the cast iron insert, the ductility must be at least 7%. As can be seen in Table 9-13A and B, the canister resists a 10 cm rock displacement for a saturated bentonite density of 2,050 kg/m^3 with a margin. Also for a rock displacement of 20 cm at a bentonite density of 2,000 kg/m^3 the strain levels are well inside the specifications. The strain levels in the copper canister lid and bottom were locally higher than in the copper tube. The largest plastic strain, 19% was found for ρ_m = 2,050, 22.5° and compression for a 10 cm shear movement. This is, however, still within the ductility limit of the copper material. The reason for this is not yet fully understood, but since the largest local strains were frequently found in the flange regions of the lid and bottom, the present design of these components could be the reason. Alternatively, the finite element model may have to be refined further in this region in order to give an accurate picture of the stress and strain states.

Failure of the canister due to creep

The current specifications for the copper canister state that the copper material must have a creep ductility of at least 10%. /Hernelind 2006/ has supplemented the calculations by /Börgesson and Hernelind 2006/ by including creep relaxation of the stresses that were introduced into the copper shell. For the case of 2,000 kg/m^3 bentonite the resulting creep strain was 7.6% for a 0.1 m shear movement and 11.5% for a 0.2 m shear movement. With reasonable safety margins, the canister will withstand a 10 cm shear movement horizontally across the deposition hole. For a 0.2 m shear movement, creep failure of the copper shell cannot be totally excluded based on the results obtained with the current creep model. Work aiming at improving the creep model is in progress and it is at this stage too early to draw any definite conclusions.

Dependence on shear velocity

A typical value of the average shear velocity for an intermediately sized earthquake, M5–M6, is roughly 1 m/s /e.g. Bullen and Bolt 1985, Lay and Wallace 1995, Madaragia and Olssen 2002/. Larger earthquakes, such as the 1999 Chi-Chi earthquake (M7.6), displayed similar values near the hypocentre though the *maximum* shear velocity reached roughly 2.5 m/s near the surface /Ma et al. 2003/. For the 1995 Kobe earthquake (M7.2), /Ide and Takeo 1997/ quoted a 0.8 m/s average shear velocity at the southern part of the fault. For the Landers earthquake (M7.2), the *maximum* velocity was estimated to 1.5 m/s /Wald and Heaton 1994/.

The structures of interest, however, are those that could be missed during mapping of tunnels and deposition holes. These are not sufficiently large to host events of larger than M4 to possibly M5. The value of 1 m/s used for the canister failure simulations can thus be regarded as a realistic estimate.

Summary of influencing factors and further studies in SR-Site

There are a number of factors that influence the calculated impact of a postulated rock shear movement on the canister. Table 9-14 is an account of how these have been treated to date and of how they will be further addressed in a probabilistic study in support of the SR-Site project.

Table 9-14. Factors influencing impact of shear movement.

Factor	Early deterministic study /Börgesson et al. 2004/	Extended deterministic studies /Börgesson and Hernelind 2006, Hernelind 2006/	Probabilistic study (SR-Site)
Rock slip.	Range studied; pessimistic value (0.2 m) used for conclusions.	10 and 20 cm.	Several cases covering range.
Shear velocity.	Best estimate.	Best estimate.	To be determined.
Buffer density.	Range studied; pessimistic value (2,050 kg/m^3 at saturation) used for conclusions.	Same range as in early study.	Several cases covering range.
Location of impact.	Two values studied; pessimistic value (impact on end section) used for conclusions.	Same range as in early study.	To be determined.
Insert material properties.	Reasonably pessimistic deterministic values.	Reasonably pessimistic deterministic values.	Distribution of properties.
Angle of intersection.	Pessimistically assumed perpendicular intersection.	Perpendicular, 22.5° and 45°.	Perpendicular.
Buffer material properties.	Unaltered properties.	Na and Ca bentonite, cementation effects and uncertainties in material properties, addressed through altering the shear strength of the buffer.	Unaltered properties.
Creep of copper canister.	Not included.	Included through preliminary model.	Updated creep model.

Conclusions

- Based on the above results, a rock shear movement exceeding 10 cm is used as failure criterion in SR-Can. In view of the current knowledge cited above, this criterion is robust and most probably overly pessimistic.
- In this reference evolution, the buffer is assumed to have reference saturated density, i.e. in the range 1,950–2,050 kg/m^3. Effects of possible densities outside this limit and other uncertainties are further addressed in a dedicated scenario, see section 12.9.

Calculation of pessimistic intersection probability

A method for estimating the probability of intersection between a canister and a discriminating fracture has been presented in /Hedin 2005/. Using site-specific DFN models, it is possible to estimate the number of canisters that, on average, will be intersected by such fractures if they are not avoided by an active deposition strategy based on fracture signatures in or close to the deposition holes. A discriminating fracture is defined as one that could possibly slip more than 10 cm in case of a nearby earthquake of a magnitude, M_L, equal to or exceeding 6 /Munier and Hökmark 2004/.

The layout has been based on a respect distance of 100 m, based on /Munier and Hökmark 2004/, which required deposition holes located within a band 100 to 200 m from a deformation zone (see Figure 9-81) capable of hosting a major earthquake to be discriminated against if they were intersected by fractures with radii exceeding 50 m. Deposition holes positioned more than 200 m from any deformation zone are, according to /Munier and Hökmark 2004/, to be discriminated against if they are intersected by fractures with radii exceeding 100 m. However, recent simulations /Fälth and Hökmark 2006/ demonstrated that the size of discriminating fractures can be increased to 75 and 150 m respectively, if fracture friction is also taken into account, in contrast to the friction-free assumption used in /Munier and Hökmark 2004/.

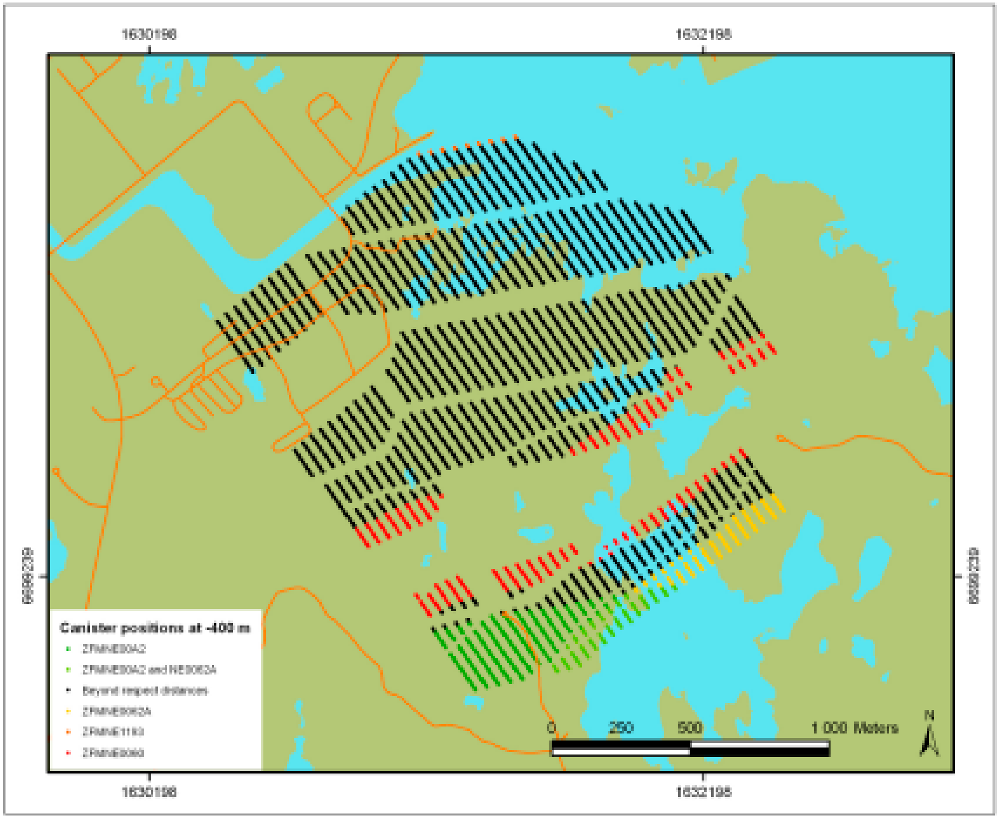


Figure 9-81. *Deposition tunnel sections with canister positions within a band 100–200 m from deformation zones (Forsmark).*

Using the method described by /Hedin 2005/, the calculated fraction of canisters being intersected by discriminating fractures, *ε*, of radius larger than 75 m is about 1.5% using best estimate parameter values from the geological DFN model of rock domain RFM029 in Forsmark /**Data report**, section 6.3/ and additional data given in Table 9-17. It is emphasized that *ε* is the expected fraction of canisters intersected by discriminating fractures if no deposition positions are discarded. In reality, a substantial fraction of these positions are expected to be found and rejected. That is, *ε* is not to be confused with the degree of utilization.

The 1.5% of canisters intersected refers to positions in the 100 to 200 m band (Figure 9-81). For positions farther away from the large deformation zones, the corresponding figure is 0.28%.

Table 9-15 lists the number of canisters within the 100–200 m band for all deformation zones requiring respect distances, within the Forsmark repository. Note that the number of canisters obtained from the design in /Brantberger et al. 2006, SKB 2004b Appendices A–C/ exceeds 6,000 to reflect loss of positions due to intersection with large fractures, but also considers high water inflow to the canister holes and spalling /SKB 2004b/. These numbers are here normalised to 6,000 canisters.

Zone ZFMNE0060 affects the largest number of canisters (495). Should this particular zone host an earthquake, we may, using ε as defined earlier, compute the *maximum* number of canisters that could be damaged as 1.5% · 495 + 0.28% · 5,505 ≈ 23 canisters. Should, instead, the earthquake occurs along one of the 15 zones with no canisters within the 100–200 m band, the maximum number of canisters that could be damaged is 0.28% · 6,000 ≈ 17. The four zones in Table 9-15 contain a total of 1,166 canisters within their 100–200 band. Averaged over all 19 zones, each zone will contain 61 canisters within the 100–200 band. We may thus compute the *mean* number of affected canisters as 1.5%·61 + 0.28% · 5,939 ≈ 17 canisters for each seismic event. Note that the mean number of canisters within the band is averaged over 19 zones, not the 4 zones listed in Table 9-15.

Similarly, Table 9-16 lists the number of canisters within the 100–200 m band for all deformation zones requiring respect distances, within the Laxemar repository (Figure 9-82). The zone ZSMEW007A affects the largest number of canisters (693), and we may compute the *maximum* number of canisters that can be damaged as 2.65% · 693 + 0.5% · 5,307 ≈ 45 canisters. Should, instead, the earthquake occurs along one of the 28 zones with no canisters within the 100–200 m band, the maximum number of affected canisters is simply 0.5% · 6,000 ≈ 30. The 5 zones in Table 9-16 contain a total of 1,535 canisters within their 100–200 band. Averaged over all 33 zones, each zone will contain 47 canisters within the 100–200 band. We may thus compute the *mean* number of affected canisters as 2.75% · 47 + 0.5% · 5,953 ≈ 31 canisters for each seismic event.

Note that in the calculations presented here, all fractures with radii exceeding 250 m (Table 9-17) are assumed to be readily observable in tunnels, using traditional mapping and geophysical measurements /Cosgrove et al. 2006/. For details on this and other assumptions, see /Hedin 2005/.

The fractures of interest, from this perspective, are those that are assumed not to be readily detectable in tunnels. In the present calculation, all fractures with radii exceeding 250 m (maximum fracture radius in Table 9-17) are assumed to be readily observable. Increasing the threshold fracture radius for observation to 500 m increases the number of intersected positions by roughly a factor of 3 for the case where the minimum fracture radius of relevance is 150 m.

Table 9-15. Number of canisters within a 100–200 m band from deformation zones in Forsmark.

Deformation zone ID	Canister positions	Normalised
A2	426	375
A2 and NE0062A	139	122
ZFMNE0060	563	495
ZFMNE0062A	180	158
ZFMNE1193	18	16
Remaining	5,498	4,834
Sum	6,824	6,000

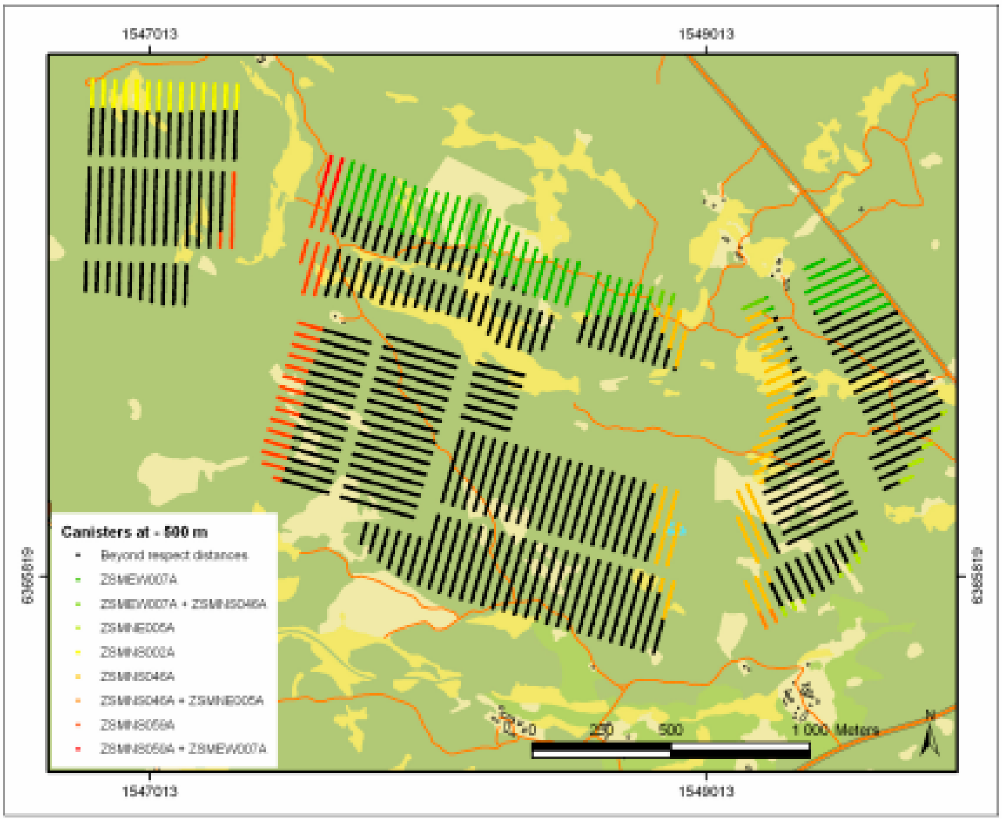


Figure 9-82. *Deposition tunnel sections with canister positions within a band 100–200 m from deformation zones (Laxemar).*

Table 9-16. Number of canisters within a 100–200 m band from deformation zones in Laxemar.

Deformation zone ID	Canister positions from /Janson et al. 2006/	Normalised
ZSMNS046A	466	373
ZSMEW007A	792	634
ZSMEW007A + ZSMNS046A	33	26
ZSMNE005A	56	45
ZSMNS002A	200	160
ZSMNS059A	314	251
ZSMNS046A + ZSMNE005A	16	13
ZSMNS059A + ZSMEW007A	41	33
Remaining	5,580	4,465
Sum	7,498	6,000

Table 9-17. Data, additional to the geological DFN data, required for the calculation of the fraction of intersected canisters.

Canister radius	0.525 m
Canister height	4.83 m
Minimum fracture radius	75 or 150 m
Maximum fracture radius (larger fractures assumed trivially observable and thus avoided)	250 m

Sensitivity analyses and variations between rock domains

The result is sensitive to uncertainties in k_r, the exponent of the power-law distribution of fracture sizes in the DFN model. This is illustrated in Figure 9-83, where the leftmost bar in the figure shows the best estimate result of 0.28% along with results obtained with upper and lower estimates of the k_r parameter for rock domain RFM029 (see **Data report**, section 6.3 for discussion). The pessimistic k_r-value yields an increase in ε of about a factor of 2.

The subsequent five bars show the corresponding results for each of the five fracture sets in the DFN model of rock domain RFM029. Results for rock domains 12, 17 and 18 are also shown in the figure, as are the effects of taking another critical parameter, the minimum fracture radius contributing to the DFN description, r_0, from either of the two DFN models developed for the hydrogeological modelling of the Forsmark site. The uncertainties in the parameters of the DFN model (Forsmark), as discussed in the **Data report**, were given as if the parameters were independent whereas, in fact, they are highly dependent. The effect is that unlikely combinations of k_r, r_0 and P_{32} (the fracture intensity) have been used for the computation of ε. The range thus obtained for ε is unrealistically large but is considered to bracket the uncertainty adequately for the purposes of SR-Can.

The sensitivity to e.g. details of the orientation distribution of fractures is considerably less pronounced, see further /Hedin 2005/. The sensitivity to k_r reflects the fact that the power-law size distributions cover a large span of fracture radii in the calculations. However, observations are essentially only available on the metre to tens of metre scale and on the scale of 1,000 m and larger. Observations in the size interval that causes the discriminating fracture intersections in the calculations cited above, i.e. 50 to several hundred metres, are scarce. It is, therefore, desirable to increase the confidence in the characteristics of this interval of the size distributions.

Conclusion: For the relevant rock domain, RFM029, the combination of uncertainties in k_r and r_0 may yield an increase in ε by at most a factor of 2.5 whereas the most favourable values of these parameters yields a reduction by more than a factor of 10.

Reduction of intersection probability through application of the EFPC criterion

In the previous section, the mean number of canisters that could be affected by a (single) seismic event was computed. The number of canisters thus obtained is based on the cautious assumption that features able to host secondary slip possess no geological signature whatsoever. Thus, all canister positions intersected by features larger than 75 m and 150 m, respectively, are included in the calculation regardless of their physical appearance.

Unlike in the computation of "ε", the Expanded Full Perimeter Criterion (EFPC), see /Munier 2006b/ for details, assumes that potentially critical features, expressed as full perimeter intersections around the deposition tunnel walls, are readily observable and can be mapped by traditional geological tunnel mapping. By applying the EFPC criterion, the number of potentially critical positions, as compared to ε, can be substantially reduced according to detection probabilities listed in Table 9-18.

The probabilities are naturally dependent on the nature of the underlying DFN models, which are associated with considerable uncertainties, see the **Data report**, section 6.3. Nevertheless, it appears that the EFPC efficiency is fairly insensitive to variations in the DFN model /Munier 2006b/ whereas the degree-of-utilisation is more affected by the properties of the DFN model. Therefore, in the context discussed here, application of the EFPC criterion appears justified despite DFN uncertainties.

Table 9-18. Detection probabilities for various fracture radii, using the EFPC criterion /extracted from Munier 2006b, Tables 5-2 and 5-3/.

Fracture radius	Forsmark	Laxemar
≥ 75	0.941	0.959
≥ 150	0.975	0.993

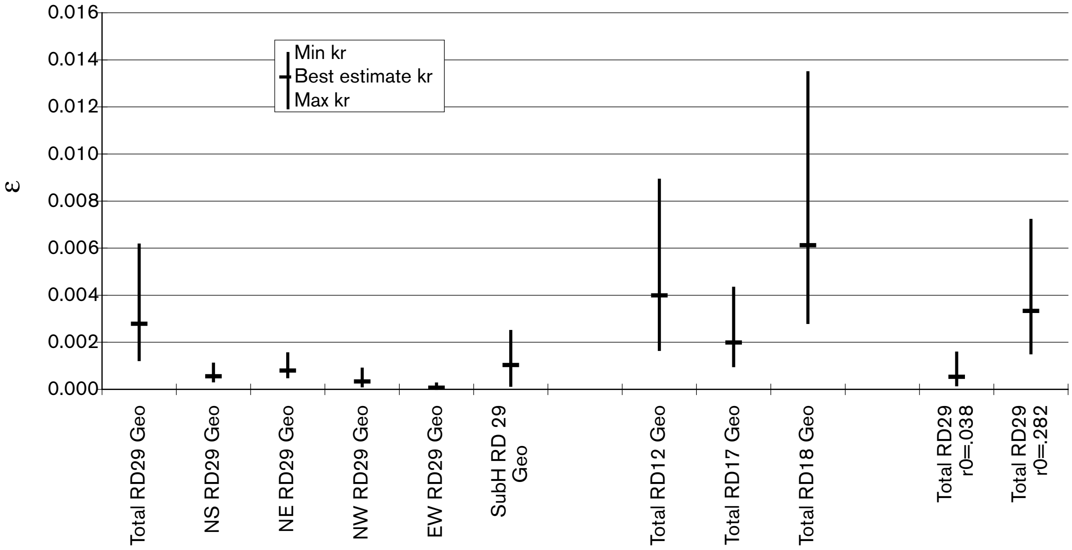


Figure 9-83. *Fraction of canisters intersected by discriminating fractures, ε. Each case shows results with best estimate, max and min values of the k_r-parameter. The leftmost bar (Total RD29 Geo) in the figure shows the best estimate result of 0.28% along with results obtained with upper and lower estimates of the k_r-parameter for rock domain RFM029. For completeness, the contribution to ε for each fracture set (NS, NE etc) and for rock domains RD12, RD17 and RD18 are also shown. Results using variants of the DFN used for RD29 are shown in the rightmost part of the figure.*

Reduction of intersection probability through detection of discriminating fractures in deposition holes

The EFPC criterion assumes that, apart from clearly visible fracture traces, potentially critical features are geologically anonymous, possessing no additional information. This is too cautious an assumption, as it is generally accepted within the geo-scientific community that many fracture properties are correlated to the fracture size.

An SKB project /Cosgrove et al. 2006/ was initiated to address the likelihood of detecting potentially critical structures by using established mapping and investigation techniques. Based on an extensive literature review, the authors concluded that it appears clear that there are several local indicators of the size of potentially critical structures, but that none of these indicators are by themselves sufficient for assessing the size. The key parameters the authors identified were:

- Fracture aperture.
- Shear displacement.
- Deformation zone thickness.
- Hydraulic conductivity.

Notoriously difficult to quantify, the authors nevertheless judge, based on sound geological and engineering considerations, that the vast majority of such structures can be detected..

Final estimate of probability of canister failures due to earthquakes

The canister intersection probabilities, ε, as defined in /Hedin 2005/ can be combined with detection probabilities of large fractures (Table 9-18) and earthquake probabilities (Table 9-5) to compute the number of canisters that *could* be affected if a large earthquake were to occur in the immediate vicinity of either of the sites.

The uncertainties associated with long-term prediction of earthquakes are appreciable. Awaiting results from on-going studies, the findings of /Hora and Jensen 2005/ are regarded as appropriate for the purposes of SR-Can.

The EFPC criterion can be used to reduce the cautious estimates of ε, the canister intersection probability. However, in addition to the assumption that full perimeter intersections are readily observable (the FPC rule), the EFPC criterion used to obtain the figures in Table 9-18 includes the idealisation that fracture planes are sufficiently planar as to be traceable over several deposition holes /Munier 2006b/. Though one might argue, supported by /Cosgrove et al. 2006/, that this is probably correct for most critical features, it is likely that, in some situations, additional fracture properties will have to be considered in the judgment. We cannot, therefore, justify the use of the findings in /Cosgrove et al. 2006/ in addition to EFPC as it is, to some extent, already included in the criterion.

Over a glacial cycle, there is a probability of $3.00 \cdot 10^{-2}$ of having a potentially damaging earthquake within a an area of 5 km radius. The probability of a particular canister to be unsuitably positioned is $7.78 \cdot 10^{-5}$ and $4.30 \cdot 10^{-5}$ for Forsmark and Laxemar, respectively. Thus, if such an earthquake were to occur, the probability of a particular canister being affected is $2.34 \cdot 10^{-6}$ and $1.29 \cdot 10^{-6}$ for Forsmark and Laxemar respectively.

Table 9-19 summarises the probabilities discussed here and presents an estimate of the total number of canisters that might be affected by earthquakes at each site. The consequences of canister failures due to earthquakes are analysed in section 10.7.

Combined effects of shear movement and isostatic load

An additional consideration is the possibility of a combination of shear movement and isostatic load on the canister.

Figure 9-84 shows stress additions from the ice load at 500 m depth, obtained from on-going ice-crust-mantle FEM analyses reported in the **Climate report**, section 3.5. The results relate to a position at 800 km distance from the NW edge of the Weichselian ice, Figure 9-85. The Lambeck ice model used here /Lund 2005/ assumed a maximum ice thickness of about 1.5 km. The crust was represented by a 100 km thick homogenous and incompressible elastic plate with uniform elastic properties and the mantle by an ideally visco-elastic medium. However, down to a depth of a few kilometres, the rock mass deformation modulus is about 1/3 of the crustal average used as input in the FEM analysis of Lund /**Climate report**, section 3.5/. This means that the flexural stresses should be about 1/3 of those actually obtained from the ice-crust-mantle analyses. In addition, the real crust is not incompressible, meaning that the Poisson ratio effect on the horizontal stresses is smaller in reality than in the ice-crust-mantle FEM model. Therefore, the horizontal stress additions shown in Figure 9-84 are reduced to 1/3 of the calculated ones.

Table 9-19. Probabilities combined to provide an estimate of the number of canisters that can be damaged by earthquakes.

	Forsmark	Laxemar	Note
Probability of M ≥ 6 earthquake over 5 km radius and per 120,000 years	$3.00 \cdot 10^{-2}$		Expert Elicitation project /Hora and Jensen 2005/ rescaled to 120,000 years and 5 km radius.
Fraction of intersected canisters (ε), weighted over all zones	$2.91 \cdot 10^{-3}$ [$2.91 \cdot 10^{-4}$–$7.27 \cdot 10^{-3}$]	$5.12 \cdot 10^{-3}$	Based on ε only. Range accounts for parameter uncertainty in DFN model.
Fraction of intersected canisters (ε), weighted over all zones, applying the EFPC criterion	$7.78 \cdot 10^{-5}$ $7.78 \cdot 10^{-6}$–$1.95 \cdot 10^{-4}$	$4.30 \cdot 10^{-5}$	Based on ε and taking account for EFPC. Detection probabilities for EFPC are obtained from Table 9-18.
Number of canisters	6,000		
Mean number of potential canister failures in 120,000 years	$1.40 \cdot 10^{-2}$ [$1.40 \cdot 10^{-3}$–$3.50 \cdot 10^{-2}$]	$7.74 \cdot 10^{-3}$	Based on canister fraction using EFPC. (Product of grey cells for each site.)
Mean number of potential canister failures in 1,000,000 years	$1.17 \cdot 10^{-1}$ [$1.17 \cdot 10^{-2}$–$2.92 \cdot 10^{-1}$]	$6.45 \cdot 10^{-2}$	Above cell up-scaled.

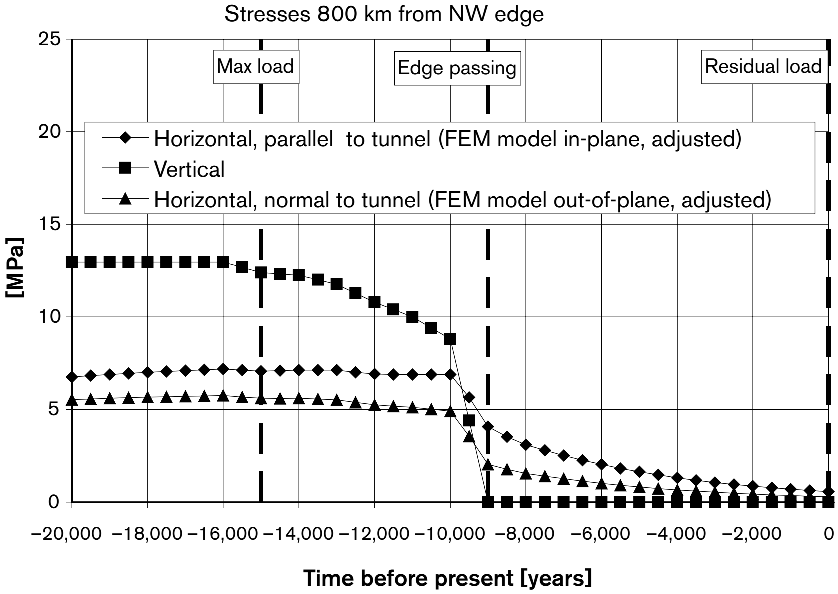


Figure 9-84. *Stresses at 500 m depth induced by ice loading.*

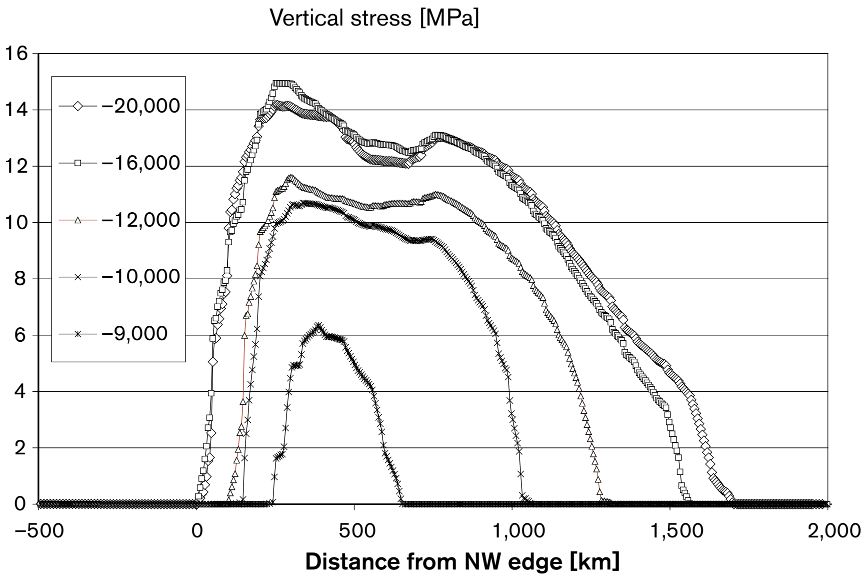


Figure 9-85. *Ice load as function of distance from the north-western ice edge at different times. /From study described in Climate report, section 3.5/. The legend gives time before present in years.*

The Lambeck ice model used to generate the stress additions in the FEM model probably underestimates the Weichselian ice thickness. Results from recent and on-going work suggest that the ice load may actually have been almost twice as large /Lund 2006/. Figure 9-86 shows ice load stresses added to corresponding present-day stresses at 500 m depth in Forsmark for two cases: the ice load stress additions shown in Figure 9-84 and the same additions doubled. Both figures confirm that deviatoric stresses decrease under the ice compared with present-day conditions, and increase under the retreating margin. This suggests that the ice stabilizes the rock during the period of actual ice cover and that a period of reduced stability may follow the passing of the retreating margin. Figure 9-86 relates to total stresses without taking account of the influence of pore pressure variations. A detailed stability analysis, based on the stress variations shown in Figure 9-86, that also accounted for significantly increased pore pressures, is provided in /Hökmark et al. 2006/. The results show that fracture shear displacements may occur under the retreating ice margin along specifically orientated fractures, but

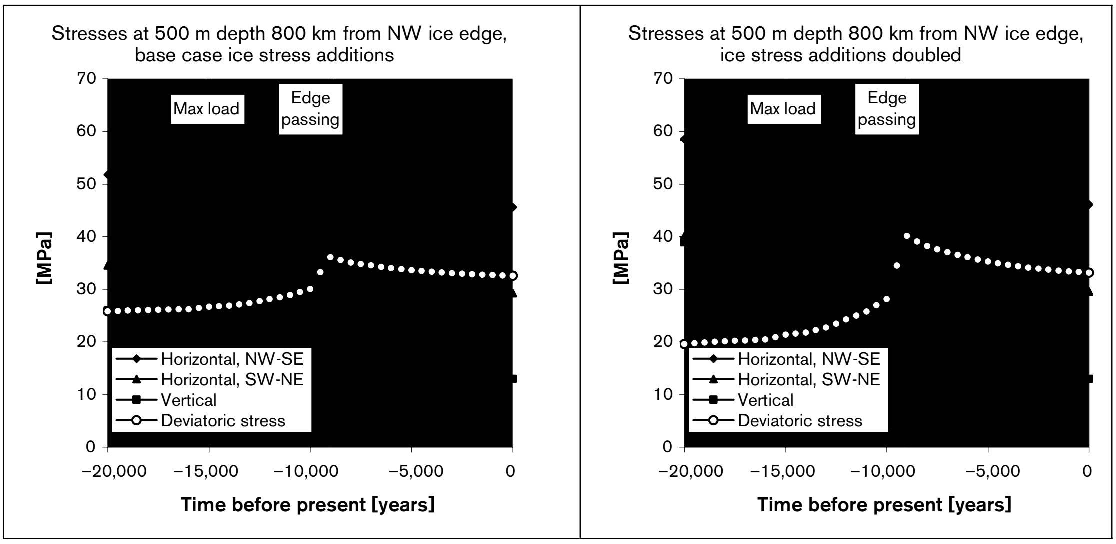


Figure 9-86. *Total stresses at 500 m depth for two ice-load assumptions. The deviatoric stress is reduced during the time of high ice load and reaches a maximum when the ice margin passes.*

that the maximum displacements will be modest. The shear displacement may amount to about 3 cm for 400 m diameter fractures and correspondingly less for smaller fractures; even if the glacial excess pore pressure is as high as 5 or 6 MPa in the region of the margin. During the period of high isostatic load there are no such large-scale shear displacements.

In summary, it is concluded that the combination of shear and isostatic load on the canister does not have to be further addressed in SR-Can.

It is, therefore, concluded that the combination of shear movement and isostatic load on the canister does not have to be further addressed in SR-Can.

Conclusions

Canister failures due to future earthquakes are avoided through the use of respect distances and acceptance criteria for deposition holes. At this stage of the analysis, it cannot, however, be fully ruled out that such failures will occur.

An estimate of the extent of this failure indicates that the probability of having a potentially damaging earthquake during the initial 120,000 year glacial cycle is $3.0 \cdot 10^{-2}$. The probability that one out of the 6,000 canisters at Forsmark is unsuitably positioned is within the interval $7.8 \cdot 10^{-6}$ to $1.9 \cdot 10^{-4}$; the mean value is estimated at $7.8 \cdot 10^{-5}$. The interval roughly accounts for uncertainty in the description of fracture statistics at Forsmark. The corresponding mean value at Laxemar is $4.3 \cdot 10^{-5}$ (no range provided). For the worst case that *all* unsuitably positioned canisters, out of the 6,000, should fail due to an earthquake, the number of damaged canisters is estimated to $1.4 \cdot 10^{-3}$–$3.5 \cdot 10^{-2}$ and $7.7 \cdot 10^{-3}$ for Forsmark and Laxemar respectively. The estimate is pessimistic as the following is assumed:

- The fracture hosts the maximum possible slip sustained by its area.
- The canister is intersected at a location at which the slip causes maximum damage.
- The canister is intersected at an angle in which the slip causes maximum damage.

Further evaluations of these factors could lead to a reduction of the estimated probability and scale of this failure mode is made.

It is also noted that a fracture having experienced a 10 cm shear movement is likely to have an increased transmissivity. This is important for consequence calculations for this failure mode. Such calculations are reported in section 10.7.

9.4.6 Hydrogeological evolution

Introduction

The safety related hydrogeological issues during periods of the permafrost and glacial domain are:

- What is the maximum groundwater pressure during a glacial episode (safety function R3b in Figure 9-2)? In particular, will it be altered in such a way that the mechanical environment is not favourable?
- What is the groundwater flow during periods of permafrost and glacial domain (safety function R2c in Figure 9-2)? In particular, will it be altered in such a way that the hydrological environment is not favourable?

These issues are address for permafrost conditions (very briefly) and glacial conditions below.

A closely related issue concerns the groundwater composition during a glacial episode. This is addressed in section 9.4.7 below.

Permafrost conditions

In SR-Can, only a limited assessment of permafrost conditions has been made for the hydrological evolution /Vidstrand et al. 2006/. This study only deals with the generation and transport of salt during permafrost conditions and is discussed in section 9.4.7 below.

In SR-Can, it is assumed that flow conditions and hydrostatic pressure similar to today's conditions occur in the un-frozen parts of the bedrock during permafrost.

In SR-Site, a more comprehensive study of groundwater flow during permafrost conditions is planned. Issues of interest include the flow pattern and exit points to the biosphere when the hydraulic conductivity close to the surface is lowered due to the permafrost, groundwater flow magnitude at repository depth during these conditions, and dilution effects at the surface.

Maximum hydrostatic pressure for glacial conditions

In section 9.4.1, it is noted that the maximum pressure exerted by the ice in the Oskarshamn area is 22 MPa, compared with 26 MPa at Forsmark. The hydrostatic pressures at 500 m (repository depth in Laxemar) and 400 m (repository depth in Forsmark) are 5 MPa and 4 MPa, respectively without ice sheets present. The highest possible groundwater pressure resulting from the ice would be to assume that the complete weight of the ice acts on the groundwater. Thus, the maximum hydrostatic pressure at repository depth would be 27 MPa and 30 MPa, respectively at Laxemar and Forsmark. However, much of the ice load could be transferred to the rock, increasing the rock stress, without affecting the groundwater pressure to the same extent. The values of hydrostatic pressure given here are thus upper extremes for this base variant of the reference evolution.

Glacial hydrological conceptual model

The hydrological system of an ice sheet consist of three parts; the supraglacial system (on the ice-sheet surface), englacial system (within the ice) and subglacial system (at the bed). A schematic section through an arbitrary southwestern sector of a Fennoscandian ice sheet large enough to cover both candidate sites is shown in Figure 9-87. Above the equilibrium line, the supraglacial system can be divided into the cold snow-, percolation- and wet snow zones, whereas below the equilibrium line there is solid ice at the surface at the end of the melting season (Figure 9-87).

Water from surface melting is produced in the wet snow zone and in the ablation area, i.e. below the equilibrium line, see Figure 9-87. In the ablation area, surface streams are common features during the melt season. These often end in crevasses or moulins, through which the surface water enters the en- and subglacial systems, see Figure 9-87 and Figure 9-88. At the ice margin, part of the surface melt water leaves the ice sheet directly by channelized surface flow, without entering into the ice sheet.

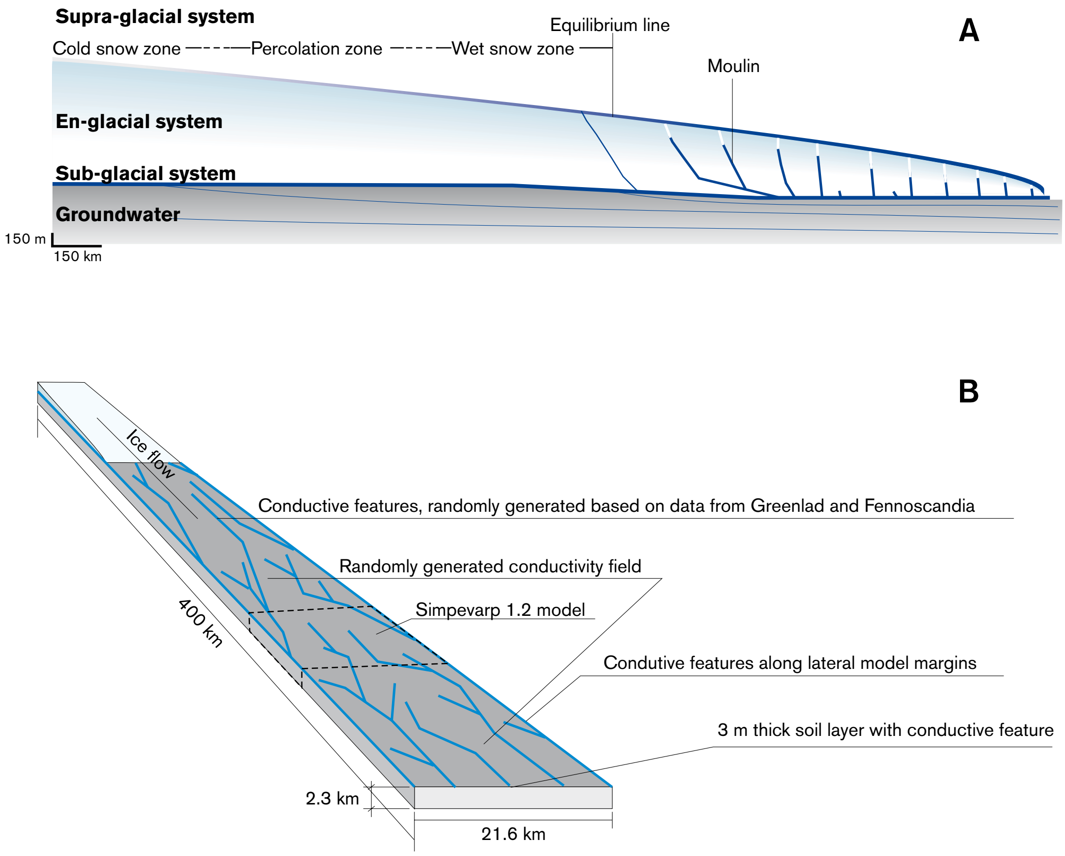


Figure 9-87. *Schematic views of the ice sheet hydrological system. A: Hydrology through an arbitrary southwestern section through a Fennoscandian ice sheet. B: Configuration of the sub-glacial system assumed in the performed modelling.*

Figure 9-88. *A supraglacial stream (A), and moulin (B) on the Greenland ice sheet photographed from the air. The active stream is 2–3 m wide, whereas the depicted moulin has a maximum diameter of 15 m. The pictures were taken at the end of the melting season (September), hence the moulin is no longer active.*

In the conceptual model, a zone of basal melting extends some hundreds of km inward from the margin. In interior elevated parts of the ice sheet, basal ice is frozen to the bed and no basal melting occurs. One of the most important characteristics of the en- and subglacial hydrological system is that they are highly dynamic. They adjust their transport capacity to any prevailing input of meltwater at the ice-sheet surface. Because of the seasonal variations in water input, and the continuously ongoing ice deformation, both the en- and subglacial conductive features experience major seasonal variations in size and capacity. In this way, there is no limit to the transport capacity of these hydrological systems, given some time for the system to develop. Further information on the supra- sub- and englacial systems are found in the **Climate report**, section 3.2, and in a report on glacial hydrology /Jansson et al. 2006/.

Amount of water produced by melting

In the reference evolution, surface melt water production for the Weichselian ice sheet typically varies up to 4–8 m of water per year in the ablation area. This can be compared with observed present average ablation rates of the Greenland ice sheet of a few metres/year /Krabill et al. 2000/ up to ~ 10 m/year /Bøggild et al. 2004/. During the deglaciation of the Weichselian ice sheet, melt rates up to values higher than 10 m/year occured /**Climate report**, section 4.2.4, Humlum and Houmark-Nielsen 1994/. Basal melt rates are typically 1–10 mm/a, and regarded as constant over the year.

Subglacial hydrostatic pressures

In spring, water fluxes and hydrostatic pressures increase in the en- and subglacial hydrological system. This in turn increases the system's water transporting capacity, which in time again lowers the hydrostatic pressure. During the melting season, basal hydrostatic pressures in the area affected by surface water vary significantly diurnally and in connection to rain events /e.g. Jansson 1997/. Hydrostatic pressures in the conduits may be as low as atmospheric pressure and occasionally as high as, or even higher than, ice overburden pressure. At the end of the melting season, when the supply of surface melt water decreases, the sub-glacial system generally has a high capacity with relatively low pressures. As conduits close during winter, pressures increase.

On a glacial cycle time-scale, the characteristics of the ice sheet's sub-glacial system can also be expected to change during different stages of ice-sheet advance and retreat due to varying amounts of surface melting. Furthermore, its characteristics depend on basal topography, ice thickness variations, basal temperature distribution, and hydrological properties of the substrate. Geological evidence, mainly on esker distribution, indicate that in large parts of Sweden, tunnel systems separated by several kilometres were present near and at the ice margin of the Weichselian ice sheet. It is plausible that conduits starting at moulins or crevasses at the ice sheet surface connected to channels at the ice/bed interface, and that these channels converged to larger conduits or tunnels towards the ice margin (Figure 9-87 and Figure 9-89). Pressures in these tunnels probably also varied considerably during a year, from atmospheric pressure close to the ice margin during winter, to pressures up to overburden or higher during spring and summer. We know very little about prevailing transverse pressure gradients towards such basal ice sheets conduits, for example how large the areas are that are affected over the year /Jansson et al. 2006/. Despite these uncertainties, the basic conceptual glacial hydrogeological model presented in Figure 9-87 and in the text is a good representation of the glacial hydrological systems as we understand them today /Jansson et al. 2006/.

Considering that SR-Can is a preparatory stage for the SR-Site assessment, the present state of knowledge is adequate for a first evaluation of the impact of subglacial hydrological conditions on repository safety. Additional work on this topic will be performed within SR-Site.

Model study of a glacial advance and retreat

For modelling of groundwater flow in the glacial domain, the hydrological system illustrated in Figure 9-87 was assumed. Zones of basal melting as well as basal melt rates, surface melt rates and ice-sheet thicknesses were generated by the ice-sheet model described in section 9.4.1 above. It is assumed that all melt water generated at the surface instantaneously reaches the sub-glacial system. Since any ice-sheet advance and retreat can be assumed to have a similar impact on groundwater flow in respect of the processes that occur and features that arise, only the last glaciation has been analysed. Based on this conceptual model of glacial hydrology, a groundwater model has been set up and applied /Jaquet and Siegel 2006/.

Figure 9-89. *Examples of ice tunnels at the margin of the Greenland ice sheet at the end of the melting season (September 2005).*

The ConnectFlow code representing the same processes as discussed in section 9.3.6 was used; specifically, both density driven flow and rock matrix diffusion of salt were included in the modelling. This model application is in SR-Can primarily used to obtain salt concentrations during the glacial advance and retreat, see section 9.4.7 below.

The model was developed for conditions relevant for the Oskarshamn region, and takes its properties from the Simpevarp version 1.2 site-descriptive model. In the model domain corresponding to the Simpevarp 1.2 regional model domain, the properties are identical. Outside this domain, stochastic simulation was performed honouring the statistics of the Simpevarp area. The model domain is approximately 400 km by 20 km in lateral extent. The flow-wetted surface value used in the Simpevarp 1.2 model is 2.0 m^2/m^3, and the matrix porosity and penetration depth are $5\cdot10^{-3}$ and 0.5 m, respectively. For comparison, the corresponding values used in the Laxemar 1.2 model described in section 9.3.6 are a flow-wetted surface between 1 and 2 m^2/m^3 in different parts of the model, a matrix porosity of $5.9\cdot10^{-3}$ and a penetration depth between 0.5 and 1 m.

At the ice/bed interface each moulin is assumed to be connected to a conductive feature which either ends at the ice margin or is connected to another conductive feature. The ice sheet advances and retreats along a transect following the modelled dominant ice flow direction. The hydraulic conductivity of the conductive features was calibrated such that the water pressure on average did not exceed the pressure of the ice; i.e. the lifting of the ice had to be globally avoided, but local exceedance was acceptable. The total recharge (surface and basal melt rates) to the groundwater flow model was truncated at either 200 or 50 mm/year; the 200 mm/year value is considered the maximum potential recharge into the rock based on /Walker et al. 1997/. When a resulting conductivity of 2 m/s is used for the sub-glacial layer, no exceedance is observed for the 50 mm/year case whereas the 200 mm/year case resulted in substantial exceedance during glacial retreat. Only the 50 mm/year case is propagated for further analyses, as discussed below.

In terms of boundary conditions, the glaciation period, lasting from 30,900 to 11,400 years BP was subdivided into the following phases:

- 30,900 years BP: End of pre-glacial period; at this initial time, no ice sheet is present.
- 30,900 to 25,100 years BP: Glacial build-up, the ice sheet progressively enters the model domain.
- 25,100 to 14,100 years BP: Glacial completeness; the ice sheet covers the model domain.
- 14,100 to 11,400 years BP: Glacial retreat; the ice sheet progressively leaves the model domain.
- 11,400 years BP: End of post-glacial retreat; the ice sheet has completely disappeared from the model domain.

Boundary conditions were extracted from the reference ice sheet model simulation /**Climate report**, section 3.1.4/ for the periods when the domain was covered by ice. For assignment of other boundary conditions, the reader is referred to /Jaquet and Siegel 2006/.

The ice margin moves continuously in the model, but results are presented for five discrete time periods, see Table 9-20. These time periods correspond to cases with extreme impact of the ice sheet on groundwater flow conditions.

In Figure 9-90 the Darcy velocity, salt concentration in the flowing fractures, and salt concentration in the matrix at repository depth in the Simpevarp area are presented as a function of time. The initial increase in salinity is a result of salt diffusing upwards from the bottom of the model where salt concentrations are higher. It is noted that up-coning effects at the ice-sheet margin also result in increased salinity levels; however, this effect cannot be seen at the repository in the figure due to resolution limitations. High groundwater flows are observed when the ice-sheet margin is located on top of the

Table 9-20. Statistics in terms of mean, standard deviation and percentiles for particle-tracking calculations with particles released at repository depth.

Direct trajectories	Time	Mean	σ	Q5	Q25	Q50	Q75	Q95	N_traj.
Travel time log [year]	–26,800	0.870	0.393	0.336	0.622	0.803	1.074	1.574	3,644
	–26,500	0.717	0.347	0.003	0.557	0.711	0.947	1.267	963
	–17,900	3.177	0.065	3.089	3.144	3.164	3.197	3.293	329
	–13,900	0.758	0.374	0.071	0.514	0.739	1.030	1.363	854
	–13,800	0.840	0.339	0.329	0.642	0.805	1.005	1.442	3,645
F-factor log [year/m]	–26,800	5.011	0.689	3.780	4.587	5.086	5.537	5.928	3,644
	–26,500	4.901	0.685	3.558	4.392	5.104	5.445	5.727	963
	–17,900	6.639	0.408	5.881	6.329	6.743	6.936	7.161	329
	–13,900	4.962	0.716	3.596	4.372	5.287	5.501	5.804	854
	–13,800	5.015	0.688	3.835	4.555	5.087	5.445	5.987	3,645

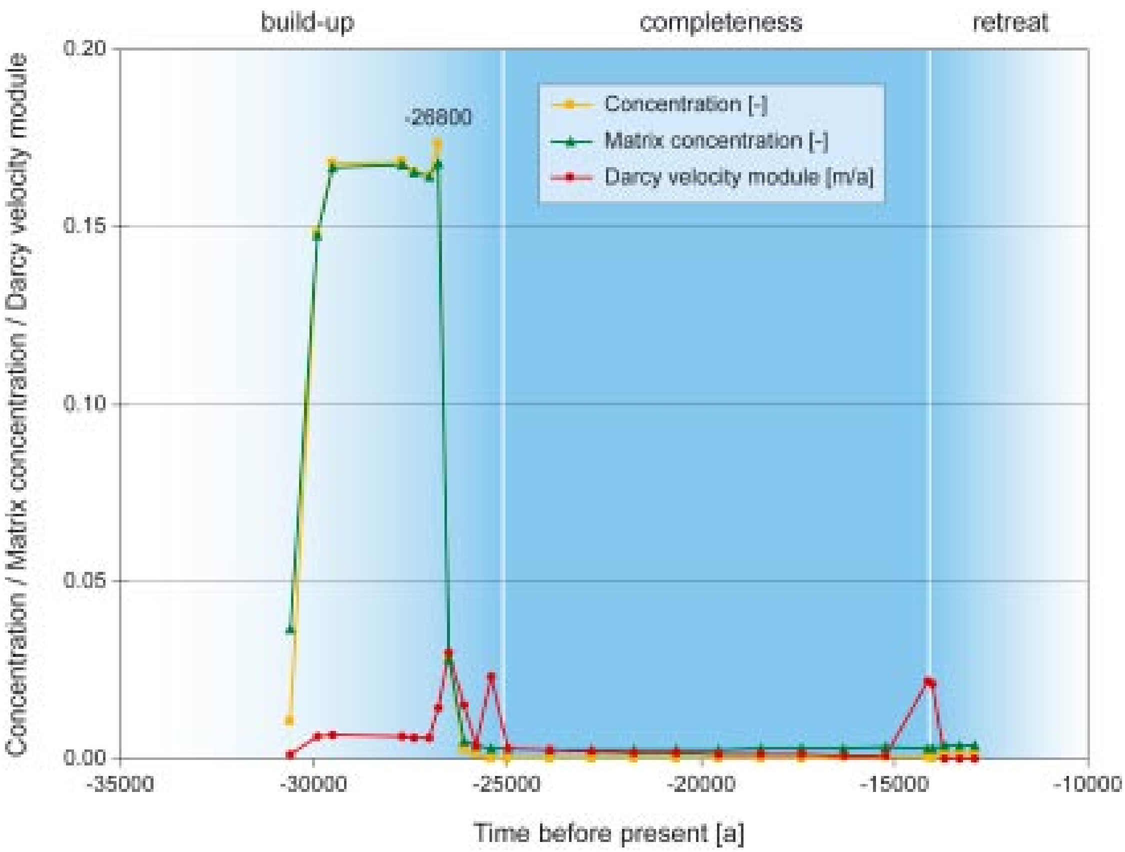


Figure 9-90. *Relative salt concentration in flowing water and matrix, respectively, and Darcy velocity as function of time.*

repository during both advance and retreat. The high flows effectively flush most salt in both fractures and matrix out of the model when the ice sheet reaches the site. The concentrations remain low during the rest of the simulation period due to the continuing flushing of glacial water into the sub-surface. The almost complete flushing of salt is believed to be an unrealistic feature of the model and may be due to too large a diffusive exchange between matrix and fractures, or to the lack of an adequate depth trend in hydraulic conductivity in the parameterisation of the bedrock that was used. The model and results shown here should thus be considered preliminary and indicative only of future efforts within SR-Site.

Issues related to salinity and water chemistry are further discussed in section 9.4.7 below.

Particle tracking with a release within the repository region was performed for the five time periods indicated in Table 9-20. The average travel times from repository depth are clearly correlated to the time periods of ice displacement; the average travel times are several orders of magnitude higher during glacial completeness (−17,900 years) than at the other time periods, see Table 9-20. Furthermore, a symmetry in results can be observed between the phases of glacial build up (−26,800 and −26,500 years) and the equivalent ice-sheet positions during glacial retreat (−13,900 and −13,800 years). The symmetry is explained by the fact that during these phases, similar quantities of melt water are provided by the ice sheet, leading to similar trajectories for the particles. For the transport resistance (F), a similar pattern of symmetry with a maximum value during glacial completeness is observed.

The values reported here can be compared with corresponding results obtained in the Site-descriptive modelling of Simpevarp 1.2 /Hartley et al. 2005b/. In the latter study, $\log_{10} F$ values were obtained with a mean value of 6.1 and a standard deviation of 0.75. During the glaciation, the F values were reduced by approximately one order of magnitude when the ice sheet front is close to the repository, whereas the F values were higher during glacial completeness relative to present day conditions. The spread in values was similar for present day conditions and the glacial cases with the ice sheet front close to the repository, whereas the glacial completeness case had a significantly smaller spread.

Simplified estimate of glacial hydrology

The simulation results above can be compared with simple estimates based on crude assumptions of conditions during a glaciation. The following main assumptions are made:

- No transverse pressure gradients caused by subglacial channels close to the ice front are assumed. In reality, channels typically occur at many ice fronts, and where they do, they may affect the pressure situation by inducing pressures both lower and as high as surrounding pressures caused by the ice load. The variations are strongly correlated to seasonal variations in surface melting and the seasonal development of the en- and subglacial drainage system /Jansson et al. 2006/. In cases of open channels, atmospheric pressure prevails in the near-frontal parts of the tunnel. However, channels are not present everywhere along an ice front. For example, major channels may be separated by several kilometres, as reflected in the Fennoscandian esker distribution.
- Another uncertainty is how large the areas surrounding channels are that are affected by the pressure variations in the channels /Jansson et al. 2006/. Given the uncertainties above, and the fact that channels may both produce steeper and lower pressure gradients than the ice-sheet surface, a first approximation of hydrostatic pressure and gradients at the bed near the ice front is to use the ice thickness and ice surface gradient of the ice sheet. This picture can subsequently be refined when more information is available. This simplification could either under- or over-estimate pressure gradients.
- It is assumed that the ice front is not heavily crevassed. This is a reasonable assumption considering that the terrain surrounding the two candidate sites is, in both cases, very flat.

In this simplified approach, an up-scaling of present-day situations with gradients from ice-sheet profiles is made. The ice-sheet profile used is a steady-state profile calculated according to /Patterson 1994/, which gives a more realistic profile than a simple parabola approximation. The calculated profile gets progressively steeper closer to the margin. Because of this, a steep near-frontal part of the ice sheet is considered in this calculation. An average surface slope of 20.7° (0.35 m/m) is obtained for the first 1,000 m of the ice thickness profile.

The total accumulated passage time by the defined part of the ice front during a glacial cycle is estimated (here denoted Case A). The repository extent is set to 1 km along the profile. In the Forsmark area, frontal retreat rates during the last deglaciation was approximately 300 m/year, and in the Laxemar area 200 m/year /Lokrantz and Sohlenius 2006/. A slower retreat rate gives a longer exposure time to steep front conditions, and therefore the rate of frontal movement was set to 200 m/year. In the Weichselian reference evolution, there are two main phases of glacial coverage of the repository sites, corresponding to four frontal passages. Taking into account the time for each passage, the total accumulated time for the steep first 1,000 m of the front covering a site was calculated to be 40 years. This situation corresponds to the typical situation for any location in Sweden during a deglaciation, namely a situation where the ice front passes the site without interruptions or halts. This is the most common situation in the standard Weichselian reference evolution, though oscillations of ice margins can occur (see below).

A more extreme case would occur if the ice front came to a temporary halt with the near-frontal part above the repository, or if the front were to pass the site more times during a glacial cycle (here denoted Case B). From geological information it is known that temporary halts took place several times during the last deglaciation, when the ice front was located in southern and southern-central Sweden /Lundqvist and Wohlfarth 2001/. The longest and most prominent halt took place under the cold Younger Dryas period. On the basis of data from the GRIP core, the Younger Dryas began around 12,800 years BP and ended around 11,500 BP. Although there is a time lag for the frontal response of the ice sheet, the GRIP data suggest that the period of still stand during the Younger Dryas was about 1,300 years long. There is however no reason to assume that the approximately 1,000 m near-frontal part of the ice over which the highest gradient increase occurs would be situated immediately above the repository. Therefore, this case B is considered as an extreme situation not further analysed in the reference evolution, other than for illustrative purposes. However, it is considered when more extreme climate evolutions are analysed in chapter 12.

The above estimates of increased gradients and applicable times can be related to present-day conditions. In the Oskarshamn area, the regional hydraulic gradient is approximately 0.2% /Follin and Svensson 2003/. The gradient imposed by the ice sheet is assumed to be 32% (0.35·0.9; the factor 0.9 applied in order to account for ice density effect). Thus, the gradient during the glacial advance is 160 times greater than the gradient imposed by the regional topography.

Scaling the mean F-value in the Simpevarp site-descriptive model version 1.2 by a factor of 160 yields a $\log_{10}$ F-value of 3.9. This value is approximately one order of magnitude smaller than the values reported in Table 9-20 for the time periods of maximum glacial effects (lowest F-factors during glaciation). The bounding estimate thus lends credibility to the more complex numerical simulation results. Furthermore, a similar bounding estimate of F-values can also be applied to the Forsmark site where site-specific modelling of groundwater flow due to a melting ice sheet has not been performed. Since the regional gradient reported for the Forsmark area is of the same order of magnitude as the one in Småland (slightly lower), a scaling factor of the same order may be applied.

The discussion above based on simplifying assumptions indicates that the elevated gradients and flows may be expected for an accumulated time of 40 years when the reconstruction of the Weichselian evolution is considered (Case A) and for 1,300 years in a more extreme case considering a long lasting and near-repository located stationary ice front (Case B). The modelling results in Figure 9-90 indicate that increased flows, compared with present-day conditions, occur during both the glacial advance and retreat. For each passage, the total period of increased flows is a few thousand years (~ 2,000 years). With a total of four ice front passages, the total time of increased flows will thus be approximately 8,000 years. However, it is only during a much shorter time that the maximum gradients and flows occur, see Figure 9-90. Furthermore, the periods of moderately increased flow are counteracted by other periods of decreased flow compared with temperate conditions.

In summary, there will most certainly be episodes of both increased and decreased groundwater flow during a glacial cycle compared with temperate conditions. In order to reasonably represent these situations when assessing the effects on the engineered barriers for the reference evolution in section 9.4.8, today's flow situation and, in addition, episodes of increased flow described by Case A were assumed. In the analyses of more extreme external climate conditions in chapter 12, today's flow situation and, in addition, episodes of increased flow described by Case B were assumed.

9.4.7 Geochemical evolution

The successions of temperate, permafrost and glacial climate domains will affect the flow and composition of the groundwaters around the repository. The evolution between climate domains will be gradual, without a clear boundary between them. For example, during a temperate domain, temperatures may slowly decrease such that permafrost regions slowly develop within parts of the repository region. In SR-Can the evaluation of geochemical effects is restricted to using separate specifications for the different climatic domains. It is expected that different groundwater compositions will prevail around the repository as a result of the different types of climate domains and their corresponding hydraulic conditions. This section discusses the groundwater chemistry for periods in which the repository is below permafrost or an ice sheet, whereas the conditions expected under a temperate domain are discussed in section 9.3.7.

For permafrost and glacial conditions, the following issues are treated:

- Evolution of salinity.
- Evolution of redox conditions.
- Evolution of concentrations of other relevant natural groundwater components.
- Effects of grouting, shotcreting and concrete on pH.

Permafrost; evolution of salinity

It is estimated that at Forsmark the ground will be frozen to a depth of 50 m or more for around 30% of the time in the glacial cycle of the reference evolution, see Figure 9-74. According to these results, the permafrost will not occur over a continuous period of time, but rather thawing will occur between more or less short periods of permafrost, see also the discussion in section 9.4.1. Some of these permafrost periods will furthermore coincide with the time when the site is covered by an ice sheet, for example the period between −68,000 and −59,000 years in Figure 9-74, showing the frozen depth, and in Figure 9-64, showing the ice volume.

Salt rejection

When water freezes slowly, the solutes present in the water will not be incorporated in the crystal lattice of the ice. During this process, salts that have been present in the surface waters and groundwaters will tend to accumulate at the propagating freeze-out front. This front is, however, not necessarily sharp, because e.g. freezing will take place over a range of temperatures, depending on the salinity and on the ratio between "free" and tightly adsorbed water molecules. The freezing process can give rise to an accumulation of saline water at the depth to which the perennially frozen front has reached. The saline waters formed in this manner within fractures and fracture zones will sink rapidly due to density gradients.

Generic calculations have been performed /Vidstrand et al. 2006/ to evaluate the fate of saline groundwaters produced during the freezing process. The concentration of the out-frozen salt has been estimated in these generic calculations assuming that before the onset of the permafrost the salinity distribution is linear from zero at the surface to 1.5% at 300 m depth. It was assumed that at the start of the simulations the frozen front had instantaneously reached 300 m depth and that the groundwater in a 10 m thick layer under the frozen rock had a salinity of ≈ 22%, that approximately represents the sum of all the salt available within the overlying 300 m (this corresponds to a groundwater with ≈ 4.2 M Cl^-). This highly saline 10 m thick layer is located at the beginning of the simulation on top of groundwaters having a salinity increasing from ≈ 1.5% at the bottom of the permafrost to 10% at 2,000 m depth, which is also set as the bottom of the model. The DarcyTools model was used on the Laxemar-Simpevarp site using the boundary conditions and site properties from the SDM version 1.1. The larger scale deformation zones in the model have an average transmissivity of $1.2 \cdot 10^{-5}$ m^2/s. For further details the reader is referred to the original report /Vidstrand et al. 2006/. The model calculations show that saline waters generated in the deformation zones will move to deeper regions due to gravitational effects in periods shorter than 300 years. In these highly conductive parts, the salinity peak at repository depth may be for a few years as high as 9% (corresponding to a groundwater with ≈ 1.6 M of Cl^-). However, in less conductive portions of the rock, outside fracture zones, saline waters are practically immobile on the time scale of the simulations (300 years). The calculations are so far quite generic, and several factors remain to be investigated in the future, such as the effect of regional flow fields and the effect of taliks on the hydrological conditions at repository depth. Furthermore, the onset of the permafrost has been considered in the modelling to be instantaneous, releasing highly saline groundwater immediately under the frozen rock.

As mentioned above, the concentration of the out-frozen salt has been estimated in these generic calculations assuming that before the onset of the permafrost the salinity distribution is linear from zero at the surface to 1.5% at 300 m depth. From the results in section 9.3.7 this appears to be an overestimation, as the groundwaters at the sites will become gradually more diluted before the start of the permafrost. Therefore, a realistic estimate of the concentration of the salt out-frozen from the top 300 m and distributed into a 10 m thick layer would be ≈ 2% (≈ 0.34 M Cl^-). Another factor that would decrease the concentration of the out-frozen salt is the fact that the downward movement of the saline waters within fracture zones appears to be faster or at least to have a velocity similar to the advance of permafrost. Moreover it can not be excluded that pockets of un-frozen saline waters could become confined within the permafrost within the less permeable bedrock, depending on the geometry and thermal- and hydraulic properties of the fracture system. This would also reduce the amount of salt rejected to the bottom of the frozen rock.

Upconing

The possibility of upconing of deep saline groundwater to repository depths during permafrost conditions was addressed in /King-Clayton et al. 1997/. This may possibly occur in the vicinity of permanent discharge features such as some taliks. Such discharge features mainly occur along more extensive conductive deformation zones, which are avoided in the repository design. However, it cannot be ruled out that saline waters may be transported through minor features to the repository area if the process occurs for long periods of time. This process is nevertheless not deemed to be a matter of concern, but may require some further assessment to be conclusively ruled out.

Permafrost decay

When the permafrost melts and decays there will be a release of dilute water from the upper highly permeable network of fracture zones and also from well-confined individual fracture zones at depth, since these will have undergone salt-exclusion. At this stage the low permeable matrix which has preserved (or accumulated) its salinity, especially at greater depths, will probably be more saline than the surrounding groundwaters. The resulting chemical gradient will then cause a gradual transfer of salinity to the more permeable rock mass. In all probability this will be a slow process and dilution by mixing will occur also within the more permeable rock mass. The more dilute waters will tend to stay on the top layers of the rock mass due to their lower density.

Conclusions

Although groundwaters will become progressively diluted during the temperate period following the closure of the repository, permafrost can move salts to repository depth from the upper parts of the site. All arguments indicate that groundwaters below permafrost will not become more diluted than under temperate conditions. Rather, saline waters may move downwards within conductive fracture zones. Thus calcium concentrations are expected to increase during permafrost periods and satisfy the criteria concerning the safety function indicator R1c in Figure 9-2, $[M^{2+}] > 1\cdot10^{-3}$ mol/L. Regarding safety function indicator R1b, the concentration of salt at repository level due to out-freezing will not become so high as to lower the swelling pressure of the buffer and the backfill, among other reasons because of the downward gravity-driven flow of saline waters. This situation will not be changed during permafrost decay as a transition to a temperate period occurs.

Permafrost; redox conditions

Geochemical processes are strongly influenced by the location of the upper boundary of the permafrost. For example, a widespread degradation of illite and the weathering of iron-containing minerals (e.g. chlorite) with further iron migration within the shallow active layer and its precipitation at the cryogenic barrier (e.g. as lepidocrocite) has been reported in /Alekseev et al. 2003/. Therefore, with respect to the overburden soils and shallow bedrock levels, all indications are that prior to, during and following permafrost decay, shallow groundwaters will be reducing due to a combination of microbial and geochemical reactions and processes.

The perennial freezing of rock volumes will effectively shut down the hydraulic circulation in the bedrock, at least locally. In this way, microbial populations could be isolated from the surface and also methane gas could be trapped as clathrates. Microbes present in the upper bedrock will survive in the permafrost and will become active during the subsequent melting. No changes in redox conditions are, therefore, to be expected unless the nutrient sources become exhausted. However, if clathrate formation has occurred, the dissociation of these compounds to release methane during permafrost decay would add to the nutrient sources for microbial populations in the bedrock, see for example the discussion in the **Geosphere process report**. In conclusion, it is not expected that redox conditions will change at repository depth during the formation or decay of permafrost, remaining reducing as demanded by the safety function indicator R1a in Figure 9-2.

Permafrost; evolution of concentrations of other relevant natural groundwater components

There is very little information concerning the chemical conditions in groundwaters under permafrost. This is due to practical difficulties when drilling and sampling at ambient temperatures where freezing of drilling fluids and groundwater samples occurs.

Chemical components not participating extensively in chemical reactions, for example chloride, sodium, calcium and sulphate are expected to follow the patterns mentioned in the previous subsection describing the evolution of salinity during periods of permafrost.

Other components, being controlled by chemical reactions, are expected to be almost unaffected by the permafrost. The study at the Lupin Mine in N. Canada /Ruskeeniemi et al. 2004/ may be used to illustrate this: the pH values for sampled groundwaters vary between 6 and 9 and bicarbonate concentrations are found to be below $5 \cdot 10^{-3}$ mol/L. For potassium, the concentrations are higher than for the groundwaters sampled at Forsmark or Laxemar: sub-permafrost groundwaters at Lupin have $< 2.6 \cdot 10^{-3}$ mol/L. For iron, most of the groundwaters sampled at Lupin had $< 54 \cdot 10^{-6}$ mol/L. Thus, the concentrations and pH values found are not far from those for groundwaters sampled elsewhere, for example at Forsmark, see Table 9-23, at the end of chapter 9.

The intensity of the production of sulphide due to microbially mediated SO_4^{2-} reduction will probably decrease due to the lower temperatures. Due to freeze-out of salts, sulphate concentrations might increase as compared with those at the end of a preceding temperate period, when diluted groundwaters of meteoric origin predominate. Reducing agents are required for any sulphate reduction to take place, and under permafrost conditions the inflow of organic matter from the surface will become negligible. However, SO_4^{2-} reduction could be sustained by the gaseous groundwater components methane and hydrogen, see the discussion in section 9.3.7. If microbial sulphide production occurs during this period, it will be limited by the availability of both SO_4^{2-} and mainly CH_4. The amounts of methane and hydrogen will be controlled by their production and flow from the deeper parts of the bedrock, by the impervious frozen layers at the top of the site, and by their incorporation in the ice as clathrates. There is not enough data at present to quantify these processes, but there are no indications that either CH_4 or H_2 should increase in concentration during this period, and there is no evidence to support increased sulphide production at permafrost sites.

It is concluded that under permafrost conditions at the sites, following a relatively long period when diluted groundwaters of meteoric origin predominate, the production and concentrations of sulphide and methane will not be larger than those found at present, i.e. after a recent period of intrusion of marine sulphate-rich waters. Based on the arguments presented in section 9.3.7 and present-day data (Figure 9-44 and Figure 9-46) it is to be expected that the sum of CH_4 and HS^- concentrations during permafrost periods will be at the levels found at present at the sites or lower, that is, on the average $\leq 10^{-5}$ M.

For major groundwater components, such as Cl, Na, Ca and sulphate the conclusion is that they will follow the trends of salinity discussed above. Other components, such as bicarbonate, potassium, iron sulphide, etc, as well as pH that are controlled by fast chemical reactions are expected to remain mostly unaffected by permafrost. Therefore, the criteria concerning the safety function indicators R1d and R1e in Figure 9-2 are expected to be fulfilled, in that pH will remain < 11 and the concentrations of K, HS^- and Fe will remain limited.

Permafrost; effects of grouting, shotcreting and concrete on pH

The processes described in section 9.3.7 for the temperate domain following repository closure will continue during permafrost periods. Given enough time all grout will be converted first into calcium silicate hydrates with low calcium to silica ratios, and finally into calcite and silica /Luna et al. 2006/. The duration of this process will depend on the velocity of the groundwaters flowing around the grouted volumes, but times longer than 10^4 years are expected.

The conclusion reached in section 9.3.7 is therefore still valid: the effect of grout in fractures will be to increase the pH in deformation zones to values ≈ 9 for relatively long periods of time. These values are, however, within the criteria for the safety function indicator R1e in Figure 9-2.

Glaciation; evolution of salinity

For the glacial cycle of the reference evolution (about 120,000 years) the Forsmark site is covered by an ice sheet during a few periods with a total duration of about 30,000 years, see section 9.4.1.

Groundwater flow in the glacial domain has been estimated using a generic model representing a large regional scale including the Oskarshamn area /Jaquet and Siegel 2006/. A fuller description of these calculations is given in section 9.4.6 and in the original report. The results of that model include evaluations of the salinity distribution beneath an ice sheet. Two extreme situations are discussed below: i) when the repository is entirely covered by a warm-based ice sheet i.e. an ice sheet with basal melting, and ii) when the ice sheet is advancing. As discussed above in section 9.4.6, the model results indicate that the system behaves symmetrically, and that the hydrogeological results from an advancing ice sheet may be used to represent the case of ice retreat.

The repository area covered by a stationary warm-based ice sheet

According to the results of the model, dilute waters are expected under a warm-based ice sheet at repository depth; see Figure 9-91 which shows that most of the waters have a calculated salinity ≤ 0.1 g/L. The composition of these waters is expected to be similar to those sampled at the Grimsel tunnel where cold meteoric waters are transported along fractures in granitic rocks. Figure 9-91 also shows that the salinity is not homogeneously distributed, and that waters having salinities between 0.1 and 10 g/L ([Cl^-] 0.0017 to 0.17 M) are not uncommon, although less frequent.

Therefore, it may not be excluded that when an ice sheet covers the repository area, dilute melt waters, with [M^{2+}] < 1 mM, would occur at repository depth, violating the criterion for the safety function indicator R1c in Figure 9-2.

Advancing or retreating warm-based ice sheet

Model results reported in /Jaquet and Siegel 2006/ illustrating the upconing of deep saline waters under an advancing warm-based ice-sheet are presented in Figure 9-92, which shows that salinities up to 5% (≈ 52 g/L TDS) may be reached locally at repository depth. In this model the ice sheet is advancing on a site that originally has groundwaters with salinities around 1–2% at repository depth. For a retreating ice sheet the hydrology is similar, but the calculated salinities are quite different as the rock volume has been extensively washed out by glacial melt waters. The calculated salinities for a retreating ice sheet are instead equivalent to those shown above in Figure 9-91. Because the advancement of the ice sheet is a relatively fast process and the retreat even more so, the high salinity conditions are predicted to last only a few centuries at most. In addition, warm-based conditions during the ice advance is a pessimistic assumption. The front of the ice sheet may well be cold-based during the advance, such as in the reference evolution, see further the **Climate report**, section 4.2.1, and in this case the basal ice is frozen to the substrate and no groundwater recharge occurs.

In conclusion, upconing is not expected to affect the swelling capacity of the backfill, corresponding to the safety function indicator R1b in Figure 9-2.

Immediately after retreat of an ice sheet

As discussed above in section 9.4.1, immediately after the retreat of an ice sheet, isostatic depression will set the ground surface at the repository site below the Baltic Sea surface level for a period of time, see Figure 9-66. In the reference evolution, which is a repetition of the last glacial cycle, the Weichselian, the Forsmark and Laxemar sites are expected to be below melt water lakes, and sea or

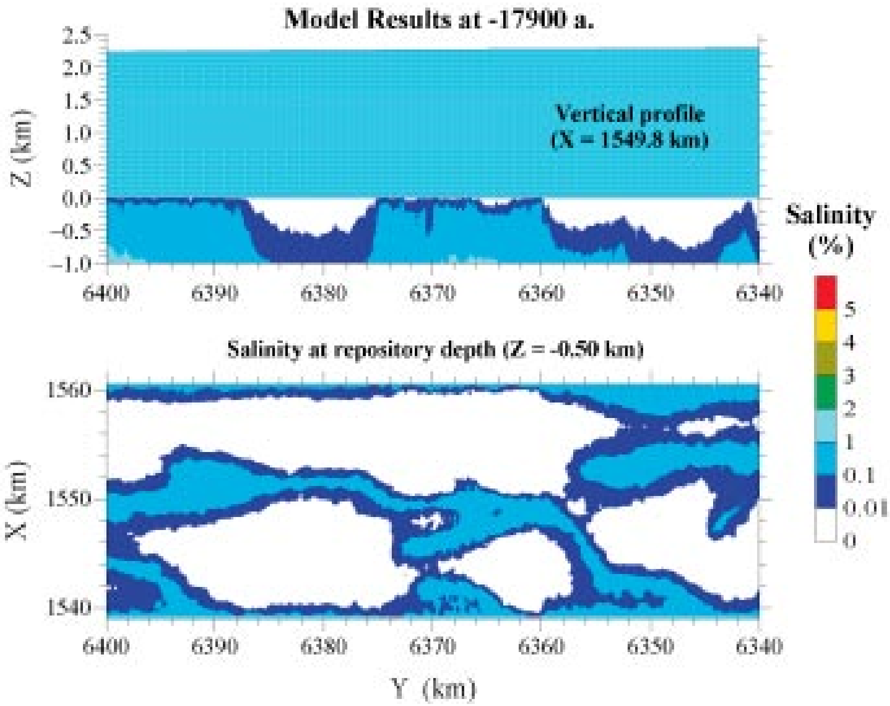


***Figure 9-91.** Contour plots showing the salinities for a site under a warm-based ice sheet calculated using the model described in section 9.4.6 /Jaquet and Siegel 2006/. The plots are focused on the Oskarshamn area: the upper diagram shows a North-South depth profile centred at the site (vertically exaggerated), and the lower diagram shows a slice at 500 m depth. The data indicate that at repository depth most of the waters have salinities below 0.01% (≈ 0.1 g/L) although some waters have salinities as high as 1% (≈ 10 g/L TDS).*

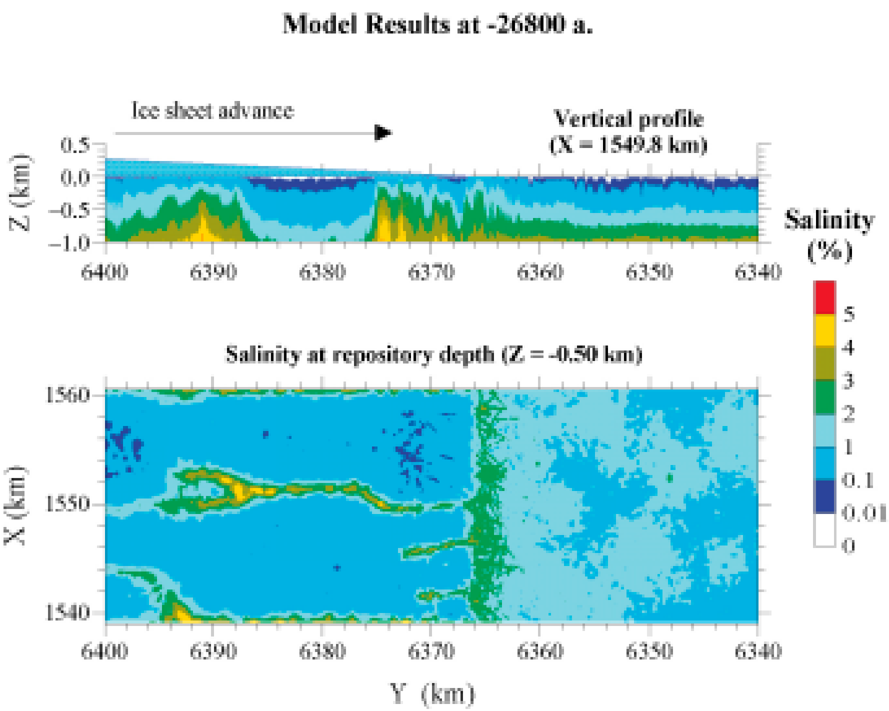


***Figure 9-92.** Contour plots showing the salinities for a site affected by an advancing ice sheet calculated using the model described in section 9.4.6 /Jaquet and Siegel 2006/. The plots are focused on the Oskarshamn area: the upper diagram shows a North-South depth profile centred at the site (vertically exaggerated), and the lower diagram a slice at 500 m depth. The data indicate that groundwaters at repository depth can reach salinities up to 5% (≈ 52 g/L) due to the upconing of deep saline waters. However, most of the waters at repository depth a few kilometres under the ice margin have salinities between 0.1 and 1%.*

brackish waters during a period of time between a few thousand years up to perhaps ten thousand years. Modelling of the Forsmark site since the retreat of the last ice sheet to the present-day situation shows a relatively fast turnover of groundwaters, where glacial melt is replaced by a succession of waters penetrating from the surface: the Yoldia sea, the glacial lake, the Litorina sea gradually evolving into the present day Baltic sea, and finally modern meteoric waters /SKB 2005e, 2006g/. The infiltration for relatively short periods of time of waters of marine origin will increase the salinity of groundwaters at repository depth that, as described above, had been diluted under a warm-based ice-sheet. It is, therefore, expected that during this period the concentration of divalent cations around the repository will increase as well to > 0.001 mol/L, corresponding to compliance with the safety function indicator R1c in Figure 9-2. As the salinities are not expected to increase above those of sea water, the swelling capacity of the backfill will not be affected, see safety function indicator R1b.

Glaciation; evolution of concentrations of other relevant natural groundwater components

There is no experimental information concerning the chemical conditions in groundwaters under ice sheets. Whereas the expected salinities have been explored in the previous sub-section with the help of a hydrogeological model, chemical reasoning must be used to estimate the consequences that a glaciation can have on specific aspects of groundwater chemistry.

As in the case of the temperate domain (section 9.3.7) and the permafrost case discussed above in this section, chemical components not participating extensively in chemical reactions, such as Cl, Na, sulphate, and perhaps to some extent Ca, will follow the salinity patterns under the ice sheet described above.

Figure 9-91 above shows that most of the waters under a warm-based ice sheet have low contents of salts, ≤ 0.1 g/L, due to the continuous influx of glacial melt waters. The composition of glacier melt waters has been reviewed in /Brown 2002/. Although as expected some of these waters are extremely dilute (1 mg/L), others have gained solutes from mineral weathering reactions, reaching salinities up to 0.2 g/L. Other examples of dilute granitic waters are those sampled in Gideå (0.33 g/L) and Grimsel (0.08 g/L). Although dilute, both these waters are close to saturation with calcite. The relatively high pH values, ≈ 9, originate from the weathering of bedrock minerals.

For upconing groundwaters that may have salinities up to 52 g/L, see Figure 9-92, mixing calculations between a deep brine and glacial meltwater and simultaneous equilibration with calcite shows that such a groundwater would have the following composition (concentrations in mol/L): Ca 0.33; Na 0.25; K $5\cdot10^{-4}$; Fe(II) $5\cdot10^{-6}$; Cl 0.9; total carbonate $2\cdot10^{-4}$; sulphate 0.0064; and pH = 7.3, Eh ≈ −200 mV /Auqué et al. 2006/.

As in the case of permafrost, the intensity of microbially mediated SO_4^{2-} reduction to produce sulphide will probably decrease under an ice sheet due to the lower temperatures. Compared with a preceding permafrost period, sulphate concentrations might increase during the short periods of upconing waters and they will decrease substantially during the longer periods of intrusion of glacial melt waters. Therefore, sulphate reduction may only occur during periods of upconing. In any case, reducing agents are required for any sulphate reduction to take place, and under glacial conditions the inflow of organic matter from the surface will become negligible. SO_4^{2-} reduction could still be sustained by the gaseous groundwater components methane and hydrogen, see the discussion in section 9.3.7. If microbial sulphide production occurs during upconing periods, it will be limited by the availability of both SO_4^{2-} and mainly CH_4. The amounts of methane will be controlled by its production and flow from the deeper parts of the bedrock. There is not enough data at present to quantify this process, but there are no indications that methane should increase in concentration during such periods, and there is no evidence to support increased sulphide production under ice sheets.

It is concluded that for glacial conditions at the sites the production and concentrations of sulphide will not be larger than those found at present, i.e. after a recent period of intrusion of marine sulphate-rich waters. Based on the arguments presented in section 9.3.7 and present-day data (Figure 9-44 and Figure 9-46), it is expected that the sum of methane and sulphide concentrations during glacial periods will be similar to the values found at present at the sites or lower, that is, on the average ≤ 10^{-5} M.

It may, finally, be concluded that major groundwater components, such as Cl, Na, sulphate, and perhaps Ca, will follow the trends of salinity discussed in sub-section above. Other components, such as bicarbonate, potassium, iron, sulphide and pH that are controlled by relatively fast chemical reactions will be less affected by the glacial conditions, and their maximum concentrations will be governed by reactions with minerals. Nevertheless, as mentioned above all the evidence points towards dilute waters with relatively high pH. Therefore the criteria concerning the safety function indicators R1d and R1e in Figure 9-2 will be fulfilled in that pH will remain < 11 and the concentrations of K, HS^- and Fe will remain limited.

As indicated previously, salinity levels are expected in general to decrease during glacial periods. Colloids are known to be strongly destabilised at high ionic strengths, and at high concentrations of divalent cations (Ca^{2+}) in particular. Therefore, during periods of glaciation, with predominantly dilute groundwaters, it cannot be excluded that colloids may perhaps be generated and transported by groundwater easily. However, a high potential stability of colloids does not necessarily implicate a high colloid concentration. It has, for example, been shown that the granitic groundwaters at Grimsel, which are quite dilute and where colloids, if formed, are quite stable, have low concentrations of colloids (≤ 0.1 mg/L). The reason for this is not clear: there might be some unknown mechanism that removes colloids at that site, or perhaps there is no significant generation of colloids at Grimsel. The conclusion is, therefore, that there is a potential for higher colloid concentrations in groundwaters during a glacial period, especially during the advance and retreat of an ice sheet when groundwater velocities are highest. An upper limit would be the highest measured colloid concentrations in groundwaters at repository depths, ≈ 1 mg/L.

Glaciation; redox condition

As discussed in previous sections, the advance of an ice sheet induces large changes in the groundwater conditions as compared with those prevailing today at the sites. Short periods of upconing of deep reducing groundwaters, illustrated in Figure 9-92, will be followed by longer periods where glacial melt waters, more or less slowly, intrude into the rock. After some time the situation may look as in Figure 9-91, i.e. with groundwaters that originate almost entirely from ice melt water in large volumes of rock. Arguments have been put forward that if glacial melt waters were rich in dissolved atmospheric gases, then reducing conditions might no longer prevail at repository depth, infringing the safety function indicator criterion R1a in Figure 9-2, see for example /Puigdomenech et al. 2001b/.

The compaction of snow into glacier ice involves the incorporation of substantial amounts of air /Martinerie et al. 1992/. Thus, glacier melt water may initially contain dissolved carbon dioxide and oxygen at above the concentrations expected for aerated waters. The O_2 concentration for pure water in equilibrium with air is temperature dependent, ≈ 8 mg/L at 25°C. For glacial melt waters, based on theoretical constraints, the maximum O_2 concentration has been estimated to be 45 mg/L /Ahonen and Vieno 1994/, and this is what is observed in some samples of glacier ice thawed under laboratory conditions. However, it has been noted that much lower values are normally measured in sampled glacial melt waters in the field, in the range 0–5 mg/L /Gascoyne 1999/. It may be argued that degassing could have partly contributed to the observed decrease in the O_2 levels of the field samples. However, glacial melt waters are very aggressive and quickly react with sub-glacial rock minerals and debris, generating solutes up to 0.2 g/L /Brown 2002, Cooper et al. 2002/, mostly from acid dissolution of calcite ($CaCO_3 + CO_2 + H_2O \rightarrow Ca^{2+} + 2\ HCO_3^-$) and pyrite oxidation ($4\ FeS_2 + 14\ H_2O + 15\ O_2 \rightarrow 16\ H^+ + 8\ SO_4^{2-} + 4\ Fe(OH)_3$). The amounts of calcium and sulphate fount in glacial melt-waters are sufficient to explain the low O_2 concentrations found.

The penetration of oxygen-rich glacial melt waters in granite fractures under a warm-based ice sheet has been the subject of several modelling efforts, the initial study being by /Neretnieks 1986 p. 175)/. /Guimerà et al. 1999/ showed that a change in the redox potential is to be expected at repository depth and that it can not be excluded that oxygenated waters may reach repository depths under special circumstances. /Sidborn and Neretnieks 2003, 2004/ considered the possible influence of microorganisms and concluded that, in the long run, abiotic reactions have a dominant effect on the consumption rate of oxygen.

The conclusion of these studies is that if glacial melt waters move at moderate rates into the rock system, with water travel times of tens of years or more, and taking into account the large amount of reducing Fe(II) minerals in the rock and in the fracture filling minerals, all dissolved oxygen will be consumed. However, the results of the hydrogeological modelling, discussed previously in section 9.4.6, show average water travel times of a few years during periods lasting for some hundreds of years, see Table 9-20 in section 9.4.6 above. The estimate of occurrence of glacial conditions presented at the end of section 9.4.6 also indicates that increased hydraulic gradients will occur only during relatively short periods of time (40 and 1,300 years for Case A and B, respectively). These short travel times would indicate that penetration of waters containing dissolved oxygen to repository depths cannot be excluded based on the model results mentioned in the previous paragraph.

The flow paths of shortest possible duration start at deposition holes intersected by single fractures and continue in larger vertical deformation zones close to the deposition holes. The evaluation of a possible O_2 intrusion has to address both high transmissive deformation zones and single fractures. Here these two systems are briefly discussed; a full discussion is given in /Auqué et al. 2006, Guimerà et al. 2006, Sidborn and Neretnieks 2006/.

For very transmissive deformation zones, with $T \approx 10^{-4}$ m²/s, matrix diffusion becomes negligible. The interaction between groundwater and fracture minerals is then governed by the rate of dissolution, which implies that the water residence time, and hence the water velocity, are important parameters. The groundwater velocity may be estimated from the advective travel time, which has a lower limit of about one year, and the length of the groundwater flow path, which is assumed to be 400 m in the deformation zone and 100 m in fractures. The modelling in /Guimerà et al. 2006/ which is a revision of the earlier work in /Guimerà et al. 1999/ has explored such a system. The new calculations involve a 1D model representing melt water travelling along a fracture zone containing calcite and Fe(II)-mica. The model simulates packets of 1 L of water travelling a distance of 400 m. The modelled system is divided into segments of 1 m at which the packet of water is allowed to react, and after regular time intervals the fluid is moved to the next segment.

For moderate O_2 inflows, the rate of penetration is directly proportional to the water flow rate and inversely proportional to the amount of reducing minerals, see e.g. /Romero et al. 1992/. For cases where the inflow of O_2 is high, which are those that have potential to create an oxidising perturbation at repository depth, the rate of Fe(II)-mineral dissolution becomes the limiting factor for the advance of oxygen. For such cases, the O_2 velocity depends on the water velocity, and on the amount and rate of dissolution of the Fe(II)-mineral. The rate of dissolution of Fe(II)-mica depends on its amount (surface area), and on the pH of the water. The amount of Fe(II) and the reacting surface area were chosen in the modelling work /Guimerà et al. 2006/ to represent a fracture zone filled with moderate amounts of gouge or fracture-filling minerals. The results of the calculations are illustrated in Figure 9-93 showing that, as expected, the rate of advance of dissolved O_2 is very sensitive to the water velocity. The figure shows that at water velocities of 31.6 m/year (0.032 m³/year), the oxygenated front advances around 60 m in 5,000 years, and this distance becomes shorter for slower water velocities. As explained in /Guimerà et al. 2006/ the results are sensitive to the assumed reactive surface area and to the reducing capacity available within the fracture zone.

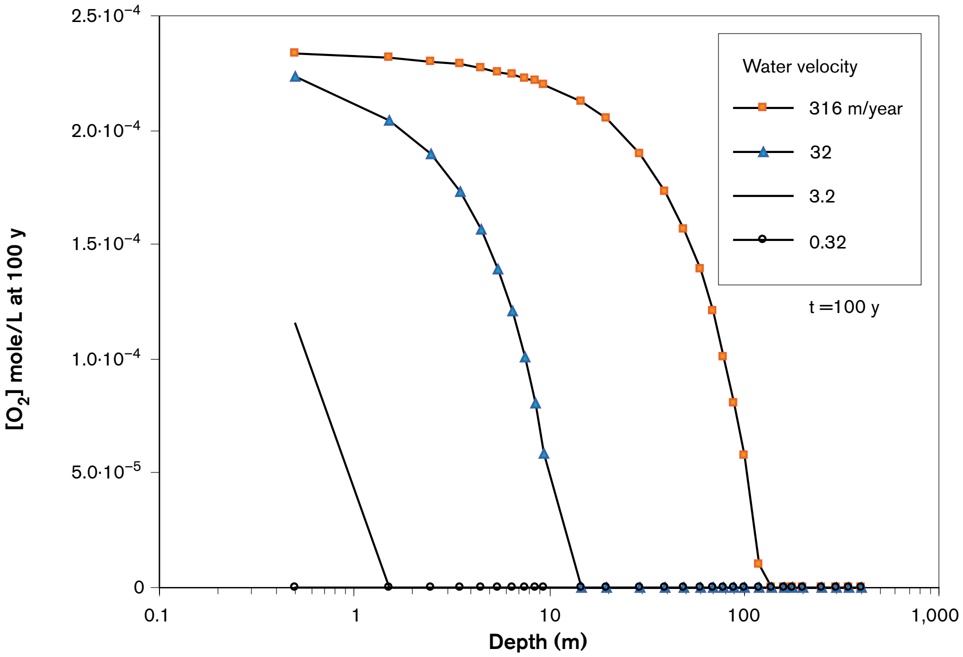


***Figure 9-93.** Calculated O_2 concentrations as a function of depth for glacial melt water travelling along a fracture at velocities ranging from 316 to 0.32 m/year /from Guimerà et al. 2006/.*

It may also be shown /Auqué et al. 2006/ that after a well-defined distance the inflow of O_2 is exactly balanced by the dissolution of Fe(II)-minerals at that distance in the fracture, and that the front between oxygen rich and reducing waters becomes stationary. The front will advance when the reducing capacity within the fracture zone is exhausted, which for a typical deformation zone is calculated to be around 1,200 years. After that time the O_2 front advances again at a velocity governed by mass balcance restrictions. For a typical deformation zone, and a groundwater velocity of 1 km/year, the O_2 front advances at a rate of 0.3 m/year.

Once the period of high O_2 inflow has ceased, matrix diffusion will again become important and the oxidising perturbation will be neutralised by the large content of Fe(II) in the rock minerals.

Although the model discussed above may be used to evaluate the fate of oxygen in glacial melt waters penetrating through a deformation zone, for single fractures it is to be expected that the amounts of fracture-filling minerals in contact with the flowing water will not be as large. In this case, it may be shown that matrix diffusion is an important mechanism to access the reducing capacity of the rock matrix adjacent to the fracture pathways. These processes may be modelled using analytical expressions initially developed in /Neretnieks 1986 p. 175)/ and further developed in /Sidborn and Neretnieks 2006/. An equivalent model was successfully applied to the redox fronts at Poços de Caldas /Romero et al. 1992/. The expressions presented in /Sidborn and Neretnieks 2006/ include advective flow in the fracture and diffusion in the matrix, and the model implicitly assumes that the dissolution of rock minerals in the matrix is fast as compared to the diffusion process. The model indicates that for single fractures with a transmissivity as high as $T \approx 10^{-7}$ m^2/s, and using a hydraulic gradient of 0.01, the calculated maximum O_2 penetration along the fracture is 23 m for **Case A** (40 years of passage of the glacier front above the repository) and 130 m for **Case B** (for a total of 1,300 years). According to the criteria described in /Sidborn and Neretnieks 2006/ the assumption that the rate of mineral dissolution is fast as compared to the diffusion process is not precisely correct for the shortest time period of 40 years (Case A), and slightly longer penetration depths should be expected for such short time periods. Nevertheless, it is clear from the results for Case B that the penetration of O_2 along single fractures during a glacial period is a very slow process.

The conclusions for the calculations performed so far are that for advective travel times longer than about one year, the rate of O_2 depletion through mineral reactions is fast enough to prevent any dissolved oxygen from reaching repository depths. The reducing capacity of the fracture-filling minerals is sufficient to widthstand the flow of oxygen for more than one thousand years. At faster water velocities, the behaviour of the system becomes more complex /Auqué et al. 2006/ and, if such fast intrusion of melt waters was to persist over periods of time longer than those defined by Case B above, eventually O_2 might reach repository depths if the reducing capacity of the deformation zone became exhausted. It is, however, expected that these fast water velocities would occur for only rather brief periods (perhaps up to 1,300 years as in Case B above), and then the penetration of O_2 to repository depth would not occur.

Since water velocities are expected to be slower than 1 km/year in deformation zones, see Table 9-20 above, it is concluded that reducing conditions will prevail at repository depth, satisfying the safety function indicator criterion R1a in Figure 9-2.

Glaciation; effects of grouting, shotcreting and concrete on pH

The processes described in section 9.3.7 for the temperate domain following repository closure will continue during the glaciation periods of the first glacial cycle, although the effects will gradually decrease. Given enough time, all cement in grout will be converted first into calcium silicate hydrates with low calcium to silica ratios, and finally into calcite and silica /Luna et al. 2006/. The duration of this process will depend on the velocity of the groundwaters flowing around the grouted volumes, but times at least of the order of 10^4 years are expected.

Therefore, the conclusion reached in section 9.3.7 is in part still valid here: the effect of grout in fractures will be to increase the pH in deformation zones for relatively long periods of time. It is expected that, with time, the pH that initially had risen to ≈ 9 will progressively homogenise with the values found in surrounding parts of the rock, and therefore within the criteria for the safety function indicator R1e in Figure 9-2.

9.4.8 Effects on buffer and backfill

Buffer freezing

As concluded in section 0, buffer and backfill freezing does not occur in the reference evolution at either Forsmark or Laxemar. Uncertainties regarding buffer freezing are further evaluated in a dedicated scenario, section 12.4.

Chemical evolution of buffer and backfill for altered groundwater compositions

Intrusion of water types other than the present-day deep groundwater in the repository area may significantly modify the chemical evolution of the system. /Arcos et al. 2006/ have modelled the consequences of intruding waters of different compositions. A composition of a deep water from Laxemar was used as an example of saline water and a composition from Grimsel was used as an example of a glacial melt water (see Table 9-23, at the end of chapter 9). The same model and boundary conditions as described in section 9.3.10 and 9.3.11 was used in the calculations. The simulations covered 60,000 years of glacial and saline water intrusion, respectively.

Glacial melt water – MX-80

Unlike present-day groundwaters at the sites, glacial melt waters are characterised by a very low salinity. The Grimsel groundwater is characterised by a high pH (pH = 9.6) and a composition dominated by Na and HCO_3^-. Once glacial melt water reaches the near-field system, the geochemical evolution of the system diverges from those evolutions described in sections 9.3.10 and 9.3.11. The pH in the bentonite pore water tends to increase (Figure 9-94) until the end of the simulation (60,000 years),

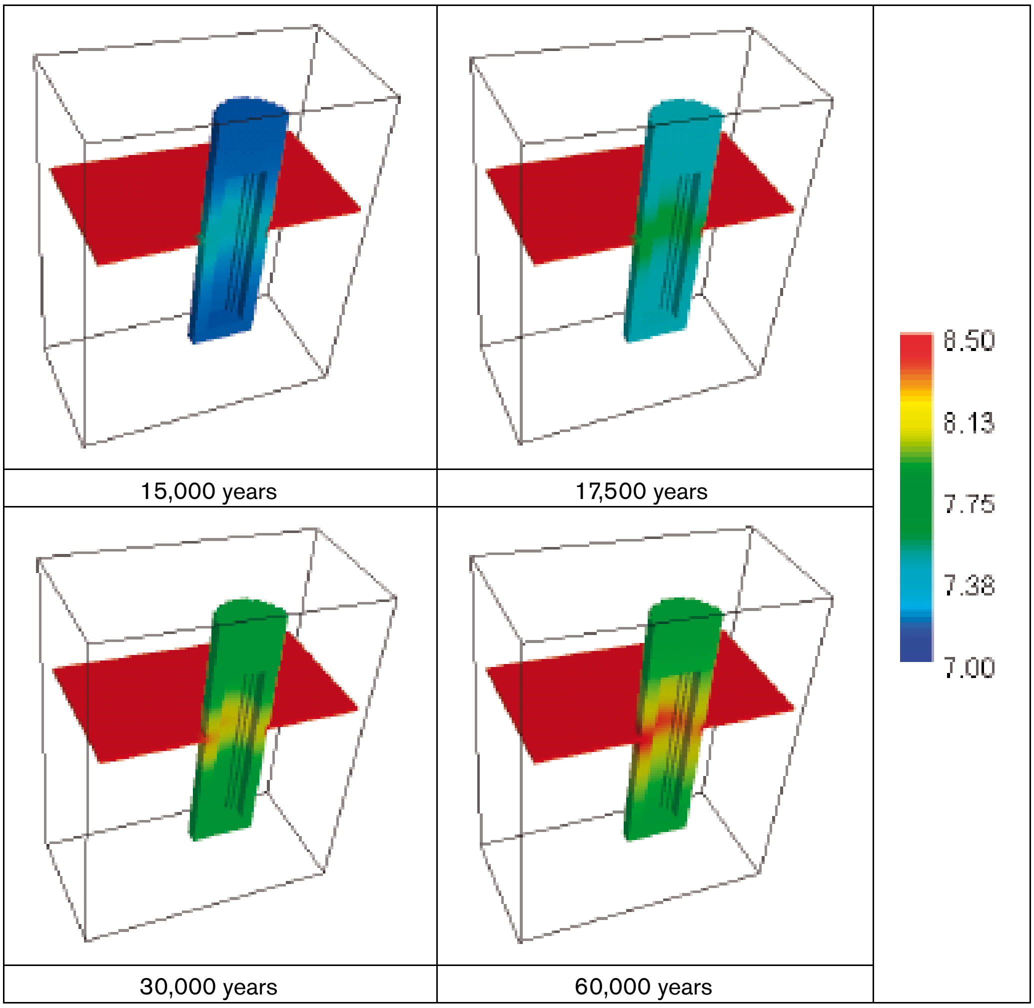
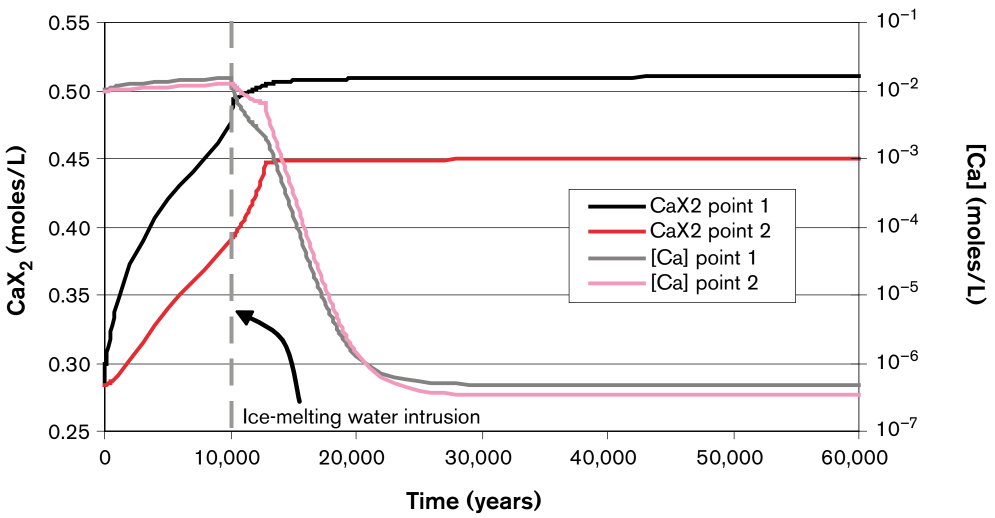


Figure 9-94. *Predicted pH evolution of the system after the intrusion of glacial melt water starting at 10,000 years of simulation (MX-80 buffer).*

with a maximum pH of approximately 8.3 in the bentonite close to the fracture zone. This increase in pH is due to the high pH of the glacial melt water, which causes a modification of montmorillonite surface acidity, leading to the deprotonation of positively charged sites mainly increasing the concentration of neutral sites. Thus, acidity reactions on the clay surface buffer the pH of pore water to lower pH values than that of the glacial melt water. No other process in the model, such as dissolution or precipitation of accessory minerals, contributes significantly to this pH increase. This limited pH increase has insignificant effect on the overall performance of the near field.

An additional effect relevant to the geochemical evolution of the system after the glacial melt water intrusion is the composition of the cation exchange sites in the bentonite. Due to the low concentration of calcium in the glacial melt water, the diffusive transport of calcium in the system reverses, calcium diffuses from the bentonite to the fracture zone and is flushed out of the near-field system.

In the case of an intrusion of glacial melt water, the concentration of Ca^{2+} in the porewater can drop to very low values. Figure 9-95 shows the calculated Ca^{2+} concentrations in the porewater in the MX-80 bentonite, from /Arcos et al. 2006/. It is clear that the concentration will drop far below the CCC value that is of importance for the occurrence of colloid release from the buffer.



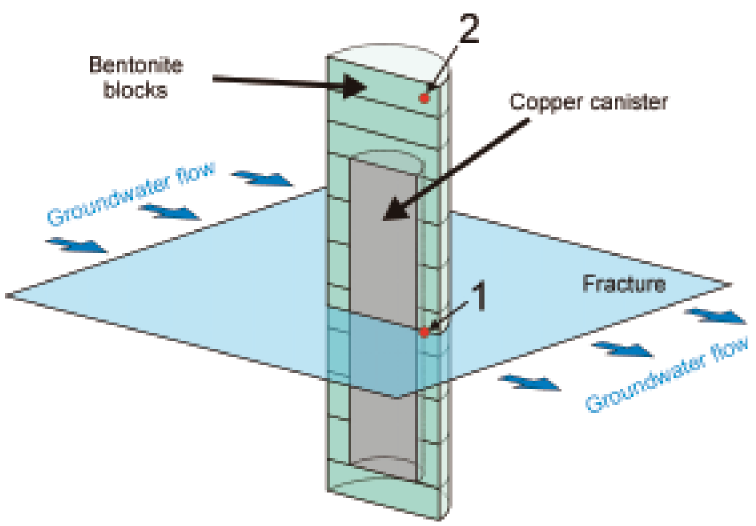


Figure 9-95. *Predicted evolution of Ca occupancy in the exchange sites and aqueous calcium concentration at two points in the MX-80 bentonite as shown in the figure (1) at the fracture level, and (2) far from the fracture intersection. Note that shortly after glacial melt water intrusion (grey dashed line) the calcium occupancy in the exchange sites is predicted to be constant.*

Glacial melt water – Deponit CA-N

The effect of the interaction of glacial melt waters with the Deponit CA-N bentonite is more complex, due to the presence of carbonate minerals (mainly calcite and dolomite). The behaviour of carbonate minerals during the interaction with dilute water of alkaline pH, could result in two opposite and competing processes: i) precipitation of carbonates to buffer the intrusion of high pH waters, and ii) dissolution of carbonates due to the out-diffusion of Ca and aqueous carbonate from the bentonite, induced by the low concentration of these two components in the inflowing groundwater.

The results of the simulation indicate that pH in the bentonite pore water increases after the intrusion of glacial melt water (Figure 9-96), reaching a maximum pH of 9.3 near the fracture plane at the end of the simulation.

The reason for this increase in pH is related to the behaviour of aqueous calcium and carbonate in the system. Once glacial melt water contacts the near field, the strong calcium concentration gradient between this water and the pore water in the bentonite leads to a fast out-diffusion of calcium from the bentonite. This initial depletion in calcium concentration increases the amount of gypsum dissolved, supplying large amounts of calcium and sulphate to the pore water. In addition, as magnesium is also strongly depleted in the bentonite pore water due to out-diffusion, dolomite dissolution increases. This geochemical evolution has an effect on the cation occupancy in the exchange sites of the bentonite. Initially, before glacial melt water intrusion, calcium and magnesium are replaced by sodium in the bentonite exchange sites. However, after the intrusion of glacial melt water, as sodium diffuses out of the bentonite faster than calcium, the exchange process reverses, and calcium and magnesium replace sodium. The rate of the replacement depends on the evolution of calcium concentration, thus it is faster while gypsum is still present and slows down once gypsum is totally dissolved.

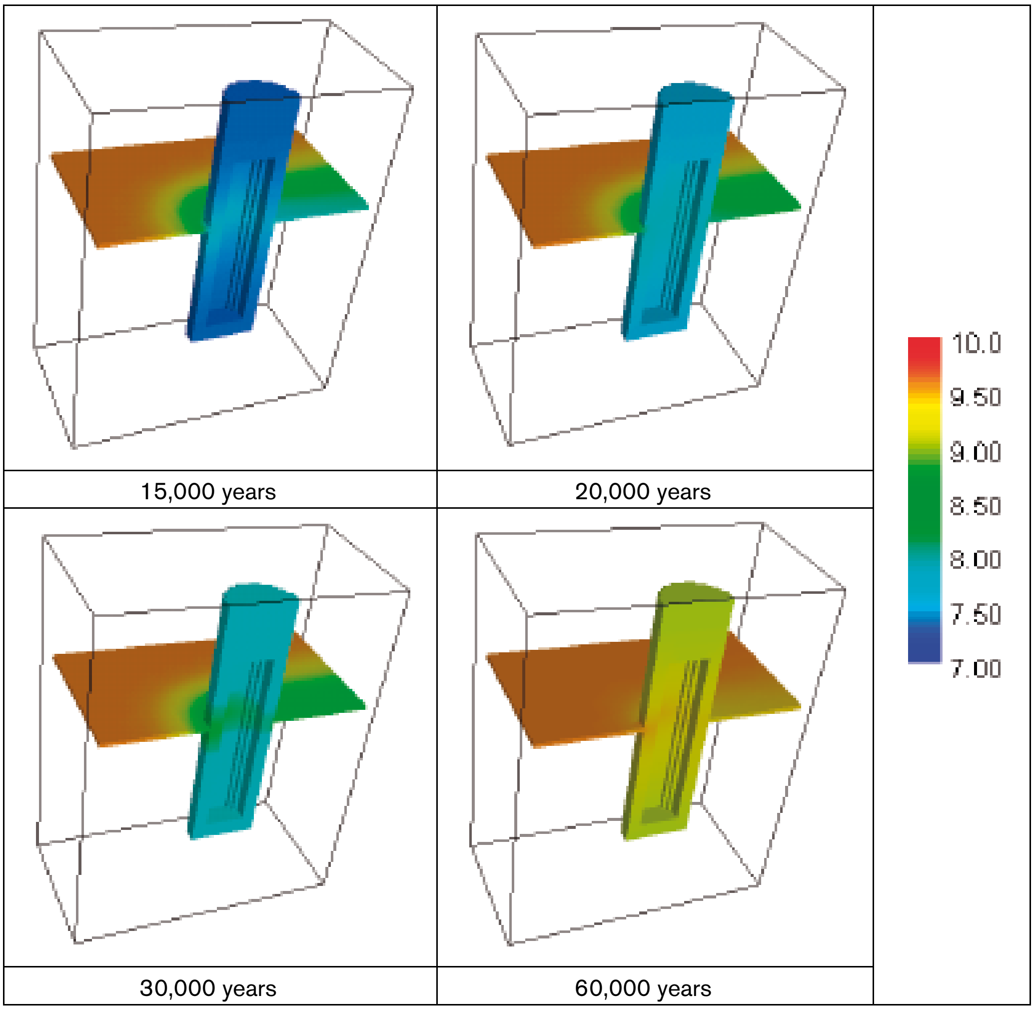


Figure 9-96. *Predicted pH evolution of the system after the intrusion of glacial melt water starting at 10,000 years of simulation (Deponit CA-N buffer).*

Figure 9-97 shows the calculated Ca^{2+} concentrations in the porewater in Deponit CA-N bentonite, from /Arcos et al. 2006/. As for the case of MX-80, it is clear that the concentration will eventually drop far below the CCC value, but the process is slower. This delayed drop is an effect of the gypsum content in Deponit CA-N. These simulations are based on an ice-melt intrusion of dilute glacial water beginning at 10,000 years. If it were to occur at later times gypsum would probablyalready have been dissolved and the calcium concentrations would be lower.

High salinity water – MX-80

The high-salinity groundwater from Laxemar (Table 9-23, at the end of chapter 9) has a very low pE leading to the predominance of reduced sulphur and carbon aqueous species. Under these conditions, and assuming that it is likely that bacterial activity in the fractured granite will facilitate sulphate to sulphide and carbonate to methane transformations, the aqueous sulphur and carbon dominant species are HS^- and CH_4, respectively, instead of S(VI) and carbonate aqueous species as in the case in which present-day Forsmark groundwater is considered. However, analytical data from Laxemar /Laaksoharju et al. 1995/ indicate that the dominant aqueous sulphur forms are S(VI) species and no methane has been detected. For modelling purposes, the Laxemar water has been assumed to be in equilibrium with gypsum, calcite and pyrite giving a slightly modified composition, see Table 9-21.

Table 9-21. Chemical composition of saline waters as reported in Table 9-23 and recalculated values for modelling purposes. The values are reported as total aqueous concentrations.

moles/L	Table 9-23	Re-calculated
pH	7.9	7.9
Eh(mV)	−300	−230
HCO_3^-	$1.0 \cdot 10^{-4}$	$3.2 \cdot 10^{-5}$
Ca	0.46	0.46
Cl	1.28	1.28
Fe tot	$8.0 \cdot 10^{-6}$	$8.0 \cdot 10^{-6}$
K	$7.0 \cdot 10^{-4}$	$7.0 \cdot 10^{-4}$
Mg	$1.0 \cdot 10^{-4}$	$1.0 \cdot 10^{-4}$
Na	0.35	0.35
SO_4^{2-}	$9.0 \cdot 10^{-3}$	$2.6 \cdot 10^{-3}$
SiO_2(aq)	$8.0 \cdot 10^{-5}$	$5.7 \cdot 10^{-5}$

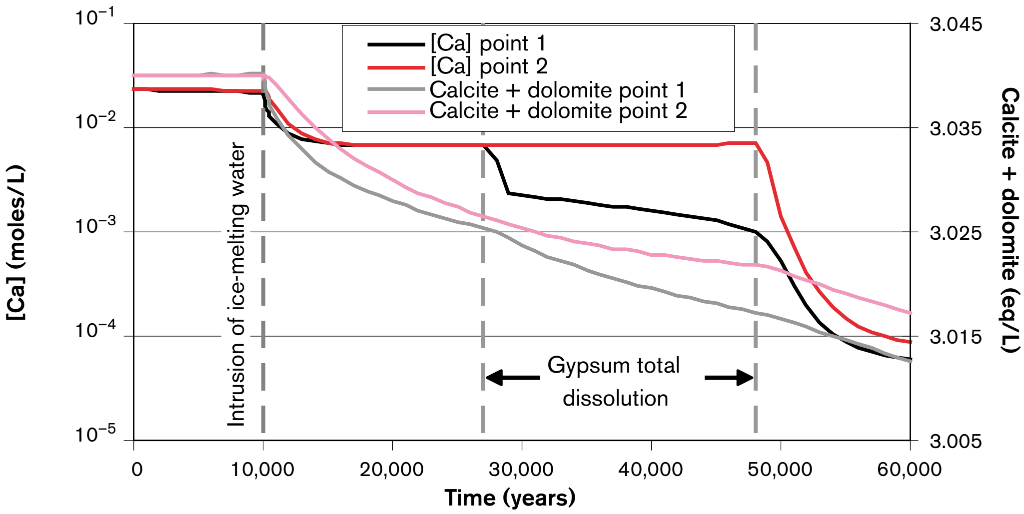


Figure 9-97. *Predicted evolution of calcium concentration in pore water and carbonate minerals at two points in the Deponit CA-N bentonite as shown in Figure 9-95, (1) at the fracture level, and (2) far from the fracture intersection. Gypsum total dissolution indicates the time range from total dissolution only in those bentonite cells located at the fracture level to total dissolution in the whole bentonite buffer.*

Intrusion of saline water will lead to a slight decrease in the pH of the porewater (to pH = 7.0). The decrease in pH coinciding with the intrusion of high-salinity water is related to the precipitation of calcite in the bentonite. The reason for the precipitation of calcite in the bentonite is the high concentration of calcium in the high-salinity water. Despite this, the high-salinity water has a carbonate concentration two orders of magnitude lower than Forsmark groundwater. However, the diffusion of aqueous carbonate out of the bentonite leads to the dissolution of the previously precipitated calcite, thus increasing again the pH of the bentonite pore water.

In addition, the diffusion of large amounts of calcium into the bentonite increases the Ca by Na replacement in the exchange sites, see Figure 9-98.

High salinity water – Deponit CA-N

The predicted geochemical evolution of the system when considering the effect of high-salinity water intrusion is related to the competition between the out-diffusion of aqueous carbonate and the in-diffusion of calcium, as in the simulation considering the MX-80 bentonite. However, in this case, the presence of carbonate minerals in the bentonite, prior to the intrusion of high-salinity water, will buffer the pH of the system.

At the same time, the large diffusion of calcium into the bentonite increases the calcium occupancy in the exchange sites and reverses the previous pattern of gypsum dissolution by leading to a slight precipitation of gypsum.

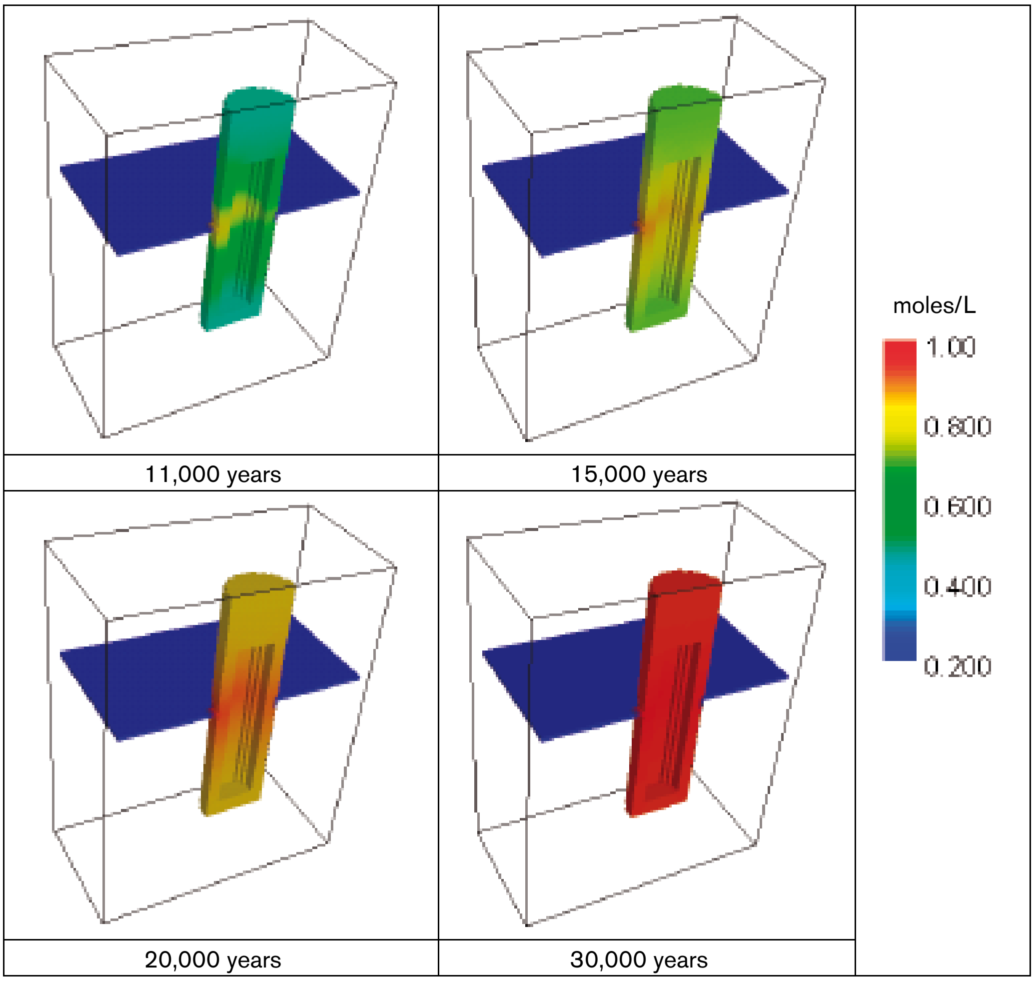


Figure 9-98. *Predicted evolution of Ca occupancy in the cation exchange sites of the MX-80 bentonite after the intrusion of high-salinity water.*

Colloid release from buffer and backfill

Colloid release was considered as unlikely during the initial temperate period after closure, since the groundwater concentration of Ca^{2+} is expected to exceed the critical coagulation concentration of the buffer, CCC, see section 9.3.11. There is no reason to believe that the groundwater composition during future temperate periods would differ from that of the initial, meaning that colloid release would be an unlikely phenomenon also for these periods.

Also for permafrost conditions, the groundwater concentration of Ca^{2+} is expected to exceed the CCC, see section 9.4.7.

For glacial conditions this is, however not the case according to section 9.4.7. In addition, there may be short periods of significantly increased flow rates when the moving ice front passes over the repository.

To estimate possible losses of buffer mass for glacial conditions, three stylised cases have been simulated. One concerns flow conditions that are similar to those at present and the other two analyse conditions of increased flow. For all these, the buffer pore water is assumed to be depleted of Ca^{2+} ions, as demonstrated to be quite possible for a glacial melt-water intrusion, see e.g. Figure 9-95. This means that Ca^{2+} ions for the prevention of colloid formation will not be supplied by the buffer. Since the groundwater is also depleted in Ca^{2+} ions, the erosion is assumed to occur at a rate that is determined by the product of the equivalent flow rate at the deposition hole and the maximum concentration of bentonite in a water suspension (50 g/L), see Appendix B. This model maximises the loss rate assuming that the mass exchange between the bentonite suspension and the flowing water is driven by diffusion. However, mechanistic understanding of the colloid release process is insufficient for robust estimation of erosion. For example, the repulsive forces between the clay particles are not considered in the model used, and these forces act to increase the loss rate. The model also assumes that the bentonite consist of only montmorillonite which is converted to a pure Na-form. There are early experimental and theoretical indications that the extent of the colloid release process could be much smaller in the case of a commercial bentonite and especially a bentonite with calcium as the dominant cation. This means that further knowledge may lead to models that yield both lower and higher loss rates.

Glacial conditions – Unaltered flow

As discussed in section 9.4.6, groundwater flow increases during parts of a glacial episode, and there may also be parts where the flow is dampened compared with temperate conditions. As one illustration of buffer erosion caused by glacial melt waters, it is, therefore, not unreasonable to assume that the groundwater flow rates at repository depth would be similar to the present rates. According to Figure 9-66, section 9.4.1, glacial conditions can be expected for about 25,000 years of the 120,000 year reference glacial cycle at Forsmark. Therefore, a stylised case of colloid release with today's flow situation for 25,000 years has been calculated, see Figure 9-99. Results with and without the influence of spalling on Q_{eq} are given.

Without spalling effects, the buffer mass loss exceeds 1,200 kg for about 3% of the deposition holes for the semi-correlated DFN model, and for none of the holes with the other two models.

Including spalling effects, 1,200 kg or more is lost at 15% of the deposition holes with the fully correlated model, 35% with the semi-correlated model and for none of the holes with the CPM model. For Laxemar, the only hydrogeological model considered yields more than 1,200 kg mass loss at about 40% of the deposition holes (not shown in the figure).

Glacial conditions – Increased flow

Periods of increased flow need also be considered in the reference evolution. This can be illustrated by applying the conditions for the stylised Case A described in section 9.4.6; 40 years of increased flow by a factor of 160 and of increased Q_{eq} by the square root of this factor. This case, however, gives insignificant added losses during the high flow period compared with the total loss during the glaciation calculated above. However, the questionable validity of the model used for the calculation of buffer losses means that the confidence in this result is limited.

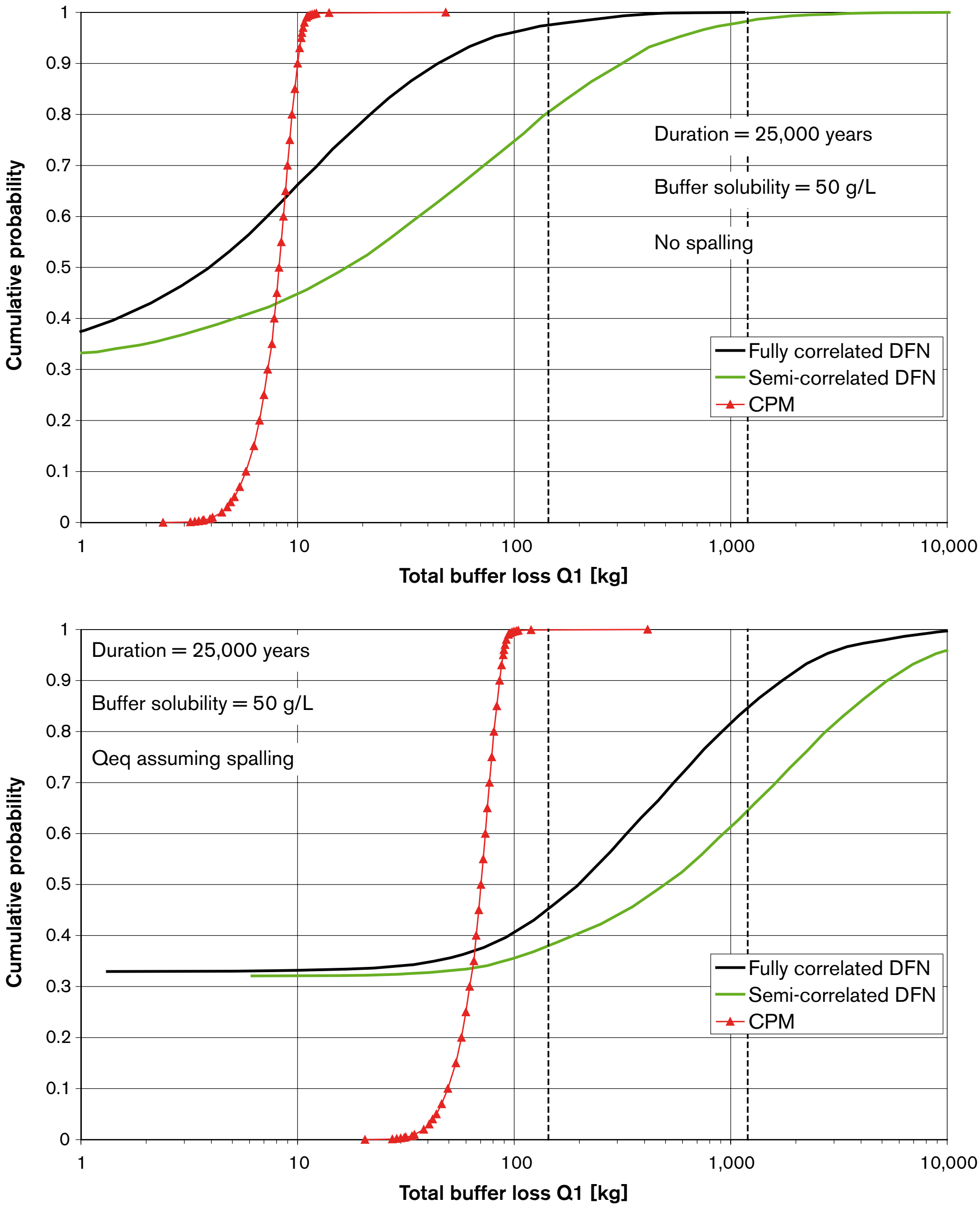


***Figure 9-99.** Colloid release for a case where today's flow conditions are assumed over 25,000 years, and where the chemical state of the buffer does not limit erosion. Q_{eq}-distributions from the hydrogeological modelling of the Forsmark site for temperate conditions have been used. Results are shown without (upper) and with (lower) effects of spalling on Q_{eq}. The vertical line at 1,200 kg denotes the local loss required to reach advective conditions. A loss of 144 kg during the initial glacial cycle corresponds to advective conditions after one million years.*

Buffer mass redistribution after colloid release

The total dry mass of buffer in a deposition hole is around 20 tonnes. A loss of e.g. 1,500 kg (applicable to about one percent of the canisters in the calculation example) corresponds to a saturated density of 1,870–1,980 kg/m^3 assuming reference initial density and that the remaining mass is *evenly distributed* in the buffer. This corresponds to a swelling pressure roughly in the interval 2.2–6.6 MPa.

As reported in section 9.3.9, /Börgesson and Hernelind 2006/ have calculated the swelling pressure for cases where one, two and three entire bentonite rings surrounding the canister have been omitted, to illustrate the effects of a *local* loss of large amounts of bentonite. The conclusion was that a mass loss of 1,200 kg to a fracture intersecting the deposition hole, would lead to conditions where advective conditions in the buffer must be considered, see further section 9.3.9.

Effects on backfill of colloid release

The effects of colloid release from the backfill have not been evaluated to any detail within SR-Can. However, a few preliminary conclusions can be drawn:

- The backfill will most likely be intersected by more water conductive features than the buffer, which possibly could increase the rate of erosion.
- The total mass of the backfill is much larger than that of the buffer, which means that a smaller fraction of the material will be lost.
- The effects of erosion is expected to be local, which means that most of the backfill mass will remain unaffected.
- The 30/70 mixture can be strongly affected by erosion, since the clay component will be selectively eroded. The effect of dilute waters on Friedland clay is basically unknown. It may be less prone to the effect since the content of other minerals is high.

It cannot be ruled out that the backfill locally will lose most of the swelling pressure and also get an increased hydraulic conductivity. The overall effect on repository is still expected to be small compared to erosion effects on the buffer. The effect of a partially eroded backfill needs to be evaluated in radionuclide transport calculations.

Conclusions

- Based on current knowledge, buffer erosion for glacial conditions cannot be ruled out. The conclusion is based on assessments of the groundwater composition for glacial conditions and on modelling of the buffer chemical evolution when intruded by glacial melt waters, resulting in groundwater and buffer chemical conditions that could yield colloid release at a high rate.
- Preliminary quantitative evaluations of the erosion process indicate that substantial losses, affecting several of the buffer safety functions negatively, cannot be ruled out, potentially for a considerable fraction of the deposition holes during the 120,000-year glacial cycle. These effects are propagated to calculations of canister corrosion and, in the case of resulting canister failures, to calculations of radionuclide transport.
- It is stressed that the model used to quantify the extent of the erosion process is preliminary. A better understanding of the erosion phenomenon could yield a model predicting either lower or higher loss rates. This is being further studied as a matter of priority.
- It is important to further evaluate the possibilities of identifying and discarding deposition positions that can be expected to have the highest flows under long-term conditions and the reliability of such identifications. In particular, the correlation between the observable inflow to an open deposition hole and the flow after deposition and saturation could be interesting to evaluate. The present calculations are based on the assumption that the so called full perimeter criterion is used for discarding deposition positions, see section 4.4.1.

Liquefaction

Liquefaction, as observed in loose clay and sand, cannot take place in a bentonite with high density, since the effective stress that holds the clay together is high due to the swelling pressure. However, a similar phenomenon has been observed during compaction of bentonite blocks at high water ratios. The process requires high pore water pressures. Collapsability is the primary condition for liquefaction and it means that the density is the controlling parameter. This has been demonstrated in earlier studies /Pusch 2000/ that have shown that only soft backfills can undergo that type of liquefaction.

Pressure increases resulting from earthquakes have been demonstrated as not being able to cause liquefaction in the buffer /**Buffer and backfill process report**, section 2.4.2/.

Another possible cause for liquefaction is pressure increases in fractures connected to the water-saturated buffer, which may occur at a glaciation. This effect has been investigated by tests in the laboratory. A bentonite sample of MX-80 with void ratio $e \sim 0.9$, i.e. a dry density of ~ 1,450 kg/m^3, was confined in a swelling pressure oedometer. The water pressure was changed and the influence on total pressure measured. The results showed that the total stress increased less than the pore water pressure and thus that the effective stress decreased. In Figure 9-100 the effective stress is plotted against the applied pore water pressure and it intersects the x-axis (representing no effective stress) at a water pressure of about 33 MPa.

/Harrington and Horseman 2003/ made similar observations, but interpreted them as a reduction in pore water pressure effect on total stress at a constant effective stress.

Only the former interpretation is of concern for the performance of the buffer.

Two separate experiments in which bentonite is exposed to high pore pressures are in progress to investigate the consequences of this process. It may also be possible to exclude the loss of effective stress based on natural analogues, but this has not been studied yet.

If the data from /Harrington and Horseman 2003/ are processed the same way as mentioned above the intercept point would be ~ 39 MPa for a dry density of 1,582 kg/m³, see Figure 9-101. This is slightly higher than expected groundwater pressures for the reference glacial cycle, i.e. about 30 MPa for the two sites (see section 9.4.6).

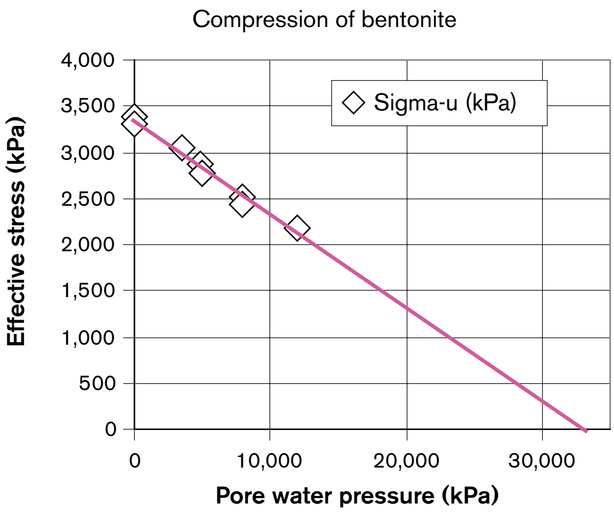


Figure 9-100. *Effective stress plotted as a function of the applied pore water pressure for an MX-80 buffer of dry density ~ 1,450 kg/m³, corresponding to a saturated density of ~ 1,920 kg/m³.*

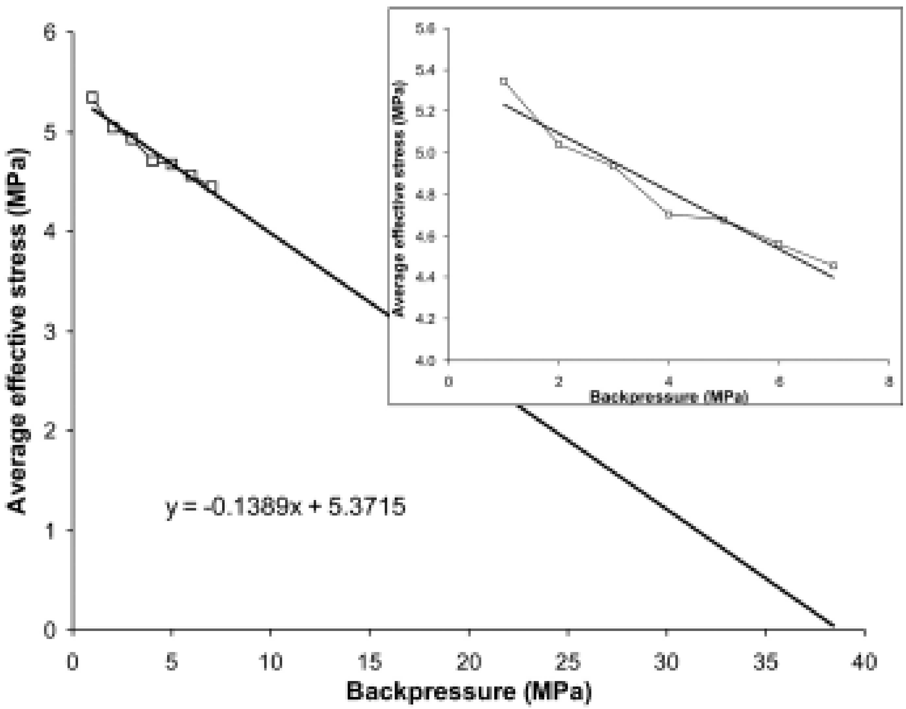


Figure 9-101. *Extrapolation of swelling pressure data assuming a linear trend. The insert graph (top right) shows the fit to the data in more detail.*

The conclusion above is based on a linear extrapolation of experimental results. In neither of the tests was the water pressure increased to the level where the swelling pressure would be totally lost. Currently, the experiments described above are being repeated to try to verify at what water pressure the swelling pressure will be lost. The results from /Harrington and Birchall 2006/ show that at water pressure of 36 MPa, on average around 89% of the increase in pore-water pressure is detected by the total stress sensors. If this trend continues, externally applied porewater pressure and average total stress will converge at a porewater pressure in excess of 65 MPa. This shows that the linear extrapolation done from low pressures in the earlier experiments grossly overestimated the effect of the loss of swelling pressure.

Based on these findings it is clear that the hydrostatic pressure in the repository will never will reach levels where there will be any significant effect on the swelling pressure.

The backfill has a lower swelling pressure than the buffer and should be less prone to liquefaction based on the reasoning of /Bucher and Müller-VonMoos 1989/. It can also be noted that the important properties of the backfill may not be severely affected by a liquefaction event. However, a possible concern is that the backfill could lose its effective stress faster than the buffer and the buffer could expand into the backfill. For a mixed backfill, it cannot be excluded that the phases will separate during a liquefaction event. This would cause an increase in hydraulic conductivity and a drop in swelling pressure in a part of the backfill. The consequences for radionuclide transport of an increased hydraulic conductivity in the backfill are analysed in section 10.5.7.

Conclusions

The issue of buffer liquefaction from high pore water pressures is resolved. It can be conclusively ruled out that very high hydrostatic pressures during a reference glacial event could reduce the effective stress (swelling pressure) of the buffer to zero.

Effects of saline water on buffer and backfill

Hydraulic conductivity and swelling pressure of the buffer and backfill, as affected by different groundwater salinities are presented in section 4.2.8. The conclusion is that the hydraulic properties of the buffer will not be significantly affected by the intrusion of a saline water. The conclusions in that section are valid at chloride concentrations of up to 3 M (17.5% NaCl). The highest expected value at Forsmark is a salinity of 4–5%, see section 9.4.7.

9.4.9 Effects on canister

Canister failure due to hydrostatic pressure

The maximum expected isostatic load on the canister at the Forsmark site is 4 MPa hydrostatic pressure, up to 13 MPa isostatic swelling pressure from the bentonite and a maximum addition of 26 MPa hydrostatic pressure from a future ice sheet in the Weichselian base case, see section 9.4.6, subheading "Maximum hydrostatic pressure for glacial conditions". The maximum total isostatic pressure the canister will be subjected to can thus be estimated to be 43 MPa.

As discussed in section 7.3.1, the design over-pressure is 44 MPa and the probabilistic analysis showed that the probability for local failure at that over-pressure is vanishingly small. Total collapse, the criterion used for canister failure, occurs at pressures above 100 MPa. As a consequence, no canister failures at the expected maximum over-pressure at the Forsmark site are expected.

At the Laxemar site, the expected maximum over-pressure is 22 MPa and the total isostatic pressure is 40 MPa in the Weichselian base case and also at this site no canister failures are, therefore, expected.

Canister failure due to shear movements

This failure mode is treated in section 9.4.5.

Canister corrosion for unaltered conditions

In cases in which the groundwater flow rate, the sulphide concentrations and the buffer properties are similar to those during the initial temperate period, the corrosion calculation results in section 9.3.12

are representative also during the reference glacial cycle. In this case, transport in the buffer is dominated by diffusion. As concluded in section 9.3.12, corrosion has an insignificant impact on the copper canister thickness in a 100,000 year perspective.

Canister corrosion for a partially eroded buffer

The results in section 9.4.8 indicate that a partial erosion of the buffer cannot be ruled out, at least for the fraction of deposition holes with the highest flow rates. It was also concluded that for buffer mass losses above 1,200 kg, advective conditions in the buffer cannot be ruled out. For such conditions, the corrosion calculation in section 9.3.12 is not valid. For corrosion when advection occurs in the buffer, /Neretnieks 2006a/ concluded that, for a very wide range of conditions, corroding agents in all groundwater that reaches a deposition hole will contribute to corrosion, meaning essentially that the equivalent flow rate, Q_{eq}, used in section 9.3.12 should be replaced by Q, the water flux through the part of the fracture that intersects the deposition hole. In addition, the water flux is increased due to the lost flow resistance in the void from the missing bentonite. /Neretnieks 2006a/ demonstrated that this effect can be bounded by multiplying the undisturbed flow by a factor of 2.

The rate of corrosion will also depend on the geometry of the eroded buffer section, which is difficult to determine. Since erosion will occur at the interface between rock fracture and deposition hole, a stylised case with a half-cylindrical section of height equal to the buffer thickness around the canister is assumed. This is considered to be a reasonable representation of the geometry since erosion would progress from the fracture in all directions into the buffer. Thus a height of 35 cm of the canister wall is assumed to be evenly corroded by all the sulphide carried by the through-flowing groundwater. A half-cylinder is assumed since loss of buffer mass can be assumed to occur predominantly on the up-stream side of the fracture.

In addition, corrosion from sulphide generated by sulphate-reducing bacteria (SRB) cannot be ruled out. It is not know to what extent the pore size of the remaining material in the eroded volume would prevent microorganisms from reaching the canister wall, so it is cautiously assumed that this is possible. The microbial activity is limited by either the supply of sulphate or that of electron donors to the sulphate reducing bacteria /Amend and Teske 2005/. Electron donors can be either hydrogen or methane and, for Swedish groundwaters, methane dominates. One mole of methane can be used by SRB to reduce one mole of sulphate according to the net equation:

$$SO_4^{2-} + CH_4 \rightarrow HS^- + HCO_3^- + H_2O$$

As methane concentrations are lower than sulphate concentrations, methane will be the limiting factor for the activity of SRB. According to section 9.4.7, the temporal average over a glacial cycle of the sum of methane and sulphide concentrations in the groundwater can be assumed to be less than 10^{-5} M. Figure 9-102 shows the corrosion rate for these conditions and assumptions for the entire ensemble of deposition holes. It is important to note that only deposition holes that experience the very highest flow rates will be penetrated during the one million year assessment period. A more detailed account of the model used for the corrosion calculations is given in Appendix B.

Periods of increased flow need also be considered in the reference evolution. As for the buffer erosion calculation, this can be illustrated by applying the conditions for the stylised Case A described in section 9.4.6; 40 years of flow increased by a factor of 160 during a glacial cycle. This, however, gives insignificant added corrosion depths during the high flow period compared with the total loss as calculated above.

Combining the results of the erosion calculation in Figure 9-99 with those of the corrosion calculations where advection is assumed in Figure 9-102 yields the distribution of canister lifetimes shown in Figure 9-103 for the semi-correlated DFN model of Forsmark. An important conclusion from this result is that the time required to obtain failure due to corrosion is considerably longer than that required for 1,200 kg of buffer to be eroded away. Thus, even if further investigations should reveal that the uncertain erosion model must be replaced by a less favourable model, this would not lead to significantly increased consequences in terms of canister failures. In fact, the red curve in Figure 9-103 represents the case where all deposition holes have a severely eroded buffer and advective conditions already at the time of deposition.

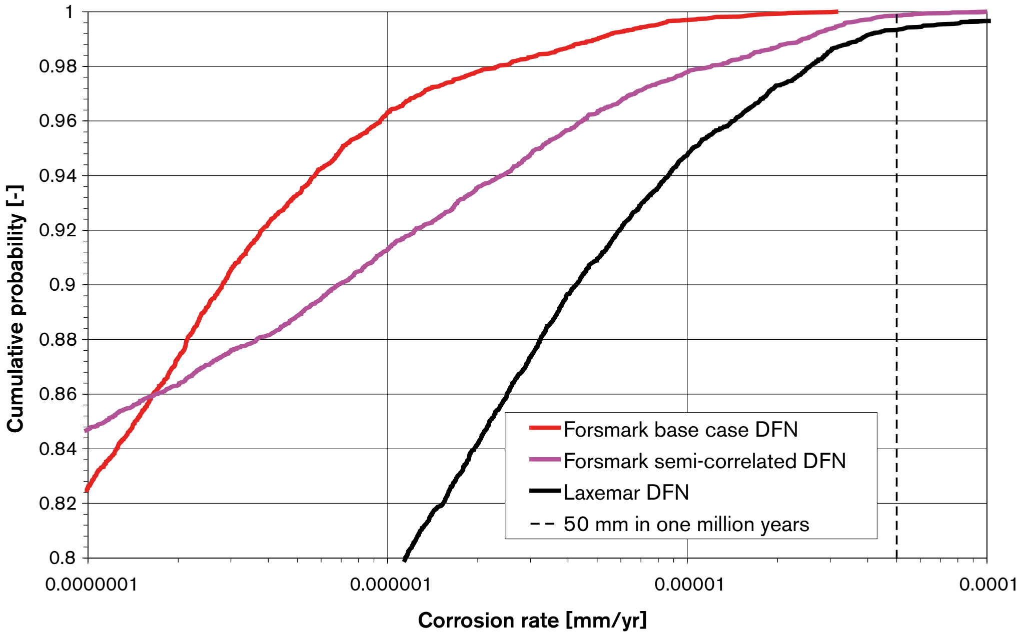


__Figure 9-102.__ Copper corrosion rate in a deposition hole where advection occurs over a 0.35 m high half-cylindrical area centred around the intersecting fracture. The vertical line at $5 \cdot 10^{-5}$ mm/yr denotes the rate required to penetrate the 50 mm copper shell in one million years. The deposition holes have been filtered in accordance with the FPC criterion (see section 4.4.1).

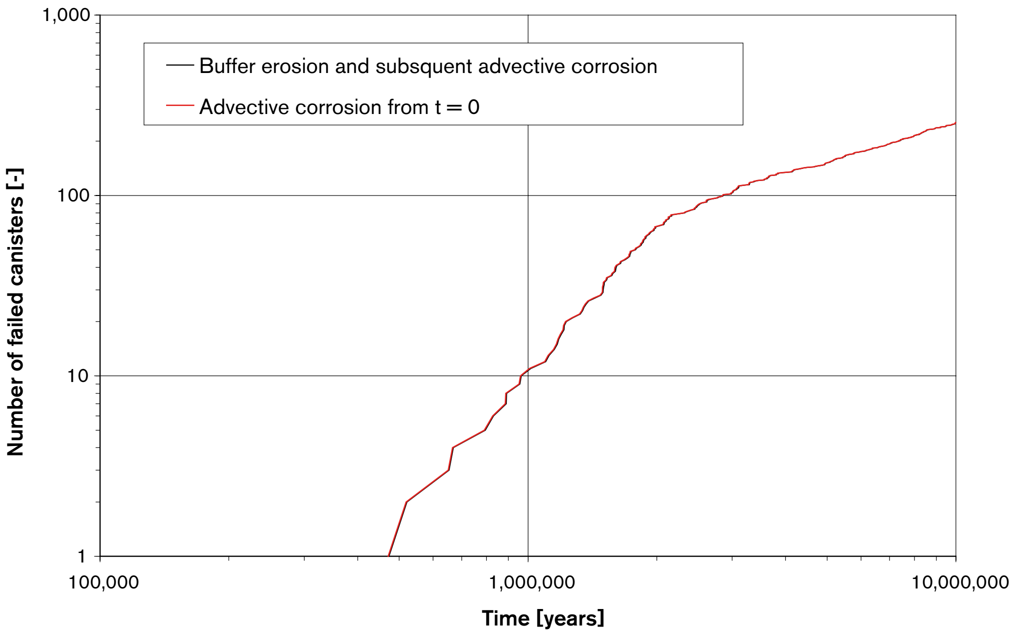


__Figure 9-103.__ Distribution of canister lifetimes combining the calculation results for buffer erosion and canister corrosion for advective conditions (black line). Assuming advective conditions from the time of deposition yields the red line, almost indistinguishable from the black. Semi-correlated Forsmark DFN model.

Table 9-22 shows the calculated number of failed canisters in one million years for several hydrogeological models and various selection criteria for the deposition holes.

A copper coverage of 50 mm was assumed in these calculations. The minimum copper coverage assumed in the reference initial state is between 40 and 50 mm for 99% of the canisters and between 35 and 40 mm for one percent of the canisters. The minima are assumed to be located at the top or bottom welds. The reasons for assuming 50 mm in these corrosion calculations are

Table 9-22. Calculated number of failed canisters in one million years due to corrosion with advection in the buffer using various deposition hole rejection criteria. Implementation of the FPC criterion is assumed in SR-Can. 6,824 and 7,483 deposition holes were modelled at Forsmark and Laxemar, respectively. The minor correction of normalising the figures to 6,000 deposition holes has not been done. The figures within parentheses are number of failures in 100,000 years.

Case	No rejection (excluding only deposition holes intersected by low confidence zones)	FPC	T > 10^{-6} m^2/s	T > 10^{-7} m^2/s	T > 10^{-8} m^2/s	FPC and T > 10^{-6} m^2/s	FPC and T > 10^{-7} m^2/s	FPC and T > 10^{-8} m^2/s
Fm base DFN	17 (0)	0	17 (0)	1 (0)	0	0	0	0
Fm semi-correlated DFN	40 (3)	10 (0)	16 (0)	1 (0)	0	7 (0)	1 (0)	0
Fm CPM	0	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Lx base case	236 (9)	50 (0)	99 (1)	9 (0)	0	26 (0)	1 (0)	0

- The corrosion attack occurs over a limited area (about 3% of the canister surface), making the likelihood of an overlap with the point of minimum coverage correspondingly small.
- A reduction of copper coverage to, say, 45 mm would not decrease the time required for penetration due to corrosion in proportion to the reduced coverage. For example, a small 5 mm cavity on the copper outer surface would be evened out as corrosion proceeds and thus cause a considerably less than 10% decrease in time to penetration. It is only cavities on the inner surface that would result in a direct decrease in penetration time.
- The minimum copper coverage has been pessimistically assessed.

Taking all these factors into account, the error committed in assuming an initial copper coverage of 50 mm is assessed as negligible compared to other uncertainties affecting the corrosion calculations.

Canister corrosion due to oxygen penetration

As discussed in section 9.4.7, oxygen is not expected to reach repository depths even for groundwater advection times as short as ≈ 1 year.

To illustrate the sensitivity to a hypothetical intrusion of O_2 during the extreme conditions prevailing under an ice sheet, a stylised and pessimistic case of oxygen penetration has been analysed for the Forsmark site data. The case is the same as Case B used for the analysis of buffer erosion above and defined in detail in section 9.4.6, i.e. 1,300 years of a 160-fold increase in flow at repository depth. Furthermore, the oxygen concentration is assumed to be that of water in equilibrium with the atmosphere, i.e. 8 mg/L (0.25 mM), which is considered to be a cautious value, see for example /Gascoyne 1999/.

Although it is known that a thin layer of Cu(I) oxide is formed at the interface between copper(II) hydroxide and copper metal, the overall stoichiometry for canister failure involves the transformation of copper metal to Cu(II) hydroxide.

The results are shown in Figure 9-104. It can be concluded that less than a millimetre is corroded even for the deposition holes with the highest flow rates.

It is furthermore noted that no credit is taken for the possibility of pyrite initially present in the buffer reacting with, and thus eliminating, the intruding oxygen. In section 9.3.12, it was demonstrated that pyrite may remain in the buffer for millions of years and in the SR 97 assessment it was shown that remaining pyrite may serve as an oxygen scavenger for hundreds of thousands of years of oxygen intrusion /Bruno et al. 1999/.

The same discussion of uncertainties as for the temperate case, section 9.3.12, is valid also here.

For Case B, with advective conditions in the buffer, 1,300 years of 0.25 mM oxygen intrusion with a 160-fold increase in flow corresponds yields no failed canisters for the Forsmark site and 22 failed canisters for the Laxemar site, using the same model as when calculating sulphide corrosion under advective conditions.

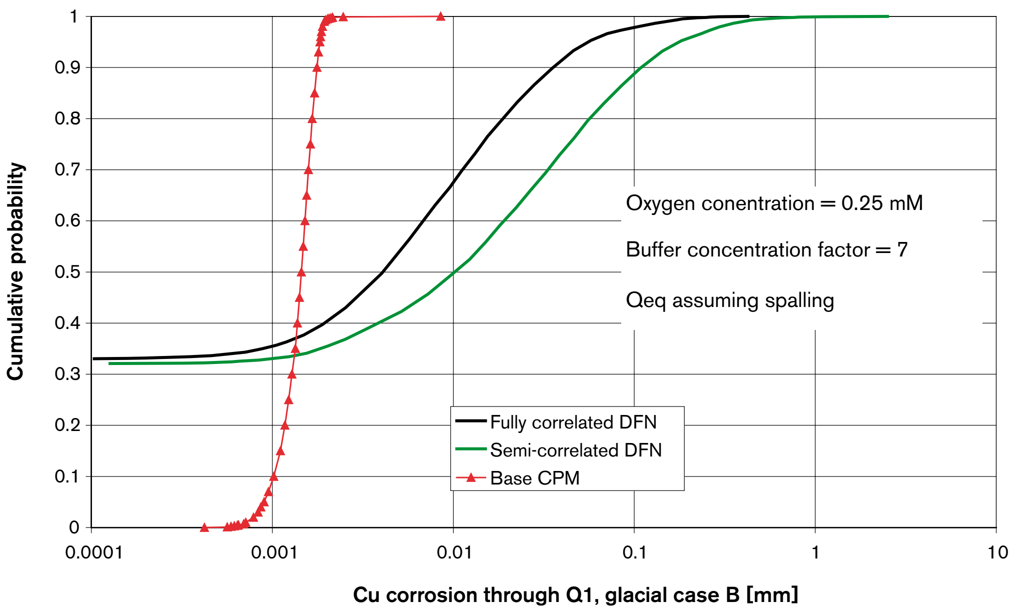


***Figure 9-104.** Copper corrosion due to intruding oxygen. A number of Q_{eq}-distributions from the hydrogeological modelling of the Forsmark site for temperate conditions have been scaled to reflect the assumptions for this calculation.*

9.4.10 Safety functions at the end of the reference glacial cycle

The following is an account of the development of all safety functions in Figure 9-2 during the reference glacial cycle.

Rock safety functions

R1. Provide chemically favourable conditions

a) Reducing conditions; Eh limited

The reducing conditions during the initial temperate period are expected to continue to exist throughout the reference glacial cycle. The only identified challenge to this conclusion concerns the possible penetration of oxygenated glacial melt water to repository depth for glacial situations with enhanced groundwater flow.

Evaluations show that this is a very unlikely phenomenon even for situations with increased flow rates driven by an ice sheet on top of the repository.

It is, therefore, concluded that reducing conditions will generally prevail during the reference glacial cycle. Possible local intrusion of oxygenated waters during relatively short periods of time will only have a limited effect on the copper thickness of the canister, see further safety function C1 below.

b) Salinity; TDS limited

For temperate domains during the reference glacial cycle, the salinity is not expected to exceed that of the initial temperate period, i.e. the salinities are well within the ranges where the buffer and backfill have favourable properties.

For permafrost conditions, out-freezing of salt above the repository may increase the groundwater salinity at repository depth. A pessimistic, generic model calculation of this effect puts an upper bound of 1.6 M Cl^-, whereas realistic estimates are considerably lower.

For glacial conditions, the highest salinities are expected as a result of possible upconing of deep saline waters driven by increased flow rates under an ice front. Salinities of up to around 50 g/L or around 1 M Cl^- were estimated in a study of the Oskarshamn area.

c) Ionic strength; $[M^{2+}] > 1$ mM

For temperate domains during the reference glacial cycle, the minimum groundwater concentration of divalent cations is not expected to fall below that of the initial temperate period.

For permafrost conditions, the concentrations of divalent cations are expected to increase in comparison with the conditions during temperate periods, see section 9.4.7. Therefore, this safety function is fulfilled also for permafrost conditions.

However, for glacial conditions, with intrusion of dilute glacial melt water, this cannot be claimed to be the case. This means that the extent of buffer erosion must be analysed for such conditions, see below.

d) Concentrations of K, HS^-, Fe; limited

For temperate and permafrost domains during the reference glacial cycle, the concentrations of these substances are expected to be similar to those occurring during the initial temperate period. This means that, at both sites, the potassium concentrations are expected to remain ≤ 0.004 mol/L, sulphide concentrations are expected to be ≤ 10^{-5} mol/L for any deposition position averaged over the time period and iron concentrations are expected to be around 10^{-5} mol/L.

For glacial conditions, the intrusion of melt waters is expected to decrease the concentrations of potassium, iron and sulphide.

e) Alkalinity; pH < 11

For temperate domains during the reference glacial cycle, the pH is expected to be similar to that of the initial temperate period, i.e. between 7 and 8.

Permafrost conditions are not expected to influence the pH values to any significant extent.

For glacial conditions, three typical groundwater types have to be considered: *a*) saline waters during upconing will have close to neutral pH values, similar to those encountered during the temperate and permafrost conditions; *b*) very dilute groundwaters from glacial melting will have relatively high pH values 9 to 10; and *c*) mixtures of these waters will have pH values intermediate between the *a* and *b* types.

In addition, leach water from grout, shotcrete and cement may exhibit pH-values of around 9 for extended periods of time. The use of low-pH formulations of these materials limits pH in these situations.

R2. Provide favourable hydrologic and transport conditions

a) Fracture frequency; limited

For both sites, the natural fracture frequency is limited at repository depth and the analyses of mechanical evolution for the reference glacial cycle have not given rise to any results that imply a change of this situation. In particular, no cause for fracturing at repository depth during the reference glacial cycle has been identified.

b) Fracture transmissivity; limited

Also, for both sites, the natural fracture transmissivities are limited. The analyses of the mechanical evolution for the reference glacial cycle have not led to any results that imply a significant change of this situation. Transmissivities are pessimistically assessed to increase at most by a factor of two due to the altered stress situation during a glacial load.

c) Hydraulic gradients; limited

Present-day hydraulic gradients at the sites, as in Sweden in general, are controlled by the topography. Since the topography is relatively flat, the gradients are limited and this contributes to the favourable hydraulic properties at the site.

For temperate domains during the reference glacial cycle, the gradients are expected to be similar to those during the initial temperate period. This implies limited gradients controlled by the local topography.

For submerged conditions, even lower gradients are expected.

For permafrost, ice-free conditions, gradients similar to, or less than, those during temperate conditions are expected. The potential occurrence of open taliks could, however, imply a more regional component of the groundwater flow, but the magnitude of the gradient would not change since the low topographical gradients prevail over very long distances (hundreds of kilometres).

For glacial conditions the gradients could be significantly increased, in particular when the ice front passes over the repository. This has considerable effects on the flow conditions in the host rock and potentially also on the engineered barriers and has been analysed by means of two stylised examples, used in the analysis of buffer erosion and copper corrosion, see below.

d) Kd, De; high

Sorption coefficients and diffusivities in the rock have not been evaluated within the description of the reference evolution. These entities are assessed in the **Data report**, where the geochemical conditions found in the reference evolution are one of the bases for the evaluation.

e) Colloid concentration; low

Colloids are destabilised at high ionic strengths. Low groundwater salinities are expected when the sites are covered by a warm-based ice sheet, during glacial retreat, or when covered by a glacial lake during the stage immediately following a retreat of an ice sheet. During these periods, with predominantly dilute groundwaters, any colloids formed can be expected to be stable. However, the expected upper concentration limit is low, namely ≈ 1 mg/L.

R3. Provide mechanically stable conditions

a) Shear movements at deposition holes < 0.1 m

The only identified cause for a shear movement of this size is an earthquake of magnitude 6 or larger in a major deformation zone on the vicinity of the repository. Respect distances and rejection criteria when selecting deposition hole positions are chosen such that the great majority of deposition holes are not expected to be negatively affected if an earthquake even of this magnitude were to occur.

During the reference glacial cycle, it can, however, not be fully excluded that earthquakes of this magnitude would occur, and this could possibly lead to detrimental shear movements at a few deposition holes.

Current, pessimistic estimates indicate that both the likelihood of magnitude ≥ 6 earthquakes and that of canister failures as a result of such events are very small at both sites. The calculated probability that a sufficiently large earthquake will occur over the period is 0.03. The probabilistically calculated average number of failed canisters due to large earthquakes is $1.4 \cdot 10^{-2}$ at Forsmark and $7.7 \cdot 10^{-3}$ at Laxemar (Table 9-19). Therefore, it is concluded that the most likely situation is failure of no canisters due to earthquakes.

b) Groundwater pressure; limited

For temperate domains during the reference glacial cycle, the groundwater pressure is expected to be similar to that of the initial temperate period, i.e. around 4 MPa at Forsmark.

For permafrost, ice-free conditions, the same groundwater pressure as for temperate conditions is expected.

For glacial conditions, the maximum groundwater pressure is determined by the thickness of the overlying ice sheet. In the reference glacial cycle, the maximum thickness at Forsmark corresponds to an increase in groundwater pressure of 26 MPa, yielding a total groundwater pressure of around 30 MPa. At Laxemar, the corresponding figures are 22 MPa and 27 MPa. Furthermore, it is pessimistic to assume that the full ice burden is translated into groundwater pressure.

R4. Provide thermally favourable conditions

For this safety function to be fulfilled, it is required that the rock temperature at repository depth exceeds the buffer freezing temperature, i.e. −5°C.

For temperate domains during the reference glacial cycle, the rock temperature is expected to be similar to that of the initial temperate period, i.e. well above 0°C at both Forsmark and Laxemar.

For permafrost, ice-free conditions, the rock temperature is expected to be lowered considerably. Calculation results reported in section 9.4.3 imply that the maximum permafrost depth for the reference glacial cycle at Forsmark is 250 m. The corresponding figure for Laxemar is 160 m.

For glacial conditions, the ice acts to insulate the bedrock from the low air temperatures, meaning that permafrost depths are less than for permafrost conditions.

It is thus concluded that this safety function is fulfilled for the reference glacial cycle.

Buffer safety functions

For the initial temperate period, it was concluded that the saturated buffer density in deposition holes where piping does not occur will be in the reference interval 1,950–2,050 kg/m^3 around the canister.

If piping occurs, a preliminary calculation showed that the density may drop to around 1,900 kg/m^3.

The only identified process through which buffer density could be lost after the initial temperate period during the reference glacial cycle is colloid release. The occurrence of this process is related to the groundwater concentration of divalent cations and the criterion to be fulfilled is that this value should be less than 1 mM. As demonstrated above, this cannot be claimed for glacial conditions.

Preliminary quantitative evaluations of the erosion process indicate that substantial losses, affecting several of the buffer safety functions negatively, cannot be ruled out, potentially for a considerable fraction of the deposition holes during the 120,000-year glacial cycle.

This influences the evaluation of several of the buffer safety function indicators, as discussed below.

Bu1. Limit advective transport

a) Hydraulic conductivity < 10^{-12} m/s

For deposition holes with reference buffer density, the hydraulic conductivity criterion is fulfilled with ample margin, also for groundwater salinities that can be expected during the reference glacial cycle, see section 9.4.8.

b) Swelling pressure > 1 MPa

For deposition holes with reference buffer density, the swelling pressure criterion is fulfilled with ample margin, also for groundwater salinities that can be expected during the reference glacial cycle, see section 9.4.8.

However, preliminary quantitative evaluations of the buffer erosion/colloid release process indicate that advective conditions cannot be ruled out, potentially for a considerable fraction of the deposition holes at the end of the 120,000-year glacial cycle. This means that both the above safety function indicators would be violated for the deposition holes.

Bu2. Filter colloids

For this safety function to be fulfilled, it is required that the saturated buffer density exceeds 1,650 kg/m^3 around a canister.

For deposition holes with reference buffer density, this criterion is fulfilled with ample margin.

For a deposition hole that has experienced loss of buffer mass due to erosion/colloid release and to the extent that advective conditions prevail, this safety function can, however, not be guaranteed.

Bu3. Eliminate microbes

For this safety function to be fulfilled it is required that the buffer swelling pressure exceeds 2 MPa around a canister.

For deposition holes with reference buffer density, the swelling pressure criterion is fulfilled with ample margin, also for groundwater salinities that can be expected during the reference glacial cycle, see section 9.4.8.

For a deposition hole that has experienced loss of buffer mass due to erosion/colloid release and to the extent that advective conditions prevail, this safety function can, however, not be guaranteed.

Bu4. Damp rock shear

For this safety function to be fulfilled, it is required that the saturated buffer density is less than 2,050 kg/m^3. 2,050 kg/m^3 is the upper bound of the reference density and as no relevant processes that would increase the buffer density have been identified, it is concluded that this safety function is fulfilled for all deposition holes.

Bu5. Resist transformation

For this safety function to be fulfilled, it is required that the buffer temperature is less than 100°C. The peak buffer temperature will occur a few tens of years after deposition. At the start of the reference glacial cycle (1,000 years after deposition), the buffer temperature will be similar to that of the ambient, natural rock temperature. There is thus no conceivable way in which the buffer temperature could exceed 100°C during the reference glacial cycle.

Bu6. Prevent canister sinking

For this safety function to be fulfilled, it is required that the buffer swelling pressure exceeds 0.2 MPa.

For deposition holes with reference buffer density, the swelling pressure criterion is fulfilled with ample margin, see above.

For a deposition hole that has experienced loss of buffer mass due to erosion/colloid release and to the extent that advective conditions prevail, this safety function can, however, not be guaranteed.

Bu7. Limit pressure on canister and rock

For this safety function to be fulfilled, it is required that the buffer temperature should exceed the buffer freezing temperature, i.e. −5°C. As mentioned regarding the rock safety function R4 above, the criterion is expected to be fulfilled with ample margin for the reference glacial cycle.

Backfill safety functions

The backfill may lose mass due to colloid release during the remaining part of the reference glacial cycle after the initial temperate period. The effect of a partially eroded backfill needs to be evaluated in radionuclide transport calculations.

BF1. Limit advective transport

a) Hydraulic conductivity < 10^{-10} m/s

For deposition holes with reference backfill density, the hydraulic conductivity criterion is fulfilled, also for groundwater salinities that can be expected during the reference glacial cycle.

If the backfill is subjected to severe erosion the hydraulic conductivity could increase to values above 10^{-10} m/s locally, see section 9.4.8.

b) Swelling pressure > 0.1 MPa

For deposition holes with reference backfill density, the swelling pressure criterion is fulfilled, also for groundwater salinities that can be expected during the reference glacial cycle.

If the backfill is subjected to severe erosion the swelling pressure could be lost locally, see section 9.4.8.

Further conclusions regarding the backfill materials are provided in sections 13.3.4 and 13.6.2.

c) Temperature > 0°C

As mentioned regarding the rock safety function R4 above, the criterion is expected to be fulfilled with ample margin for the reference glacial cycle.

Canister safety functions

C1. Provide corrosion barrier

For this safety function to be fulfilled, it is required that the minimum copper coverage exceeds zero. Given the initial, pessimistically estimated minimum copper thickness of between 40 and 50 mm for 99% of canisters and between 35 and 40 mm for the remaining one percent, the corrosion calculations for the reference glacial cycle indicate that no canister failures will occur due to corrosion if the buffer is intact.

Even for a partially eroded buffer, no canister failures are expected during the initial glacial cycle.

Sensitivity analyses demonstrate a considerable potential to withstand episodes of oxygen penetration.

C2. Withstand isostatic load

For this safety function to be fulfilled, it is required that the canister strength exceeds the isostatic loads to which it is subjected.

The maximum expected isostatic load on the canister at the Forsmark site is 4 MPa hydrostatic pressure, up to 13 MPa isostatic swelling pressure from the bentonite and a maximum additional 26 MPa hydrostatic pressure from a future ice sheet in the Weichselian base case. The maximum total isostatic pressure the canister will be subjected can thus be estimated to be 43 MPa.

The probability for local canister insert damages at 44 MPa over-pressure is vanishingly small, as demonstrated by probabilistic calculations, see section 12.8.2. Furthermore, the criterion for failure is that a global collapse occurs, which is not expected for pressures below 100 MPa, see further section 12.8.2. As a consequence, no canister failures are expected at the maximum over-pressure that could be experienced at the Forsmark site in the reference evolution.

The Laxemar site is expected to experience lower pressures, hence no failures are expected there either.

C3. Withstand loads due to shear movements

For this safety function to be fulfilled, it is required that the canister rupture limit exceeds the shear stress to which it is subjected.

Canister failures due to future earthquakes are avoided through the use of respect distances and acceptance criteria for deposition holes, adapted to the ability of the canister to resist shear movements.

At this stage of the analysis, it cannot be fully ruled out that such failures will occur, see discussion of rock safety function R3a above for estimates of likelihoods of such failures.

Conclusions for consequence calculations

The following conclusions for radionuclide transport can be drawn.

- The only cause for canister failure that has not been ruled out for the reference glacial cycle is an earthquake caused by changes in the glacial load. The likelihood of this type of failure is low at both sites.
- As for the initial temperate period, the EDZ developed during construction needs to be considered in the RN-transport analyses.
- The hydrogeological analyses have provided distributions of F, t_w and Q_{eq} to be used in radionuclide transport calculations for temperate periods of the glacial cycle. For other climate periods, crude estimates of these quantities, in many cases as stylised examples, have been derived.
- The geochemical assessments have provided geochemical conditions for which retention properties in the host rock for radionuclide transport can be derived.
- The buffer and backfill assessments have provided buffer conditions for which retention properties in the buffer for radionuclide transport can be derived.

- The effect of a partially eroded backfill needs to be evaluated in radionuclide transport calculations.
- Spalling may affect the equivalent flow rates, Q_{eq}, in deposition holes.
- pH increase from cement may affect geosphere retention in larger, grouted fractures, potentially throughout the glacial cycle.

9.5 Evolution for subsequent glacial cycles

For the reference climatic evolution, the first glacial cycle is simply assumed to be repeated until the end of the one million year assessment period. This is also in line with suggestions given in SSI's general guidance. With a cycle period of around 120,000 years, this means about seven repetitions of the initial Weichselian glacial cycle, i.e. a total of eight such cycles.

Reversible phenomena like the thermal, geohydrological and geochemical evolution of the bedrock are essentially expected to follow the cyclic variations of external conditions controlling them. This is also the case for biosphere development at the sites.

Irreversible phenomena like buffer erosion, canister corrosion and possibly earthquake- induced effects are essentially expected to occur to an extent eight times greater than that during the initial glacial cycle. Particular implications of this are listed below.

- Buffer erosion caused by dilute glacial melt water, that could be a significant phenomenon during the initial glacial cycle, has to be considered for subsequent glacial cycles. Essentially, eight times more erosion could be expected at the end of the one million year assessment period.
- The pessimistic evaluations of canister corrosion for the initial glacial cycle indicate that, for an unaltered buffer, corrosion would not cause canister failures even in a million year perspective. For a buffer that has been partially eroded to the extent that advective conditions must be assumed in the deposition hole, preliminary and pessimistic estimates yield canister failures according to Table 9-22. In these cases, also microbially mediated corrosion is considered.
- The analysis of canister failures due to earthquakes for the initial glacial cycle is extended to one million years, yielding estimated probabilities of canister failures according to Table 9-19. The probabilistically calculated average number of canister failures due to earth quakes in one million years is 0.12 and 0.065 for the Forsmark and Laxemar sites, respectively.

There are also phenomena like ion exchange in the buffer that could require millions of years to equilibrate with the average ionic contents of the groundwater over a glacial cycle. Furthermore, the residual power will affect the thermal conditions in the rock only during the initial glacial cycle. Thereafter, the thermal evolution is determined by naturally occurring phenomena.

9.5.1 Safety functions at the end of the assessment period

The following is an account of all safety functions in Figure 9-2 at the end of the one million year assessment time, often as a comparison to the situation after the initial glacial cycle reported in section 9.4.10.

Rock safety functions

R1. Provide chemically favourable conditions

a) Reducing conditions; Eh limited

No challenges to the conclusion for the initial glacial cycle, that reducing conditions will prevail, have been identified. It is, therefore, concluded that reducing conditions will prevail throughout the assessment period.

b) Salinity; TDS limited

Repetitions of the same pattern of variations as for the initial glacial cycle are expected, meaning that salinity levels will remain limited.

c) Ionic strength; $[M^{2+}] > 1$ mM

Repetitions of the same pattern of variations as for the initial glacial cycle are expected, meaning that additional periods of glacial conditions where this safety function indicator is not fulfilled must be assumed.

d) Concentrations of K, HS^-, Fe; limited

Repetitions of the same pattern of variations as for the initial glacial cycle are expected, meaning that concentrations of K and Fe will remain limited and that sulphide concentrations are expected to be $\leq 10^{-5}$ mol/L for any deposition position averaged over the time period.

e) Alkalinity; pH < 11

Repetitions of the same pattern of natural variations as for the initial glacial cycle are expected, meaning that pH is not expected to exceed 10. Possibly, continued releases of leach water from grout, shotcrete and cement may exhibit pH-values of around 9 also after the initial glacial cycle.

R2. Provide favourable hydrologic and transport conditions

a) Fracture frequency; limited

As for the initial glacial cycle, there are no indications that the natural, limited fracture frequency at repository depth would be altered.

b) Fracture transmissivity; limited

As for the initial glacial cycle, there are no indications that the natural, limited fracture transmissivity would be altered. Transmissivities are pessimistically assessed to increase at most by a factor of two due to the altered stress situation during repeated glacial loads.

c) Hydraulic gradients; limited

Repetitions of the same pattern of variations as for the initial glacial cycle are expected, meaning that long periods of limited gradients will possibly be interrupted by short periods of high gradients when an ice front passes over the repository.

d) Kd, De; high

Sorption coefficients and diffusivities in the rock have not been evaluated within the description of the reference evolution. These entities are assessed in the **Data report**, where the geochemical conditions found in the reference evolution are one of the bases for the evaluation.

e) Colloid concentration; low

Repetitions of the same pattern of variations as for the initial glacial cycle are expected, meaning that the expected upper concentration limit is low; ≈ 1 mg/L.

R3. Provide mechanically stable conditions

a) Shear movements at deposition holes < 0.1 m

As for the initial glacial cycle, the only identified cause for a shear movement of this size is an earthquake of magnitude 6 or larger in a major deformation zone on the vicinity of the repository.

The probabilistically calculated average number of failed canisters due to large earthquakes for the entire assessment period is 0.12 at Forsmark and 0.065 at Laxemar (Table 9-19). Therefore, it is concluded that the most likely situation is failure of no canisters due to earthquakes, also for the one million year period.

b) Groundwater pressure; limited

Repetitions of the same pattern of variations as for the initial glacial cycle are expected, meaning that increased pressures will occur for glacial conditions. As for the initial glacial cycle, this yields maximum total groundwater pressures of around 30 and 27 MPa at the Forsmark and Laxemar sites, respectively.

R4. Provide thermally favourable conditions

For this safety function to be fulfilled, it is required that the rock temperature at repository depth exceeds the buffer freezing temperature, i.e. −5°C.

Repetitions of the same pattern of variations as for the initial glacial cycle are expected, meaning that that the maximum permafrost depths for the reference glacial cycle of 250 m at Forsmark and 160 m at Laxemar are expected to increase by up to 40 m since the residual power from the fuel will not appreciably counteract the development of permafrost after the initial glacial cycle, see further the **Climate report**, section 3.4.4.

It is thus concluded that this safety function is fulfilled for the entire assessment period.

Buffer safety functions

As for the initial glacial cycle, preliminary quantitative evaluations of the buffer erosion process indicate that substantial losses, affecting several of the buffer safety functions negatively, cannot be ruled out, potentially for a considerable fraction of the deposition holes during the one million year assessment period. These potential losses would be higher than for the initial glacial cycle.

This influences the evaluation of several of the buffer safety function indicators, as discussed below.

Bu1. Limit advective transport

a) Hydraulic conductivity < 10^{-12} m/s

For deposition holes with reference buffer density, the hydraulic conductivity criterion is fulfilled with ample margin, also for groundwater salinities that can be expected during the reference glacial cycle, see section 9.4.8.

b) Swelling pressure > 1 MPa

For deposition holes with reference buffer density, the swelling pressure criterion is fulfilled with ample margin, also for groundwater salinities that can be expected during the reference glacial cycle, see section 9.4.8.

However, preliminary quantitative evaluations of the buffer erosion/colloid release process indicate that advective conditions cannot be ruled out, potentially for a considerable fraction of the deposition holes at the end of the assessment period. This means that both the above safety function indicators would be violated for these deposition holes.

Bu2. Filter colloids

For this safety function to be fulfilled, it is required that the saturated buffer density exceeds 1,650 kg/m^3 around a canister.

For deposition holes with reference buffer density, this criterion is fulfilled with ample margin.

For a deposition hole that has experienced loss of buffer mass due to erosion/colloid release and to the extent that advective conditions prevail, this safety function can, however, not be guaranteed.

Bu3. Eliminate microbes

For this safety function to be fulfilled it is required that the buffer swelling pressure exceeds 2 MPa around a canister.

For deposition holes with reference buffer density, the swelling pressure criterion is fulfilled with ample margin, also for groundwater salinities that can be expected during the assessment period, see section 9.4.8.

For a deposition hole that has experienced loss of buffer mass due to erosion/colloid release and to the extent that advective conditions prevail, this safety function can, however, not be guaranteed.

Bu4. Damp rock shear

For this safety function to be fulfilled, it is required that the saturated buffer density is less than 2,050 kg/m^3. 2,050 kg/m^3 is the upper bound of the reference density and as no relevant processes that would increase the buffer density have been identified, it is concluded that this safety function is fulfilled for all deposition holes.

Bu5. Resist transformation

For this safety function to be fulfilled, it is required that the buffer temperature is less than 100°C. As for the initial glacial cycle, there is thus no conceivable way in which the buffer temperature could exceed 100°C during assessment period.

Bu6. Prevent canister sinking

For this safety function to be fulfilled, it is required that the buffer swelling pressure exceeds 0.2 MPa.

For deposition holes with reference buffer density, the swelling pressure criterion is fulfilled with ample margin, see above.

For a deposition hole that has experienced loss of buffer mass due to erosion/colloid release and to the extent that advective conditions prevail, this safety function can, however, not be guaranteed.

Bu7. Limit pressure on canister and rock

For this safety function to be fulfilled, it is required that the buffer temperature should exceed the buffer freezing temperature, i.e. −5°C. As mentioned regarding the rock safety function R4 above, the criterion is expected to be fulfilled with ample margin for the entire one million year assessment period.

Backfill safety functions

The backfill may lose mass due to colloid release during the remaining part of the reference glacial cycle after the initial temperate period. The effect of a partially eroded backfill needs to be evaluated in radionuclide transport calculations.

BF1. Limit advective transport

a) Hydraulic conductivity < 10^{-10} m/s

For deposition holes with reference backfill density, the hydraulic conductivity criterion is fulfilled, also for groundwater salinities that can be expected during the reference glacial cycle.

If the backfill is subjected to severe erosion the hydraulic conductivity could increase to values above 10^{-10} m/s locally, see section 9.4.8.

b) Swelling pressure > 0.1 MPa

For deposition holes with reference backfill density, the swelling pressure criterion is fulfilled, also for groundwater salinities that can be expected during the reference glacial cycle.

If the backfill is subjected to severe erosion the swelling pressure could be lost locally, see section 9.4.8.

Further conclusions regarding the backfill materials are provided in sections 13.3.4 and 13.6.2.

c) Temperature > 0°C

As mentioned regarding the rock safety function R4 above, the criterion is expected to be fulfilled with ample margin for the entire assessment period.

Canister safety functions

C1. Provide corrosion barrier

For this safety function to be fulfilled, it is required that the minimum copper coverage exceeds zero. Given the initial, pessimistically estimated minimum copper thickness of between 40 and 50 mm for 99% of canisters and between 35 and 40 mm for the remaining one percent, the corrosion calculations for the reference glacial cycle indicate that no canister failures will occur due to corrosion, also when these calculations are extended to one million years.

For a buffer eroded to the extent that advective conditions prevail in the deposition hole, canister failures can not be ruled out during the one million year assessment period. Preliminary and pessimistic estimates yield canister failures according to Table 9-22, i.e. at most 10 canisters at Forsmark and 50 at Laxemar. In these cases, also microbially mediated corrosion is considered.

C2. Withstand isostatic load

For this safety function to be fulfilled, it is required that the canister strength exceeds the isostatic loads to which it is subjected.

Since repetitions of the maximum loads experienced during the initial glacial cycle are expected for the remainder of the assessment period, it is concluded that also for the one million year assessment time, this safety function will be upheld.

C3. Withstand loads due to shear movements

For this safety function to be fulfilled, it is required that the canister rupture limit exceeds the shear stress to which it is subjected.

Canister failures due to future earthquakes are avoided through the use of respect distances and acceptance criteria for deposition holes, adapted to the ability of the canister to resist shear movements.

At this stage of the analysis, it cannot be fully ruled out that such failures will occur, see discussion of rock safety function R3a above for estimates of likelihoods of such failures.

Conclusions for consequence calculations

The following conclusions for radionuclide transport can be drawn.

- One cause for canister failure that has not been ruled out for the one million year assessment period is an earthquake caused by changes in the glacial load. The likelihood of this type of failure is low at both sites, also when the entire assessment period is considered.
- Also failure due to corrosion for advective conditions in a partially eroded buffer must be considered for the one million year assessment time. Pessimistic estimates suggest that at most 10 canisters may fail at Forsmark and 30 at Laxemar due to this cause.
- All other conclusions regarding consequence calculations drawn for the initial glacial cycle, see section 9.4.10, are assumed to be valid also for repeated cycles.

9.6 Greenhouse variant

9.6.1 External conditions

As one variant of the reference evolution, a case with an increased greenhouse effect has been investigated. There are two main reasons for doing this; 1) modelling studies of the climate response to increased greenhouse gas emissions, mainly CO_2, indicate that global temperatures will increase in the future under such conditions /e.g. Cubash and Meehl 2001/, and 2) climate cycles are believed be driven by changes in insolation. The coming 100,000 year period is initially characterised by exceptionally small amplitudes of insolation variations /Berger 1978/, possibly making the present interglacial exceptionally long. /Berger and Loutre 2002/ and others suggest it may not end until ~ 50,000 years from now.

In the greenhouse variant, it is assumed that the temperate domain will prevail for another 50,000 years before the relative mild onset of the next glacial cycle. After that, the first 70,000 years of the reference evolution is assumed to follow. The first major ice advance will, therefore, occur after ~ 90,000 years. This development is in broad agreement with results simulated for two greenhouse-warming cases within the BIOCLIM project /BIOCLIM 2003/.

Due to the near-coastal locations of Forsmark and Laxemar, one question related to future greenhouse warming is the response of the present ice sheets, and associated changes in shore line position. The Greenland ice sheet is much more sensitive to increases in temperature than are the Antarctic ice sheets /Huybrechts and de Wolde 1999/. An increase in annual temperature of ~ 3° or more over Greenland could result in an irreversibly decreasing ice sheet and increased sea-level /Huybrechts et al. 1991/. Excluding complex processes that could counterbalance a simple warming-melting situation, such as changes in oceanic circulation, many studies suggest that the Greenland ice sheet gets drastically reduced in size and contributes considerably to global sea-level rise under various future greenhouse gas scenarios. In a worst-case CO_2 scenario with an 8 degree climate warming by the year of 2100 /IPCC 2001b/, the warming would lead to a complete and irreversible collapse of the Greenland ice sheet over the next 1,000 years /Huybrechts and de Wolde 1999, Gregory et al. 2004, Alley et al. 2005/.

The present volume of the Greenland ice sheet corresponds to a global sea-level rise of about 7 m. The maximum contribution to future global sea-level change from melting glaciers and ice caps (i.e. excluding the Greenland and Antarctic ice sheets) is considerably smaller, no more than 0.5 m (corresponding to the total volume of water stored in glaciers and ice caps at present).

According to /Huybrechts and de Wolde 1999/ the decay of the Greenland ice sheet under a warming climate is a relatively smooth function of the temperature increase, although instabilities with fast-flowing ice streams could occur, producing jumps in sea level. For the purpose of the present assessment, it is adequate to assume that the Greenland ice sheet completely melts away at a linear rate during the coming 1,000 years, resulting in a 7 m sea-level rise. The effect of this sea-level rise on the development of the Baltic shore level is investigated by means of Global Isostatic Adjustment-modelling /**Climate report**, section 3.3/. The resulting evolution of the shore level at Forsmark and Laxemar is shown in Figure 9-105. As can be seen in Figure 9-105, the rise of global sea levels due to the melting of the Greenland ice sheet is of minor importance for the development of the shore level at Forsmark and Laxemar. At these sites, the isostatic rebound is larger than the rise of sea level. For the present day, calculated rebound rates are, however, larger than the measured values and, in the early phase of the greenhouse variant, this means that relative sea level could be constant or even rise.

One factor that has not been included in the analysis is the thermal expansion of oceans in a warming climate. Because of the large heat capacity of the ocean, thermal expansion would continue for many centuries after a warmer climate had been stabilised /IPCC 2001b/. The final contribution to sea-level change from thermal expansion would thus be much larger than at the time of climate stabilisation.

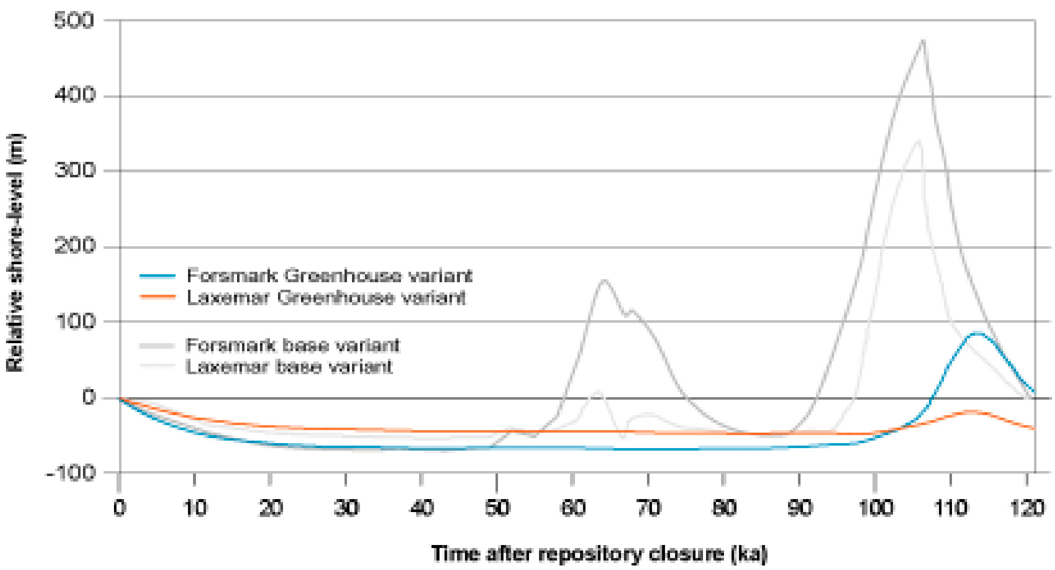


Figure 9-105. *Evolution of the shore line at Forsmark and Laxemar for the greenhouse variant of the reference evolution. Negative numbers indicate that the area is situated above sea-level.*

The IPCC estimates the total sea-level increase due to thermal expansion in the next 1,000 years to be between 1 and 4 m, depending on the chosen CO_2 emission scenario /IPCC 2001b/. There is general agreement that the rate of global sea-level rise from thermal expansion of ocean water would initially be low and then increase later in the 1,000 year period.

In the early phase of the greenhouse variant, after an initial period of slow thermal expansion of the oceans, inclusion of this effect could possibly also contribute to a constant or slightly increasing relative sea-level. Another factor that also could contribute to this would be a contribution from collapse of the West Antarctic Ice Sheet /e.g. Nicholls and Lowe 2006/, although this is a very uncertain event. However, after an early phase in the greenhouse variant with these uncertainties, the results of the isostatic modelling suggest that in the long run both sites will be situated above sea level.

The greenhouse variant of the reference evolution is shown in Figure 9-106, Figure 9-107 and Figure 9-108. Naturally, the temperate domain is the dominant consideration, with temperate conditions prevailing for 78,000 years (65% of the time) at Forsmark, and for 86,000 years (72% of the time) at Laxemar. Permafrost conditions prevail for 28,000 years (23% of the time) at both sites, whereas glacial conditions prevail for 11,000 years (9% of the time) at Forsmark and for 6,000 years (5% of the time) at Laxemar.

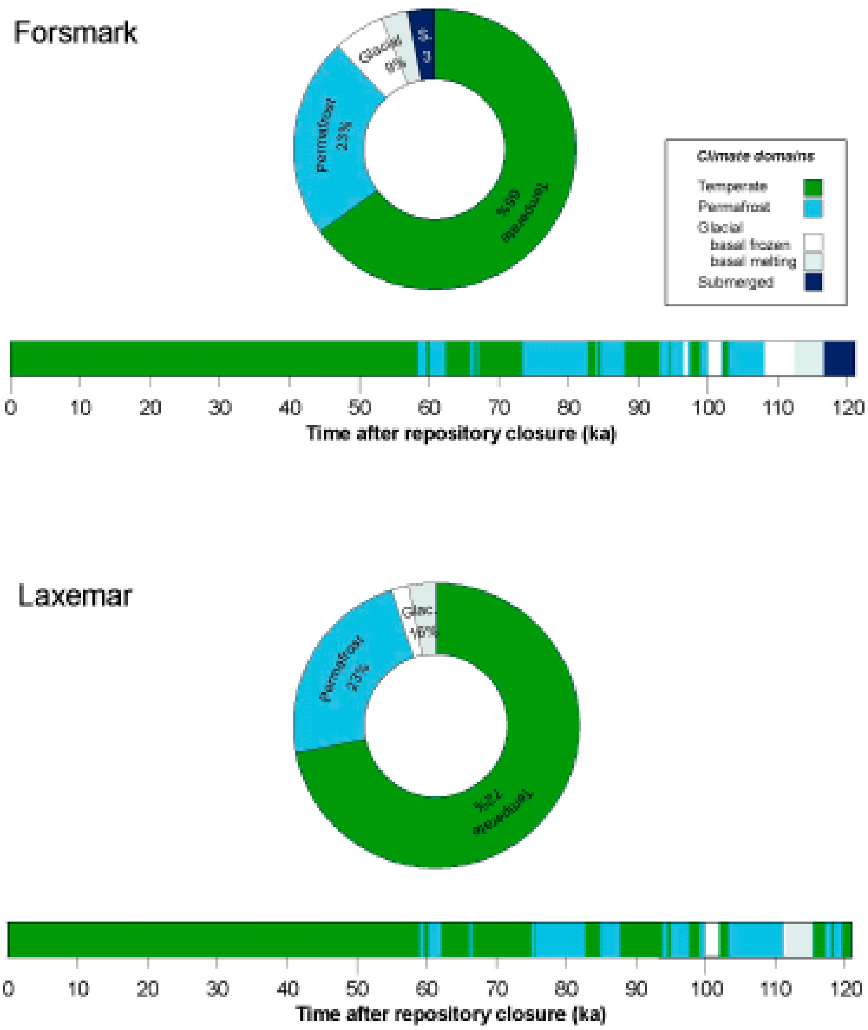


Figure 9-106. Duration of climate domains at Forsmark and Laxemar, expressed as percentage of the total time for the greenhouse variant of the reference evolution. The bar below the pie charts shows the development of climate-related conditions at each site for the greenhouse variant as a time series of climate domains and submerged periods.

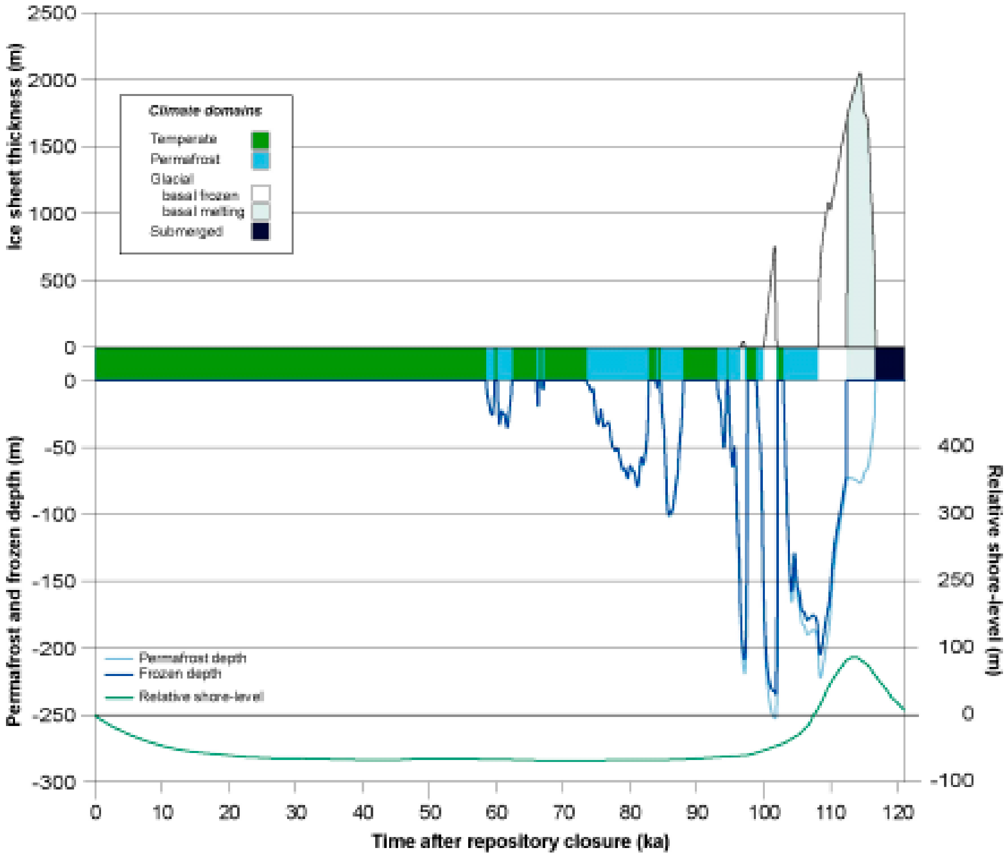


Figure 9-107. Evolution of climate-related conditions at Forsmark as a time series of climate domains and submerged periods for the greenhouse variant of the reference evolution.

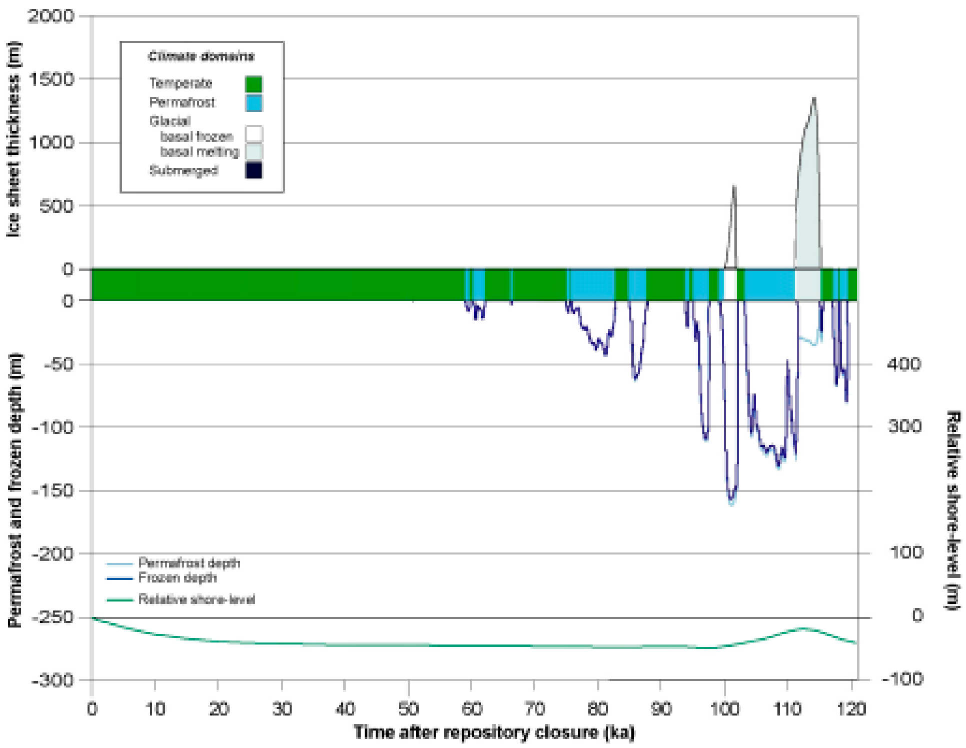


Figure 9-108. Evolution of climate-related conditions at Laxemar as a time series of climate domains and submerged periods for the greenhouse variant of the reference evolution.

For both candidate sites, the climate is dominated by an initial ~ 100,000 year long warm period without ice-sheet coverage, a period that gets successively colder towards the end. During a large part of this warm period, mean annual air temperatures at the candidate sites may be as warm as, or warmer than, at present. During this initial long warm period, it is likely that climate within the temperate domain may vary significantly, with a range that may be larger than that during the Holocene.

The length of the initial period of temperate domain in the SR-Can greenhouse variant should not be taken as a prediction or statement on future greenhouse climate change. Under a future warming climate, this period could be shorter or longer than that described here.

In a warming climate due to an increased greenhouse effect, the warmer temperatures at the ground surface would not affect repository safety functions at either of the sites. If precipitation increases, this would not affect groundwater formation significantly, since, on a regional scale, the major part of the groundwater aquifer is filled by present-day precipitation rates. However, low groundwater salinity due to persistent infiltration of meteoric water during the prolonged temperate periods in the greenhouse variant may affect the function of the clay buffer, see section 9.6.3.

Subject to the uncertainties and assumptions used in the climate modelling undertaken in the BIOCLIM and SWECLIM projects /BIOCLIM 2003, Rummukainen 2003/, and the limited range of emission scenarios chosen in these studies, the results of these climate modelling studies suggest that the climate in the Forsmark and Laxemar regions will experience increased summer temperatures of 2–3°C within the initial long period of temperate conditions. The climate model results also suggest increased winter temperatures in these regions. Precipitation is also predicted to increase, especially in summer /**Climate report**, section 4.3.1/.

During the second half of the greenhouse variant (Figure 9-107 and Figure 9-108), climate varies within the same range as during the first part of the base variant, and consequently the climate-related processes will act in the same way as in the base variant. The greenhouse variant reduces the effects of most climate-related processes of importance for repository safety, such as the time of glacial domain conditions, with the possible exception of changes in groundwater salinity.

Another possible course of events within a generally warming climate due to an increased greenhouse effect, is that the thermohaline circulation in the North Atlantic is reduced or shut-down /e.g. Wu et al. 2004, Schlesinger et al. 2006, Yin et al. 2006/. This would result in less heat being transported towards Fennoscandia by the North Atlantic Drift sea current, which in turn would lead to a regional cooling over Fennoscandia. This cooling could occur even earlier than the cooling described in the base variant of the reference evolution. In the SR-Can assessment, such a cooling case is covered by an additional scenario that includes a pessimistic variant of permafrost development in a cold and dry climate, see section 12.4 and the **Climate report**, section 4.4.1.

9.6.2 Biosphere

Climate change or variability due to increased greenhouse gas-induced warming over the coming 1,000 years, considered in the variant of the reference evolution, is also expected to influence important parameters in the biosphere such as the hydrological cycle, sea level, and salinity of the Baltic Sea. The hydrological cycle may be altered for the greenhouse variant and increased precipitation (see section 9.6.1) could lead to higher runoff, if not balanced by increased evapotranspiration due to higher temperatures. The expected changes of sea levels will reduce, stop or reverse the shore-level displacement and thus maintain the sites and surface ecosystems close to the sea. Thus, the water turnover rates will be dominated by the sea for the ecosystems closest to the repository. The salinity of the sea is dependent on the runoff to the Baltic Sea /Gustafsson 2004ab/, which might decrease if the runoff increases.

The effects on vegetation of the increase in temperature are expected to be small in relation to present inter-annual variations /Moberg et al. 2006/. Due to higher winter temperatures (see section 9.6.1), the vegetation period can increase and thus give higher productivity and a shift in species composition of vegetation. This will only have a minor impact when regarding the limited impact that the north- south gradient of climate in Sweden has on vegetation today.

In the alternative greenhouse variant, with changes in the thermo-haline circulation in the North Atlantic (see section 9.6.1), the surface ecosystem will more rapidly develop into a permafrost ecosystem, as described in section 9.4.2.

9.6.3 Repository evolution

Geochemistry

For the greenhouse variant, atmospheric CO_2 levels increase, temporarily up to ≈ 1,000 ppm /IPCC 2001a/, corresponding to about 4 times the pre-industrial values. The consequences of the increased acidity of superficial waters on a granitic aquifer were analysed in /Wersin et al. 1994/, where it was concluded that several tens of thousands of years would be necessary to exhaust the calcite present in fracture-filling minerals. In addition, silicate weathering and ion-exchange processes also contribute to neutralise the increased inflow of carbonic acid in infiltrating waters. It may thus be concluded that the groundwater conditions will be similar to those of the reference evolution, with the difference that a longer period of exposure to groundwaters of meteoric origin is expected at repository depth. The composition of the waters is, however, not expected to vary substantially during the temperate period, as shown by the hydrogeological modelling results for the Forsmark and Laxemar sites discussed in section 9.3.6 and the results in /Wersin et al. 1994/. Groundwater compositions from sites in temperate countries, such as Spain, may be used as examples. Samples from the granitic sites of El Berrocal /Bruno et al. 1998/ and Los Ratones /Gómez et al. 2006/ give evidence of fresh groundwaters with concentrations of divalent cations (Ca^{2+} and Mg^{2+}) around 1 mM.

The conclusions are, therefore, similar to those presented in sections 9.3.7 and 9.4.7. For the whole first temperate period following repository closure, anoxic groundwater conditions will prevail at repository depth, in spite of the increasing proportion of meteoric waters with time, thus satisfying the criterion for the safety function indicator R1a in Figure 9-2. Salinities during this period will be limited, ensuring that the swelling properties of the buffer and backfill are not negatively affected, cf the safety function indicator R1b in Figure 9-2. However, calcium concentrations at repository depth will be close to or slightly below 0.001 mol/L, i.e. near to the limit where montmorillonite colloids start to become stable. The concentration of sulphide, which is another important parameter, is expected to be $\leq 10^{-5}$ on the average. For colloids, concentrations are expected to remain at the levels that have been measured during the site investigations, around 50 micrograms/L.

Groundwater composition for an extended initial temperate period will be further analysed in SR-Site.

Buffer and deposition tunnel backfill

The buffer and deposition tunnel backfill will not be significantly affected by the different evolution in the greenhouse variant. The main difference is that the glacial conditions will occur later, which means that the uncertainties concerning altered groundwater chemistries, etc will also impact the assessment at a later stage. Concerning the possibility of calcium concentrations below 0.001 mol/L mentioned above, such a situation would not imply a larger extent of buffer colloid release than that assumed in the base variant of the reference evolution, where zero concentration is assumed for the extended periods of glacial conditions.

Canister

An initial 100,000 year long warm period will have negligible impact on canister performance. The prolonged period before the first occurrence of permafrost is expected to lead to a larger fraction of meteoric water in the groundwater composition. Since the water would still be oxygen-free, this will have no impact on canister corrosion, apart from possibly lower sulphide content in the water due to a lowering of its sulphate content from dilution with meteoric water.

The reduced ice-sheet thickness will, of course, lead to a lower mechanical load on the canister during the first glacial cycle. This may also lead to a lowering of the risk for the occurrence of larger earthquakes, i.e. smaller shear movements over the few canisters in locations where they would be significantly affected.

9.6.4 Safety function indicators for the greenhouse variant

Based on the contents of section 9.6.3, the status of the safety function indicators at the end of a prolonged period of temperate climate can be expected to be very similar to those reported for the initial temperate period in section 9.3.14. Therefore, no detailed account of the safety function indicators is given here. The following is noted:

- Canister corrosion is expected to proceed at the same rate as for the initial temperate period, meaning that negligible corrosion is expected also for a 60,000 year temperate period.
- The probability for canister failures due to earth quake induced shear movements is assumed to be proportional to time in the base variant of the reference evolution (although it is recognised that major earthquakes may be less frequent under a glacier and cluster around post-glacial episodes). Hence, the probabilistically calculated average number of failed canisters due to earth quakes is the same for a prolonged temperate climate as for an equally long part of the reference glacial cycle.
- As noted above, more detailed evaluations of the geochemical development will be carried out in SR-Site, allowing an update of the preliminary result presented above and thus a better founded assessment of the safety function indicators related to geochemistry.

9.7 Conclusions from the analysis of the reference evolution

Conclusions regarding all the identified safety functions, related to their indicators have been given in section 9.2.7 for the excavation/operation period, in section 9.3.14 for the initial period of temperate climate, in section 9.4.10 for the first glacial cycle and in section 9.5.1 for the entire assessment period for the base variant of the reference evolution. These conclusions are not repeated in detail here.

The conclusions concern also information to be propagated to consequence calculations. Canister failures resulting from the evolution are analysed in the next chapter, for barrier conditions representative of the reference evolution.

Brief conclusions regarding the greenhouse variant of the reference evolution are provided in section 9.6.4. These are also considered in consequence calculations in the next chapter.

In addition to these conclusions directly related to safety, additional conclusions concerning e.g. feedback to repository engineering, to needs of research and development etc could to some extent be developed based on the findings in the reference evolution. This discussion is, however, postponed to the development of final conclusions in chapter 13 where a fuller account, based also on results of consequence calculations and of the analyses of additional scenarios, can be given.

Regarding the two alternatives for backfill material, Friedland clay and a 30/70 mixture of bentonite (MX-80 or Deponit CA-N) and crushed rock, already the results of the reference evolution clearly indicate that the former is to be preferred. These findings are, therefore, presented below, leading to the conclusion that only Friedland clay needs to be considered in further analyses, thus simplifying the reporting of SR-Can.

Conclusions about the selected backfill materials

Two different types of backfill materials have been considered in SR-Can. The first is a mixture of the buffer bentonite together with crushed rock from the site in the proportions of 30/70. The second is a pure swelling clay. In SR-Can, a clay from Friedland in Schleswig-Holstein has been selected as the reference material.

Based on the current status of backfilling techniques it has been assumed in SR-Can that it will be necessary to use pre-compacted blocks together with pellets. It will then be possible to achieve dry densities of 1,930 kg/m^3 for the mixture and 1,780 kg/m^3 for the Friedland clay. These are minimum densities in the tunnels. There is no upper limit for the backfill density.

Section 4.2.8 and the conclusions in sections 9.3.14 and 9.4.10 show that both materials will meet the safety function indicators (Figure 9-2) at reference density. Both materials are also able to maintain the buffer density in the deposition hole at the required density (section 9.3.9) However, there is a clear difference in the two materials when it comes to the margins to the safety function indicators.

- The swelling pressure of the Friedland Clay will be maintained at high values even for a substantial drop in dry density. The swelling pressure of the 30/70 mixture will drop to values close to 0.1 MPa for a drop in dry density of about 5% (Figure 4-9 and Figure 4-10).
- The hydraulic conductivity of Friedland Clay is around two orders of magnitude lower than that of the 30/70 mixture at reference density. It is also rather insensitive to the ionic strength of the groundwater. The hydraulic conductivity of the 30/70 mixture is very sensitive to increased salinity and it will increase to values higher than 10^{-10} m/s for a small density drop at higher salinities (Figure 4-11 and Figure 4-12).
- The Friedland Clay will be able to maintain the saturated buffer density at the canister top at 2,000 kg/m^3 (or actual buffer density). With the 30/70 mixture, there will be a slight drop in buffer density at the canister top due to buffer expansion into the backfill (Table 9-7 and Table 9-8).
- Piping with erosion in the early stage will have a more severe impact on the 30/70 mixture, since the amount of swelling material is less and this material will be selectively eroded. It is not obvious that the material will self-heal after a piping event, section 9.2.4.
- Colloid release on the long time scale will affect the 30/70 mixture more severely in the same manner as piping/erosion, section 9.4.8.

The 30/70 mixture is very sensitive to variations initial density and requires a well-developed quality control system.

It is clear that the Friedland Clay has several advantages compared with the 30/70 mixture, from the point of view of long-term performance. No area where the mixture has any advantages has been identified. With current knowledge, there are no decisive technical or economical advantages either.

As a consequence of this, only the Friedland backfill material is pursued in the additional scenarios and consequence calculations in SR-Can.

Table 9-23. Examples of groundwater compositions. All concentrations except pH are total concentrations in kmoles/m³.

	Forsmark	Laxemar	Äspö	Finnsjön	Gideå	Grimsel: interacted glacial meltwater	"Most saline" groundwater at Laxemar	"Most saline" groundwater at Olkiluoto	Cement pore water	Baltic seawater	Ocean water	Maximum salinity from glacial upconing
pH	7.2	7.9	7.7	7.9	9.3	9.6	7.9	7.0	12.5	7.9	8.15	7.9
Na	0.089	0.034	0.091	0.012	0.0046	0.00069	0.349	0.415	0.002	0.089	0.469	0.25
Ca	0.023	0.0058	0.047	0.0035	0.00052	0.00014	0.464	0.449	0.018	0.0024	0.0103	0.27
Mg	0.0093	0.00044	0.0017	0.0007	0.000045	0.0000006	0.0001	0.0053	< 0.0001	0.010	0.053	0.0001
K	0.0009	0.00014	0.0002	0.00005	0.00005	0.000005	0.0007	0.0007	0.0057	0.002	0.01	0.0005
Fe	$33 \cdot 10^{-6}$	$8 \cdot 10^{-6}$	$4 \cdot 10^{-6}$	$32 \cdot 10^{-6}$	$0.9 \cdot 10^{-6}$	$0.003 \cdot 10^{-6}$	$8 \cdot 10^{-6}$	$60 \cdot 10^{-6}$	$\leq 10 \cdot 10^{-6}$	$0.3 \cdot 10^{-6}$	$0.04 \cdot 10^{-6}$	$2 \cdot 10^{-6}$
HCO_3^-	0.0022	0.0031	0.00016	0.0046	0.00023	0.00045	0.00010	0.00014	≈ 0	0.0016	0.0021	0.00015
Cl^-	0.153	0.039	0.181	0.0157	0.0050	0.00016	1.283	1.275	≈ 0	0.106	0.546	0.82
SO_4^{2-}	0.0052	0.0013	0.0058	0.00051	0.000001	0.00006	0.009	0.00009	≈ 0	0.0051	0.0282	0.01
HS^-	≈ 0	$3 \cdot 10^{-7}$	$5 \cdot 10^{-6}$	–	$< 3 \cdot 10^{-7}$	–	$< 3 \cdot 10^{-7}$	$< 1.6 \cdot 10^{-7}$	≈ 0	–	–	$< 3 \cdot 10^{-7}$
O_2 fugacity (bar)	$<< 10^{-20}$	$<< 10^{-20}$	$<< 10^{-20}$	$<< 10^{-20}$	$<< 10^{-20}$	$< 10^{-0.17}$ [(a)]	$<< 10^{-20}$	$<< 10^{-20}$	$\approx 10^{-20}$	$10^{-0.7}$	$10^{-0.7}$	$<< 10^{-20}$
Ionic strength (kmol/m³)	0.19	0.053	0.24	0.025	0.006	0.0013	1.75	1.76	0.057	0.13	0.65	1.09
TDS (g/L)	9.32	2.78	11.1	1.33	0.33	0.08	73.7	73.4	1.63	6.81	35.1	47.2
Reference	1	2	3	3	3	4	5	6	7	2	8	2
Notes	Borehole KFM02A; 512 m depth	Borehole KLX03; 380 m depth	Repository depth	Repository depth	Repository depth	O_2 fugacity only to illustrate effect	Depth ≈ 1,500 m	See also /Pitkänen 1999/ depth = 863 m; sample 42		Sampled at Simpevarp		Laxemar water at 1,350 m

[(a)] Oxygen fugacity for glacial conditions: The maximum content is $1.4 \cdot 10^{-3}$ M for glacial meltwater at 0°C. The corresponding maximum fugacity at 0°C is 0.67 bar /Ahonen and Vieno 1994/. In Grimsel the O_2 content is less than $3 \cdot 10^{-8}$ M.

References: 1 = /SKB 2005e/, 2 = /SKB 2006g/, 3 = /Laaksoharju et al. 1998/, 4 = /Hoehn et al. 1998/, 5 = /Laaksoharju et al. 1995/, 6 = /Pitkänen et al. 2004/, 7 = /Engkvist et al. 1996, Berner 1987/, 8 = /Stumm and Morgan 1996/.

10 Radionuclide transport and dose calculations for reference canister failure modes

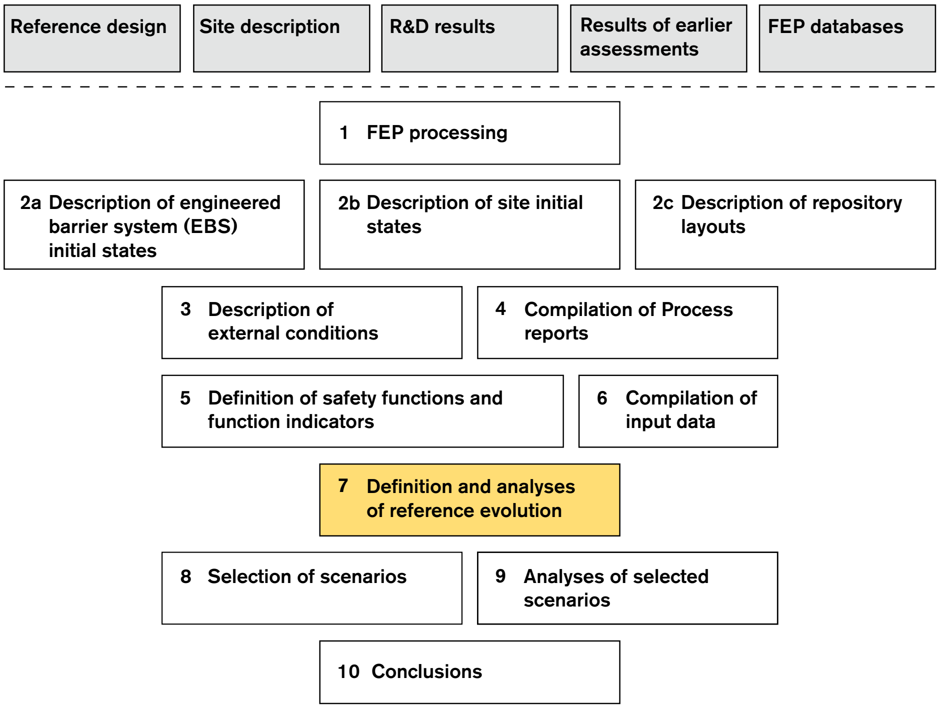


Figure 10-1. *The SR-Can methodology in ten steps (section 2.2), with the present step highlighted. This chapter deals with the analysis of the retardation potential of the repository.*

10.1 Introduction

This chapter describes analyses of radionuclide release, transport and dose impacts for potential failure modes of canisters identified in the analysis of the reference evolution. The purpose is to assess the retention properties of the system for these failure modes. Four failure modes, illustrated in Figure 10-2, are analysed.

1. The initial, growing pinhole defect. This failure mode was not explicitly addressed in the reference evolution in chapter 9, since the initial state of the canisters suggests that there will be no penetrating pinhole defects in the copper shell. An analysis of this failure mode is, however, suitable for addressing important aspects of the internal evolution of the canister. The buffer and the geosphere are assumed to have intact retention properties in this case. It is, therefore, also a convenient case for demonstrating the retarding capacity of the buffer and the geosphere and for exploring uncertainties relating to these components of the repository.

   Furthermore, as will be demonstrated below, an initially small defect is eventually expected to evolve into a large defect, which resembles the case of a failure caused by general corrosion of the canister, when the buffer is still intact. Although the likelihood of this latter failure mode was found negligible in the reference evolution, it is of interest to understand its consequences.

   This mode will be referred to as **the growing pinhole failure**, see further section 10.5.

2. Failure due to copper corrosion for an eroded buffer. This failure could occur if the buffer erodes, as could be the case for intrusion of dilute glacial melt waters. If the extent of the erosion is considerable, advective conditions may result in the remaining buffer, leading to an enhanced corrosion rate. This was found to potentially affect a few canisters in the analysis of the reference evolution in chapter 9, but the uncertainties are considerable. For this failure mode, both the canister and buffer are short-circuited, and the rock retention is small since substantial copper corrosion after buffer erosion only occurs in deposition holes with high flow rates, which is strongly correlated to low geosphere retention. This mode will be referred to as **the advection/corrosion failure**, see further section 10.6.

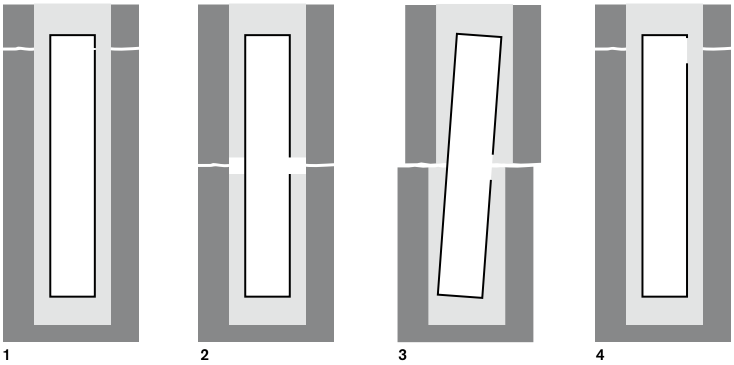


Figure 10-2. The four failure modes considered in this chapter: 1 The growing pinhole failure, 2 The advection/corrosion failure, 3 The shear movement failure and 4 The isostatic load failure.

3. Failure due to shear movement. This failure could occur as a consequence of secondary rock movements induced by a large earthquake in the vicinity of the repository. The analysis of the reference evolution in chapter 9 implies that its likelihood is small but non-negligible. For this failure mode, the canister is short-circuited, the thickness of the buffer is reduced due to the experienced shear movement, and the rock retention is small, since a fracture experiencing a major shear movement must have a considerable size and thus likely low retention. This mode will be referred to as **the shear movement failure**, see further section 10.7.
4. Failure due to isostatic collapse. This failure could occur as a consequence of the increased isostatic pressure due to a glacial overburden. The analysis of the reference evolution in chapter 9 implies that the likelihood of this failure mode is negligible. For this failure mode, the canister is short-circuited, whereas the buffer and the geosphere have intact retention properties. It thus resembles the final state of the first case. This mode will be referred to as **the isostatic load failure**, see further section 10.8.

Two issues related to radionuclide transport and dose calculations that can to a large degree be treated independent of the nature of the failure mode are addressed first in this chapter:

- The modelling of radionuclide transport and dose estimation in the biosphere is described in some detail in section 10.2.
- The issue of potential criticality for a failed canister is treated in section 10.3.

The models used for radionuclide transport in the water phase for the near field and the geosphere are then described in section 10.4 and the analyses of the four failure modes are described in sections 10.5 to 10.8. Analyses of radionuclide transport in the gas phase are described in section 10.9. Additional cases to illustrate barrier functions are analysed in section 10.10.

Much of the modelling and many of the modelling results are discussed in more detail in the SR-Can **Radionuclide transport report**.

10.2 Modelling of radionuclide transport and dose estimation in the biosphere

10.2.1 Introduction

Over the time scales of relevance to the safety assessment, the biosphere will undergo considerable changes, in particular due to expected future climate changes involving periods of permafrost and glacial conditions or extended interglacial periods. Regardless of the evolution of the repository, a realistic, site-specific handling of the biosphere is likely to yield very low doses during most of the assessment period for several reasons. Due to expected shore-line displacements over a glacial period, coastal sites are likely to be submerged for extended periods of time, see section 9.4.1, leading to both stagnant groundwater and potentially a considerable dilution of any releases from the geosphere. There is also the possibility of accumulation in bottom sediments, which, as long as the sediments are submerged, retards the release of radionuclides. Glacial conditions, meaning that the site is covered by ice, will for obvious reasons lead to very low, if any, doses. The highest doses are expected for the periods when the site is not submerged /Avila et al. 2006/. As is evidenced by e.g. the reference evolution in chapter 9, no canister failures and hence no releases of radionuclides are expected for thousands of years into the future, by which time today's biosphere will have undergone considerable changes.

Nevertheless, it is essential to obtain a thorough understanding of the behaviour of radionuclides released to the current biosphere, since this is the best available basis for a description of future biosphere conditions during temperate periods. Also, an important factor affecting the biosphere structure in an interglacial period is the position of the shoreline which is fairly predictable, partly since it is strongly related to the local topography. Furthermore, much of the knowledge required to describe the functioning of the biosphere is generic in nature, meaning that results relating to the current biosphere are applicable, possibly after adaptation, also for altered future biosphere conditions. Studying and analysing the biosphere is, therefore, an essential part of the ongoing site investigations and the results of these studies are of direct relevance for the safety assessment.

In the following, the method used for modelling of a landscape and its development during an interglacial period is described in section 10.2.2, followed by a description of the method for calculating annual effective doses to humans located in such a landscape in section 10.2.3. Biosphere modelling for permafrost and glacial periods and for the greenhouse variant of the reference evolution is described in section 10.2.4. Modelling of doses to biota is briefly discussed in section 10.2.5. The application of the methodology to the present interglacial period at Forsmark and Laxemar is described in sections 10.2.6 through 10.2.9 and for other climate conditions in section 10.2.10.

10.2.2 Landscape modelling during an interglacial period

For estimation of radiation doses caused by releases of radionuclides from the repository, a spatially distributed landscape model is used. Based on the scientific understanding of the biosphere at the site and its development during an interglacial period, biosphere models are constructed in which the turnover of radionuclides is analysed and time-dependent concentrations in environmental media are calculated. The methodology and the available tools for this are described in detail in /SKB 2006hi, Avila et al 2006/. Below, an overview of the modelling strategy is given.

The temporal development of the biosphere during an interglacial period is handled by building biosphere models for the succession of situations based on different sources of information (Figure 10-3). The digital elevation model (DEM) is a central source of information for predicting or retrodicting the locations, characteristics and evolution of past and future rivers, lakes, mires, coasts and surface hydrology. The information on the overburden (Quaternary maps, marine geological maps, lake sediment characteristics and soil profiles) is important for predicting the potential for future agricultural land use or forestry.

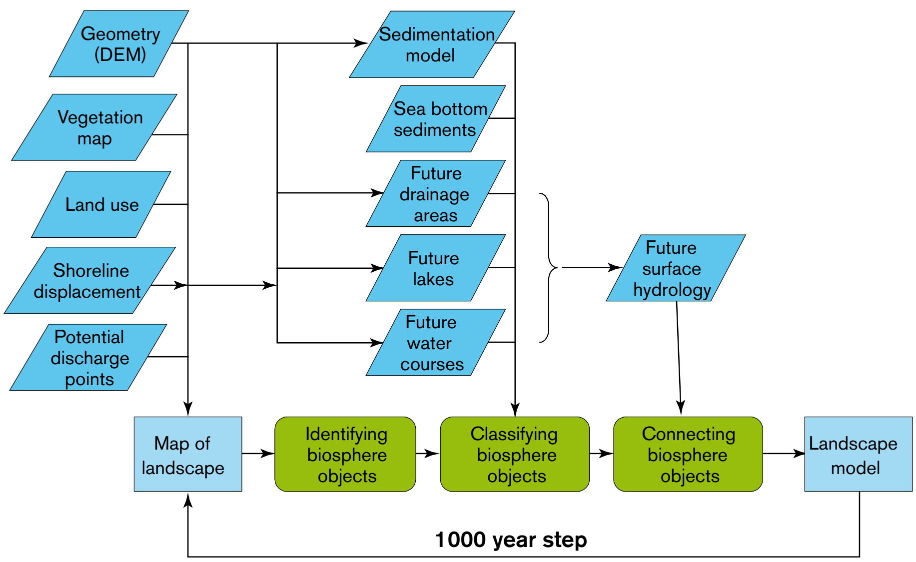


Figure 10-3. *Flow chart describing the iterative process of constructing a landscape model. The blue rhombi show different input models, green boxes represent activities. This process generates a landscape model in 1,000 year steps, describing the configuration and succession of biosphere objects in the landscape. Further details in text and in /SKB 2006hi/.*

For the present temperate period, the overall development of the biosphere at the site is outlined in a 1,000 year perspective and beyond, essentially based on the ongoing shore-line displacement and the understanding of the impact this has on the biosphere /SKB 2006hi/. The past development from deglaciation to today is inferred from geological records and associated reconstructions of the shore-line.

For each time step of 1,000 years, the landscape at the site is described as a number of connected biosphere objects constituting an integrated landscape model, see e.g. Figure 10-5 in section 10.2.6. The descriptions of the biosphere objects are based on the ecosystem models and on site data /SKB 2006hi/.

The two main categories of ecosystems, aquatic and terrestrial, are further subdivided into a number of more specified ecosystem types. Aquatic ecosystems include marine systems, lakes and running water and examples of terrestrial systems are agricultural land, mire and forest.

The surface environment in the area overlying the repository location is represented as an interconnected set of landscape objects (cf Figure 10-5 and Figure 10-8). Through hydrogeological modelling that includes an analysis of flow and transport pathways from different locations within the repository, locations at which discharges of radionuclides to the surface environment could occur are identified and partitioned between the various landscape objects.

The release points from reference cases for Forsmark and Laxemar in the hydrogeological modelling /Hartley et al. 2006a, Hartley et al. 2006b/ were plotted in the landscape. The results generally show that discharge points are attracted to nearby low points in the landscape, e g shorelines, lakes and mires in the same sub-catchment area /SKB 2006hi/. To identify all possible biosphere objects (at repository closure and forward in time), the potential discharge points were plotted on the map of future identified sub-catchment areas, lakes and running waters. Thus, a pattern with clusters of potential discharge points was used to identify distinct biosphere objects. Very few points were found isolated from the clusters. Isolated points were transferred to the closest object downstream.

The potential exit points, with the time for advective transport added to the release time, were also plotted in time. These time-dependent maps show when the earliest releases to the biosphere objects are expected for radionuclides without retardation in the geosphere. The location of these points can be affected by hydraulic changes after release from the repository, but such hydraulic changes were not included in the model /Hartley et al. 2006ab/. During the time for advective transport to the biosphere object, the shoreline will move further. For transport times shorter than 1,000 years, this will not affect the results because the resolution of the time-dependent maps is 1,000 years. For longer transport times the fraction of exit points on land will be overestimated. Objects with release times later than 20,000 AD were omitted as single objects from the landscape model and the associated discharge points were added to the closest biosphere object. This is cautious, as it underestimates transport times for these discharge points.

The fractions of potential discharge points in each object and time period were used to weight the importance of the different objects.

By introducing radionuclides at different locations in the integrated model, it is possible to follow their fate as they move through the connected ecosystem objects, and to assess where and to what extent they are predicted to accumulate in the system. In combination with information on calculated locations of radionuclide releases from the geosphere to the surface hydrological system, this gives a view of how radionuclides become distributed through the integrated landscape model over time /Avila et al. 2006/.

Wells constitute one of several important pathways for human exposure to potential releases from the repository. The approach to modelling of wells in SR-Can is based partly on site-specific information and also consideration of constraints on the size of a population that can utilise a local well. It is assumed that the contaminated groundwater plume always intersects a well before discharging into the landscape. The concentration of a radionuclide in the well water is calculated by dividing the release rate from the geosphere by the well capacity, estimated from data obtained from existing wells, and results from pump tests at the site. This is cautious, as it is impossible for a well to capture all the contaminated groundwater. Doses were calculated for a subsistence farmer who drinks water only from this well and eats only food that has been contaminated by the well water via irrigation or ingestion of water by cattle. The well dose conversion factor (DCF) was compared with the LDF (Table 10-1 and Table 10-2).

10.2.3 Method for calculation of landscape doses

In order to assess doses to humans, given the calculated distribution of radionuclides in the landscape, a number of assumptions have to be made concerning living habits and exploitation of the landscape. One assumption is that humans are supposed to have an intake of food corresponding to 110 kgC y^{-1}. Organic carbon is used as a unit of caloric intake to weight different food items proportional to their nutritional value as is commonly done in ecosystem studies /Odum 1983/. Another assumption is that humans maximally exploit the contaminated landscape, thus eating all potentially edible food produced within the objects. Thus, the number of people that can live off one object is constrained by the annual productivity of edible products and the size of the object.

In principle, it is possible to drive the landscape model with time-dependent fluxes of radionuclides derived from a model of the repository, and of flow and transport through the geosphere. Such an approach would give time-dependent radionuclide concentrations in the environmental media of which the various landscape objects are composed and hence time-dependent effective dose rates to individuals utilising those landscape objects. However, in practice and as will be demonstrated below, radionuclide fluxes emerging from the repository near field would vary slowly with time. It is also convenient to decouple the calculation of those fluxes from calculations of their radiological impacts made using the landscape model, both from a practical point of view and for purposes of transparently demonstrating the nature of all steps of the calculations leading from a canister failure to annual effective dose. Therefore, in conformance with previous SKB practice /SKB 1999a/, and using an approach that is widely adopted internationally, radiological impacts are calculated for constant unit release rates of radionuclides to the surface environment. By this approach, Landscape Dose Factors (LDFs), i.e. effective dose rates for unit flux of each radionuclide, are derived. These LDF values can then be multiplied by radionuclide fluxes emerging from the geosphere for radiological impact estimation.

In applying this approach, various cautious assumptions are made concerning the duration of the period of chronic release and the additivity of contributions from different radionuclides. These cautious assumptions are described in more detail below.

The periods of temperate climate of relevance are both from the present day until the next major episode of climatic cooling and also subsequent temperate periods after that episode of cooling. In order to include the potential for application of LDF values in either of these contexts, an extended period of release is assumed, beginning after the glacial ice has retreated from the area (approx. 8,000 BC in the Holocene period of temperate climate) and finishing when the first effects of permafrost are projected to start (e.g. at 10,000 AD in the current temperate period (cf section 9.4.1). This allows the maximum reasonable time span for radionuclides to accumulate in the surface environment and also ensures that a comprehensive range of temperate environments is studied, as over this period post-glacial isostatic and eustatic changes are fully expressed, with the associated changes to the location of the coastline and the characteristics of local marine and terrestrial ecosystems, as discussed in sections 9.3.3 and 9.4.2.

In a non-evolving landscape with a constant rate of input of a radionuclide, concentrations of that radionuclide in the various environmental media would be expected to increase monotonically and, if the period of discharge was sufficiently long, would eventually be expected to stabilise at constant values /Bergström et al. 1999/. However, with an evolving landscape, as is represented in the landscape model, such a concept of equilibrium is not applicable. For example, radionuclides can accumulate in marine or lacustrine sediments, but give rise to an increased radiological impact when, as a consequence of shore level displacement, those sediments are converted to agricultural land. To allow for this, the LDF values used are the maximum values of effective dose rate that apply over the period of release. This is a cautious assumption, as it implies that the geosphere release is sufficiently protracted for the maximum value to be realised. Furthermore, the maxima for different radionuclides occur at different times, so multiplying geosphere fluxes by these maximum values and summing the results, as is done, will over-estimate the overall effective dose rate, as when one radionuclide is exhibiting its maximum effective dose rate others will be exhibiting less than their maximum effective dose rates /Avila et al. 2006/.

Because the individual landscape objects are interconnected and radionuclide discharges can occur to several of them, radionuclide concentrations in environmental media not only vary with time but also differ in the various landscape objects. In principle, individuals can occupy, consume or otherwise utilise environmental media from several different landscape objects and it is this overall pattern of utilisation that determines the time-averaged effective dose rate that they receive. However, the regulatory requirements place emphasis on the most highly exposed subgroup of individuals in the population (see section 1.4.1 and Appendix A). Consequences should be calculated for a representative individual in the group exposed to the greatest risk (the most exposed group). SSI's general guidance indicates that the delimitation of the group could be determined by including "the individuals that receive a risk in the interval from the highest risk down to a tenth of this risk".

In order to ensure that the effective dose rate to the most exposed subgroup is identified, calculations of effective dose rate are made for population groups that occupy a single landscape object and obtain all their resources from that object. This ensures that individuals make maximum reasonable use of local resources and that the effective dose rate arising from utilising the most contaminated part of the landscape is not diluted by utilisation of less contaminated parts of the landscape.

Having adopted this approach, it is possible to estimate not only the effective dose rate to individuals utilising a particular landscape object, but also the number of individuals that object can fully support. For the object giving the highest effective dose rate, this is the maximum number of people that could be associated with that effective dose rate. In practice, some individuals would utilise resources from more than one landscape object, so the effective dose rate that they received would be lower.

The number of individuals that the landscape objects studied can support varies from less than one (as low as 0.0001 in some instances) for some terrestrial objects to many thousands in the case of some marine objects /Avila et al. 2006/. Clearly, where the object that gives the highest effective dose rate based on sole utilisation can support less than one person, that effective dose rate is too high to be applicable to the most exposed individual, since an individual utilising that object would also have to utilise resources from other objects. Conversely, where the object that gives the highest effective dose rate based on sole utilisation can support a large number of people, heterogeneities in environmental concentrations would mean that, in practice, some individuals would receive higher effective dose rates than that calculated, whereas others would receive lower effective dose rates. To illustrate this further, consider the results that would have been obtained had the landscape object giving the highest effective dose rate instead been represented as two landscape objects. These would have supported the same total number of people, but people associated with one of the objects would have received a higher effective dose rate than that previously computed, whereas those associated with the other object would have received a lower effective dose rate /Avila et al. 2006/.

To eliminate these problems, which essentially arise from the representation of the landscape as a finite number of objects, results from the effective dose rate calculation at each time of evaluation are plotted as a complementary cumulative distribution function (CCDF) in which the number of people exceeding a particular effective dose rate is plotted against the effective dose rate (see Figure 10-4) and /Avila et al. 2006/. Because these plots are based on calculations for finite-size landscape objects that will fully support specific numbers of people, they exhibit stepwise characteristics. However, examination of these CCDFs shows that they are typically well fitted by log-normal distribution functions, see Figure 10-4.

In considering whether it is justified to use the smoothed version of the curve for assessment purposes, two different issues arise. We can envisage that if individuals utilised resources from more than one landscape object, the curve would be smoother, as the stepwise distinction of numbers of people associated with particular effective dose rates would disappear. However, the curve would also tend to narrow, as individuals would move away from full utilisation of landscape objects associated with the highest and lowest effective dose rates. Alternatively, if the landscape was decomposed into a greater number of landscape objects, the curve would also become smoother, but it would not narrow. In justifying use of a smoothed curve, we take account of the latter consideration and view smoothing the curve as being an approach that moves from a discrete to a continuous representation of the landscape. However, no narrowing of the curve is permitted, as the emphasis still needs to be placed on the individual making maximum reasonable use of local resources, /Avila et al. 2006/.

Once a smooth curve has been generated, it can be used to make an estimate of the effective dose rate to the most exposed individual. This is the effective dose rate at which the CCDF has a total number of individuals exceeding that effective dose rate of 1.0. This is a real upper bound on individual effective dose rate within the context of the modelling assumptions. To choose an effective dose rate higher than this would be to adopt a contaminated area that would support less than one individual. Thus, any individual utilising that area would also have to utilise other areas, so reducing the effective dose rate received.

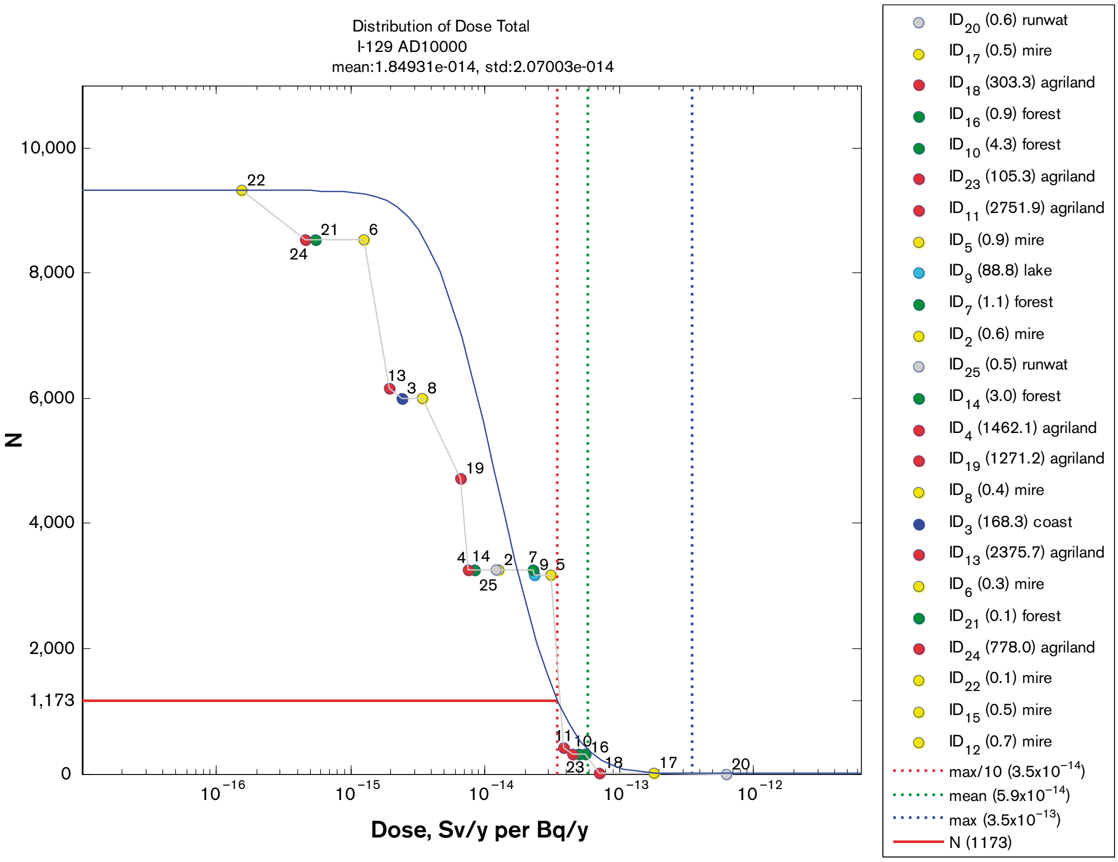


Figure 10-4. *Total effective dose rate from I-129 associated with different landscape objects at 10,000 AD at Forsmark. The blue curve is the fitted log-normal distribution. The legend gives the object number (cf Figure 10-5), ecosystem type and number of people (in brackets) that can be sustained for each landscape object. The Landscape dose factor (LDF) is the average for a population receiving an annual effective dose in the range from the maximum dose to 1/10 of the maximum, i.e. 5.9·10^{-14} Sv/Bq in this case (green vertical line). The number of people in the most exposed group is 1,173 (red horizontal line), /Avila et al. 2006/.*

However, having determined the effective dose rate to the most exposed individual, consideration has to be given to identifying a representative individual from the most exposed group and determining the effective dose rate to that individual. Regulatory guidance indicates that the degree of variation in individual doses within that group should not be greater than a factor of ten, see SSI's General Guidance in Appendix A. For this reason, the effective dose rate to the representative individual from the most exposed group is obtained by finding the arithmetic mean of the fitted log-normal distribution in the interval between the effective dose rate to the most exposed individual and one tenth of that value.

To avoid speculations about the age of the most exposed individual the maximum dose conversion factor for all age groups are used /Avila and Bergström 2006/, which thus overestimates the risk.

In summary, the method adopted for calculating effective dose rates and hence individual risks in SR-Can is to:

- Use the landscape model to calculate effective dose rates as a function of time for unit flux of each radionuclide of interest partitioned over the various landscape objects in accordance with results obtained from geosphere flow and transport calculations.
- At each of a set of reference times (for practical convenience taken as every 1,000 years) and for each radionuclide to calculate the CCDF of number of individuals against effective dose rate for all the landscape objects considered in the model.
- Fit a log-normal distribution to each CCDF and use that to calculate the effective dose rate at each reference time and for each radionuclide to the most exposed individual, i.e. the effective dose rate at which the fitted CCDF gives one person exceeding that effective dose rate.

- Find the effective dose rate to a representative individual from the most exposed group at each reference time and for each radionuclide by finding the arithmetic mean of the fitted log-normal distribution in the interval between the effective dose rate to the most exposed individual and one tenth of that value.
- Find the maximum of the effective dose rate to the representative individual over the reference times considered for each radionuclide and define this as the LDF for that radionuclide.

For radionuclides with decay chains, the distribution of daughter nuclides in the landscape and their contribution to the doses, resulting from unit release rates of the parent, were taken into account. Hence, for radionuclides with decay chains, the LDF also includes the contribution of the daughter radionuclides to the dose. For example, the LDF for Ra-226 includes the contribution to the dose from the daughters Po-210 and Pb-210 /Avila et al. 2006/. It also includes contributions from shorter-lived daughters treated as being in secular equilibrium.

10.2.4 Biosphere modelling for the permafrost, glacial and greenhouse case situations

Permafrost

Permafrost conditions occur in several episodes in the reference evolution covering the Weichselian glacial cycle. At both sites, the first permafrost episode starts about 10,000 AD following the present interglacial, see section 9.4.1. At both sites, the coastline is some distance from the repository at this time and major discharge areas are not located offshore. The situation is similar at the end of an interglacial when global sea levels are falling. To simulate permafrost conditions, it is assumed that the spatial distribution of landscape objects is similar to that at the end of the temperate interglacial period, except that agricultural land is replaced by forest or mires, reflecting the consideration that a significant degree of agriculture would not be tenable in such a context. For calculating the LDF, a release of 1Bq/y is assumed until 50,000 AD.

The glacial period

During the glacial period there can be periods when the repository is at the ice margin and submerged under the sea, see section 9.4.1. For this period the LDF for the site directly after the ice has melted away is used, i.e. the LDF at the beginning of an interglacial, but in the calculation the release of 1Bq/y is continued for 50,000 years.

The greenhouse case

For the greenhouse variant of the reference evolution, the landscape and ecosystems at the end of the interglacial are used and the LDF is calculated for a continuing release of 1Bq/y until 50,000 AD.

10.2.5 Doses to biota

To assess the potential impact on non-human biota the graded approach developed within the ERICA project (EU – 6th Framework Programme) was applied. Two release cases were considered, see sections 10.5.5 and 10.6.6, respectively. For these cases, the peak values of the release rates were used as constant input to the Forsmark landscape model and simulations were carried out for the whole interglacial period. From the landscape model, the concentrations in the major substrates (soil and water) of different habitats were obtained. These concentrations were divided by the Environmental Media Concentration Limits (EMCL) derived within the ERICA project to obtain a Risk Quotient (RQ) for screening purposes (Tier 1 in the ERICA graded approach). The rationale with screening is that if the RQs are below 1, then it is assured that risks to biota are insignificant and no further assessments are required. If the RQ are above one then more detailed assessments are required to decide whether or not there is a potential risk to non-human biota. See further sections 10.5.5 and 10.6.6.

10.2.6 Landscape development at Forsmark

At Forsmark, three time periods with different conditions can be identified, the sea period from 8,000 BC to about 1,000 AD, a coastal period from 1,000 AD to about 5,000 AD, and a terrestrial period until 10,000 AD. For the first 10,000 years after deglaciation, the site is submerged under the sea. During this period the number of the biosphere objects is small and only three objects are modelled: the basin above the repository (17) the entire Öregrundsgrepen (3) and the rest of the Baltic Sea (1). The coastal period starts with a situation similar to that prevailing today at the site, with 4 objects on land; a mire (21) and three lakes (22, 23, 24). There are two future objects situated in the sea today (11 and 18), which both have a modelled discharge of radionuclides during this period. The shore-level displacement gradually reveals more objects and an ongoing succession of existing biosphere objects (e.g. from mire to agricultural land) make the landscape dynamic. The diversity and spatial heterogeneity of objects is highest during this period. From 7,000 AD and onwards there are few sea objects (1, 3) and few lakes (9), the rest are forests and several mires, some of which are transformed to agricultural land. After 9,000 AD, the sea objects disappear, but the lake (9) persists as a lake to about 20,000 AD assuming current climatic conditions. See further Figure 10-5 and Figure 10-6.

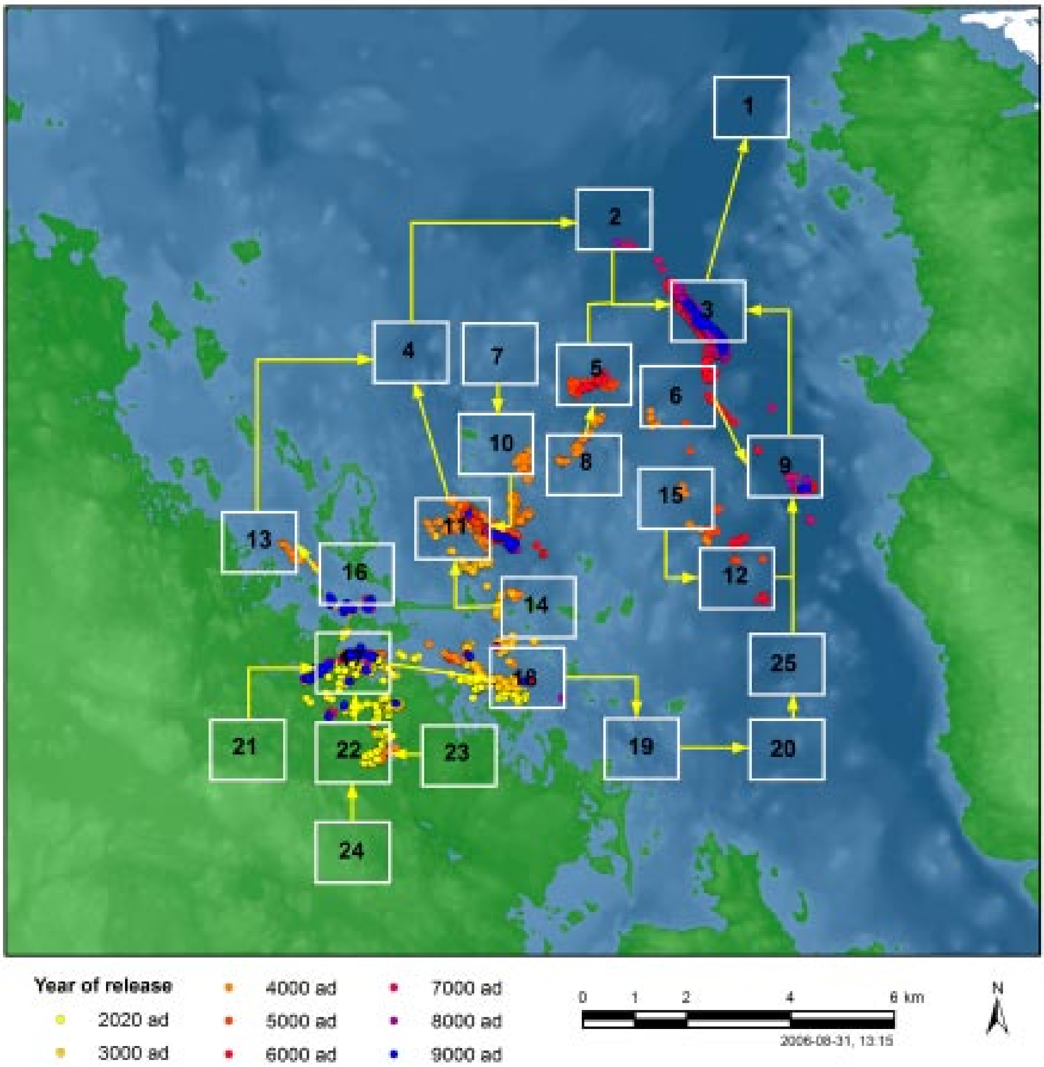


Figure 10-5. Biosphere objects and hypothetical release points from the geosphere (from hydrogeological modelling described in section 9.3.6) into the biosphere from 2,000 AD to 20,000 AD. The underlying map shows today's shoreline.

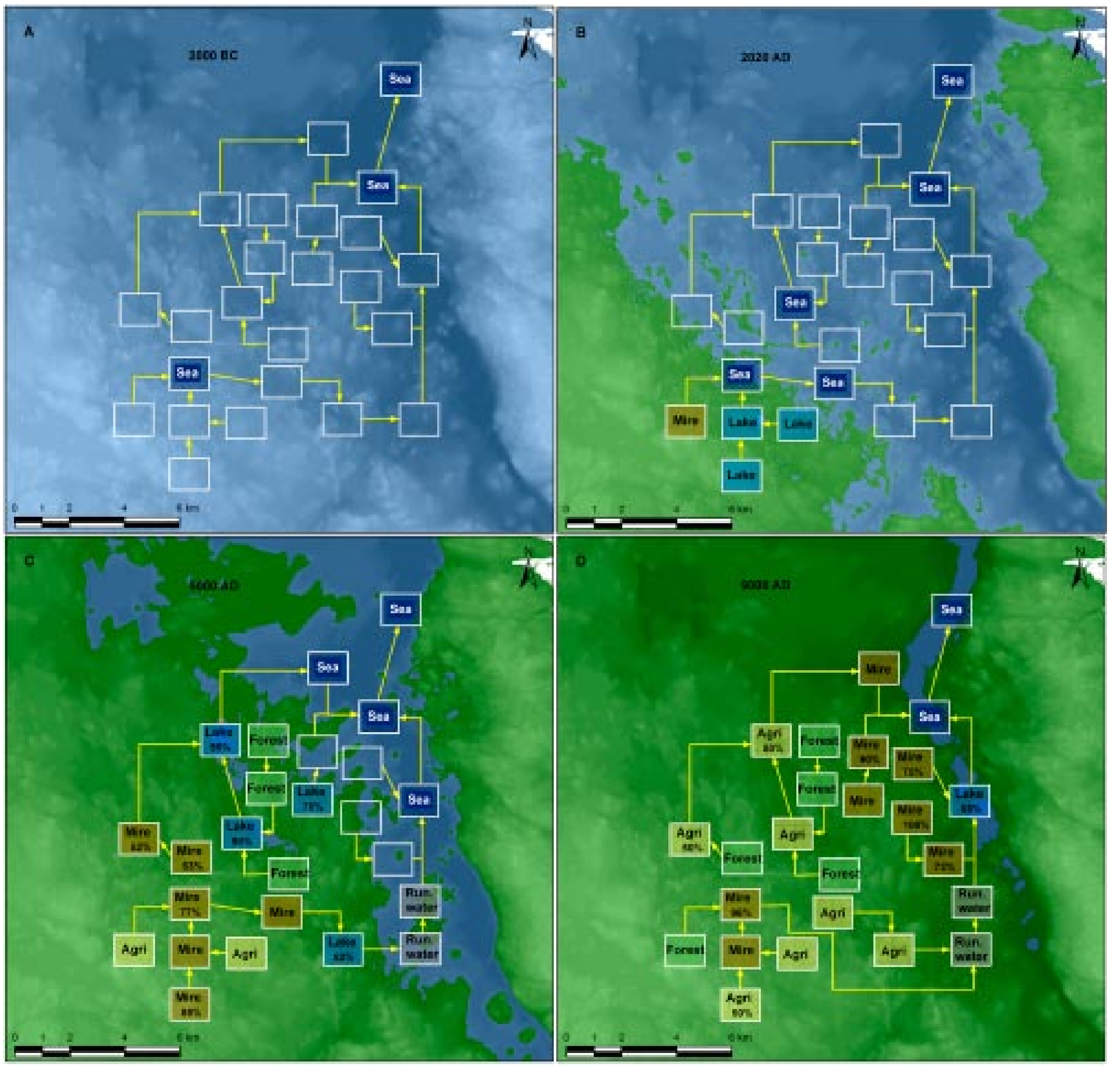


Figure 10-6. *Example of a succession of biosphere maps for temperate conditions at Forsmark. The maps represent different time periods with different biosphere objects and data. Marine stage from 8,000 BC to 1,000 AD (A), the coastal stage today (B) and at 5,000 AD (C) and the terrestrial stage from 7,000 AD and onwards (D). The glacial ice-margin stage is identical to A and the continued greenhouse state is represented by D, while permafrost is similar to D but with agricultural land replaced by mires or forest.*

10.2.7 Landscape dose factors for Forsmark

The LDF values obtained for Forsmark are presented in Table 10-1. The values range from around 10^{-17} to around 10^{-11} Sv Bq^{-1}. The maximum values occur at different times for the different radionuclides, either during the coastal or the terrestrial periods. The number of individuals in the most exposed group also differs between radionuclides. The selection of radionuclides for the SR-Can assessment is discussed in section 10.5.3.

The dose conversion factors increase towards the end of the period for all radionuclides (Figure 10-7). The submerged period gives values that are generally 3 to 4 orders of magnitude lower than those for the coastal and terrestrial stages. The differences over different time periods mainly depend on the properties of the ecosystems (e.g. volumes, areas, discharge rates). Only a small part is due to the fact that a larger inventory has accumulated towards the end of the period /Avila et al. 2006/.

For the entire reference glacial cycle, the LDF values are highest during the interglacial period and lowest during the glacial period, see tables in /SKB 2006h, Avila et al. 2006/. For the greenhouse variant, the LDF values are similar to the values of the interglacial LDFs.

Table 10-1. Landcape Dose Factors (LDFs) for an interglacial period at Forsmark expressed in units of Sv/y per Bq/y. N is the number of persons in the most exposed group. Time is time for maximum LDF. Well DCF in Sv/y per Bq/y.

RN	LDF	N	Year (AD)	Well	Maximum
Cl-36	$1.3\cdot10^{-14}$	128	2,500	$3.5\cdot10^{-15}$	LDF
Ca-41	$1.7\cdot10^{-15}$	41	8,000	$5.3\cdot10^{-16}$	LDF
Ni-59	$4.2\cdot10^{-16}$	67	8,000	$2.4\cdot10^{-16}$	LDF
Ni-63	$4.2\cdot10^{-16}$	23	8,000	$5.6\cdot10^{-16}$	Well
Se-79	$6.7\cdot10^{-14}$	23	3,000	$1.2\cdot10^{-14}$	LDF
Sr-90	$1.7\cdot10^{-13}$	18	8,000	$1.0\cdot10^{-13}$	LDF
Zr-93	$6.3\cdot10^{-15}$	36	6,000	$4.0\cdot10^{-15}$	LDF
Nb-94	$1.3\cdot10^{-11}$	422	4,000	$6.2\cdot10^{-15}$	LDF
Tc-99	$4.4\cdot10^{-15}$	301	2,500	$2.5\cdot10^{-15}$	LDF
Pd-107	$2.0\cdot10^{-16}$	67	3,000	$1.4\cdot10^{-16}$	LDF
Ag-108m	$6.9\cdot10^{-11}$	421	4,000	$8.8\cdot10^{-15}$	LDF
Sn-126	$4.2\cdot10^{-13}$	52	5,250	$1.8\cdot10^{-14}$	LDF
I-129	$5.5\cdot10^{-12}$	42	2,750	$4.2\cdot10^{-13}$	LDF
Cs-135	$6.3\cdot10^{-13}$	19	3,000	$7.5\cdot10^{-15}$	LDF
Cs-137	$1.2\cdot10^{-12}$	19	2,750	$4.8\cdot10^{-14}$	LDF
Sm-151	$6.6\cdot10^{-17}$	68	8,000	$3.6\cdot10^{-16}$	Well
Ho-166m	$1.9\cdot10^{-11}$	422	4,000	$7.3\cdot10^{-15}$	LDF
Pb-210	$2.6\cdot10^{-12}$	22	8,000	$2.5\cdot10^{-12}$	LDF
Ra-226	$9.0\cdot10^{-12}$	22	8,000	$1.0\cdot10^{-12}$	LDF
Th-229	$6.9\cdot10^{-12}$	741	4,000	$1.8\cdot10^{-12}$	LDF
Th-230	$8.1\cdot10^{-12}$	64	10,000	$7.7\cdot10^{-13}$	LDF
Th-232	$1.3\cdot10^{-12}$	119	10,000	$8.4\cdot10^{-13}$	LDF
Pa-231	$4.0\cdot10^{-13}$	89	8,000	$2.6\cdot10^{-12}$	Well
U-233	$4.8\cdot10^{-14}$	414	3,000	$1.9\cdot10^{-13}$	Well
U-234	$6.8\cdot10^{-14}$	47	7,250	$1.8\cdot10^{-13}$	Well
U-235	$4.4\cdot10^{-14}$	414	3,000	$1.7\cdot10^{-13}$	Well
U-236	$4.4\cdot10^{-14}$	414	3,000	$1.7\cdot10^{-13}$	Well
U-238	$4.2\cdot10^{-14}$	414	3,000	$1.6\cdot10^{-13}$	Well
Np-237	$1.4\cdot10^{-13}$	129	3,000	$4.0\cdot10^{-13}$	Well
Pu-239	$1.4\cdot10^{-13}$	103	6,000	$9.2\cdot10^{-13}$	Well
Pu-240	$1.4\cdot10^{-13}$	98	5,500	$9.2\cdot10^{-13}$	Well
Pu-242	$1.4\cdot10^{-13}$	99	6,000	$8.8\cdot10^{-13}$	Well
Am-241	$1.6\cdot10^{-12}$	860	4,000	$7.3\cdot10^{-13}$	LDF
Am-243	$3.7\cdot10^{-12}$	1,033	4,000	$7.3\cdot10^{-13}$	LDF
Cm-244	$1.4\cdot10^{-13}$	113	5,500	$4.4\cdot10^{-13}$	Well
Cm-245	$1.7\cdot10^{-12}$	1,046	4,000	$7.7\cdot10^{-13}$	LDF
Cm-246	$1.0\cdot10^{-12}$	433	4,000	$7.7\cdot10^{-13}$	LDF

The ecosystem models that were used in the landscape models for derivation of the LDFs are not directly applicable for C-14, due to the special behaviour of this radionuclide in the environment. The existing dose models need to be modified before they can be applied to C-14, and this will be done for SR-Site. It was, therefore, decided to not include this radionuclide in the LDF calculations, meaning that doses for C-14 are not assessed in SR-Can. However, it was checked that the calculated C-14 releases do not contribute significantly to the total dose by using the dose conversion factor (EDF value) from the SR-Can Interim report, /SKB 2004a/.

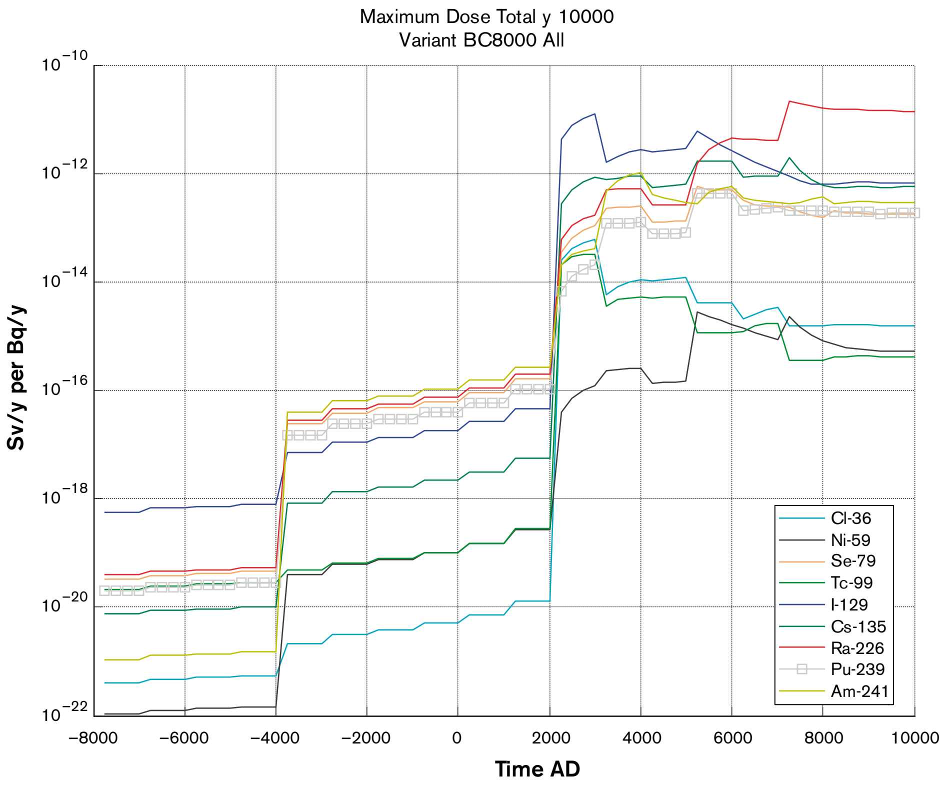


Figure 10-7. *The maximum dose for some radionuclides at different times when 1 Bq y⁻¹ is released starting from 8,000 BC. The results are plotted for each period of 250 years. The stepwise character of the curves is due to the fact that most parameters and classifications are altered on time steps of 1,000 y whereas others change more frequently (250 y steps). The large changes at 4,000 BC and 2,000 AD are transitions from accumulating to a resuspending sediment and from sea to a terrestrial systems, respectively /Avila et al. 2006/.*

10.2.8 Landscape development at Laxemar

At Laxemar, 21 objects were identified in the landscape Figure 10-8. Also, at Laxemar three main periods of the development of the landscape were identified during the present interglacial /SKB 2006i/. However, the duration and timing of these periods differs from that at Forsmark, see Figure 10-9. Quite early, about 8,000 BC, after the deglaciation, parts of the hills closest to the repository are small islands. They are then resubmerged during a transgression occurring between 7,000 BC and 5,000 BC. All release points are modelled to enter to the sea until 3,000 BC. Thereafter, a coastal period starts, during which mires and lakes are formed in narrow valleys around the repository footprint and already around 2,000 BC the first potential agricultural areas are formed. From 2,000 BC, release points occur also in terrestrial ecosystems. At around 0 AD, the landscape resembles that at present at Laxemar, with several small potential agricultural areas in the long and deep valleys. Most lakes and mires have transformed to agricultural land, since such transformations are assumed if it is consistent with the properties of the objects. At 4,000 AD, the coastal period ends and a terrestrial landscape dominates the surroundings of the repository. Most of the objects close to the repository are assumed to be agricultural land. Thereafter, the remaining bays are gradually infilled. Bornholmsfjärden (object 14, Figure 10-8) will remain a lake until 20,000 AD due to its steep shores and depth. The coastline outside the Simpevarp peninsula changes only slightly through to 20,000 AD when an archipelago is formed, see Figure 10-9.

The more pronounced topography at Laxemar results in a smaller temporal variation of discharge areas compared with Forsmark and almost all objects receiving such discharges are potential agricultural land at Laxemar. The period of submergence is about 4,000 years shorter at Laxemar than at Forsmark.

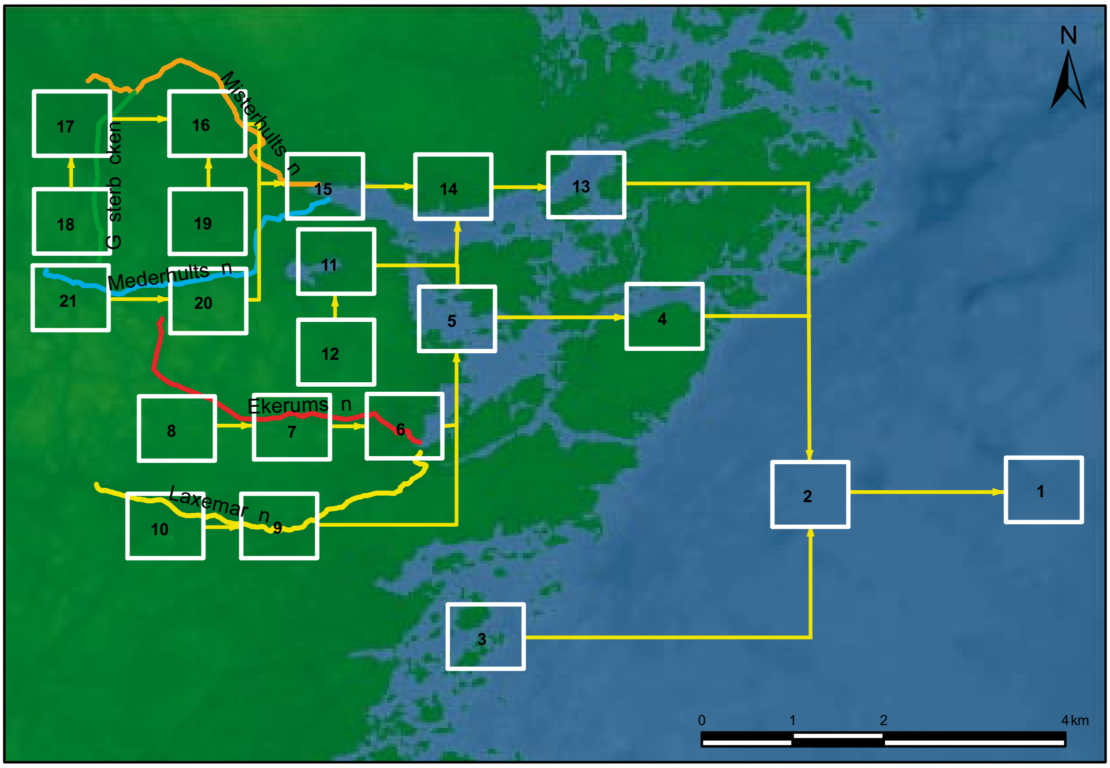


Figure 10-8. The landscape at Laxemar. Boxes indicate objects that are interconnected by flows of radionuclides (arrows). The five streams modelled are indicated with coloured lines.

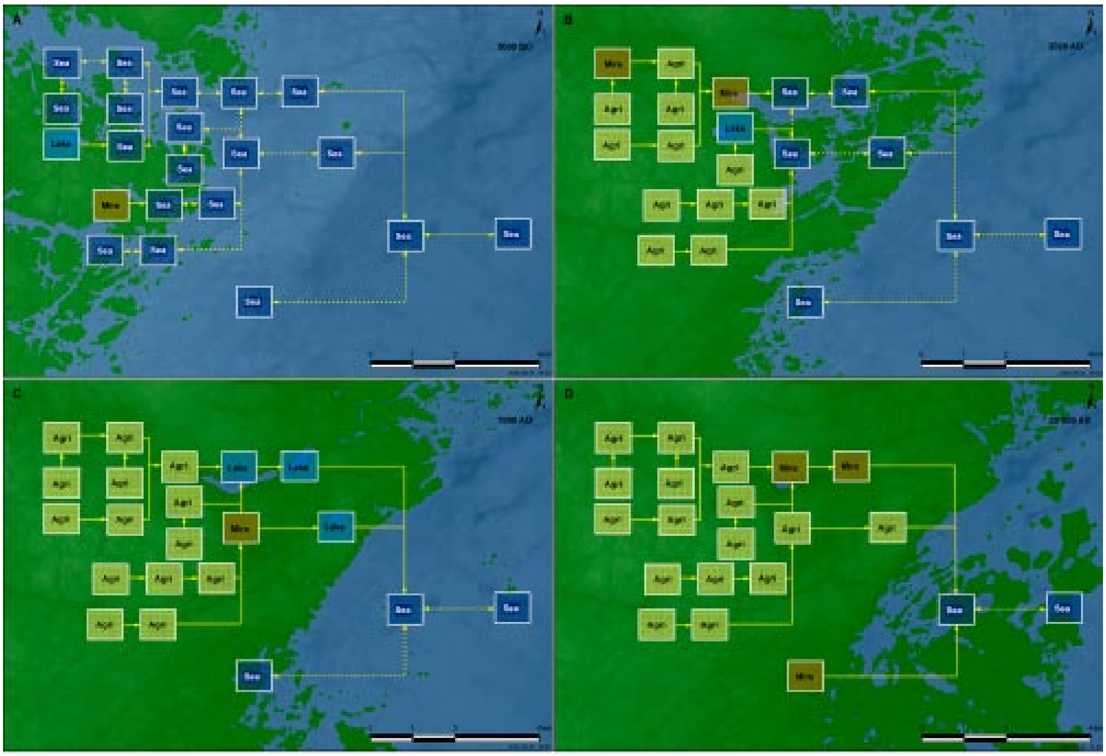


Figure 10-9. Example of succession of landscapes during an interglacial at Laxemar. The maps represent different time periods: the marine stage, the coastal stage (here shown at 2,000 BC and 2,020 AD) and the terrestrial stage (here shown at 8,000 AD). The glacial ice-margin stage is identical to A and the continued greenhouse variant is represented by D, whereas permafrost is similar to D but with agricultural land replaced by mires or forest.

10.2.9 Landscape dose factors for Laxemar

Over the interglacial period, the dose conversion factors increase 3–4 orders of magnitude at around 3,000 BC when the discharge starts occurring to terrestrial objects, see Figure 10-10. During the remaining terrestrial period, the dose conversion factors are fairly constant.

The LDF values obtained for Laxemar are shown in Table 10-2. For most radionuclides, higher LDF values were obtained for Laxemar than for Forsmark, whereas the number of individuals in the most exposed group was generally higher at Forsmark than at Laxemar. A detailed analysis of the differences between Forsmark and Laxemar can be found in /Avila et al. 2006/. A main reason for the differences is that the sizes of the objects were smaller at Laxemar than at Forsmark, reflecting an observed site-specific difference. This leads to higher radionuclide concentrations in the environment at Laxemar and to a smaller numbers of individuals potentially exposed to those concentrations.

10.2.10 Landscape dose factors over the reference glacial cycle and for the greenhouse variant

As explained in section 10.2.4, site-specific situations illustrating permafrost conditions, glacial ice margin conditions and effects of greenhouse warming have also been modelled. These stages are depicted in Figure 10-6 for Forsmark and Figure 10-9 for Laxemar. The marine stage (A) is representative of the glacial-ice margin stage and the terrestrial stage (D) is representative of the continued greenhouse variant, whereas the terrestrial stage with agricultural land replaced by mires or forest is representative of the permafrost stage.

For the reference glacial cycle, the LDF values are highest during the interglacial period and lowest during the glacial period /Janson et al. 2006/. For the permafrost period, the LDF values are similar to those at end of the interglacial period. The greenhouse case yields lower LDFs than the temperate period for almost all nuclides. Figure 10-11 gives an overview of the results obtained.

For the interglacial period, the LDF values for Laxemar are consistently higher than the values for Formark, with differences within a factor of 10 for most radionuclides. The dose conversion factors for the well are also ten times higher at Laxemar. A detailed analysis of the results /Avila et al. 2006/ indicates that the differences between Laxemar and Forsmark can be explained by differences in parameter values between the sites. The results indicate that the topography, which affects the drainage area, the hydrology, the sedimentation environment and the size of the biosphere objects, is an important factor.

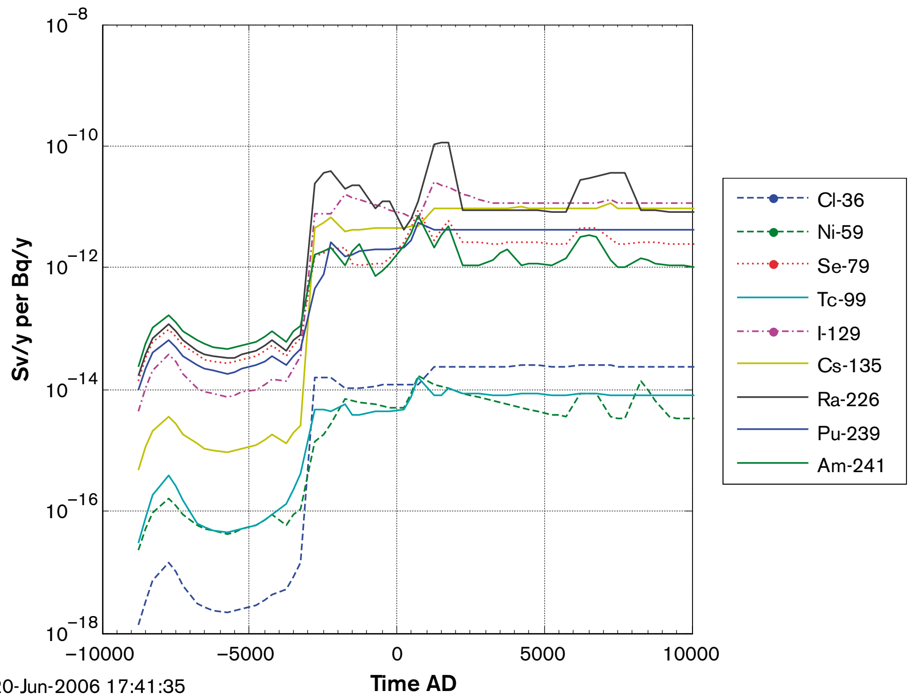


Figure 10-10. *The maximum effective dose rate for some radionuclides at different times when 1Bq y^{-1} is released starting from 8,000 BC at Laxemar /Avila et al. 2006/.*

Table 10-2. Landcape Dose Factors (LDF) for an interglacial period at Laxemar expressed in units of Sv/y per Bq/y. N is the number of persons in the most exposed group. Time is time for maximum LDF. Well DCF in Sv/y per Bq/y.

RN	LDF	N	Year (AD with BC indicated as negative values)	Well	Maximum
Cl-36	$8.1 \cdot 10^{-15}$	905	7,250	$3.8 \cdot 10^{-14}$	Well
Ca-41	$5.6 \cdot 10^{-14}$	106	1,250	$5.6 \cdot 10^{-15}$	LDF
Ni-59	$4.4 \cdot 10^{-15}$	147	750	$2.5 \cdot 10^{-15}$	LDF
Ni-63	$3.8 \cdot 10^{-15}$	41	750	$6.0 \cdot 10^{-15}$	Well
Se-79	$1.1 \cdot 10^{-12}$	28	750	$1.3 \cdot 10^{-13}$	LDF
Sr-90	$8.0 \cdot 10^{-13}$	46	1,750	$1.1 \cdot 10^{-12}$	Well
Zr-93	$2.9 \cdot 10^{-14}$	68	7,250	$4.3 \cdot 10^{-14}$	Well
Nb-94	$2.1 \cdot 10^{-11}$	207	1,500	$6.7 \cdot 10^{-14}$	LDF
Tc-99	$3.1 \cdot 10^{-15}$	520	750	$2.7 \cdot 10^{-14}$	Well
Pd-107	$2.2 \cdot 10^{-15}$	133	1,250	$1.5 \cdot 10^{-15}$	LDF
Ag-108m	$1.0 \cdot 10^{-10}$	82	1,750	$9.4 \cdot 10^{-14}$	LDF
Sn-126	$2.0 \cdot 10^{-12}$	35	2,250	$1.9 \cdot 10^{-13}$	LDF
I-129	$1.6 \cdot 10^{-11}$	141	1,250	$4.4 \cdot 10^{-12}$	LDF
Cs-135	$2.3 \cdot 10^{-12}$	18	–1,750	$8.0 \cdot 10^{-14}$	LDF
Cs-137	$4.1 \cdot 10^{-12}$	18	7,250	$5.2 \cdot 10^{-13}$	LDF
Sm-151	$2.0 \cdot 10^{-16}$	221	750	$3.8 \cdot 10^{-15}$	Well
Ho-166m	$2.9 \cdot 10^{-11}$	100	1,500	$7.9 \cdot 10^{-14}$	LDF
Pb-210	$5.3 \cdot 10^{-12}$	27	–2,250	$2.7 \cdot 10^{-11}$	Well
Ra-226	$4.7 \cdot 10^{-11}$	45	6,250	$1.1 \cdot 10^{-11}$	LDF
Th-229	$3.2 \cdot 10^{-12}$	2,513	–2,250	$1.9 \cdot 10^{-11}$	Well
Th-230	$1.0 \cdot 10^{-10}$	60	6,250	$8.2 \cdot 10^{-12}$	LDF
Th-232	$1.2 \cdot 10^{-12}$	2,513	–2,250	$9.0 \cdot 10^{-12}$	Well
Pa-231	$7.6 \cdot 10^{-12}$	556	8,250	$2.8 \cdot 10^{-11}$	Well
U-233	$3.7 \cdot 10^{-13}$	140	750	$2.0 \cdot 10^{-12}$	Well
U-234	$2.4 \cdot 10^{-12}$	78	6,250	$1.9 \cdot 10^{-12}$	LDF
U-235	$3.2 \cdot 10^{-13}$	175	750	$1.8 \cdot 10^{-12}$	Well
U-236	$3.4 \cdot 10^{-13}$	139	750	$1.8 \cdot 10^{-12}$	Well
U-238	$3.2 \cdot 10^{-13}$	140	750	$1.8 \cdot 10^{-12}$	Well
Np-237	$8.7 \cdot 10^{-13}$	135	750	$4.3 \cdot 10^{-12}$	Well
Pu-239	$9.5 \cdot 10^{-13}$	241	750	$9.8 \cdot 10^{-12}$	Well
Pu-240	$9.1 \cdot 10^{-13}$	234	750	$9.8 \cdot 10^{-12}$	Well
Pu-242	$8.9 \cdot 10^{-13}$	258	750	$9.4 \cdot 10^{-12}$	Well
Am-241	$6.3 \cdot 10^{-13}$	144	750	$7.8 \cdot 10^{-12}$	Well
Am-243	$5.6 \cdot 10^{-12}$	198	1,750	$7.8 \cdot 10^{-12}$	Well
Cm-244	$6.6 \cdot 10^{-14}$	1,116	–2,250	$4.7 \cdot 10^{-12}$	Well
Cm-245	$7.0 \cdot 10^{-13}$	337	750	$8.2 \cdot 10^{-12}$	Well
Cm-246	$7.5 \cdot 10^{-13}$	215	750	$8.2 \cdot 10^{-12}$	Well

Laxemar has a larger topographic variation with its narrow valleys, where also the potential discharges from the geosphere are situated. This leads to smaller biosphere objects, since only the flat bottom of the valleys can hold agriculture areas or lakes. Usually, the drainage areas of these objects are small. Also, the total area at Laxemar that can be potentially affected by the discharges is about ten times smaller than the potentially affected area at Forsmark. The total retention of radionuclides in both areas is similar, which gives, in combination with a smaller area, higher concentrations and consequently higher doses at Laxemar. The topography, where also the bathymetry is considered, affects also the sedimentation environment in the sea which is different for Forsmark and Laxemar. It appears that accumulation bottoms, which favour radionuclide retention in sediments, are more predominant at Laxemar than at Forsmark, due to the long sheltered bays that exist at Laxemar for extended periods.

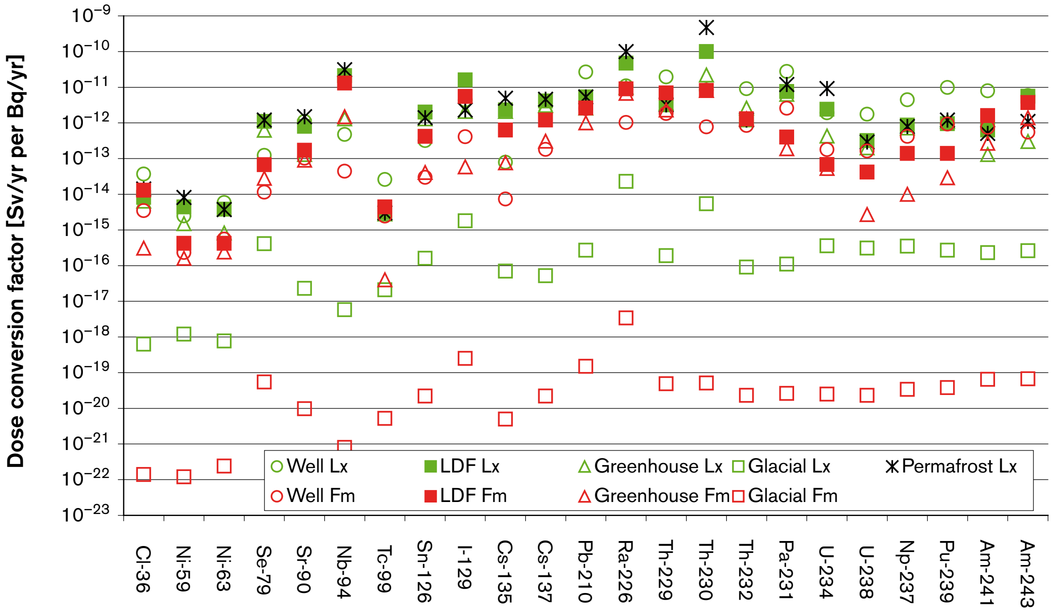


Figure 10-11. *Modelled LDF values for a selection of radionuclides at the two sites and under a number of climate conditions. Permafrost results have been obtained for Laxemar only.*

The conclusions are confirmed by the sensitivity analysis in /Avila et al. 2006/, that shows that the parameters with the largest effect on the predictions of the retention of radionuclides in the landscape and the doses received are those that affect the fluxes through the different objects (i.e. drainage areas, runoff, object size) and the retention of the radionuclides in the objects (i.e. distribution coefficients and fraction of accumulation bottoms).

The topography is a robust property, it is rather well understood at the sites and predictable in time, especially where the regolith is thin and topography is mainly determined by the solid rock. The differences between the sites are thus explainable, see further the discussion in /SKB 2006hi/. The differences in the well DCF values directly reflect the estimated well capacity, which is measured at the sites and dependent on the geology of the rock. This is also a fairly robust result valid over long time periods.

Even if there are explainable differences between the sites, the question is if they are significant in the light of the uncertainties in assumptions and parameter values. A preliminary analysis of the uncertainties of the derived LDF values, based on the results of the sensitivity study /Avila et al. 2006/, indicates that the differences observed between Laxemar and Forsmark fall within the uncertainty range. Variation of the most sensitive parameters within their range of uncertainty leads to differences in the maximum doses of a factor of ten or more. It should also be taken into account that several conservative assumptions are introduced in the process of derivation of the LDF values, such as selecting the highest LDF value over all time periods and the assumption that the whole radionuclide inventory that is accumulated in sea and lake sediments becomes available when these become transformed to terrestrial ecosystems. The degree of conservatism in these assumptions might be different for Laxemar and Forsmark. This will be further investigated in the SR-Site programme.

The LDF values for the glacial ice-margin period are several orders of magnitude less than the values for the interglacial period, because it is assumed that the sites are submerged, if open water exists. The observed differences in LDF values between the interglacial period and the permafrost and greenhouse conditions fall within one order of magnitude. For permafrost conditions, two alternative cases were considered, one with mires and the other with forests prevailing in the landscape /Avila et al. 2006/. The differences between these cases were also within a factor of ten. The assumptions and parameter values for the other climatic stages have higher uncertainties and thus it is expected that differences of one order of magnitude will be within the uncertainty ranges of the interglacial stage.

Finally, it is pointed out that the use of LDFs as described here does not cover the large part of the assessment period when the repository is expected to be below the sea or a glacier so that considerably smaller risks to humans are expected.

10.3 Criticality

If a canister failure occurs, the issue of nuclear criticality has to be considered, since, if this occurred, it would have a strong influence on the further development of the system.

The possibility of nuclear criticality in the canister interior, process F3 Induced fission (criticality) in the process table for the fuel in section 6.4.1, has been dismissed in a number of studies, see e.g. the SR 97 report /SKB 1999a/. The issue has most recently been analysed by /Agrenius 2002/.

In the repository, the spent fuel normal criteria for safety against criticality must apply. This means that the effective neutron multiplication factor k_{eff} including uncertainties must not exceed 0.95. /Agrenius 2002/ has calculated the effective neutron multiplication factor k_{eff} for a number of cases in which the fuel is dry or water is in contact with the fuel. In nominal conditions the canister is leak-tight and the fuel is fresh. In this case, with no water present, the effective neutron multiplication factor is less than 0.5 and the system is strongly subcritical.

If it is assumed that the canister is leaking and that the canister storage positions and the fuel assemblies are water filled the reactivity will increase. With all storage locations in the canister filled with water the following results are found:

BWR: $k_{eff} = 0.9050 \pm 0.0012$
PWR: $k_{eff} = 1.0550 \pm 0.0012$

It can be concluded that the reactivity criteria could not be met with the conservative assumption that the fuel is fresh. A more realistic assumption would be to take credit for the burnup of the fuel, which will decrease the reactivity. /Agrenius 2002/ also calculated the neutron multiplication factor for irradiated fuel with various initial enrichments including the isotopic concentrations for three sets of isotopes. These calculations showed using state-of-the-art methods and a reasonable assessment of the uncertainties and taking credit for the burn-up of the fuel, the criterion $k_{eff} \leq 0.95$ could be met for both BWR and PWR fuel. The results are further discussed in the **Fuel and canister process report**, section 2.1.3.

The risk of criticality as a result of redistribution of material has been analysed by /Behrenz and Hannerz 1978/ and /Oversby 1996/. In both cases, the conclusions were that criticality outside the canister has a vanishingly small probability, requiring several highly improbable events.

In conclusion, the risk for criticality is negligible at a KBS-3 type repository in the Swedish bedrock.

10.4 Models for radionuclide transport and dose calculations

Figure 10-12 shows the models and data used in the radionuclide transport and dose calculations. In the following, a brief description is given of the near-field model COMP23 in section 10.4.1 and of the far field model FARF31 in section 10.4.2, which also describes a separate model for colloid-facilitated transport in the geosphere. The hydrogeological model CONNECTFLOW is presented in section 9.3.6.

Radionuclide transport and dose consequences for some cases have been calculated with a simplified, analytical model that yields similar results to the numerical models. The analytical model is briefly explained in section 10.4.4.

10.4.1 The near-field model COMP23

The near-field radionuclide transport model used in SR-Can to handle radionuclide transport in the water phase is COMP 23 /Cliffe and Kelly 2006/. This is an updated version of the compartment model used in the SR 97 assessment and it was originally developed from the NUCTRAN code /Romero 1995, Romero et al. 1999, Cliffe and Kelly 2006, Kelly and Cliffe 2006/. In SR-Can a Matlab/Simulink implementation /Vahlund and Hermansson 2006/ was used to solve the COMP23 model instead of the original Fortran implementation.

COMP23 models processes related to radionuclide release and transport in the canister interior, the buffer and the deposition tunnel backfill, i.e. the summary processes F16, Bu23 and BfT21, respectively in the process tables in section 6.4. These incorporate the processes radioactive decay (F1), metal corrosion (modelled as instantaneous release, F11), fuel dissolution (F12), dissolution of gap

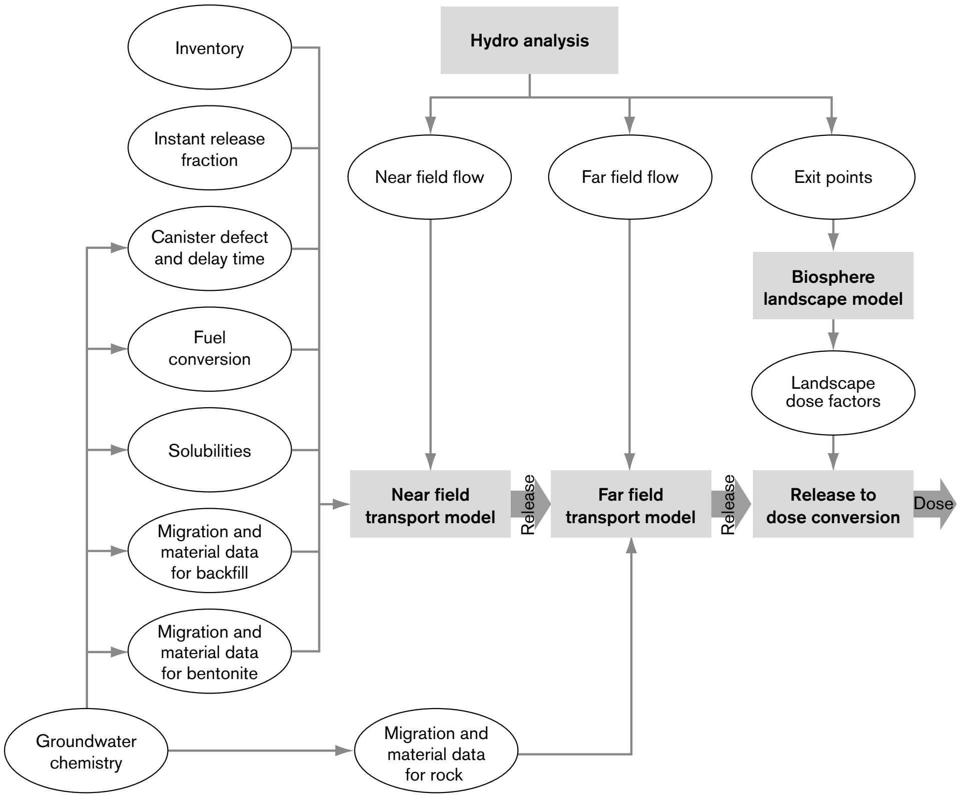


Figure 10-12. *Models and data for the consequence calculations.*

inventory (modelled as instantaneous release, F13), speciation of radionuclides (i.e. dissolution/precipitation of nuclides with shared elemental solubilities, F14), diffusion (Bu11) and sorption (Bu12) in the buffer and advection (BfT9), diffusion (BfT10) and sorption (BfT11) in the deposition tunnel backfill. It also handles the release of radionuclides to exit paths from the near field, see below.

COMP23 is a multiple-path model that calculates transient nuclide transport in the near field of a repository by use of a network of coupled resistances and capacitances in analogy with an electrical circuit network. Analytical solutions, instead of fine discretisation, at sensitive zones, for example at the exit point of a small canister hole and at the entrance to fractures, are embedded to enhance calculation speed.

Figure 10-13 shows the canister, deposition hole and the deposition tunnel backfill and how these are modelled by COMP23 in SR-Can. Three exits from the near field are included: a fracture intersecting the deposition hole at the vertical position of the canister lid, denoted Q1, an excavation damaged zone, EDZ, in the floor of the deposition tunnel, Q2, and a fracture intersecting the deposition tunnel, Q3. In the hydrogeological modelling, the number of fractures intersecting a deposition hole and the properties of these fractures are determined statistically based on the DFN description of the rock, see further the **Data report**, section 6.6. If more than one fracture intersects a deposition hole, the transport capacity of the several fractures are added and pessimistically assigned to the single fracture modelled by COMP23. The equivalent flow rate through Q2 is also calculated as an integral part of the hydrogeological modelling. Data on transport properties for the EDZ used in these calculations are given in the **Data report**, section 6.5. The flow rate in the deposition tunnel and the distance to the nearest Q3 fracture through which radionuclides are released to the geosphere from the tunnel are given by the hydrogeological modelling. Transport by advection/diffusion in the tunnel is included in the near field simulations and the computational domain is extended in the downstream direction to include the Q3 fracture.

Effects of *spalling in deposition holes* are treated by a modification of the input equivalent flow rates for the transport path Q1, as described in section 9.3.6 and further in the **Data report**, section 6.6. The handling of spalling does not require any modification of the model.

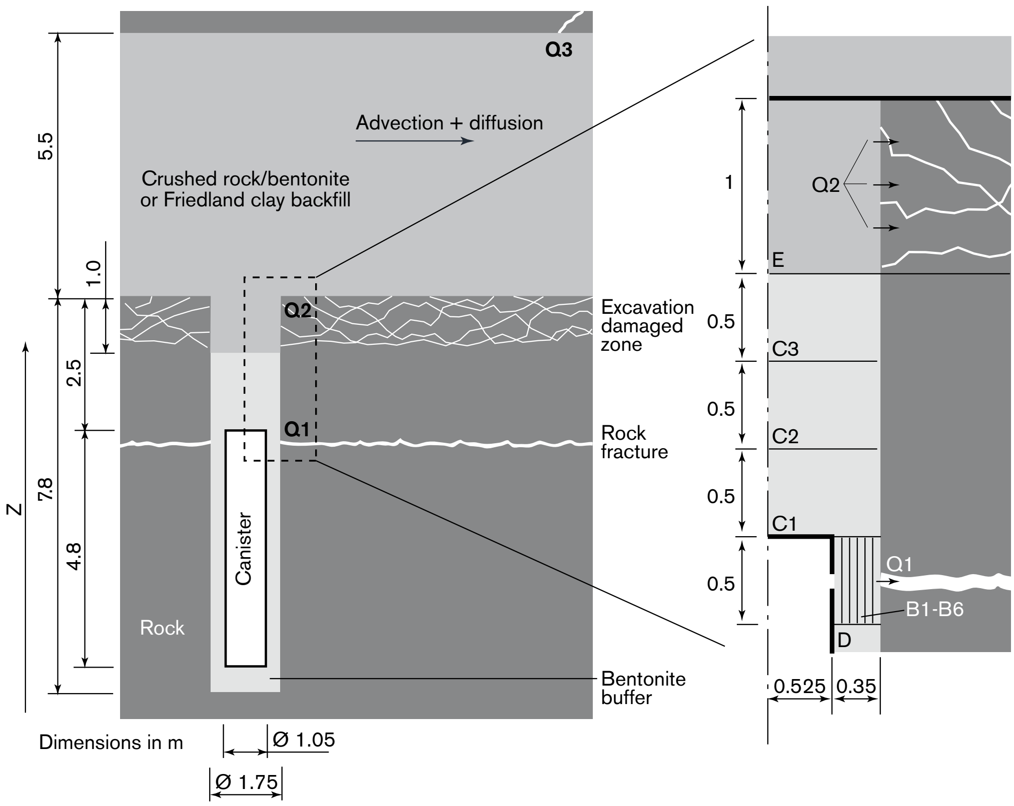


Figure 10-13. *The near field and detail of its model representation as compartments B1–B6, C1–C3 and E in the model COMP23. The transport paths Q1, Q2 and Q3 to a fracture intersecting the deposition hole, to the excavation damaged zone, and to a fracture intersecting the deposition tunnel, respectively, are also shown. (There is also a minor EDZ around the deposition hole that is not shown in the figure.)*

Advective conditions in the buffer are simply treated by assigning the properties of water to the buffer compartments and equating the outflux from the canister interior compartment with the release to Q1.

10.4.2 The far-field model FARF31

The far-field radionuclide transport model used in SR-Can to handle radionuclide transport in the water phase is FARF31 /Norman and Kjellbert 1990, Elert et al. 2004/. The model solves the migration along a one-dimensional path and handles, using the nomenclature in the process tables in section 6.4, the process Ge24 'Transport of radionuclides in the water phase', consisting of the sub-processes advection (an aspect of process Ge11), dispersion, matrix diffusion with equilibrium sorption (Ge12 and Ge13), and radioactive decay (F1, including decay chains).

The equations are solved analytically in Laplace space and subsequently numerically inverted to obtain the breakthrough curves. It is noted that the equations are expressed in terms of accumulated travel time rather than distance along the flow path. This feature makes it easy to calculate travel times in a stand-alone groundwater flow model, cf section 9.3.6, and subsequently radionuclide transport in a decoupled fashion.

FARF31 was originally developed to be used with a groundwater flow model adopting a continuum representation of the rock. In SR-Can, groundwater flow is modelled through a discrete fracture network (DFN) where individual fractures are represented explicitly. Here, the conceptualisation of a migration path is slightly different than in a continuum-based groundwater flow model. Rather than macroscopic streamtubes encompassing both rock and flow paths, the equation now describes flow paths through the actual open pore space, i.e. through the connected fracture network /RETROCK 2005/. However, the governing equations are identical for the two conceptualisations. The entities calculated in the DFN-based groundwater flow models are the advective travel time (t_w) and transport resistance (F). FARF31 has been modified to use these inputs directly.

Immobilisation processes, known to occur in the field, are not readily quantified and not included in the analysis. This is motivated by the fact that it is hard to convincingly show that these processes are valid over the spatial and temporal scales of interest for safety assessment applications. The handling is judged cautious in terms or resulting doses for most relevant situations, with the possible exception of the case in which there is precipitation with subsequent dissolution due to e.g. changed chemical conditions /RETROCK 2005/. No such situations regarding chemical conditions have been identified in SR-Can, and the phenomenon is, therefore, provisionally considered insignificant. If necessary, the issue can be handled by scoping calculations. This is demonstrated, for other purposes, in the calculation of total, accumulated releases from the repository, see sections 10.5.6 and 10.6.7. A more detailed assessment of the phenomenon will be undertaken in SR-Site.

Furthermore, colloid-facilitated transport is not included in FARF31; however, FARF31 has been discretised using the finite volume method /Vahlund and Hermansson 2006/ and in this numerical version of FARF31 colloid-facilitated transport can be included. However, based on the conclusions of the analyses of the reference evolution in chapter 9, colloid-facilitated transport does not have to be included in the consequence calculations, with the possible exception of glacial conditions. Therefore, the possible impact of colloid-facilitated transport is bounded by a case where geosphere retention is neglected for glacial conditions, see section 10.5.8.

A limitation with the migration path concept is that only steady-state velocity fields can be addressed (adopting the snapshots in time approach for transport modelling), whereas clearly the flow field will evolve in time due to shoreline displacement. A second limitation with the current utilisation of the F-factor integrated over the migration path as an input parameter is that the solution is formally correct for single-member decay chains only. For longer decay chains, use of the integrated parameter F is strictly not correct if the channel width to flow ratio varies in space. An entirely new transport code under development, based on a Particles On Random Streamline Segments (PORSS) approach, will be able to handle both transient flow and variable conditions (including variable matrix parameters) for transport of single nuclides and decay chains /Painter et al. 2006/. A first application of the new code, in parallel with FARF31, is planned within SR-Site.

10.4.3 Biosphere representation

The biosphere is simply represented by multiplying the radionuclide releases from the geosphere by an appropriate dose conversion factor, i.e. the LDF, derived as explained in section 10.2.

10.4.4 Simplified analytical model

Analytical simplified versions of the near- and far-field transport models have been developed /Hedin 2002b/. These models use the same input data as the corresponding numerical models and doses are calculated using the same LDF values as in the numerical approach. The models may be executed probabilistically and yield results in good agreement with the deterministic and probabilistic calculation cases in the SR 97 assessment /Hedin 2002b, SKB 2004a/. A single realisation with the analytical models executes in around 0.1 second on a 2 GHz Personal Computer, making them well suited for massive probabilistic calculations. The corresponding calculation time for the numerical models is of the order of one minute.

The analytical model has been benchmarked against the numerical models for several calculation cases in this chapter and used for most of the calculations. The considerable number of probabilistic calculations would not have been possible with the numerical models. This calculation strategy is being considered also for the SR-Site assessment. This would require more developed quality assurance procedures for the analytic model.

Apart from being a practical tool for massive probabilistic calculations, the use of two complementary sets of models, building on the same concepts and using the same input data, provide quality assurance for the handling of probabilistic calculations. The analytical model is also useful for gaining insights into the meaning of the calculated results.

10.5 The growing pinhole failure

10.5.1 Introduction

As mentioned in the introduction, this failure mode was not explicitly addressed in the reference evolution in chapter 9, since the initial state of the canisters suggests that there will be no penetrating pinhole defects in the copper shell. An analysis of this failure mode is, however, relevant in addressing important aspects of the internal evolution of the canister. For the pinhole failure mode, the canister possesses no transport resistance, whereas the buffer and the geosphere have intact retention properties. It is, therefore, also a convenient case for demonstrating the retarding capacity of the buffer and the geosphere and for exploring uncertainties relating to these components of the repository. Furthermore, as will be demonstrated below, an initially small defect is eventually expected to evolve into a large defect, which resembles the case of a failure caused by general corrosion of the canister, when the buffer is still intact. Although the likelihood of this latter failure mode was found negligible in the reference evolution, it is of interest to understand its consequences.

The evolution of the near field (canister and buffer) after canister failure for the pinhole case is discussed in section 10.5.2. Input data for the transport models, valid for the pinhole case, are given in section 10.5.3. A base-case, building on the analysis of the reference evolution, is formulated and analysed in section 10.5.4. Doses to biota are assessed in section 10.5.5, and an alternative safety indicator is used in section 10.5.6. Cases to illustrate key uncertainties identified in the reference evolution are analysed in section 10.5.7. Climate conditions other than temperate are addressed in 10.5.8. Geosphere transmission is analysed in section 10.5.9. Finally, some issues related to the probabilistic nature of the calculations are addressed in section 10.5.10.

10.5.2 Evolution of the near field after canister failure

Canister evolution

The evolution of a failed canister is complex and depends on a number of uncertain factors. Water is likely to intrude into the canister, causing corrosion of the cast iron insert with hydrogen gas generation. The build-up of gas pressure in the canister can be considerable and lead to the suppression of further water entry and also to gas release through the buffer.

As the corrosion proceeds, corrosion products, occupying a larger volume than the corresponding amount of metallic iron, will exert a mechanical pressure on the copper canister, potentially leading to an expansion of the original defect in the copper shell. The corrosion will also cause a weakening of the cast iron insert. This loss of strength will affect the canister's ability to withstand isostatic pressure. It could also lead to expansion of defects in the canister insert.

The evolution will also be influenced by external factors such as the external mechanical load on the canister and the thermal conditions. Based on results presented in previous chapters, no failures are expected during the initial 1,000 years when elevated temperatures will prevail in the repository.

In the radionuclide transport calculations, the canister interior is pessimistically assumed to possess no transport resistance and no sorbing capacity. Rather, as soon as the canister is filled with water, a continuous pathway between the spent fuel and the canister exterior is assumed and the canister interior is represented as an inert water volume in which radionuclides are dissolved and diffuse freely. Transport resistances or barrier functions of the inner structural parts of the canister, the fuel and the fuel cladding are, thus, disregarded once the transport pathway is established.

Key issues for the transport calculations are therefore reduced to the following:

- After canister failure, when will a continuous water pathway between the spent fuel and the canister exterior be established?
- What is then the size of the passage through the copper shell (the only transport resistance in the canister taken into account) and of the void volume in which radionuclides are dissolved?
- How will the defect size and the void volume evolve over time?

A further issue to consider is the possibility of nuclear criticality in the interior of a failed canister. This is discussed and dismissed from further consideration in section 10.3.

In the **Data report** (section 4.4), different possibilities for the internal evolution of the canister are summarised, based on the understanding of the underlying processes and, to some extent, modelling of the evolution. Conceivable outcomes range from situations where the full isolation potential is essentially maintained to situations where a water pathway is established within a few thousands of years and the initially small damaged area expands to a larger region in tens or hundreds of thousands of years.

In order to include uncertainties related to the canister evolution in the overall quantification of consequences, the following simplified treatment was adopted, based on the **Data report**:

- The small defect is assumed to be present at deposition. It is assumed to be circular and to have a radius of 2 mm. This is a quite large defect given the observed distribution of pore sizes from friction stir welding, which is the process to be used to seal the canisters.
- It is assumed that 1,000 years will elapse after deposition before a continuous aqueous transport path between the fuel and the canister exterior is established. This assumption is based on the slow water ingress rate, further decreased by the gradual build-up of an internal counter pressure due to hydrogen gas formation, as well as on the barrier functions of the cast iron insert and of the fuel cladding. Any one of these factors is likely to provide more than 1,000 years of delay.
- The further development is assumed to eventually lead to a large failure of the copper canister, potentially to the extent that the canister offers no transport resistance to radionuclides. The different possibilities for the evolution outlined in the **Data report** suggest that this may occur at any time between 1,000 years and 100,000 years after the 1,000 year delay time. A triangular distribution is recommended in the **Data report** if this uncertainty is to be captured by a distribution. For this stylised calculation it is, however, assumed that the large defect in the single canister considered occurs 10,000 years after deposition, i.e. 9,000 years after the delay time. This has the benefit of eliminating a major cause for risk dilution, see further below. Pessimistically, no transport resistance for the canister is assumed when the large defect has developed.

An additional uncertainty concerns the effect on the buffer of the canister damage. If the hole in the canister is sufficiently large, the bentonite will be able to intrude into it. The amount of bentonite that will intrude into the canister is strongly dependent on the size, shape and location of the enlarged defect. It will also be affected by the amount of iron corrosion products already present in the void space. For a given geometry, it is fairly straightforward to estimate the amount of bentonite that will enter the void. However, the geometry of the hole is unknown and no calculation of this has been done within SR-Can. A rough estimate based on the geometry of the fuel channels and the friction between the bentonite and the canister materials indicates that the mass loss of buffer will be limited and that the bentonite within the canister will have a low density. This will be further considered in the SR-Site assessment.

Gas transport through the buffer

The corrosion of the insert will generate hydrogen according to:

$3Fe + 4H_2O \rightarrow Fe_3O_4 + 4H_2$

A corrosion rate of 0.1 μm/year will generate 0.42 litres (STP) of hydrogen per m^2 of iron surface per year.

A gas pressure build-up is expected within the canister, since the surrounding water-saturated bentonite is impermeable to gas flow. Transport by diffusion of hydrogen dissolved in the buffer pore water for different conditions has been estimated by /Wikramaratna et al. 1993/.

The formation of a gas phase is not possible in failure mode 2 (advection/corrosion failure, see section 10.1), since there is no buffer that can contain the gas in that case. It should be noted that a similar situation may occur also for failure mode 3 (shear movement failure) and failure mode 4 (isostatic load failure). The following description is thus valid also for these failure modes.

A small defect in the copper would give a capacity for diffusive transport which is much lower than the expected production rate, meaning that the gas pressure in the canister will increase.

The understanding of the mechanisms behind gas migration through a water-saturated bentonite is incomplete. The treatment of the process in SR-Can is essentially based on experimental observations. This is further discussed in the **Buffer and backfill process report**, section 2.3.3.

At a certain pressure, a pathway (most likely one or several fractures) in the bentonite will open and allow gas to pass through. In the SR 97 assessment, this pressure was assumed to be the sum of the swelling pressure and the hydrostatic pressure. However, recent experiments have shown that the entry pressure for gas into bentonite can be substantially higher than this.

/Harrington and Horseman 2003/ has measured breakthrough pressures of up to 22.1 MPa. Maximum gas pressures in the range of 20–25 MPa can, therefore, not be ruled out. A build-up of such pressures would take at least 14,000 years with a corrosion rate of 0.1 µm/year, even if the entire surface of the insert were available for corrosion.

The fractures generated by the gas are expected to stay open as long as there is gas production within the canister. Experiments show that gas transport leads to no or very little desaturation of the bentonite. The buffer is, therefore, expected to retain its properties throughout the gas-transport period. When gas production ceases, the fractures are likely to close and seal.

The gas transport is, therefore, not expected to lead to an increased hydraulic conductivity of the buffer. The formation of a gas phase could push water out of the canister. However, this is only possible for water located above the defect.

Based on current understanding, the hydrogen gas from corrosion is expected to have no negative effects on the performance of the buffer. However, high pressures can be expected in the near-field, although limited by the breakthrough pressure when the gas can be transported into the rock. The pressure increase would decrease the tangential stress in the deposition hole wall, but this would only be a problem in a strongly anisotropic stress field and if the deposition tunnels had been perpendicular to the main principal stress. Such a layout would not be considered, see section 4.4. Gas penetrating the fractures would decrease the normal stress, potentially leading to opening or even propagation of such fractures. However, the gas pressure will decrease rapidly along such fractures and the effect would only be very local around the deposition hole. Also, contaminated water may be pushed out by the gas under certain conditions. This issue is addressed in a special calculation case in section 10.5.7.

If the gas pressure is built up during a period of glaciation, the hydrostatic pressure from the ice has to be added to the gas breakthrough pressure. This may lead to internal pressures of ~ 50 MPa inside the canister.

10.5.3 Input data to transport models

Input data for the pinhole case are derived from results for the reference evolution, except for the canister defect that is postulated. Table 10-3 gives an overview of the input data for the pinhole case. Justification for all these data is provided in the **Data report** where detailed tables of data are also found. Some aspects of the data selection are discussed further below.

Selection of radionuclides

The radionuclide inventory is, in the SR-Can calculations, for BWR fuel of a burn-up of 38 MWd thermal output. In addition, inventories for other fuel types and burn-ups are given in the **Data report**, section 3.1. The limitation on allowed residual power in one canister puts an upper limit to the amount of fuel that it can hold, which means that high burn-up fuel has to be mixed with low burn-up to get the allowed residual power. Therefore the effect of varying burn-up on the radionuclide inventory in a canister will be small. Table 10-4 shows a comparison of the inventories of some of the most important radionuclides in the assessment for canisters with different fuel types and burn-up, but equal residual power at deposition.

The calculated inventories used in the SR-Can assessment have been compared with inventories used in other assessment projects. The inventories rarely differ by more than a factor of two and are in very good agreement for many of the most important nuclides (Cs-isotopes, I-129 and Pu-239), see further the **Data report**, section 3.1.

Table 10-3. Input data for the pinhole case.

	Nuclide/ Element specific	The growing pinhole failure
Number of failed canisters	–	One. (Postulated number; no pinhole failures are expected.)
Radionuclide inventory	N	Data for 38 MWd/kgU BWR fuel. **Data report** section 3.1.
Instant release fraction (IRF) of inventory	N	Triangular distributions for all simulated nuclides except actinides, Sm-151 and Zr-93 (zero IRF) and Ca-41, Nb-94, Ni-59 and Ni-63 (100% IRF). **Data report** section 3.2.
Time for onset of radionuclide transport	–	1,000 years.
Time between onset and complete loss of transport resistance in canister	–	Single canister: 10,000 yrs. Triangular (0, 10^5, 10^5) yrs to illustrate uncertainties and risk dilution. **Data report** section 4.4.
Canister defect sizes		Between onset and complete loss: 2 mm radius penetrating pinhole. After complete loss: Full contact between canister interior and bentonite compartment (height = 0.5 m) next to initial defect.
Fuel dissolution rate	–	Log-triangular (10^{-8}/yr, 10^{-7}/yr, 10^{-6}/yr). **Data report** section 3.3.
Concentration limits	E	Calculated distribution based on site-specific groundwater composition. **Data report** section 3.4. (Forsmark data used for both sites.)
Buffer porosities		Anions: Triangular (0.12, 0.17, 0.24) Cations: Constant = 0.43 (The difference derives from the inclusion of anionic exclusion from part of the pore space.) **Data report** section 5.3.
Buffer diffusivities	E	Triangular distributions. **Data report** section 5.4.
Buffer sorption coefficients	E	Log triangular distributions. **Data report** section 5.4.
Backfill diffusivities	E	Triangular distributions. **Data report** section 5.5.
Backfill sorption coefficients	E	Log triangular distributions. **Data report** section 5.5.
Rock porosities		Lognormal, site-specific distribution. **Data report** section 6.7.
Rock diffusivities	E	(Log-normal, site-specific formation factor) × (element specific diffusivity considering also anion exclusion). **Data report** section 6.7.
Rock sorption coefficients	E	Log triangular distributions, same for both sites. **Data report** section 6.7.
Hydrogeological data related to flow and transport Water flow in the deposition tunnel* Equivalent flow from deposition hole to fracture(s) intersecting deposition hole (Q1), to EDZ (Q2), and to fractures intersecting deposition tunnel (Q3); data for Q1 available with and without effect of spalling* Darcy flow at deposition hole (U1)* Rock transport resistance, F for paths beginning at Q1, Q2 and Q3* Rock advective travel time, t_w for paths beginning at Q1, Q2 and Q3* *Correlated distributions covering ensemble of deposition holes	–	Data distributions from several model calculations propagated from hydrogeological analyses, **Data report** section 6.6: *Forsmark* CPM DFN fully correlated case DFN semi-correlated case *Laxemar* DFN semi-correlated case
Rock Peclet number, Pe	–	Constant = 10. **Data report** section 6.6.
Max. penetration depth in rock matrix, D_{Pen}	–	Triangular distribution (0.01, 10, 10) m, same for both sites. **Data report** section 6.7.
Biosphere LDF factors	N	Calculated LDF values, see section 10.2.

Table 10-4. Inventories (Bq) in one canister of the most important radionuclides at 300,000 years for different fuel types and burn-up (MWd/kg U).

	BWR 38	PWR 42	BWR 55	PWR 60
Ra-226	$9.3\cdot10^{10}$	$8.9\cdot10^{10}$	$8.9\cdot10^{10}$	$8.6\cdot10^{10}$
Th-229	$7.0\cdot10^{10}$	$7.7\cdot10^{10}$	$5.3\cdot10^{10}$	$5.8\cdot10^{10}$
Th-230	$9.3\cdot10^{10}$	$8.8\cdot10^{10}$	$8.8\cdot10^{10}$	$8.6\cdot10^{10}$
I-129	$2.6\cdot10^{9}$	$2.5\cdot10^{9}$	$2.4\cdot10^{9}$	$2.3\cdot10^{9}$

At the time of deposition, the radionuclide inventory consists of several hundreds of different nuclides. For most, the inventories and half-lives are such that they are negligible from the point of view of long-term safety. A method for choosing nuclides important for the analysis is described in the **Data report,** section 1.10. The method is similar to that used in previous assessments and is based on mobility, amount available and half-life of the nuclides. The following nuclides were included: C-14, Cl-36, Ca-41, Ni-59, Ni-63, Se-79, Sr-90, Zr-93, Nb-94, Tc-99, Pd-107, Sn-126, Ag-108m, I-129, Cs-135, Cs-137, Sm-151 and the 4n (Cm-244, Pu-240, U-236 and Th-232), 4n+1 (Cm-245, Am-241, Np-237, U-233 and Th-229), 4n+2 (Cm-246, Pu-242, U-238, U-234, Th-230 and Ra-226) and 4n+3 (Am-243, Pu-239, U-235 and Pa-231) decay chains.

Pb-210 in the 4n+2 chain, with a half-life of 22.3 years, is not included in the near-field and geosphere calculations since it has a high sorption coefficient in the buffer as documented in the **Data report**, section 5.4. It is, however, included in the biosphere calculations, since it could contribute to the calculated dose through in-growth from Ra-226, see section 10.2.3. For the same reason, Po-210 is also included in the biosphere calculations.

Concentration limits

The concentration limit calculations for SR-Can are described in the **Data report** (section 3.4) and in detail in /Duro et al. 2006/. In a first step, the solubility limiting phases for some reference groundwaters were determined using the computer code PHREEQC and the thermodynamic database SKB-TDB (based on Nagra/PSI TDB 01/01 /Hummel et al. 2002/). Based on these calculations, phases judged to be unrealistic for the present system, i.e. due to mass balance considerations or reaction kinetics, were removed, generating a subset of the thermodynamic database. This subset, which is more problem- and site-specific, was then used to calculate elemental concentration limits for a given groundwater composition. By taking into account the distribution of groundwater compositions from the hydrogeological calculations reported in section 9.3.6, a distribution of concentration limits was obtained. This approach is based on the observation that it is uncertainties in the groundwater composition, rather than those in the thermodynamic databases or the conceptual understanding that has the dominant impact on the resulting uncertainties in solubility limits, see further /Duro et al. 2006/.

Hydrogeological data related to flow and transport

As seen in Table 10-3, and further explained in the **Data report** (section 6.6), these data comprise:

- Equivalent flow into fractures intersecting the deposition hole (Q1), equivalent flow into the EDZ (Q2), and equivalent flow into fractures intersecting the deposition tunnel (Q3). Equivalent flow rates for the path Q1 are available both with and without the effects of spalling, as reported in section 9.3.6.
- Transport resistance, F, in rock for paths beginning at Q1, Q2 and Q3. The calculated F-values are divided by 10 to approximately account for channelling effects, see further the **Data report** where it is concluded that the use of a factor 10 is cautious since most of the channelling stems from the geometry of the discrete fracture network rather than from internal variability. The fracture network geometry is explicitly accounted for in the simulations.
- Advective travel time, t_w, in rock for paths beginning at Q1, Q2 and Q3.

All the above data are propagated as correlated distributions covering the ensemble of deposition holes from the hydrogeological modelling reported in section 9.3.6.

For Forsmark three different cases, reflecting the current uncertainty in conceptualising the hydraulic characteristics are assessed:

- a base-case hydrogeological DFN interpretation of the Forsmark site, assuming full correlation between fracture sizes and transmissivities,
- a semi-correlated case,
- a multi component Continuum Porous Medium (CPM) model case.

For Laxemar, only the semi-correlated base-case has been propagated to the consequence calculations.

Furthermore, cases illustrating an extensive excavation damaged zone, EDZ, and a deposition tunnel with deteriorated backfill of a high hydraulic conductivity are available as variations of the base case.

10.5.4 Base-case calculation for the growing pinhole failure

Introduction

As a base case for the analysis of the pinhole failure mode, the base case hydrogeological interpretations of the sites were adopted, i.e. the fully correlated case for Forsmark and the semi-correlated case for Laxemar.

In accordance with the results of the analyses of the reference evolution, section 9.3.5, it was assumed that the equivalent flow rates for the path Q1 are affected by spalling in the way reported in section 9.3.6.

Furthermore, the FPC criterion has been applied for the base case, i.e. canister positions intersected by fractures that also intersect the entire tunnel perimeter have been discarded. This means that 399 deposition holes at Forsmark and 749 deposition holes at Laxemar have been filtered from the results of the hydrogeological calculations, see further section 9.3.6.

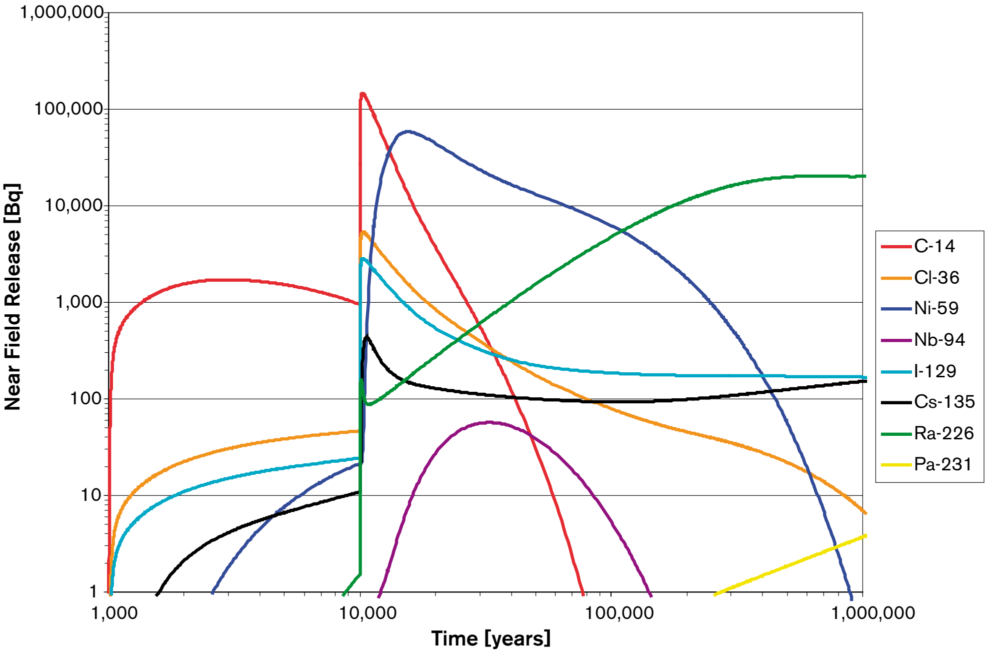
The following is a brief description of the development of the system, driven by the processes that are quantified in the transport models, as an introduction to the presentation of the results of the calculations.

1. No releases occur from the canister before a continuous water pathway has been formed between the fuel and the exterior of the failed canister, which could take thousands of years. Radioactive decay reduces the radionuclide content and total radiotoxicity of the fuel.
2. As soon as a continuous water pathway has formed, the instant release fraction of the inventory dissolves in the water in the canister void. If the solubility limit is reached, the concentration of the dissolved nuclide in the water does not increase further. The nuclides dissolved in the water begin to diffuse out of the canister. The release of nuclides embedded in the fuel is determined by the fuel dissolution rate. Also in this case, the solubilities of the nuclides limit the concentrations that can occur in the water.
3. The nuclides are sorbed with varying efficiency in the buffer and the diffusion and sorption properties determine the time for diffusion through the buffer. If this time is shorter than a few half-lives of the nuclide, it passes out into the rock.
4. In the rock, the nuclide's sorption properties, together with the rock's transport properties, determine the time for transport through the rock to the biosphere. As in the buffer, the half-life of the nuclide determines whether it passes through the geosphere before decaying to a substantial degree.
5. In the biosphere, the nuclide gives rise to a dose that is dependent on its inherent radiotoxicity and its turnover in the biosphere type to which it is released. Both of these factors are included in the LDF value used.

In general, nuclides with a relatively high instant release fraction also tend to be readily soluble and relatively mobile in both buffer and rock. Several percent of the inventory of I-129, for example, is instantly released; iodine has a very high solubility and is not sorbed in either buffer or rock. Plutonium isotopes, on the other hand, lie completely embedded in the fuel matrix, have low solubility and are sorbed strongly in both buffer and rock. Isotopes of uranium, thorium and americium have similar properties to plutonium.

Deterministic calculations

Figure 10-14 shows the result of the deterministic calculations of near-field releases through Q1 for the most important radionuclides using the numerical and the analytic models. Data were taken as peak (mode) values for all parameters with triangular and log-triangular distributions in Table 10-3 and additional data are given in Table 10-5. The differences in peak doses are, in general, within a factor of 2. This is in agreement with several other benchmark calculations, for example deterministic calculations based on the SR 97 data set /Hedin 2002b/ and a comparison of peak doses for 5,000 probabilistic realisations of the data set used in the SR-Can Interim report /SKB 2004a/. Note in particular the good agreement for I-129 and Ra-226, the two radionuclides that almost always dominate the total dose. Numerically calculated releases through Q2 and Q3, which are considerably smaller than those through Q1, are shown in the last section of Appendix B.



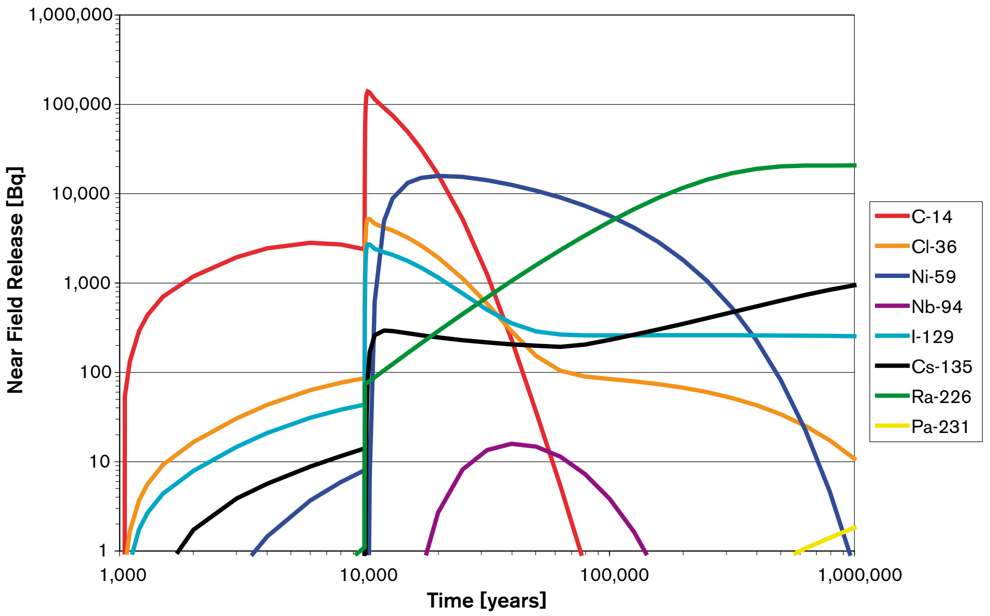


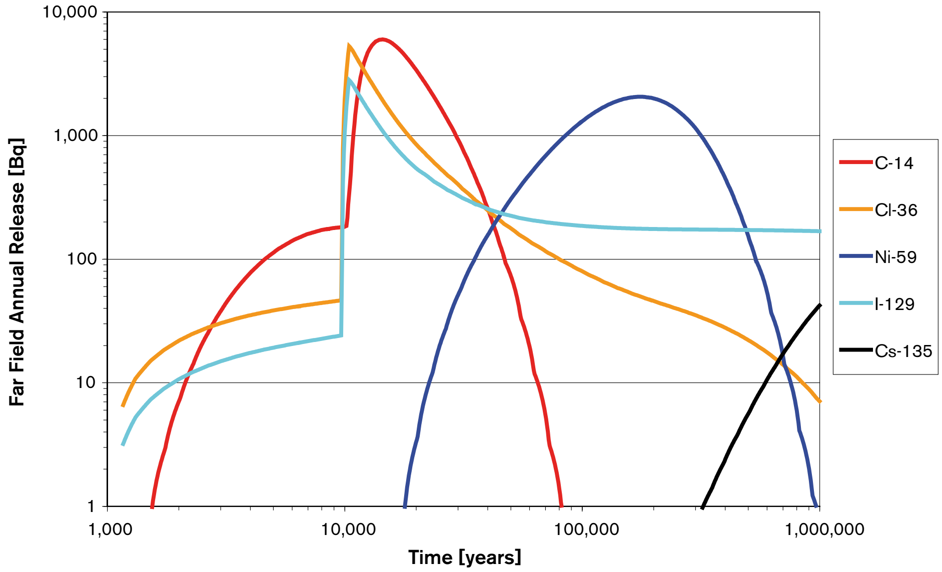
Figure 10-14. *Deterministic calculations of near-field releases through Q1, using the numerical (upper) and analytic (lower) models.*

Table 10-5. Hydrogeological data used for the deterministic calculations.

Entity	Deterministic value
Equivalent flow from deposition hole to fracture(s) intersecting deposition hole (Q1)*, to EDZ (Q2), and to fractures intersecting deposition tunnel (Q3)	$5 \cdot 10^{-6}$, $1 \cdot 10^{-5}$ and $5 \cdot 10^{-3}$ m^3/y
Darcy flow at deposition hole (U1)	$6 \cdot 10^{-6}$ m/y
Rock advective travel time, t_w for paths beginning at Q1, Q2 and Q3	40, 60 and 60 y
Rock transport resistance, F for paths beginning at Q1, Q2 and Q3	$4 \cdot 10^6$, $6 \cdot 10^6$ and $6 \cdot 10^6$ y/m

* Spalling is assumed around the deposition hole and the equivalent flow rate for Q1 is calculated, using data in the **Data report**, section 6.6, to $2.25 \cdot 10^{-4}$ m^3/y.

Figure 10-15 shows the corresponding comparison for releases from the far-field resulting from the near-field releases through Q1. Note that the differences for Ni-59 are essentially explained by the differences in input from the near-field as shown in Figure 10-14.



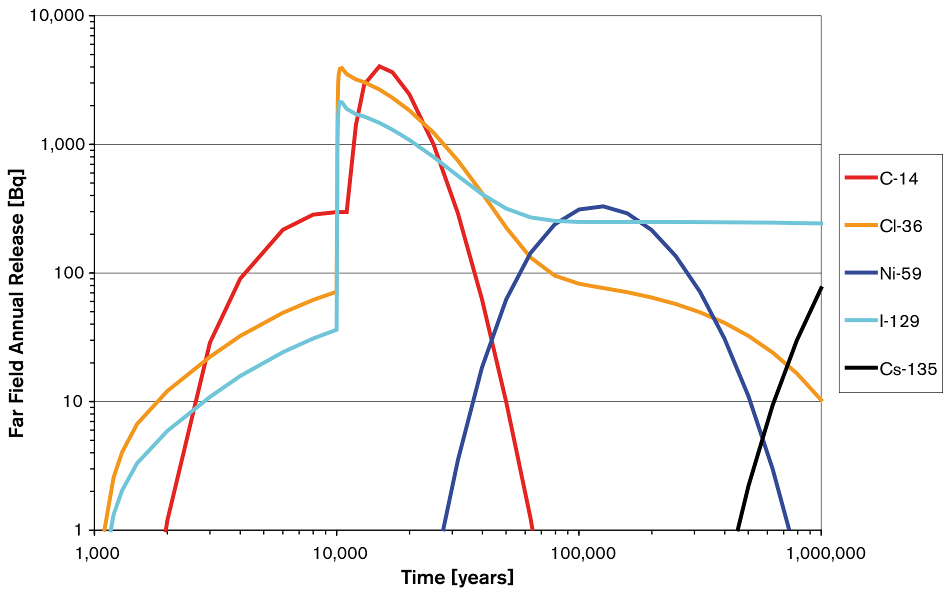


Figure 10-15. *Deterministic calculations of far-field releases resulting from near-field releases through Q1, using the numerical (upper) and analytic (lower) models.*

Probabilistic calculations

Figure 10-16 and Figure 10-17 show the results of the probabilistic calculations of the base case of the growing pinhole failure mode for Forsmark and Laxemar, respectively. Data are according to Table 10-3; the fully correlated hydrogeological DFN model for Forsmark is used and spalling is assumed to occur in all deposition holes. The time for the large failure is assumed to be 10,000 years. One canister, randomly chosen in the repository layout is assumed to have an initial pinhole defect. The grey backgrounds in the figures signify that the regulatory limit applies in a strict sense over the first 100,000 years. This is, however, a stylised case not included in the risk assessment for the repository.

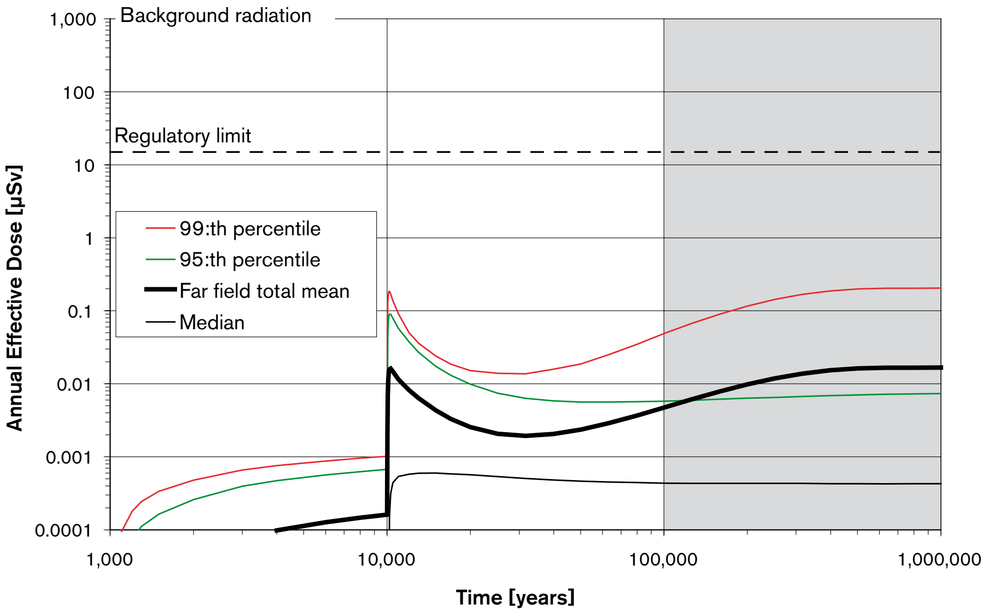


Figure 10-16. *Result of the probabilistic base case calculation of the pinhole failure mode for Forsmark. The 1st and 5th percentiles are both zero since a fraction of the deposition holes are not connected to geosphere transport paths that reach the surface. Analytic calculation; the corresponding result obtained with numerical models is shown in Figure 10-20.*

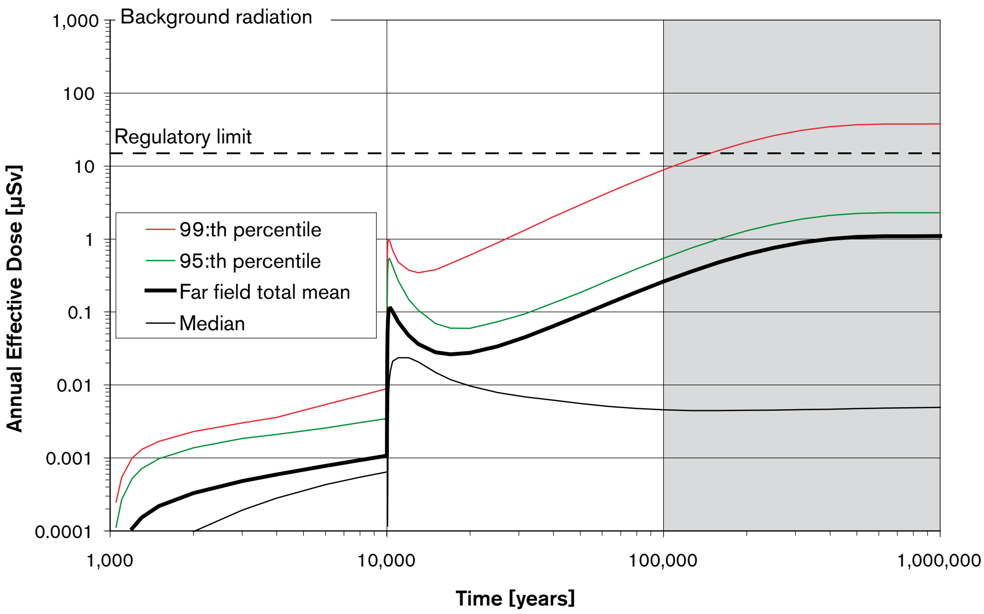


Figure 10-17. *Result of the probabilistic base case calculation of the pinhole failure mode for Laxemar. The 1st and 5th percentiles are both zero since a fraction of the deposition holes are not connected to geosphere transport paths that reach the surface; the corresponding result obtained with numerical models is shown in Figure 10-22.*

The difference in results between the sites reflects differences in hydrogeology and in LDF values. For the two nuclides most important for these results, I-129 and Ra-226, the Laxemar LDFs are higher by factors of 2.9 and 5.2, respectively. It is noted that the not yet fully assessed uncertainties in the LDF factors are likely to be of at least this order of magnitude, so this should not be seen as a strong discriminator between the sites. The site-specific hydrogeological input is discussed in section 9.3.6.

The base case results for Forsmark are decomposed in Figure 10-18. Ra-226 and I-129 are the most important contributors to effective dose for the Forsmark base case. In fact, the sum effective dose from these two nuclides is indistinguishable from the total effective dose. Also, the Q1 release path dominates heavily over Q2. This is particularly because Q1 is affected by spalling. The result of excluding spalling effects from the calculation is addressed in section 10.5.7. The figure also shows the effect of neglecting geosphere retention for the base case. The result is an increase in effective dose by about a factor of 50. Similar conclusions can be drawn from the results of the numerical calculations, see Figure 10-19 and Figure 10-20. Also for these, the 1st and 5th percentiles are zero.

Applying the well DCF instead of the LDF gives only minor changes. As seen in Figure 10-11, for Forsmark, most nuclides, and in particular the dominant Ra-226 and I-129, have well DCFs that are about an order of magnitude lower than the LDFs. The resulting dose curves would be correspondingly lower. LDFs for altered climate conditions are addressed in section 10.5.8.

Comparisons with numerical models

The above results were obtained with the analytical model. Base case results for Forsmark from the numerical model are shown in Figure 10-19 (doses from near-field releases) and Figure 10-20 (doses from far-field releases). The corresponding results for Laxemar are shown in Figure 10-21 and Figure 10-22. 6,824 and 7,483 realisations were run for Forsmark and Laxemar, respectively. The results are similar to those obtained with the analytical model. The discrepancies between e.g. the peak doses from releases from the geosphere at the end of the assessment period obtained with the two sets of models (about a factor of 1.5 for Forsmark and less for Laxemar) are comparable with the uncertainty due to the limited number of realisations for the numerical calculations, see section 10.5.10.

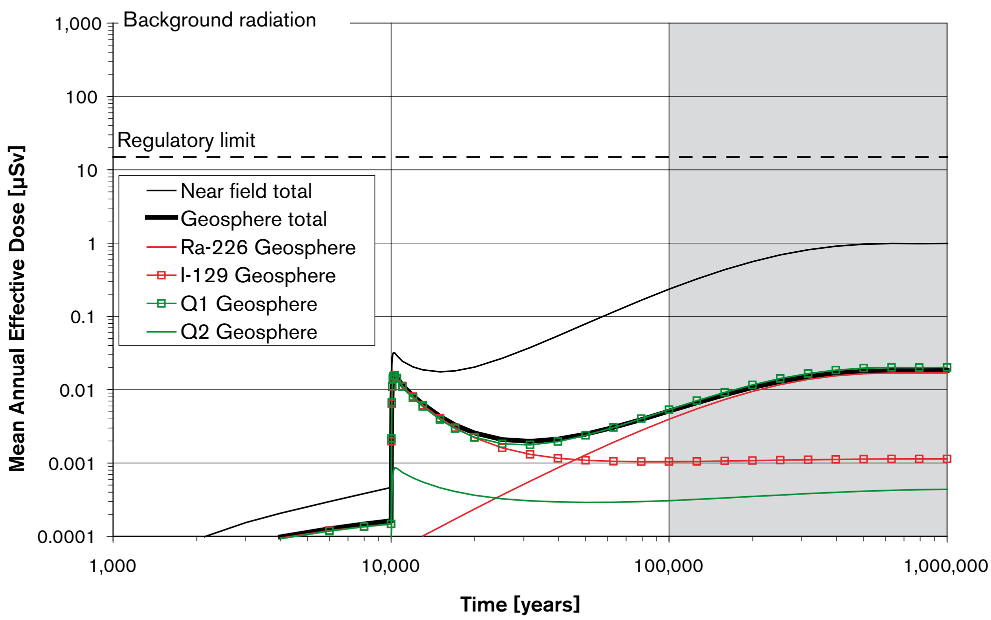


Figure 10-18. *The Forsmark pinhole failure base case (geosphere total, i.e. LDF values applied to releases from the far-field model) decomposed with respect to dominant nuclides (Ra-226 and I-129) and release paths (Q1 and Q2). The effect of discarding geosphere retention is also shown (near field total, i.e. LDF applied to releases from the near field model). 10,000 realisations analytic model.*

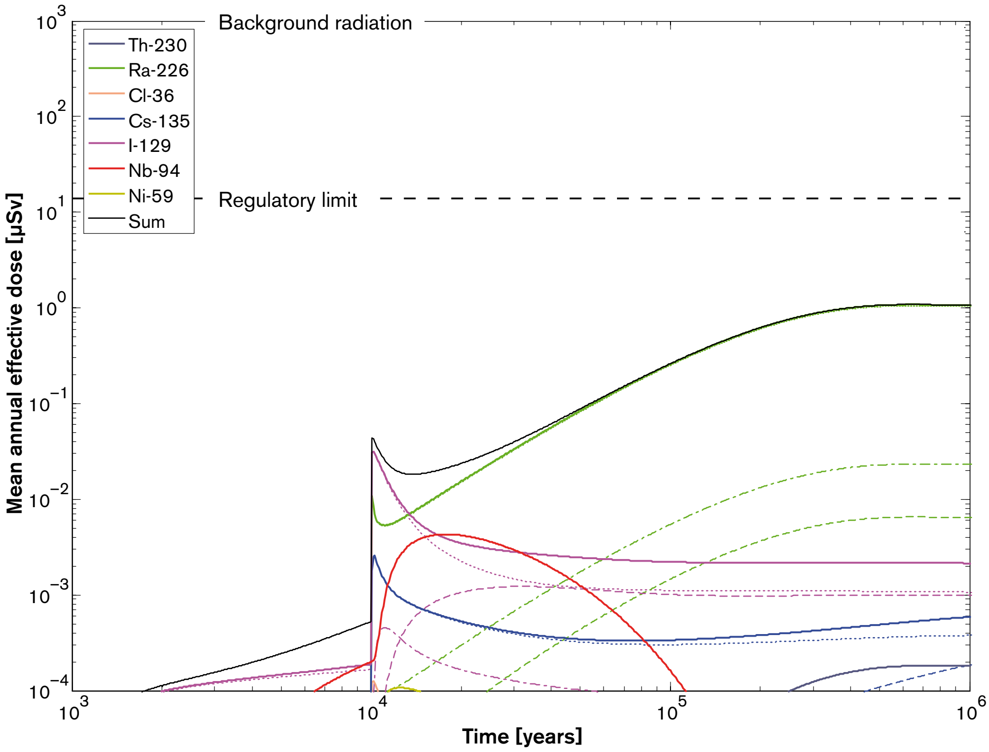


Figure 10-19. *Mean annual effective dose for release from the near field for the Forsmark base case. Sum doses from all near-field release paths (solid lines), decomposed into Q1 (dotted lines), Q2 (dash-dotted lines) and Q3 (dashed lines).*

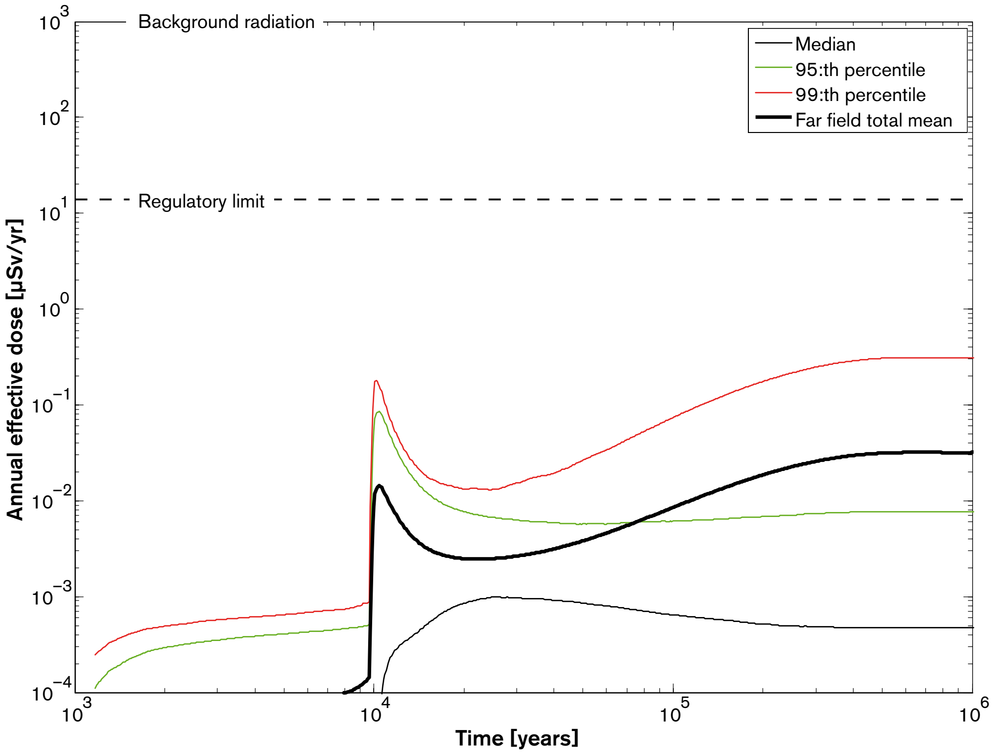


Figure 10-20. *Result of the probabilistic base case calculation of the pinhole failure mode for Forsmark. The 1st and 5th percentiles are both zero since a fraction of the deposition holes are not connected to geosphere transport paths that reach the surface. Numerical models.*

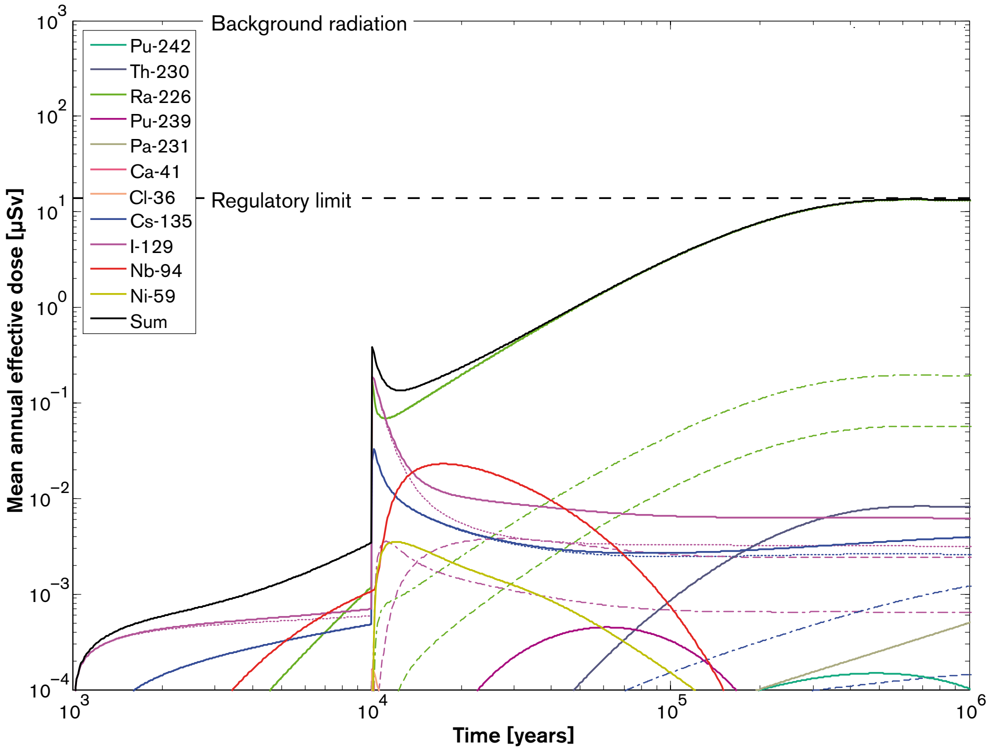


Figure 10-21. *Mean annual effective dose for release from the near-field for the Laxemar base case. Sum doses from all near field release paths (solid lines), decomposed into Q1 (dotted lines), Q2 (dash-dotted lines) and Q3 (dashed lines).*

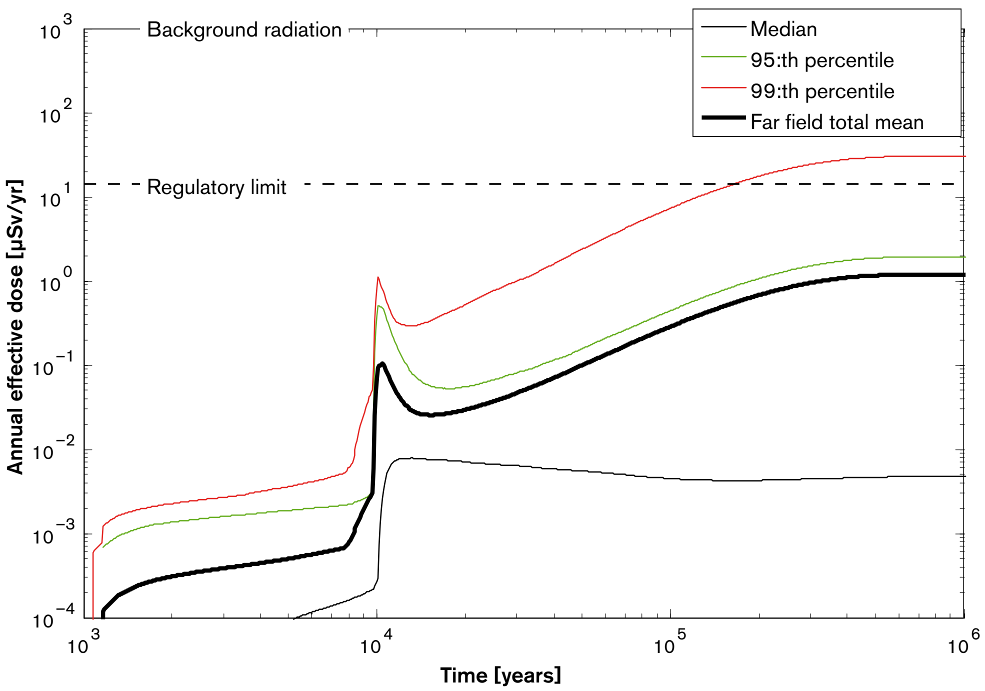


Figure 10-22. *Result of the probabilistic base case calculation of the pinhole failure mode for Laxemar. The 1st and 5th percentiles are both zero since a fraction of the deposition holes are not connected to geosphere transport paths that reach the surface. Numerical models.*

10.5.5 Doses to biota for the pinhole failure mode base case

As explained in section 10.2.5 the potential impact on non-human biota was assessed for Forsmark using the methodology developed within the EC Project ERICA. The Risk Quotients (RQs) are below 1 for all radionuclides for the mean annual release in the pinhole failure base case, which indicates that risks to non-human biota are insignificant and that there is no need for more detailed assessments. The highest RQ in this case are observed for Po-210, from the Ra-226 decay chain: $3.6 \cdot 10^{-3}$ for freshwater ecosystems, $4.9 \cdot 10^{-3}$ for terrestrial ecosystems and $4.2 \cdot 10^{-4}$ for marine ecosystems. The results of the assessments are presented in more detail in /SKB 2006h/.

10.5.6 Alternative safety indicator for the pinhole failure mode base case

Finnish activity constraints

As mentioned in section 2.9.3, the constraints on activity release from the geosphere issued by the Finnish regulator STUK is used as one alternative safety indicator in SR-Can. This yields an index calculated as described in section 2.9.3. Figure 10-23 shows the result of applying this activity constraint to releases calculated for the Forsmark base case. The releases from the geosphere are around four orders of magnitude lower than the regulatory limit.

Comparison to natural radionuclide content in biosphere

Another alternative indicator is the calculated accumulated release from the geosphere, which can be compared to the natural content of radionuclides in the regolith (i.e. the overburden) above the repository.

Assuming that the area above the repository is $1{,}000 \cdot 1{,}000$ m^2, the average depth of the regolith is 6 m and the bulk density is 767 kg/m^3, gives a total dry weight of $4.6 \cdot 10^9$ kg of regolith above the repository. This is multiplied by the maximum concentration of some measured radionuclides in a transect from a mire at the Laxemar site /Lidman 2006/ to obtain the natural content of radionuclides above the repository, see Table 10-6.

This total content is compared to the accumulated release, taking decay into account. Of the nuclides in Table 10-6, only Ra-226 is released from the repository in any appreciable amount. The accumulated release of Ra-226 is compared to the total contents of this nuclide in Figure 10-24. As seen in the figure, the accumulated release is about five orders of magnitude lower than the natural content.

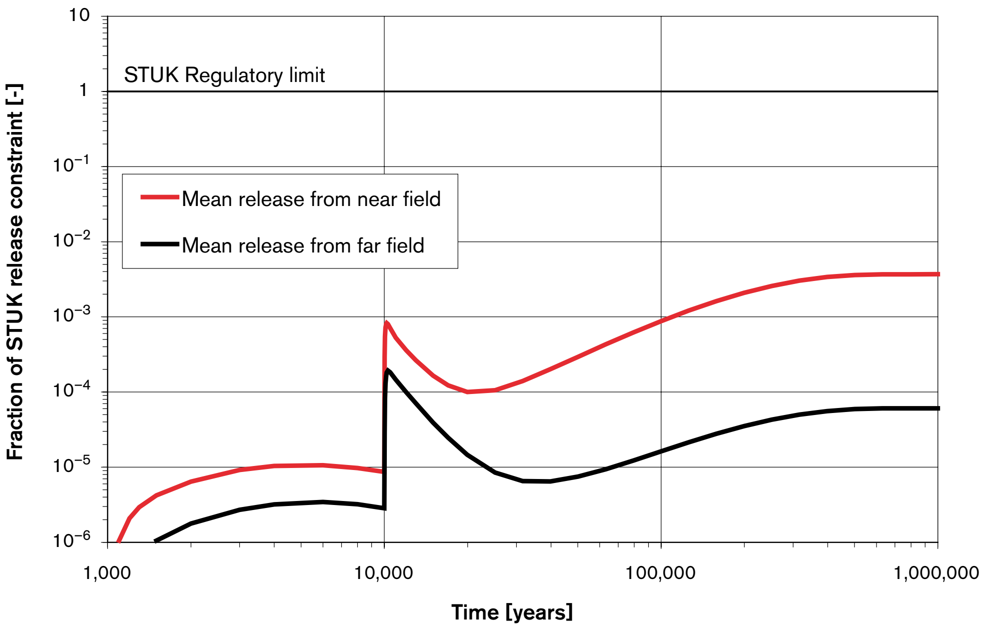


Figure 10-23. *Releases as a fraction of the activity release constraint index issued by the Finnish regulator.*

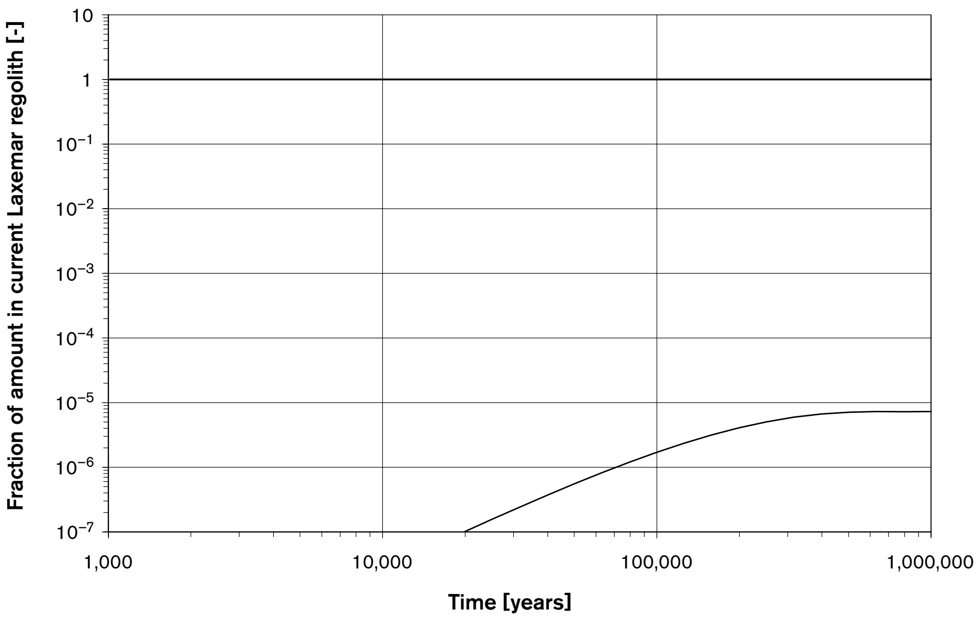


Figure 10-24. *Accumulated release of Ra-226 as a fraction of the total contents of the same nuclide in the regolith above the repository.*

This estimate can be compared also with the natural elemental composition at the sites from /Lidman 2006/ for Laxemar and /Strömgren and Brunberg 2006/ for Forsmark, see Table 10-7.

The total concentration of $2.7 \cdot 10^{-5}$ kg/(kgDW) uranium in Table 10-7 corresponds to 330 Bq/(kgDW) U-238. This is in good agreement with the 270 Bq/(kgDW) U-238 in Table 10-6 considering the measurements uncertainties.

Table 10-6. Maximum concentration of isotopes in a mire profile from Oskarshamn /Lidman 2006/ upscaled to the total content in the regolith above a repository.

Nuclide	Half-life [yr]	Concentration [Bq/(kgDW)] Oskarshamn	Total amount [Bq] Oskarshamn
U-238	$4.47 \cdot 10^{9}$	270	$1.2 \cdot 10^{12}$
U-234	244,000	459	$2.1 \cdot 10^{12}$
Th-230	77,000	150	$6.9 \cdot 10^{11}$
Ra-226	1,600	120	$5.4 \cdot 10^{11}$
Pb-210	22.3	80	$3.7 \cdot 10^{11}$
U-235	$7.04 \cdot 10^{8}$	15	$6.9 \cdot 10^{10}$
Pa-231	32,800	15	$6.9 \cdot 10^{10}$
Th-232	$1.4 \cdot 10^{10}$	80	$3.7 \cdot 10^{11}$
Ra-228	5.75	80	$3.7 \cdot 10^{11}$
Th-228	1.91	80	$3.7 \cdot 10^{11}$

Table 10-7. Contents of Th and U based on /Lidman 2006/ for Oskarshamn and /Strömgren and Brunberg 2006/ for Forsmark.

	Total concentration [kg/(kgDW)] Laxemar	Total concentration [kg/(kgDW)] Forsmark	Total amount [kg] Laxemar	Total amount [kg] Forsmark
U	$2.7 \cdot 10^{-5}$	$1.0 \cdot 10^{-4}$	120,000	460,000
Th	$1.9 \cdot 10^{-5}$	$1.3 \cdot 10^{-5}$	88,000	60,000

10.5.7 Cases to illustrate key uncertainties identified in the reference evolution

Alternative hydrogeological interpretations of the Forsmark site

Figure 10-25 shows doses calculated with alternative interpretations of the Forsmark site, and all other data as for the base case. The results for the two DFN models for Forsmark are fairly similar, whereas the CPM model yields lower doses. This is expected since the geosphere transport resistance, F, is higher for the CPM model, see section 9.3.6. The effect is a diminution in importance of the Ra-226 releases in the CPM model.

The equivalent flow rates, controlling the releases from the near field to the far field are also lower for the CPM model. This is particularly important for I-129 after the occurrence of the large failure. The relatively sharp peak for the DFN models is eliminated by the slower release rate from the near field in the CPM model.

The differences between the models are preserved when releases to the near field are compared, i.e. when neglecting geosphere retention, see Figure 10-25.

All curves in Figure 10-25 are dominated by Ra-226 in the long-term, except the CPM curve for the gesophere releases, in which I-129 dominates, due to the high geosphere transport resistance for other nuclides in that model.

Effect of spalling

As discussed in section 9.3.5, thermally induced spalling cannot be excluded for any deposition hole at either of the sites. There are, however, uncertainties in both the likelihood of this phenomenon, the resulting damage to the near-field rock and the model that describes the transport properties in the spalled zone (section 9.3.6). In the base case, all these factors are treated cautiously yielding a considerable effect on the equivalent flow rate, Q_{eq}, for the release path Q1. Therefore, a case where spalling is assumed not to occur in any deposition hole has been analysed, see Figure 10-26.

The effect is a decrease in dose by almost an order of magnitude over most of the one million year assessment period. Furthermore, the peak occurring at 10,000 years, the assumed time for the large canister damage, is much less pronounced when spalling is neglected. This is caused by the fact that Q2, for which releases are more dispersed than for Q1, is now an equally important release path for I-129 as Q1. For longer times, doses from Ra-226 through Q1 are comparable with those from I-129 through Q1 and Q2. Note also that the difference between near field and geosphere doses is smaller when spalling is not taken into account, since then much of the retention occurs in the buffer/rock interface.

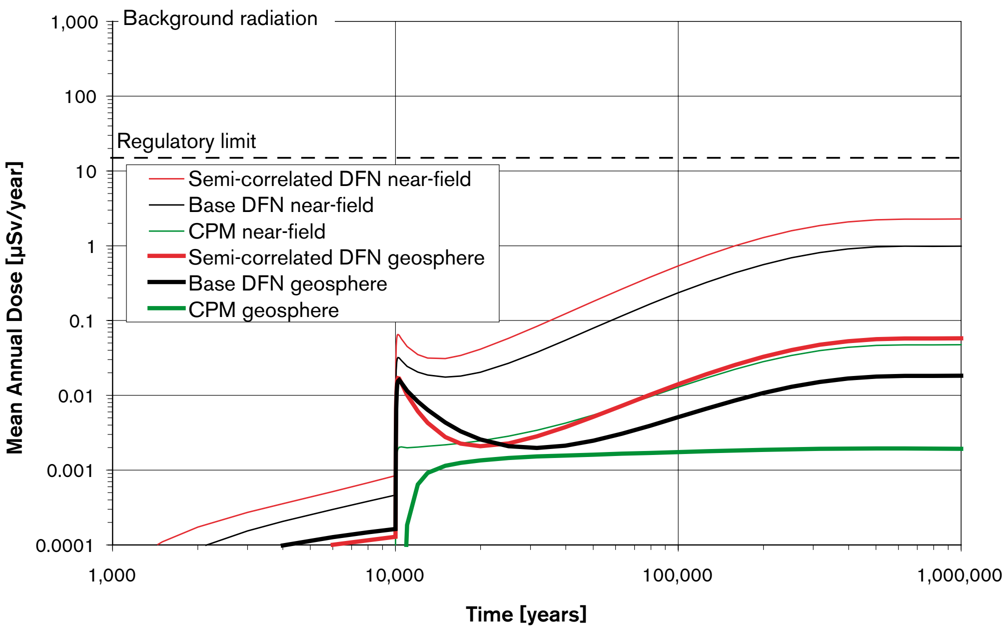


Figure 10-25. *Alternative hydrogeological interpretations of the Forsmark site. Thick lines are doses for releases from the geosphere; thin lines are doses for near-field releases. 10,000 realisations, analytic.*

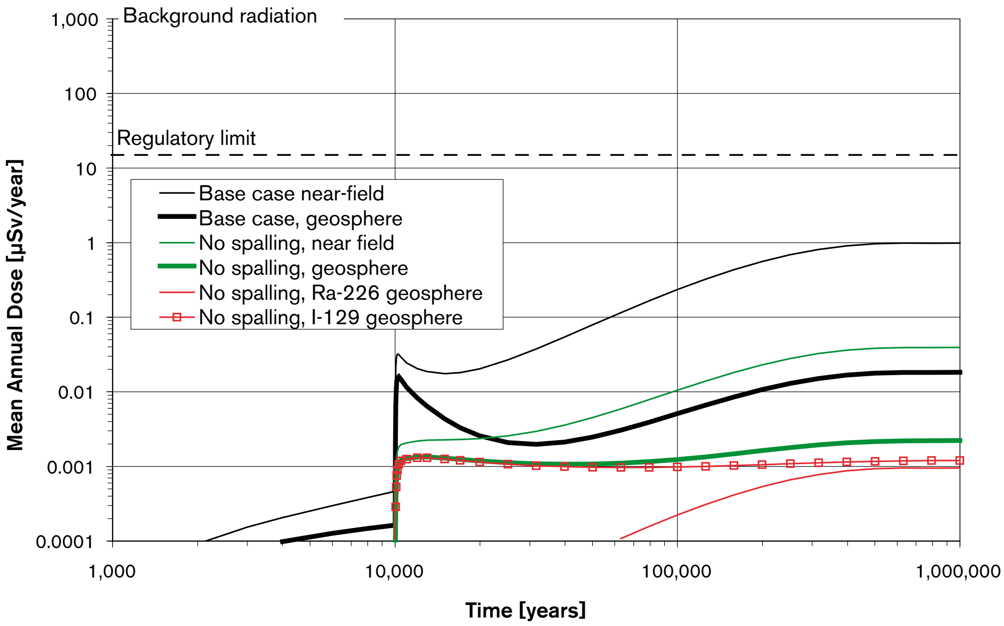


***Figure 10-26.** The effect of spalling for the Forsmark base case. 10,000 realisations analytic.*

Effect of extensive EDZ

Figure 10-27 shows the mean annual dose for a release from the near-field for the base case and a case where the conductivity of the excavation damaged zone is increased by two orders of magnitude. Contributions to the total dose from each of the three near-field exit paths, Q1-Q3 are shown. The results were obtained with the numerical models COMP23 and FARF31, since these give a more accurate representation of, in particular, the release paths Q2 and Q3. The releases through the Q2 and Q3 exit paths are moderately increased for the extensive EDZ case. However, it is obvious that the overall difference between the two cases is very limited, since releases through Q1 dominate the total dose. The dominant role of Q1 is further emphasised through the effects of spalling, which is included in both cases shown in Figure 10-28.

Effect of high hydraulic conductivity in deposition tunnel

Figure 10-28 shows the mean annual dose for a release from the near field for the base case and a case where the hydraulic conductivity of the deposition tunnel backfill is increased from 10^{-10} m/s to 10^{-8} m/s. The results were obtained with the numerical models COMP23 and FARF31, since these give a more accurate representation of, in particular, the release paths Q2 and Q3. As for the case with the increased hydraulic conductivity of the EDZ, it is obvious that the difference between the two cases is very limited, since releases through Q1 dominate the total dose. The dominant role of Q1 is further emphasised through the effects of spalling, which is included in both cases shown in Figure 10-28.

Effect of lost swelling pressure in tunnel backfill

If the swelling pressure of the deposition tunnel backfill is lost, a conductive channel could develop at the tunnel ceiling. The effect of this has been investigated numerically and an implementation in the near-field model COMP23 has been suggested /Neretnieks 2006c/.

The numerical investigation concluded that even for high flow rates in the conductive channel the effect on radionuclide transport was limited.

The suggested modification to the near-field model COMP23 has been developed, but not applied to the SR-Can data. Also, a proper treatment of this case requires an analysis of the effects of lost swelling pressure on the global hydrogeological situation. Further analyses will be carried out for SR-Site.

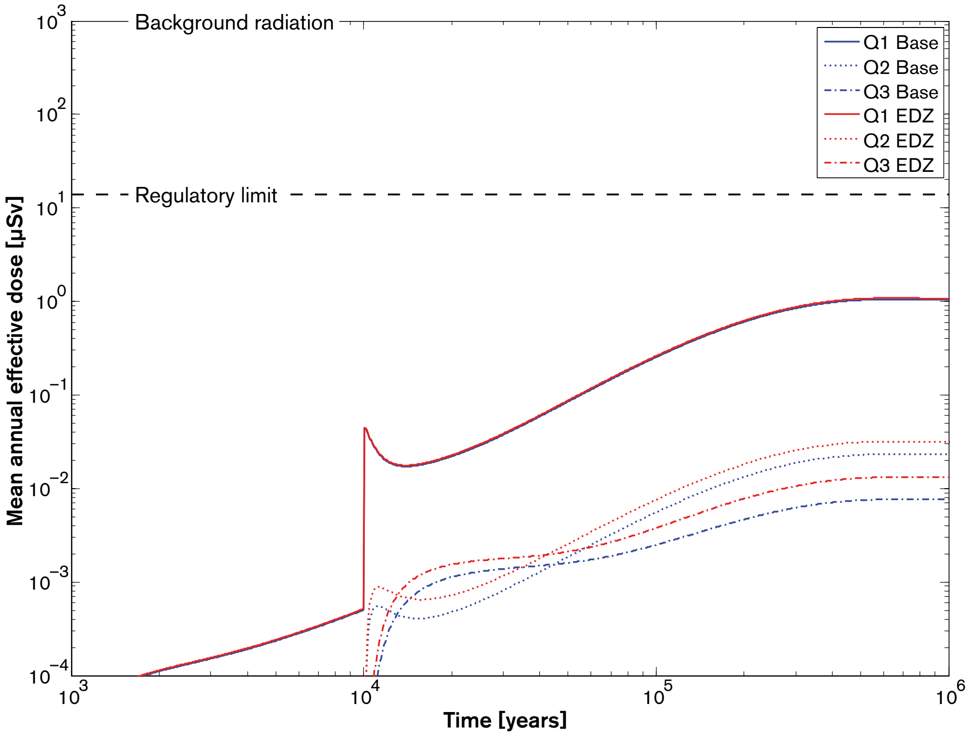


Figure 10-27. *Annual effective dose for release from the near-field for the Forsmark base case and the highly conductive EDZ case.*

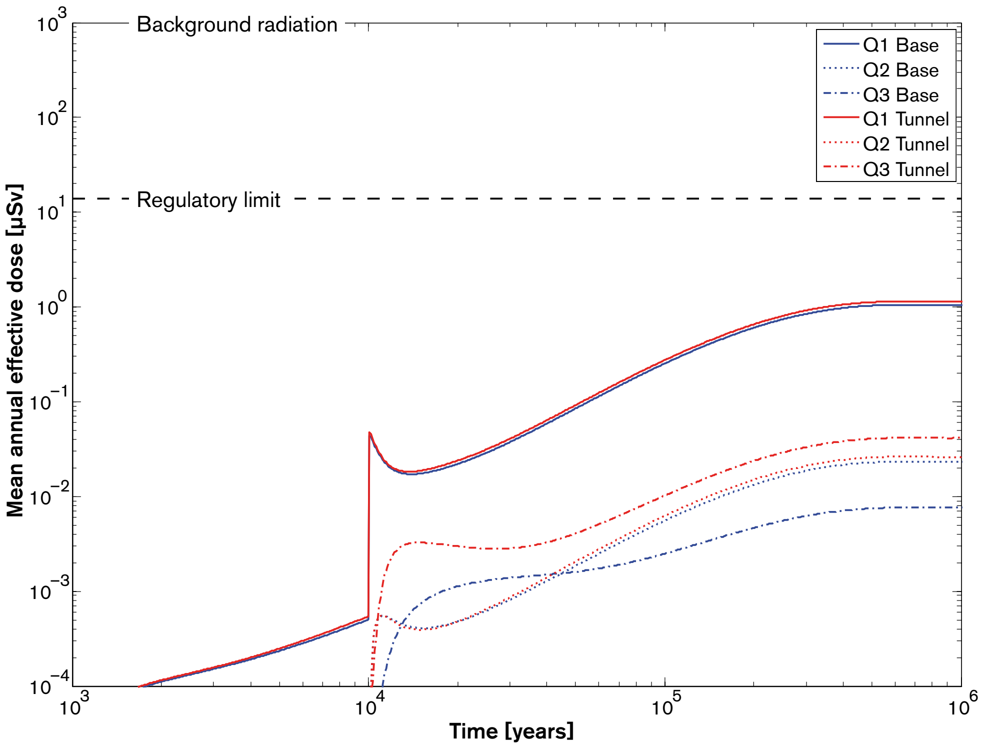


Figure 10-28. *Annual effective dose for release from the near-field for the Forsmark base case and the highly conductive tunnel case.*

Effect of gas in canister interior pushing out contaminated water

As discussed in connection with gas generation in the canister interior following canister failure, section 10.5.2, the gas could act to push out contaminated water from the canister interior to the buffer.

The sequence of events in this case is assumed to be:

- There is a penetrating defect in the lower part of the canister and water can enter and fill the entire canister void (~ 1 m^3).
- Corrosion of the iron insert will generate hydrogen gas.
- The gas will accumulate in the top of the canister void.
- As the gas pressure increases, the water in the void will be pushed out through the defect.
- With a corrosion rate of ~ 0.1 µm/year it will take thousands of years to expel all the water in the void. However, in this calculation, no credit is taken for this delay.

The effects of such a situation are illustrated by a case where the inventory of radionuclides dissolved in the interior of the canister is redistributed to the buffer surrounding the canister. Hence the IRF inventory is released instantaneously to a buffer compartment with a water volume of ~ 1 m^3 (corresponding to 1.5 m height of hollow cylinder shaped buffer surrounding the canister).

Figure 10-29 shows releases from the near field translated to doses using the LDF factors for a deterministic calculation case. The comparison to the deterministic base case in the figure shows that the effect of gas pushing contaminated water out of the canister is limited. In fact, by redistributing highly sorbing radionuclides like Nb-94 and to some extent Ra-226 further away from the Q1 fracture, the annual doses from these are less than in the deterministic base case. The relatively sharp peak associated with I-129 is, in part, due to an inadequate discretisation of the near-field model. Also, the geosphere would act to disperse this pulse in time.

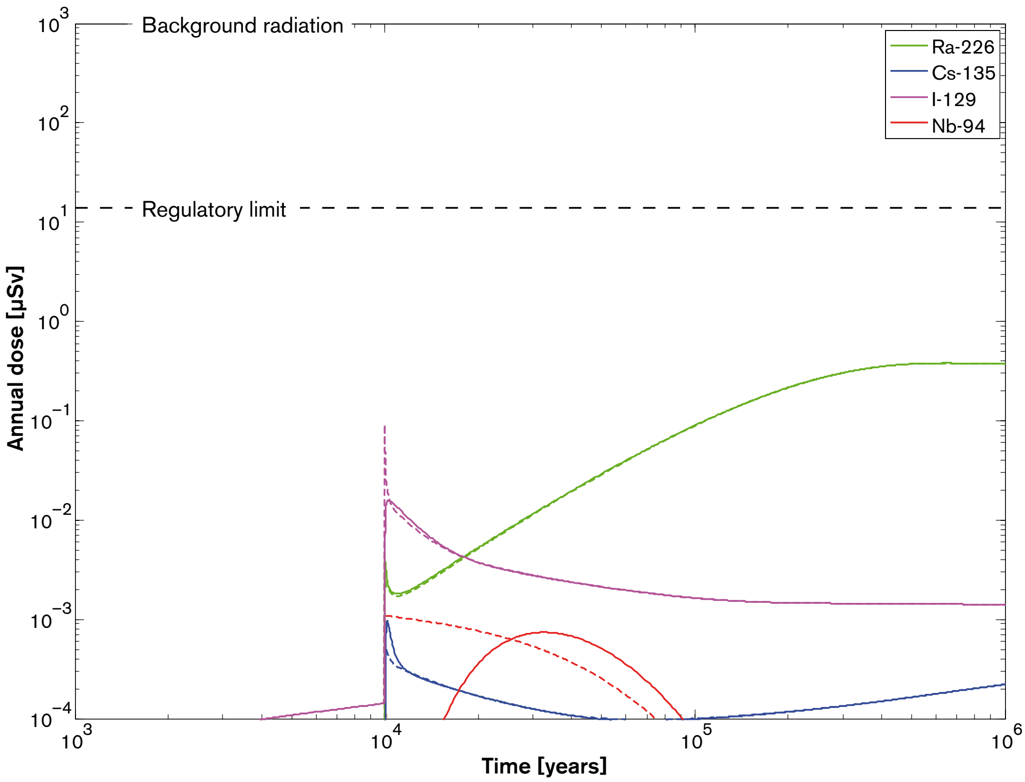


Figure 10-29. *Comparison of near-field releases for the gas case (dashed lines) and the deterministic base case (solid lines). Deterministic calculation, numerical model.*

Sensitivity to deposition hole acceptance/rejection criteria

Figure 10-30 shows the sensitivity of the calculated annual effective doses for the pinhole base case to different deposition hole acceptance/rejection criteria. The base case assumes that the FPC criterion has been implemented. No rejection and different fracture transmissivity criteria are tested.

The differences in results between the criteria applied are moderate, suggesting that, for the pinhole case, the relatively few positions that are rejected do not have a dominant impact on the consequences. In the further discussion of deposition hole acceptance criteria in this report and for the future development of more definitive criteria, it is, therefore, concluded that the pinhole case is of limited interest when evaluating the impact of the criteria.

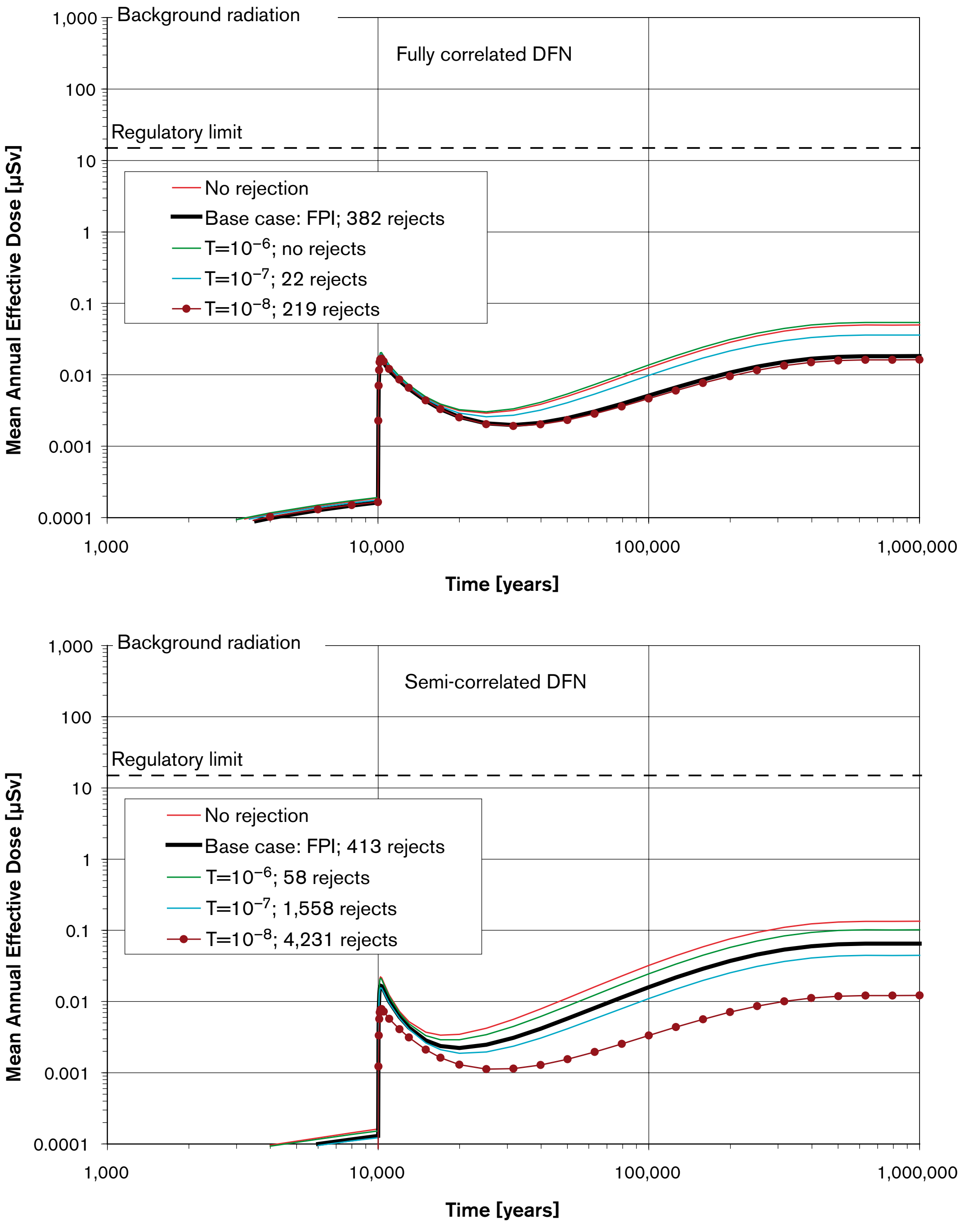


Figure 10-30. *Sensitivity to deposition hole rejection criteria for the two DFN interpretations of the Forsmark site. The number of rejected deposition positions, out of the total of 6,824, is also indicated in each case. (17 positions are always rejected since they are intersected by fracture zones.) 10,000 realisations, analytic model.*

Co-precipitation of radium

Co-precipitation, in particular of radium in the canister, could lead to lower radionuclide solubilities. In the SR 97 assessment it was suggested that co-precipitation of Ra with Ba generated from the decay of Cs-137 could lead to radium solubilities that are three orders of magnitude lower than if this process is not taken into account /Bruno et al. 1997/. In the consequence calculations for SR 97, co-precipitation was, however, pessimistically neglected.

Co-precipitation was neglected also when deriving the radium solubilities for SR-Can /Duro et al. 2006/. To elucidate the importance of co-precipitation, the pinhole failure base case was recalculated with 1,000 times lower radium solubilities. The effect on the mean total annual effective dose is a lowering by a factor of about 10 at the end of the assessment period, see Figure 10-31. The dose is dominated by I-129 rather than by Ra-226. If only the radium releases are compared, the lowering is a factor of abut 100 in the base case.

A more detailed analysis of the results shows that in some realisations, the lowered solubility does not affect the release of Ra-226, i.e. radium did not reach its concentration limit inside the canister even with the lowered solubility. The other extreme is realisations where the concentration limit of radium is reached already in the base case, and the lowering of the solubility by a factor of 1,000 results in a corresponding lowering of the Ra-226 release.

In conclusion, there is a great potential for reducing the calculated releases of Ra-226 if co-precipitation effects can be taken into account.

10.5.8 Illustration of consequences for altered climate conditions

The calculations presented above are representative of a temperate period. This affects primarily the biosphere, but also the geochemical and flow conditions in the geosphere. As illustrated in Figure 9-66, cyclic successions of temperate, permafrost, glacial and submerged conditions are expected in the long term. To illustrate the implications of other climate conditions, the following cases were studied for Forsmark:

- use of the LDFs for permafrost conditions (see section 10.2.10) with today's flow,
- use of the LDFs for glacial (ice margin) conditions with today's flow and increased flow according to the stylised cases described in section 9.4.6,
- use of the LDFs for greenhouse case conditions (see section 10.2.10) with today's flow.

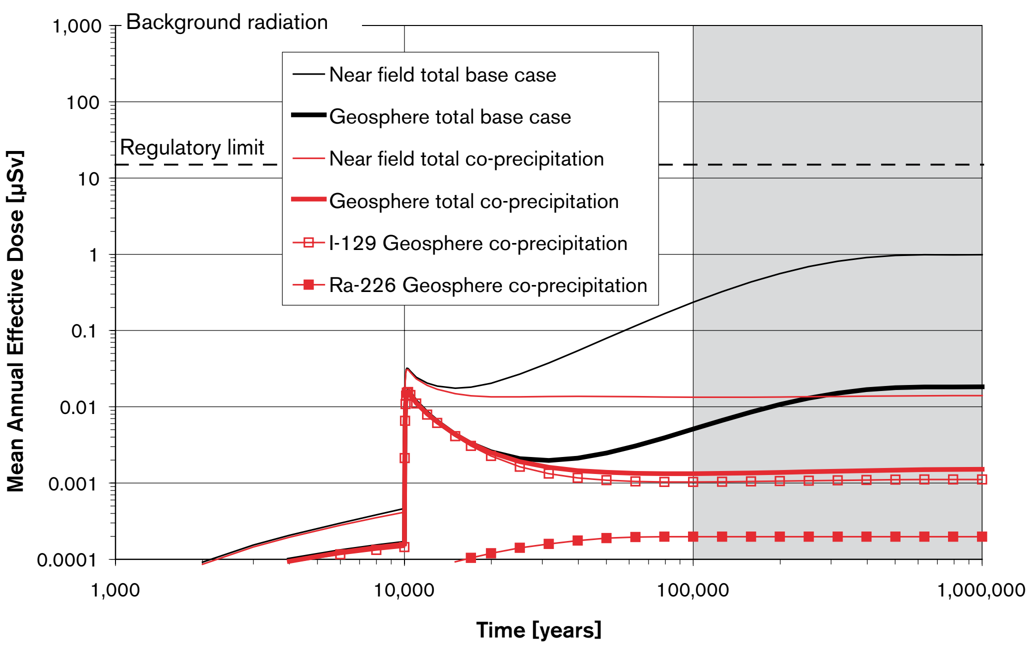


Figure 10-31. *Illustration of possible effect of co-precipitation of radium.*

Figure 10-32 shows the results of these calculations. The highest effective doses are obtained for the permafrost conditions, due to the higher LDF for Ra-226 for such conditions. The glacial (ice margin) conditions yield considerably lower doses also for the case with the 160-fold increased flow (denoted q+ in the figure), reflecting the low LDF-values for the ice margin landscape (see section 10.2.10).

The results of the greenhouse case are not included in the figure. The LDFs of all significant radionuclides and in particular the dominant Ra-226 and I-129 for the greenhouse case are slightly lower than those for temperate conditions. Note that the LDF modelling of the greenhouse case covers the period from *the end* of the normal temperate period until 50,000 AD, explaining why LDFs for the greenhouse case are generally slightly lower than those for the temperate period.

The two stylised cases of increased flow for ice-margin conditions described in section 9.4.6 have been used to illustrate the transient behaviour of the near field releases for such conditions. Figure 10-33 shows that an increase in flow over 40 and/or 1,300 years results in an increased release from the near-field during the corresponding time period.

It is noted that the increased release is slightly higher for all radionuclides during the early part of the increased flow period relative to the later part of the period (this is particularly noticeable for I-129). This is due to release of radionuclides previously accumulated in the near-field; once the accumulated radionuclides are released, a steady-state release rate corresponding to the new groundwater flow regime is established. In Figure 10-34, the corresponding doses are presented. LDF values for glacial ice-margin conditions are used for the limited period of increased flow and LDF values for temperate climate otherwise. It is seen that the dose levels drop significantly during the glacial period with increased flows; this is due to the low LDF values for the glacial conditions. Thus, the increased release rates from the near-field seen in Figure 10-33 are not of concern when dose levels are considered. The result in Figure 10-34 concern releases form the near field and thus also put a bound on possible effects of colloid facilitated transport in the geosphere.

It has also been demonstrated, in preliminary calculations, that radionuclide releases from the geosphere after a temporarily increased flow situation, quite rapidly return to the normal situation when the flow rate returns to normal values. The finite volume implementation of the numerical far-field model FARF31 was used for this purpose.

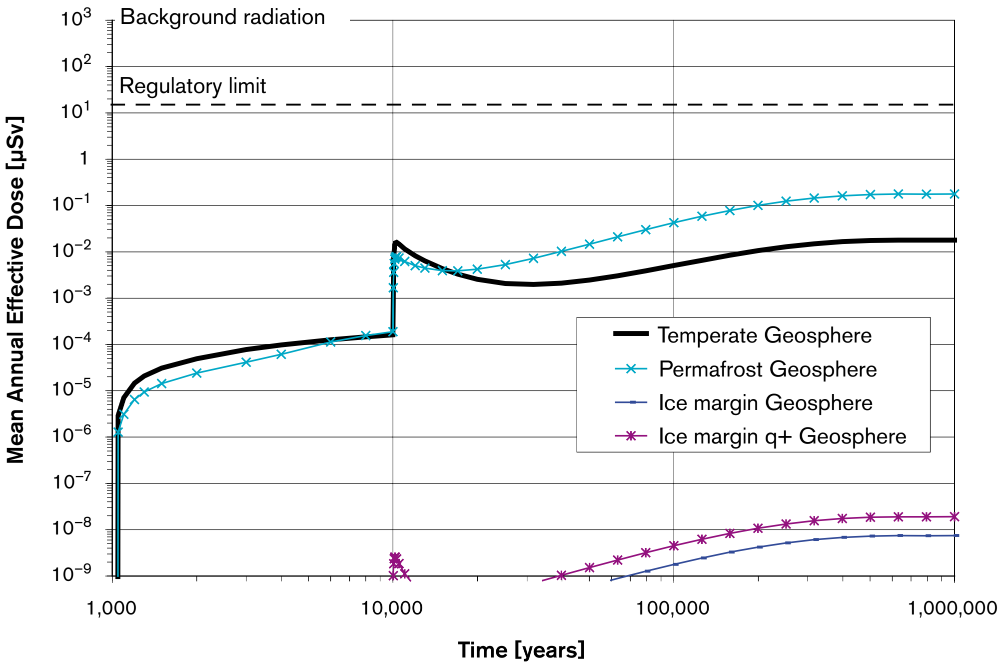


Figure 10-32. *Annual effective doses for altered climate conditions at Forsmark. 10,000 realisations, analytic model.*

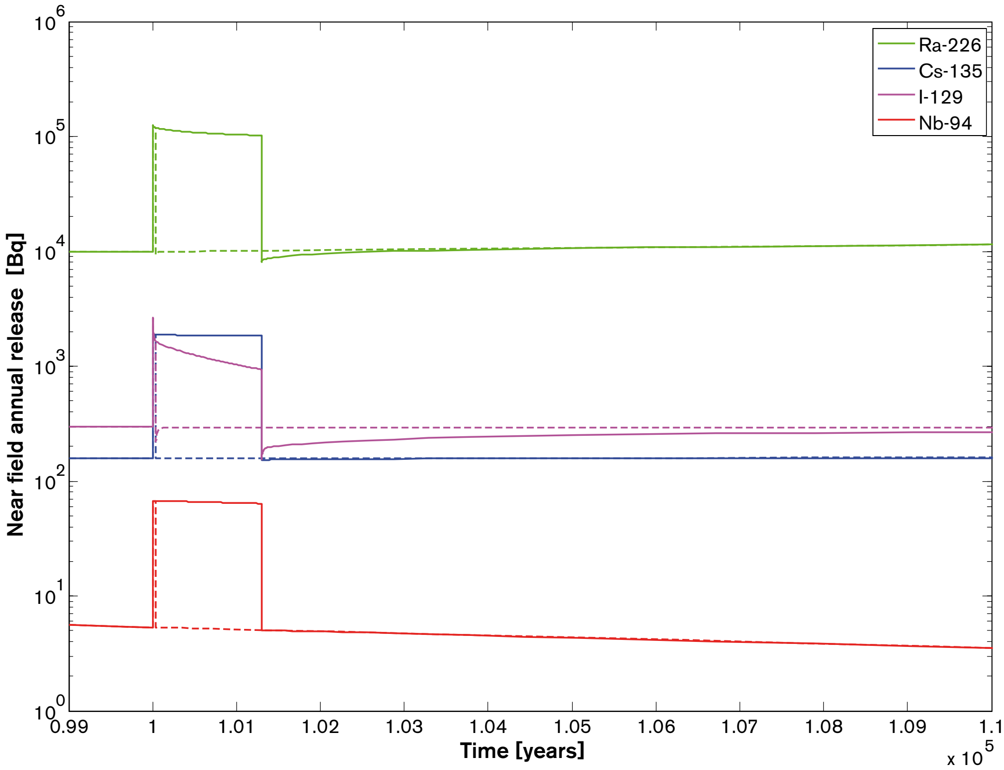


Figure 10-33. *Near field annual releases of dose dominating nuclides during the glacial period with increased flow. Solid lines represent a 1,300 year and dashed lines a 40 year ice-marginal glacial period. Deterministic calculation, numerical model.*

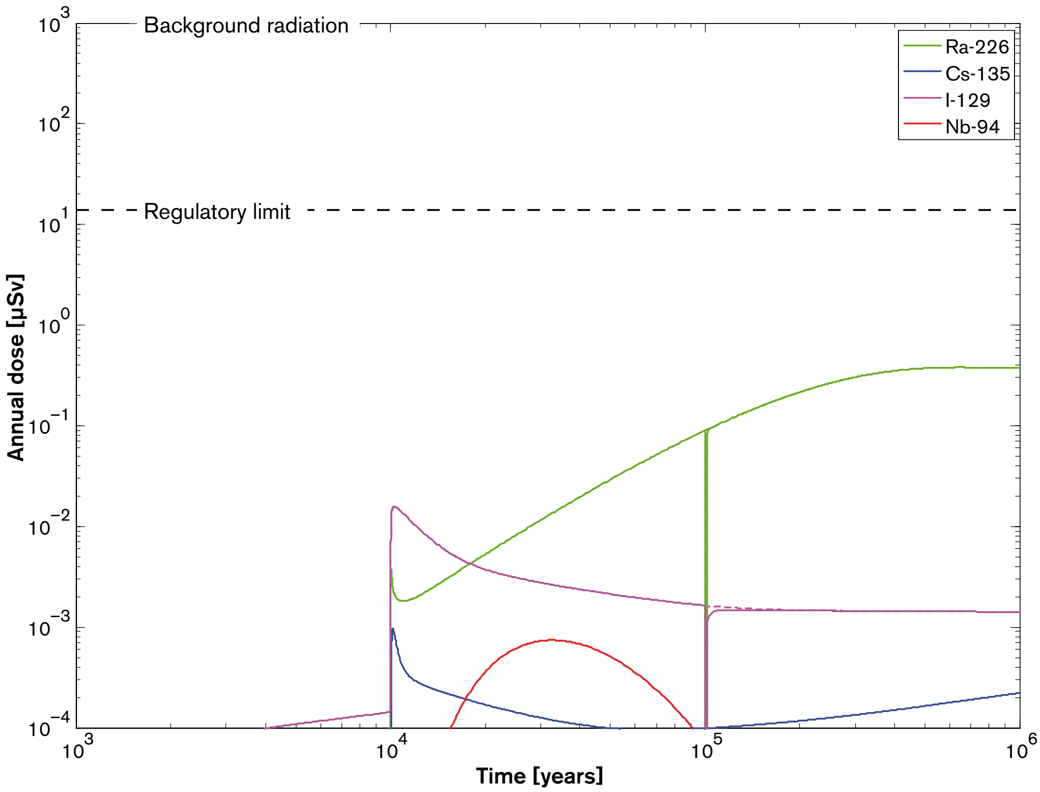


Figure 10-34. *Annual near field releases converted to dose for the glacial deterministic case. Solid lines represent a 1,300 year and dashed lines a 40 year ice-marginal glacial period. During the ice-marginal glacial period, dose conversion factors for glacial conditions are used. Deterministic calculation, numerical model.*

It is furthermore noted that:

- All LDF-values are maximum values over the climate conditions they represent, according to the method for determination of LDFs presented in section 10.2.3.
- In particular the LDFs for permafrost and ice margin conditions are the results of a first attempt to describe these landscapes and need to be further developed.
- Long periods of glacial and submerged conditions are projected during which no doses to humans are expected since the site is not habitable, see Figure 9-66.

For compliance discussions, the LDFs for temperate conditions are used although permafrost conditions yield slightly higher doses. This is motivated by the preliminary nature of the modelling of the permafrost landscape, whereas that of the temperate landscape is considerably more mature.

10.5.9 Geosphere transmission

The retarding function of the rock can be analysed by using the rock transmission, T_R, defined as the fraction of a radionuclide release to the geosphere that passes through it without decaying. For the conceptualisation of geosphere transport used in the far-field model, T_R is given by an analytic expression involving the F-factor, the advective travel time and the Peclet number for the transporting fracture, the porosity, depth, diffusivity and sorption coefficient of the rock matrix and the half-life of the radionuclide /Sudicky and Frind 1982/. The expression is given in Appendix B.

This expression was evaluated probabilistically for the base case input distributions of the geosphere transport parameters. The resulting cumulative T_R distributions for transport properties for release paths starting at Q1 for a selection of nuclides are shown in Figure 10-35 for Forsmark and Laxemar. Note that a considerable number of the deposition holes are not associated with transport paths that are connected to the biosphere (section 9.3.6, Figure 9-30 and Figure 9-35), reflected by the fact that all curves start at 0.6 and 0.5 for Forsmark and Laxemar, respectively. Figure 10-35 demonstrates that non-sorbing, long-lived nuclides like I-129 and Cl-36 are readily transmitted through the geosphere. A sorbing nuclide like Pu-239, on the other hand, is efficiently retarded by the rock. Note also the higher transmission of Ra-226 at Laxemar, causing the difference in total effective dose between the sites.

The half-life of the nuclide is crucial for its transmission properties. A stable element has unit transmission irrespective of rock conditions. This is the reason for the relatively high transmission of the strongly sorbing U-238, which has a half-life of $4.5 \cdot 10^9$ years. Ra-226, in contrast, with a half-life of only 1,600 years, has a low transmission despite being relatively weakly sorbed in the geosphere. (The dominant releases of Ra-226, e.g. in the base case, are due to the relatively small portion of the deposition holes for which the geosphere transport properties lead to a high transmission. The continuous production of Ra-226 from in-growth and its low sorption in the buffer also contribute to the high releases of Ra-226 in the base case.)

This type of transmission calculation is seen as a useful diagnostic tool by which e.g. distributions of rock transport parameters from variants of groundwater flow calculations can be quickly evaluated.

The sensitivities of rock transmission distributions to their input parameters can be determined with the rank regression method used in section 10.5.4 for dose sensitivities. This was done for a similar data set in the SR-Can Interim report /SKB 2004a section 12.4.5/, and demonstrated that the F-value is the dominant parameter for all nuclides.

10.5.10 Issues related to the probabilistic nature of the calculations

A number of issues related to the probabilistic nature of the calculations arise. These include convergence of the results, correlations between input parameters, the selected shape of the input parameter distributions, and risk dilution. These issues are addressed below.

Uncertainty related to lack of understanding vs natural variability

The input distributions reflect both uncertainty due to lack of understanding of an issue (dominant for, e.g. the fuel dissolution rate or the input data related to canister failure) and variability (dominant in the cases of number of canister failures as a function of time and the statistical data obtained from the

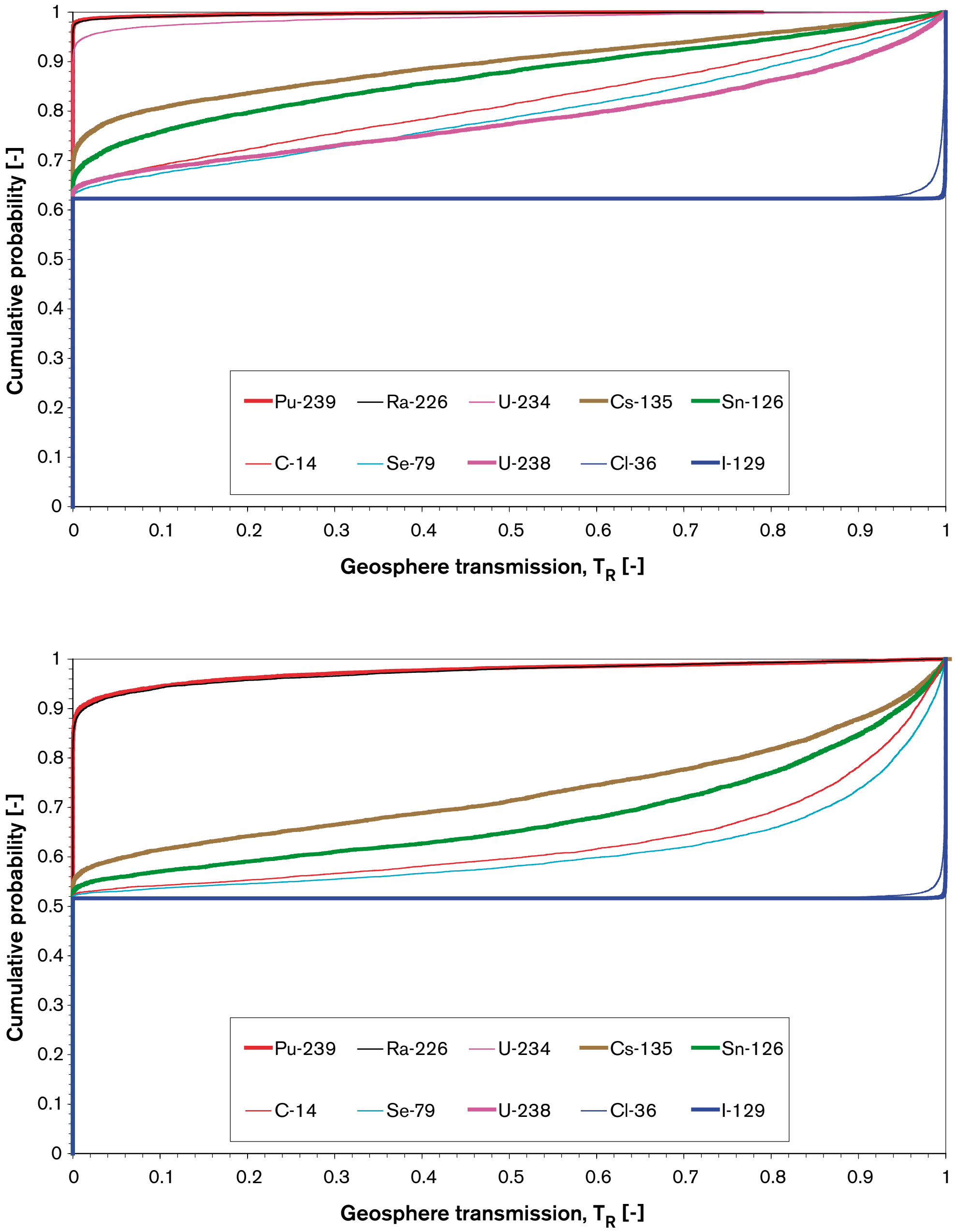


Figure 10-35. *Geosphere transmission distributions, T_R, for a selection of radionuclides, calculated probabilistically for the input distributions used in the Forsmark (upper) and Laxemar base cases. Note that the curves for Pu-239 and Ra-226 almost coalesce.*

hydrogeological modelling). The two types of uncertainty, epistemic and aleatory, are thus sometimes mixed in the probabilistic calculations. There are also issues where these uncertainties are not mixed, e.g. in the alternative model interpretations. Lack of understanding of the hydraulic properties of the rock at Forsmark is e.g. handled by the formulation of alternative models that are each propagated through the safety assessment and evaluated one by one, as demonstrated in section 10.5.7 above.

An attempt to illustrate the impact of the two types of uncertainty on the results has been made by fixing data where uncertainty is mainly related to lack-of-knowledge to fixed values, while data related to spatial variability is treated probabilistically. Several probabilistic runs have been made in which all the data affected by uncertainty related to lack-of-knowledge have been set to pessimistic, average or favourable values. The treatment of data is described in Table 10-8.

Table 10-8. Data used in the illustration of uncertainty due to lack-of-knowledge and spatial variability. References to the Data report are the same as those listed in Table 10-3 and not repeated here. "=" means "same as for growing pinhole failure".

	Nuclide/ Element specific	The growing pinhole failure	Separation of uncertainty related to lack-of-knowledge (green) and spatial variability (yellow)
Number of failed canisters	–	One. (Postulated number; no pinhole failures are expected.)	=
Radionuclide inventory	N	Data for 38 MWd/kgU BWR fuel.	=
Instant release fraction (IRF) of inventory	N	Triangular distributions for all simulated nuclides except actinides, Sm-151 and Zr-93 (zero IRF) and Ca-41, Nb-94, Ni-59 and Ni-63 (100% IRF).	Min, mode and max values used in three illustrative cases.
Time for onset of radionuclide transport	–	1,000 years.	=
Time between onset and complete loss of transport resistance in canister	–	Single canister: 10,000 yrs. Triangular (0, 10^5 , 10^5) yrs to illustrate uncertainties and risk dilution.	Single canister: 10,000 yrs.
Canister defect sizes		Between onset and complete loss: 2 mm radius penetrating pinhole. After complete loss: Full contact between canister interior and bentonite compartment next to initial defect.	=
Fuel dissolution rate	–	Log-triangular (10^{-8}/yr, 10^{-7}/yr, 10^{-6}/yr).	Min, mode and max values used in three illustrative cases.
Concentration limits	E	Calculated distribution based on site-specific groundwater composition.	=
Buffer porosities		Anions: Triangular (0.12, 0.17, 0.24). Cations: Constant = 0.43. (The difference derives from the inclusion of anionic exclusion from part of the pore space.)	Anions: Min, mode and max values used in three illustrative cases. Cations: Constant = 0.43.
Buffer diffusivities	E	Triangular distributions.	Min, mode and max values used in three illustrative cases.
Buffer sorption coefficients	E	Log triangular distributions.	See above.
Backfill diffusivity coefficients	E	Triangular distributions.	See above.
Backfill sorption coefficients	E	Log triangular distributions.	See above.
Rock porosities		Lognormal, site-specific distribution.	=
Rock diffusivities	E	(Log-normal, site-specific formation factor) × (element specific diffusivity considering also anion exclusion).	=
Rock sorption coefficients	E	Log triangular distributions, same for both sites.	Min, mode and max values used in three illustrative cases.
Hydrogeological data related to flow and transport Water flow in the deposition tunnel* Equivalent flow from deposition hole to fracture(s) intersecting deposition hole (Q1), to EDZ (Q2), and to fractures intersecting deposition tunnel (Q3); data for Q1 available with and without effect of spalling* Darcy flow at deposition hole (U1)* Rock transport resistance, F for paths beginning at Q1, Q2 and Q3* Rock advective travel time, t_w for paths beginning at Q1, Q2 and Q3* *Correlated distributions covering ensemble of deposition holes	–	Data distributions from several model calculations propagated from hydro analyses: *Forsmark* CPM DFN fully correlated case DFN semi-correlated case *Laxemar* DFN semi-correlated case	Fully correlated DFN Forsmark with spalling used in most cases.
Rock Peclet number, Pe	–	Constant = 10	=
Max. penetration depth in rock matrix, D_{Pen}	–	Triangular distribution (0.01, 10, 10) m, same for both sites	=
Biosphere LDF factors	N	Calculated, constant LDF values, see section 10.2	=

Three probabilistic calculations were carried out:

1. All data affected primarily by uncertainty related to lack-of-knowledge were set to *pessimistic* values whereas the full distributions of data exhibiting spatial variability were represented. Distributions of hydrogeological data from the Forsmark fully correlated base-case DFN model were used.
2. As 1, but with all data affected by lack-of-knowledge set to *average* values.
3. As 1, but with all data affected by lack-of-knowledge set to *favourable* values.

The results of the calculations are presented in Figure 10-36, where also the results of the fully probabilistic base-case calculation are shown. For each probabilistic calculation, the mean value (thick lines), 99th and 95th percentiles and median values are shown. All 5th percentiles are equal to zero since no releases to either Q1 or Q2 are predicted for a considerable fraction of the deposition holes.

It is obvious that both spatial variability and lack-of-knowledge have a considerable impact on the results. It is noteworthy that the fully probabilistic calculation (thick black line) yields a higher result than the case where all uncertainty due to lack-of-knowledge is set to average values (thick red line). It is also obvious that for more favourable data related to lack-of-knowledge, the impact of spatial variability is less. This is seen when the range of the statistics of the favourable case is compared with those of the pessimistic case. Compare, for example, the range covered by the light blue curves (favourable values) to the considerably wider range covered by the green curves (pessimistic values) in Figure 10-36.

The analysis can be extended to also include uncertainty due to lack-of-knowledge regarding the choice of hydrogeological model and the treatment of spalling. An extremely unfavourable case is obtained with the semi-correlated DFN model for Forsmark, assuming spalling and using pessimistic data when uncertainty is due to lack-of-knowledge. The opposite is obtained with the CPM model for Forsmark, neglecting spalling and using favourable data when uncertainty is due to lack-of-knowledge. The mean values of these to case are shown in Figure 10-37, along with the mean values of all the cases analysed above.

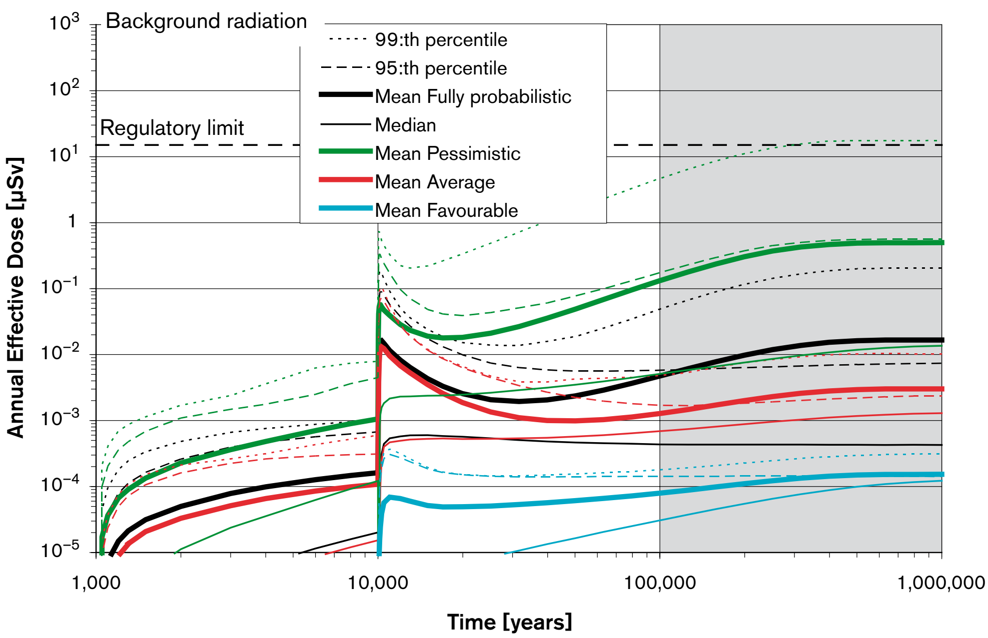


Figure 10-36. *Illustration of relation between uncertainty due to lack-of-knowledge and spatial variability. Thick lines: Mean values taken over spatial variability for a number of assumptions regarding all data affected by lack-of-knowledge (all pessimistic, all average, all favourable). Thin lines: Other statistics of the calculation cases, to illustrate spatial variability within each case. All 5th percentiles are equal to zero since no releases to either Q1 or Q2 are predicted for a considerable fraction of the deposition holes.*

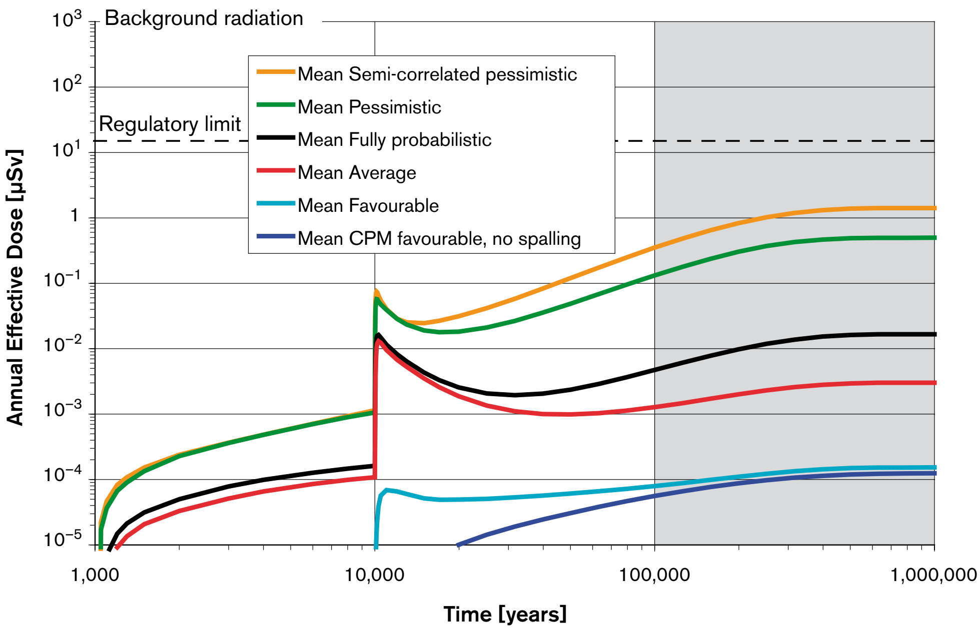


Figure 10-37. *Extension of the analysis, including also the semi-correlated hydrogeological DFN model for Forsmark with pessimistic data and the CPM model with favourable data and neglecting spalling (all other results with the base-case fully correlated hydrogeological DFN model).*

The results presented here are a first attempt to elucidate the impact of the two types of uncertainty on the assessment results. Already at its current level, the analysis illustrates that reducing the uncertainty in understanding would potentially impact the estimated risk and continued efforts in the Site Characterisation and R&D programmes are thus warranted. In particular, reducing uncertainty in the hydrogeological understanding would potentially reduce estimated risk, since currently this uncertainty necessitates a propagation of the different modelling concepts and a risk estimate based on the case leading to the highest risk, see further chapter 12.

The analysis also shows that there is a substantial influence of spatial variability on the results. This influence is a property of the sites and the repository concept, and would, in principle, not be reduced by further R&D or characterisation efforts.

Convergence

For the analytic base-case simulations, there is a variation of about a factor of 2 in the mean value of the annual effective dose for 1,000 realisations and about a factor of 1.2 for 10,000 realisations, using Latin Hypercube Sampling (LHS) in both cases. Therefore, 10,000 realisations and LHS was used for all the analytic calculations.

For the calculations with the numerical codes, the calculation time is longer, and the need for optimising the number of realisations is more pronounced. For the Forsmark calculations (the base case, the highly conductive tunnel and the highly conductive EDZ cases) 6,824 realisations were run, corresponding to the number of canister positions used in the Forsmark hydro model. Of these potential positions, some are not used in the final risk calculations where positions are rejected in accordance with to the full perimeter intersection criterion (FPC), resulting in 6,425 realisations actually being used. The corresponding numbers for the Laxemar simulation are 7,483 and 6,734 positions. Figure 10-38 shows the mean dose for near- and far-field releases for the Forsmark base case at 1,000,000 years as a function of the number of realisations, using Monte Carlo sampling. Although the mean dose reaches a constant value for the near field, some fluctuations remain after 6,425 realisations for the far field. These are, however, small in comparison to the impact of many of the data uncertaintiesaffecting the result.

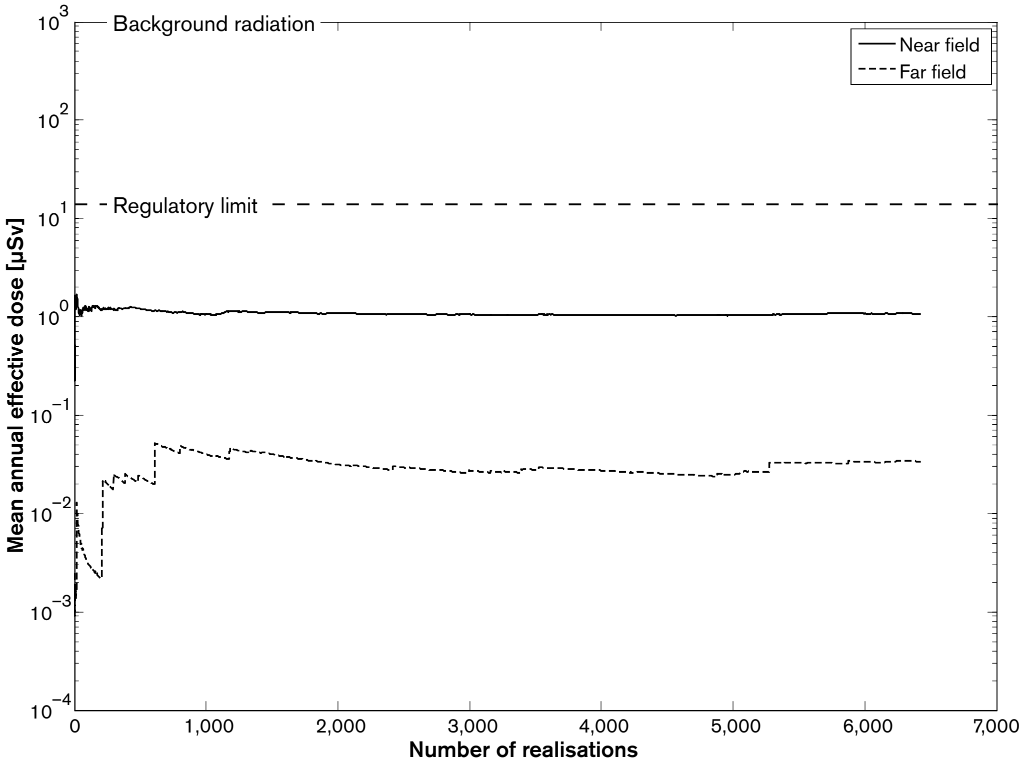


Figure 10-38. *The annual dose for the Forsmark base case at 1,000,000 years as function of the number of realisations.*

Correlations not reflected in input data distributions

Several of the input data for the base case calculation take correlations into account: All probability distributions calculated by the hydrogeological model are correlated, i.e. the distributions of transport resistances, advective travel times, equivalent flow rates and Darcy velocities. Also, the distributions of concentration limits are correlated since one groundwater composition is sampled in each realisation and used to generate concentration limits for all relevant elements. As discussed in the **Data report** (sections 3.4 and 6.1), the groundwater composition is the main source of uncertainty for the concentration limits.

The sampled groundwater composition is, however, not used when determining sorption coefficients for the buffer and the geosphere. Rather, distributions of sorption coefficients are provided for several groundwater types and the type yielding the lowest coefficients is pessimistically used as a basis for selecting values, see further the **Data report**. Thus, the groundwater types adopted as a basis differ between elements. The so selected K_d-distributions are not correlated between elements although such correlation structures are suggested in the **Data report**.

This omission is not deemed to have any significance for the results, based on results for similar data presented in the SR-Can Interim report /SKB 2004a section 12.5.1/. There, a case with the parameters related to the chemical environment fully correlated so that the sampled data are favourable or unfavourable simultaneously indicates that the potential influences of geochemically related correlations on the overall calculation results are not important. This finding is also consistent with the results of a similar test /Hedin 2003/ made on the SR 97 data set.

The influence of input distribution shapes

In the SR-Can Interim report /SKB 2004a section 12.5.2/, it was demonstrated that the influence of altering the, often triangular or log-triangular, shapes of the input distributions where the shapes have been subjectively selected, is minor. Several alternatives were tested, including constant values equal to the pessimistic bounds of the triangular distributions. This finding is consistent with the results of a similar test /Hedin 2003/ made on the SR 97 data and with results presented in the SR-Can Interim report. The data sets in both these tests are similar to those used in the pinhole failure mode calculations. Therefore, these calculations have not been repeated.

Risk dilution

So called risk dilution may occur if there is e.g. uncertainty in the time at which a single canister fails. By calculating probabilistically using a distribution of failure times, the peak dose may occur at different times in different realisations, so that the mean dose at a certain point in time is composed of a few realisations where the failure time gives large doses, 'diluted' by many realisations where the doses are considerably lower. In order to avoid this effect, the failure time is cautiously set to a fixed value in the base case calculation.

Figure 10-39 shows the effect of assuming a triangular distribution (0; 10^5, 10^5) years of the time of occurrence of the large failure of the single canister considered in the reference pinhole case, rather than a fixed time of 10,000 years. As seen, the difference between the two cases is quite pronounced at 10,000 years, i.e. the time when the large failure occurs in the latter case. The peak at 10,000 years is due to releases of I-129. The effect is more noticeable than in earlier assessments due to the effects of spalling, as this eliminates an important transport resistance in the near-field and hence a dispersive property of the system. For longer times, the doses are dominated by releases of Ra-226 that increase due to in-growth beyond 100,000 years i.e. after the longest failure times in the triangular distribution.

Thus, this is a case where a probabilistic treatment of the failure time would have resulted in a considerable risk dilution around 10,000 years.

There are also other uncertain factors that could act to disperse the releases in time, thus causing risk dilution, like uncertainties in sorption coefficients in the buffer and the geosphere. These can, however, be shown to be of minor importance. The risk dilution shown in this calculation case is related to releases of I-129 that is taken not to sorb either to the buffer or to the rock.

Sensitivity analyses

Methods for sensitivity analysis of probabilistic results of the type emerging from the calculations of the growing pinhole case were presented in the SR-Can Interim report /SKB 2004a section 12.4.5/. A rank regression method for global sensitivity analysis, identifying parameters that contribute most to overall uncertainty in the result and a method for identifying the parameters that are associated with the highest consequences were presented. The methods were applied to the calculation results in the Interim report. It was demonstrated, through a verification exercise, that the most important contributors to overall uncertainty had been identified. The motives for choosing these methods are summarised in the SR-Can Interim report and advantages and disadvantages with the chosen methods are discussed in numerous references cited in that report.

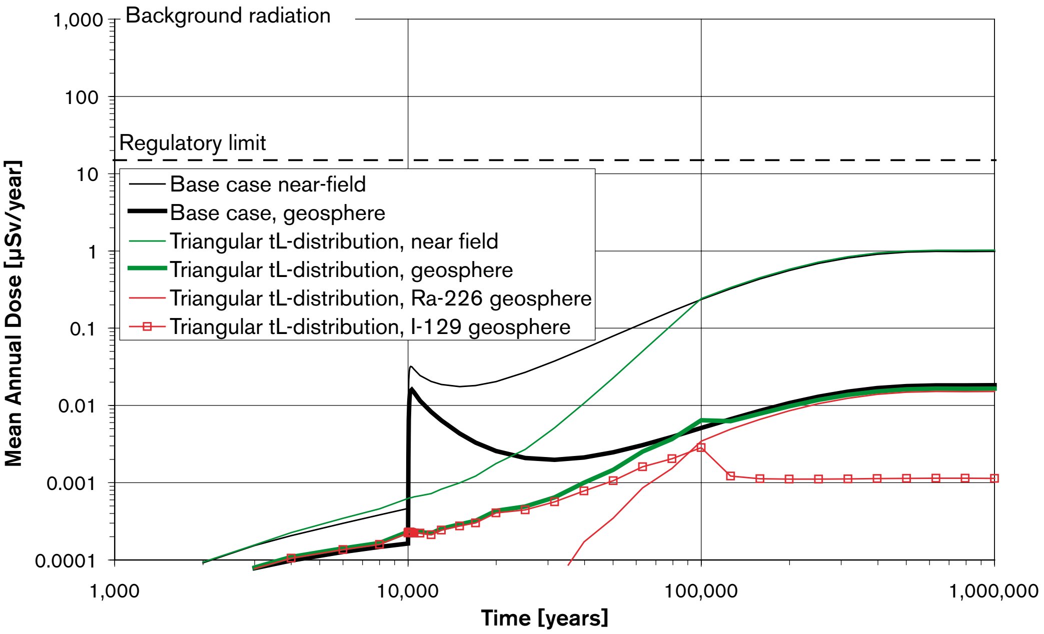


Figure 10-39. *Illustration of risk dilution caused by the uncertainty in the time of occurrence of the large failure of the single canister considered in the reference pinhole case. Analytic calculation, 10,000 realisations.*

These methods are applicable also to the results of the probabilistic calculations of the growing pinhole failure in this report. Such analyses have not been repeated. As the data set is similar to that in the Interim report, it is expected that the same important variables would be identified. For example, Ra-226 is again the dose dominating nuclide and the parameters determining the release of Ra-226 are similar to those in the Interim report.

The role of this type of sensitivity analysis in a more general context of is further discussed in section 10.11.

10.6 The advection/corrosion failure mode

10.6.1 Introduction

As reported in chapter 9, a failure mechanism that cannot be ruled out given the reference evolution of the repository is the case in which the buffer erodes and subsequent enhanced canister corrosion due to advective conditions in the buffer leads to canister failure. This was found to potentially affect a few canisters in the analysis of the reference evolution, but the uncertainties are considerable. For this failure mode, both the canister and buffer are bypassed, and the rock retention is small since substantial copper corrosion after buffer erosion only occurs in deposition holes with high flow rates, which are strongly correlated to low geosphere retention.

10.6.2 Evolution of the near field after canister failure

Canister evolution

According to the analysis of copper corrosion for the advection case, section 9.4.9, a band, 0.35 m high and covering half the circumference of the canister, is assumed to be evenly corroded. This means that when penetration occurs, a large amount of damage must be assumed in the copper shell.

The time required to penetrate the cast iron insert is assumed to be triangularly distributed between 1,000 and 100,000 years with the peak at 100,000 years, based on the same reasoning as for the time for the large failure to occur in the pinhole case, see section 10.5.2. The background to the choice of the triangular distribution in the pinhole case is the consideration of a number of cases of combined effects of corrosion of and mechanical loads on the insert, eventually leading to failure. This is further elaborated in the **Data report**, section 4.4. Similar corrosion rates and mechanical load situations can be expected for a larger opening in the copper shell. It is noted that, in the pinhole case, small releases are assumed to occur through the pinhole defect already after 1,000 years, pessimistically assuming that the insert is not initially tight. No corresponding small releases are assumed in the present case.

Since penetration of the copper shell in general occurs after several hundred thousand years for the few canisters exposed to the highest corrosion rates, the additional time to penetrate the cast iron insert is of less importance. Risk dilution effects potentially introduced by the distribution of cast iron insert failure times are discussed in section 10.7.1.

Once the cast iron insert has failed, the void in the insert is assumed to be rapidly filled with water due to the high flow rate and the lack of transport resistances in the absence of the buffer and with a large amount of damage also to the canister insert.

10.6.3 Conceptualisation of transport conditions

Advective conditions in the buffer must be assumed also for the consequence calculations for the buffer advection case. There is no buffer hindering the outward transport of radionuclides meaning that this is controlled by the flow rate through the deposition hole, Q. The following two contributions to the outward transport can be distinguished.

- The instantaneously accessible fraction of radionuclides that is assumed to be rapidly dissolved in the water void volume and subsequently flushed out of the canister. This gives rise to a pulse of uncertain duration.

- A contribution from the fuel dissolution and the congruent release of radionuclides embedded in the fuel matrix. The flow rates in the affected deposition holes are in general sufficiently high to flush out all the congruently released radionuclides, meaning that concentration limits do not become effective. Rather, the release into the fracture is controlled by the fuel dissolution rate alone. The one exception concerns the dissolution of uranium, for which a concentration limit is still an effective constraint on release, due to the large amount of U-238 present in the fuel. This limits the near-field releases of the uranium isotopes, but also leads to increased releases of Th-230, Th-229 and Pa-231 generated by the re-precipitated U-234, U-233 and U-235, respectively. As an alternative model, confinement of also thorium is considered, see further section 10.6.5.

Furthermore, as the flow rate in the intersecting fracture is high, the retention of the rock is in general limited for these deposition holes. Geosphere transport is represented analytically, using the transmission factor approach described in section 10.5.9.

The model is described in more detail in Appendix B, where it is also benchmarked against numerical calculations.

The pulse contribution

Activation products: The inventory of activation products in the metal parts of the fuel has normally been assigned to the instantaneously accessible fraction, since it has been considered unnecessary to develop a model for the metal parts as nuclides in these are dispersed by the buffer. However, in the advection/corrosion case this assumption would lead to unrealistically high releases of Ni-59 and Nb-94. In this case it is, therefore, assumed that the radionuclides present in the metal parts will be released over a period of 1,000 years. This is still judged to be a gross overestimate of the release rate, since the metal parts consist of corrosion-resistant alloys.

Geosphere pulses: A pulse release from the near field will be dispersed and retained in the geosphere, so that an instantaneous release of a mass M_0 to the geosphere yields a peak release rate from the geosphere of M_0/τ. τ can be calculated analytically as

$$\tau = F^2 D_e \left[\varepsilon + (1-\varepsilon) K_d \rho\right] 2\sqrt{\pi}\,(e/6)^{3/2}$$

see further Appendix B. Hydrodynamic and molecular dispersion in the flowing fracture is pessimistically neglected when this expression is used. Also, radioactive decay is neglected in the expression since no appreciable decay will take place during the short transients of concern here.

Pulse releases in the biosphere: The LDF values are calculated for constant releases over long periods. These long periods allow near steady-state situations to develop and ensure that the effects of downstream accumulation are included in the dose calculation. For a pulse, steady state does not develop for many radionuclides and downstream accumulation is very low compared to the primary object to which release occurs. Moreover, the annual average lifetime risk will be lower for a short release occurring over less than a lifetime, i.e. less than about 50 years. (Preliminary analyses show that LDF values overestimate the dose about one order of magnitude for a pulse released over less than 1 year /Avila 2006, SKB 2006i/.)

In this assessment, a pulse release of X Bq to the biosphere is converted to a constant release occurring over a life-time, assumed to be 50 years, i.e. to X/50 Bq/yr, to which the LDF-value is applied. This approximation is considered to be a cautious way of estimating doses from pulse releases to the biosphere.

Pulse releases are handled according to the following rules.

- The inventory of activation products in metal parts is assumed to be released over 1,000 years, or reduced by the factor obtained from the geosphere dispersion, τ, whichever yields the lowest dose. Doses are calculated with the LDF.
- The instantaneously accessible fraction of other nuclides is spread over a life time (50 years) or divided by the reduction factor obtained from the geosphere dispersion, τ, whichever yields the lowest dose. Doses are calculated with the LDF.

The results are presented in Table 10-9.

Table 10-9. Calculations of consequences of pulse releases. All LDFs are for Forsmark. τ is calculated for F = 1,000 y/m (based on F-values in Table 10-11 reduced by a factor of 10 to account for channelling) and with D_e, K_d and ε as central values in the distributions in Table 10-10.

Nuclide	Ni-59	Nb-94	Cl-36	I-129	Se-79	Tc-99	Sn-126	Cs-135
Accessible inventory in 38 MWd BWR fuel at 100,000 years, Inv [Bq]	$7.35 \cdot 10^{10}$	$1.98 \cdot 10^{8}$ (About 9 times higher for PWR)	$4.54 \cdot 10^{7}$	$2.69 \cdot 10^{7}$	$1.64 \cdot 10^{6}$	$1.71 \cdot 10^{9}$	$7.18 \cdot 10^{5}$	$4.24 \cdot 10^{8}$
LDF [Sv/yr/Bq/yr]	$4.2 \cdot 10^{-16}$	$1.3 \cdot 10^{-11}$	$1.3 \cdot 10^{-14}$	$5.5 \cdot 10^{-12}$	$6.7 \cdot 10^{-14}$	$4.4 \cdot 10^{-15}$	$4.2 \cdot 10^{-13}$	$6.3 \cdot 10^{-13}$
τ [yr]	24	3,500	(0.00028)	(0.00011)	3.5	3,500	3,500	307
Inv/50·LDF [μSv/yr]	0.62	52	**0.012**	**3.0**	**0.0022**	0.15	**0.0060**	5.3
Inv/τ·LDF [μSv/yr]	1.31	**0.74**	–	–	0.032	**0.0022**	0.087	**0.87**
Inv/1,000·LDF [μSv/yr]	**0.031**	2.5793	–	–	–	–	–	–
Upper bound on annual dose [μSv]	0.031	0.74	0.012	3.0	0.0022	0.0022	0.0060	0.87

Note that it is pessimistically assumed that the development of the canister failure is such that all the fuel rods become accessible simultaneously, i.e. a sudden collapse of the fuel rod structure is assumed.

The handling assumes that if several canisters fail, no two canisters will affect the same biosphere object simultaneously. This is justified by the fact that only a few canisters fail due to advection/corrosion and that these failures are spread over hundreds of thousands of years. A number of nuclides with an IRF, and with half-lives up to 10,000 years (e.g. Sr-90, Cs-137, C-14), were excluded from the analysis since they would decay to insignificance before a failure would occur.

In conclusion, this pessimistically simplified analysis indicates that doses caused by releases of the instantaneously accessible fraction of radionuclides are well below the regulatory limit of 15 μSv, even for the extreme geosphere conditions associated with the deposition holes where advection/corrosion failures could possibly occur.

10.6.4 Input data to transport models

All input data are given in Table 10-10, where a comparison with the pinhole reference case is also given.

Concentration limits

In a case where the buffer is severely eroded, a colloid filter (buffer function indicator Bu2) cannot be guaranteed. This means that the use of elemental solubilities as a limit for radionuclide release could be questioned. In this case, however, this is of minor concern, since the flow through the deposition hole is too high for solid phases to precipitate (with the exception of uranium). It is pessimistic to assume that all uranium stays within the canister and continues to produce daughter nuclides.

Fuel dissolution rate

The spent fuel is assumed to have the same alteration rate in this case as in the growing pinhole case. The reasons for this are as follows.

- The increase in water flow rate (water exchange rate) at the canister surface is also in the advection case sufficiently low so that for the fuel dissolution it still approaches static conditions.
- The first canister will be penetrated after more than 100,000 years of advective corrosion.
- After failure of the copper canister, corrosion of the cast iron insert will begin. The time required to penetrate the cast iron insert is assumed to be triangularly distributed between 1,000 and 100,000 years with the peak at 100,000 years, based on the same reasoning as for the time for the large failure to occur in the pinhole case, see section 10.5.2.
- In spite of the large canister defect, as long as there is actively corroding iron, both H_2 and Fe(II) concentrations will be sufficient to assure reducing conditions similar to those in the pinhole case.

Table 10-10. Input data for the advection cases. Data for the pinhole reference cases are given for comparison. '=' means same as pinhole case. References to the relevant sections of the Data report are given in Table 10-3.

	Nuclide/ Element specific	The growing pinhole failure	The advection/corrosion failure
Number of failed canisters	–	One. (Postulated number; no pinhole failures are expected.)	As calculated with corrosion model, see section 9.4.9. 10 and 50 canisters fail at Forsmark and Laxemar, respectively.
Radionuclide inventory	N	Data for 38 MWd/kgU BWR fuel.	=
Instant release fraction of inventory	N	Triangular distributions for all simulated nuclides except actinides, Sm-151 and Zr-93 (zero IRF) and Ca-41, Nb-94, Ni-59 and Ni-63 (100% IRF).	=
Time for onset of radionuclide transport	–	1,000 years.	Failure times according to calculations in section 9.4.8.
Time between onset and complete loss of transport resistance in canister	–	Single canister: 10,000 yrs. Triangular (0, 10^5 , 10^5) yrs to illustrate uncertainties and risk dilution.	Triangular (1,000, 10^5, 10^5) yrs.
Canister defect sizes		Between onset and complete loss: 2 mm radius penetrating pinhole. After complete loss: Full contact between canister interior and bentonite compartment next to initial defect.	N/A
Fuel dissolution rate	–	Log-triangular (10^{-8}/yr, 10^{-7}/yr, 10^{-6}/yr).	=
Concentration limits	E	Calculated distribution based on distribution of site-specific groundwater composition.	All U pessimistically assumed to precipitate. Other released elements fully dissolved due to high water turn-over in the near field.
Buffer porosities		Anions: Triangular(0.12, 0.17, 0.24). Cations: Constant = 0.43.	N/A
Buffer diffusivities	E	Triangular distributions.	N/A
Buffer sorption coefficients	E	Log triangular distributions.	N/A
Backfill diffusivities	E	Triangular distributions.	N/A
Backfill sorption coefficients	E	Log triangular distributions.	N/A
Rock porosities		Lognormal, site-specific distribution.	=
Rock diffusivities	E	(Log-normal, site-specific formation factor) × (element specific diffusivity considering also anion exclusion).	=
Rock sorption coefficients	E	Log triangular distributions, same for both sites.	=
Hydrogeological data related to flow and transport Water flow in the deposition tunnel* Equivalent flow from deposition hole to fracture(s) intersecting deposition hole (Q1), to EDZ (Q2), and to fractures intersecting deposition tunnel (Q3); data for Q1 available with and without effect of spalling* Darcy flow at deposition hole (U1)* Rock transport resistance, F for paths beginning at Q1, Q2 and Q3* Rock advective travel time, t_w for paths beginning at Q1, Q2 and Q3* *Correlated distributions covering ensemble of deposition holes	–	Data distributions from several model calculations propagated from hydrogeological analyses: *Forsmark* CPM DFN fully correlated case DFN semi-correlated case *Laxemar* DFN semi-correlated case	=, but only deposition holes where failures occur are included. Only F and t_w used. Also, deposition holes with flow paths that do not exit the geosphere (primarily due to numerical reasons) are excluded from the analysis. For SR-Site, these numerical artefacts are to be resolved, see section 9.3.6.
Rock Peclet number, Pe	–	Constant = 10.	=
Max. penetration depth in rock matrix, D_{Pen}	–	Triangular distribution (0.01, 10, 10) m, same for both sites.	=
Biosphere LDF factors	N	Calculated LDF values, see section 10.2.	=

Another important factor to be considered in this case is the much longer time of the first water contact as compared with the pinhole cases. This means that the alpha activity of the fuel at the time of water intrusion and especially after all iron has corroded is expected to have decreased to such low levels that there will be no measurable effect of alpha radiolysis on fuel dissolution under such conditions /Rondinella 2004/.

Hydrogeological data related to flow and transport

The same hydrogeological data as for the pinhole failure mode were used, obtained from the modelling described in section 9.3.6. However, it is only data for the few deposition holes for which canister failures due to corrosion occurs that are used for this advection/corrosion case. This means that all deposition holes of concern experience a high flow rate and in general also a low geosphere transport resistance, since these properties are strongly correlated. Data for the ten deposition holes of relevance, identified using the Forsmark semi-correlated DFN model, are given in Table 10-11.

The channelling factor, i.e. a reduction of the F-values by a factor of 10 was applied to these values (as was done for the pinhole case).

It is noted that the calculated hydraulic and transport properties of these deposition holes are extreme tails of distributions derived from a complex hydrogeological model with stochastic components (the generated fracture network). Furthermore, only one realisation of the hydrogeological model was executed, and hence only one realisation of the fracture network was generated. This is considered sufficient to capture the central values and the spread around the central values of the calculated properties /Hartley et al. 2006a/. However, in order to accurately characterise the extreme tails of interest here, more extensive hydrogeological calculations may be required. This will be considered in the SR-Site assessment if a similar situation, with assessment results being sensitive to tails of hydrogeological calculation results, arises.

10.6.5 Base-case calculation

Introduction

The Forsmark base-case DFN model assuming application of the FPC criterion when selecting deposition holes yields no canister failures due to advection/corrosion during the one million year assessment period, according to Table 9-22, section 9.4.9. Therefore, the semi-correlated DFN model for Forsmark was used as the base case for the advection/corrosion failure mode. Spalling was assumed when bentonite erosion was quantified as described in section 9.4.8, but spalling has insignificant influence on canister corrosion and radionuclide transport since these phenomena are driven by advection.

Table 10-11. Data for the ten deposition holes where canisters fail due to advection/corrosion for the Forsmark semi-correlated DFN model.

Time of failure (yr)	Rock transport resistance, F (yr/m)	Water travel time, t_w (yr)	Advective flow through deposition hole q (m^3/yr)
473,266	401,600	17.7	1.89
521,078	31,181	6.2	1.56
653,804	21,490	11.5	0.99
669,361	12,260	4.8	0.94
794,208	91,260	7.3	0.67
830,519	49,510	15.3	0.61
888,967	4,146,000	127.2	0.54
891,007	16,581	5.4	0.53
957,046	92,190	24.8	0.46
964,377	60,890	8.1	0.46

Deterministic calculations

Figure 10-40 shows near-field releases converted to doses for a stylised, deterministic case where a canister (copper shell and insert) is assumed to fail at 100,000 years after deposition. Advection occurs in the buffer void and the releases are primarily determined by the fuel dissolution rate. The doses, obtained with the LDF-values for Forsmark, are dominated by Th-229. All uranium isotopes released from the fuel are assumed to remain precipitated in the canister, since the concentration limit of uranium always applies because of the large amount of U-238 present. The precipitated uranium isotopes U-234, U-233 and U-235 generate the daughter nuclides Th-230, Th-229 and Pa-231, respectively, which are flushed out of the canister and contribute significantly to the total dose. Ra-226 plays a less dominant role since its mother nuclide Th-230 is, contrary to the case of the pinhole failure mode, not accumulated in the canister. The analytic calculation has been benchmarked against a numerical calculation and the agreement is very good. This was expected since the situation to model is simple and the release rates straightforward to express analytically.

Alternative model

As mentioned, Th-230 is not assumed to accumulate in the canister in the above model since i) its concentration limit is not sufficiently low to cause precipitation for the high flow rates and, thus, high water turn-over in the deposition hole and ii) sorption is not expected to be sufficiently efficient to confine this nuclide to the canister or deposition hole for a time comparable to its 77,000 year half-life. However, it can not be fully excluded that co-precipitation processes and sorption/immobilisation in the remaining bentonite in the deposition hole could confine Th-230 to the near field. If this is the case, its daughter nuclide, the considerably more mobile Ra-226, would be released. The situation where all Th-230 decays to Ra-226 in the canister is, therefore, considered as an *alternative model*. The so generated Ra-226 is assumed to be released to the flowing groundwater in the fracture intersecting the deposition hole. This model causes higher releases of Ra-226, since there is a contribution not only directly from the fuel dissolution, but also from the confined Th-230. It is, furthermore, noted that Ra-226 is expected to be efficiently transmitted through the rock for the extreme flow conditions in the fractures intersecting these deposition holes. Releases from the near field calculated with the alternative model are shown in Figure 10-41. Since in-growth in the geosphere is neglected in the calculations of this failure mode, the alternative model also addresses the issue of possible accumulation of Th-230 decaying to Ra-226 in the geosphere. (In-growth in the biosphere is handled in the biosphere models.)

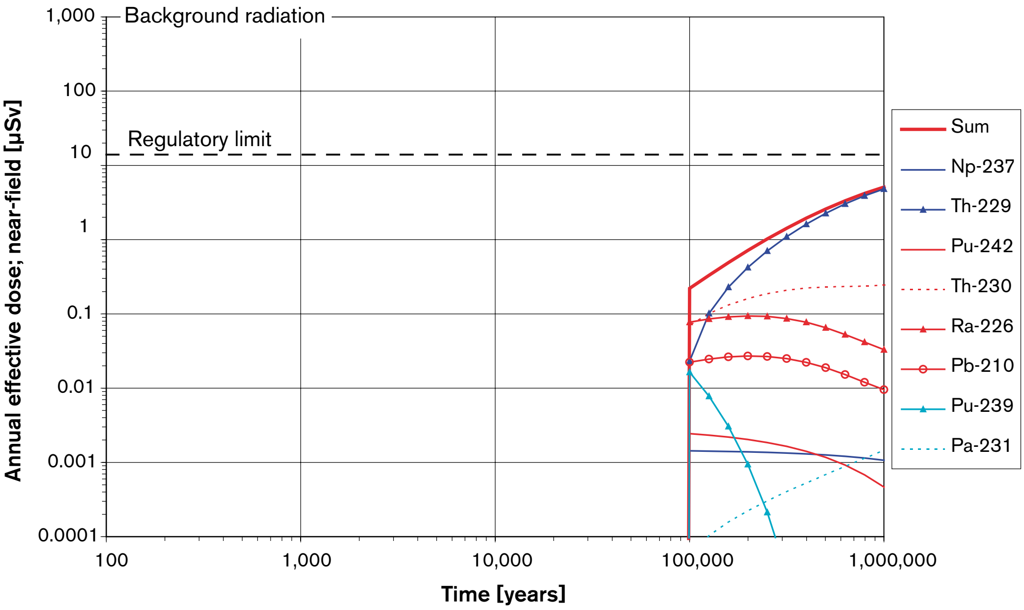


Figure 10-40. *Near-field annual effective dose for a stylised, deterministic case illustrating one canister failing due to corrosion with advective conditions in the buffer. The failure is assumed to occur at 100,000 years after deposition. The dissolution rate of the fuel matrix is 10^{-7}/yr. Analytic calculation. LDF values for Forsmark.*

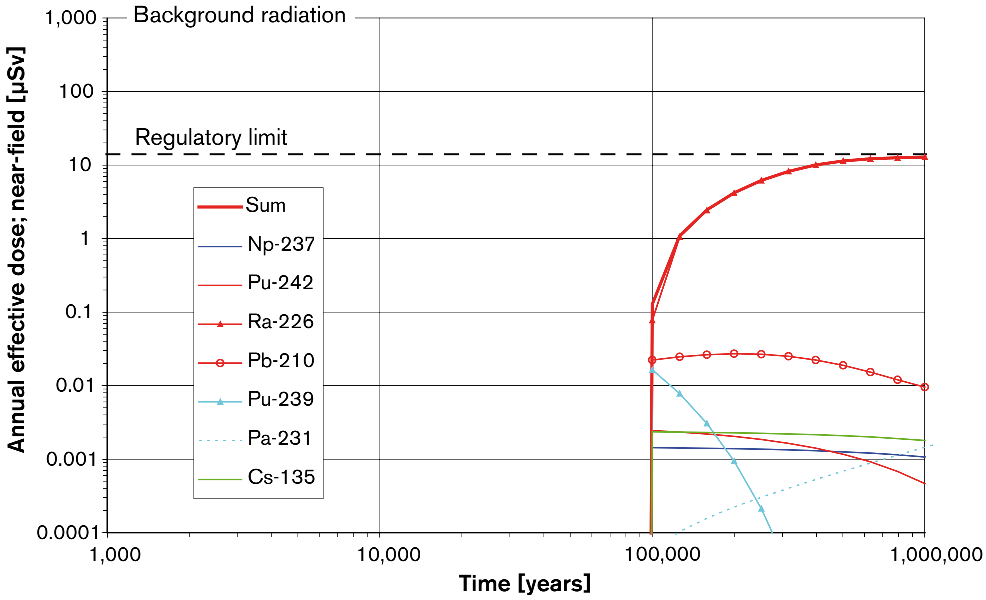


Figure 10-41. *Alternative release model where Th-230 is confined in the canister and its daughter nuclide, Ra-226 is released. The sum release is indistinguishable from that of Ra-226. The sum release is indistinguishable from that of Ra-226.*

The fates of the radionuclides in the U-238 chain are documented in Table 10-12. The table covers both models. Note that they differ only for Th-230 and Ra-226. For the other decay chains, there is not a corresponding problem.

For the U-238 chain it needs also to be considered whether Ra-226 can be confined and lead to releases of Pb-210. However, the chemical properties of Ra and Pb suggest that Pb is more strongly confined due to co-precipitation, sorption and crystallisation processes than Ra. Furthermore, the half-life of Pb-210 is only 22.3 years, compared with 1,600 years for Ra-226. Therefore, it is concluded that if Ra-226 were to be confined, then also Pb-210 would be confined and the releases would be considerably lowered. Thus, Pb-210 was not considered in the near-field analysis of the advection/corrosion failure mode.

Table 10-12. Handling of the members of the U-238 chain in the transport model for advective conditions.

Nuclide	Half-life	Source in canister	Fate in canister	Fate in far field
U-238	$4.47 \cdot 10^9$ y	Fuel dissolution	Precipitates (+ minor fraction released to rock with passing groundwater with U-238 at concentration limit)	Released fraction mostly transmitted
Th-234	24 days	Fuel + precipitated U-238	Decays	–
Pa-234m	1.2 min	Fuel + Th-234 from precipitated U-238	Decays	–
U-234	246,000 y	Fuel + Pa-234 from precipitated U-238	Precipitates (+ minor fraction released; shared concentration limit with U-238 and U-233)	–
Th-230	77,000 y	Fuel + precipitated U-234	*Base model:* Released to rock *Alternative model:* Sufficiently confined by sorption or precipitation to fully decay to Ra-226	Mostly transmitted
Ra-226	1,600 y	Base model: Fuel only Alternative model: Fuel + decay of confined Th-230	Released to rock	Mostly transmitted
Pb-210	22.3 y	Fuel	Released to rock	Mostly decays

The difference between the models (the two figures below) is modest for Forsmark. It is, however, much more pronounced for Laxemar, since the dose conversion factor is much higher for Ra-226 at Laxemar. Hence, the alternative model gives considerably higher consequences than the base model at Laxemar.

Therefore, the alternative model is cautiously selected in the analyses to follow of the advection/corrosion failure mode.

Probabilistic base case calculation

Figure 10-42 shows a probabilistic calculation with failure times and geosphere transport data from the Forsmark semi-correlated DFN model, where 10 canisters fail during the assessment period. The grey area signifies that the regulatory limit is not, in a strict sense, applicable beyond the first 100,000 years. The first releases occur after around 500,000 years. The doses caused by releases from the near-field and the geosphere are totally dominated by Ra-226. Most of the Ra-226 released from the near field is transmitted through the geosphere since the failed canisters are located in deposition holes intersected by large, highly transmissive fractures with low retention. This case has been benchmarked against a numerical model result with excellent agreement, see Appendix B.

Figure 10-43 shows the base case calculation for Laxemar, using the semi-correlated Laxemar DFN model, where 50 canisters fail during the assessment period. Note the very low retention of Ra-226 in the geosphere for this case.

Contrary to the cases illustrating the growing pinhole failure mode, that are stylised and postulated in order to illustrate key retention properties of the system, the above two cases represent situations that are a direct consequence of the analysis of the reference evolution. They, therefore, represent a contribution to the calculated risks associated with releases from the repository. These risks are further addressed in chapter 12.

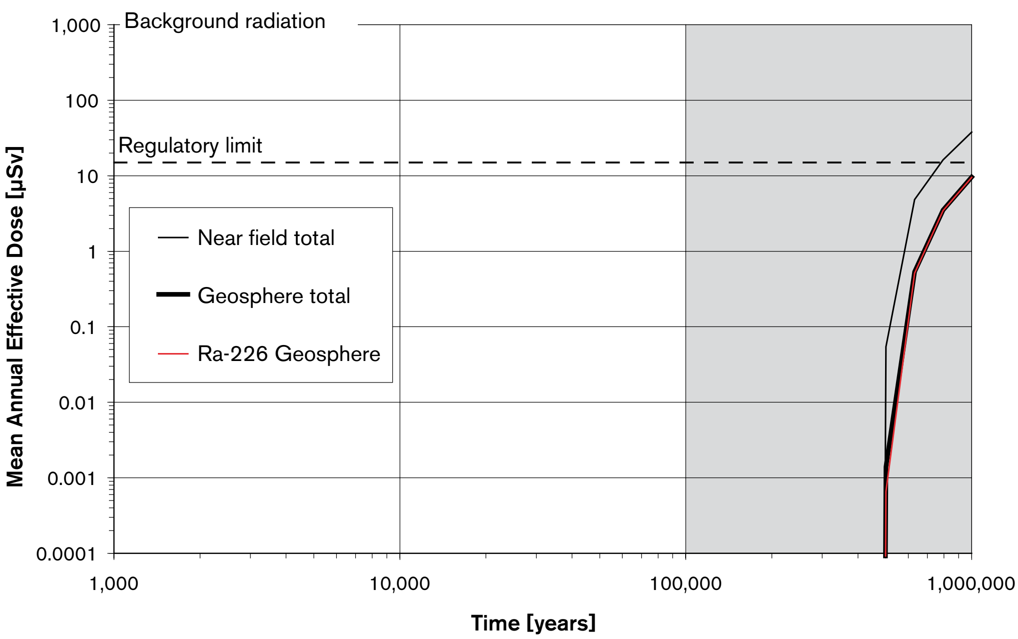


Figure 10-42. *Probabilistic calculation of near-field and far-field annual effective doses for the Forsmark semi-correlated hydrogeological DFN model. 10 canisters fail during the one million year assessment period. Failure times and rock transport data according to the Forsmark semi-correlated hydrogeological DFN model, Table 10-10. Canister positions selected in accordance with the FPC criterion.*

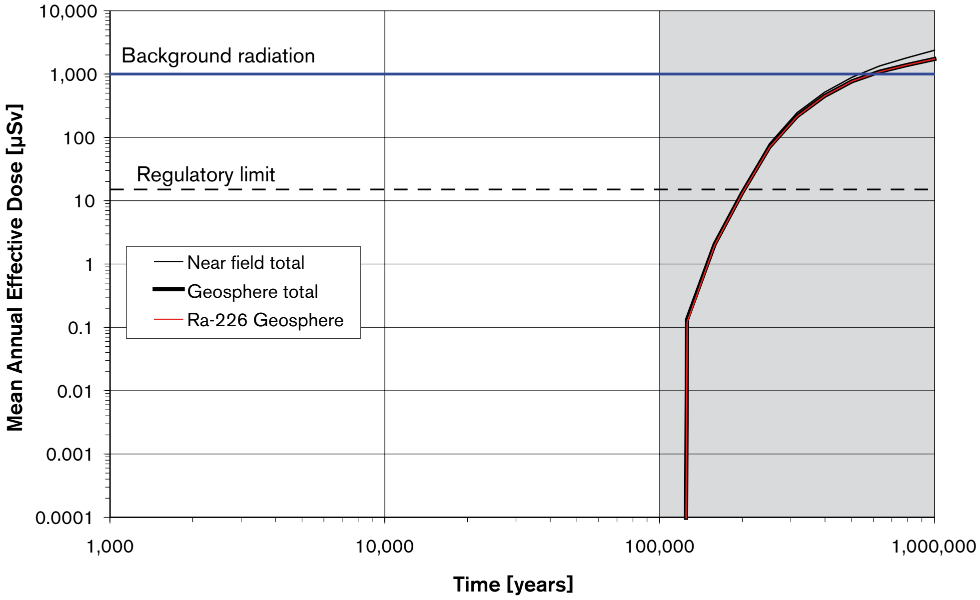


Figure 10-43. *Probabilistic calculation of near-field and far-field annual effective doses for the Laxemar base case (semi-correlated) hydrogeological DFN model. 50 canisters fail during the one million year assessment period. Failure times and rock transport data according to the Laxemar semi-correlated hydrogeological DFN model. Canister positions selected in accordance with the FPC criterion.*

Sensitivity analysis of base case calculation

There are few parameters that are varied probabilistically in the advection/corrosion case. The most significant of these is the fuel dissolution rate, which is assumed to be log-triangularly distributed on (10^{-8}, 10^{-7}, 10^{-6}) y^{-1}. To elucidate the sensitivity to this input parameter, probabilistic cases with fixed fuel dissolution rates have been calculated, see Figure 10-44. As seen in the figure, the doses are almost linearly dependent on the dissolution rate up to rates of 10^{-6} y^{-1}, in which case the entire fuel matrix is dissolved during the one million year calculation period. Increasing further the dissolution rate to 10^{-5} y^{-1} yields a less than linear increase in consequences and an increase beyond 10^{-5} yr^{-1} does not further increase the consequences.

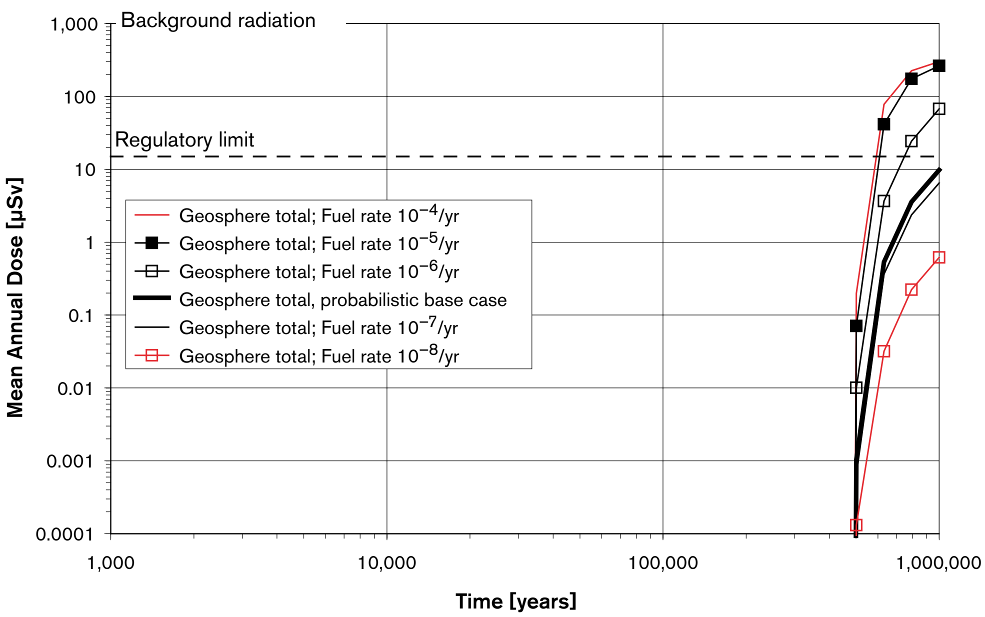


Figure 10-44. *Sensitivity of the base case result to the fuel dissolution rate. Semi-correlated hydrogeological DFN model for Forsmark. 1,000 realisations of the analytic model for each case.*

It is clear that the fuel dissolution is the most important process that limits the releases of radionuclides in the advection/corrosion case.

Sensitivity to concentration limits

In this case, no credit is taken for the concentration limits of the individual radioelements. Thorium and radium are the elements of most concern, since they are the main dose contributors. In order for concentration limits to be important controls on the release of thorium and radium, the concentration limits have to be around $5 \cdot 10^{-9}$ and $2 \cdot 10^{-9}$ mol/l respectively, which is about two orders of magnitude lower than the recommended values for SR-Can /Duro et al. 2006/. This may actually be the case if co-precipitation is considered, see section 10.5.7, sub-heading "Co-precipitation of radium".

10.6.6 Doses to biota for the advection/corrosion base case

As for the pinhole failure and as explained in section 10.2.5, the potential impact on non-human biota was assessed for Forsmark using the methodology developed within the EC Project ERICA. For most radionuclides the Risk Quotients (RQs) are below 1, which indicates that risks to non-human biota are insignificant and that there is no need for more detailed assessments. However, at the end of the one million year assessment period for Ra-226 and the daughter nuclide Po-210, the RQs are above 1 for the three ecosystem types freshwater (4.8 for Ra-226 and 9.9 for Po-210), terrestrial (17 for Ra-226 and 13.5 for Po-210) and marine (1.2 for Po-210). This means that, for these cases, more realistic assessments are required. A preliminary comparison of the maximum concentrations predicted in soils and waters shows that these fall either within or slightly above the range of background concentrations /FASSET 2004/. The results of the assessments and the comparison with the background levels are presented in more detail in /SKB 2006h/.

10.6.7 Alternative safety indicators for the advection/corrosion base case

Using the methods described in section 10.5.6, alternative safety indicators have been applied also for the advection/corrosion case for Forsmark. The results are shown in Figure 10-45 and Figure 10-46. The STUK regulatory limit is not exceeded and the accumulated releases of Ra-226 and Pa-231 are more than two orders of magnitude below the natural contents of these nuclides in the biosphere.

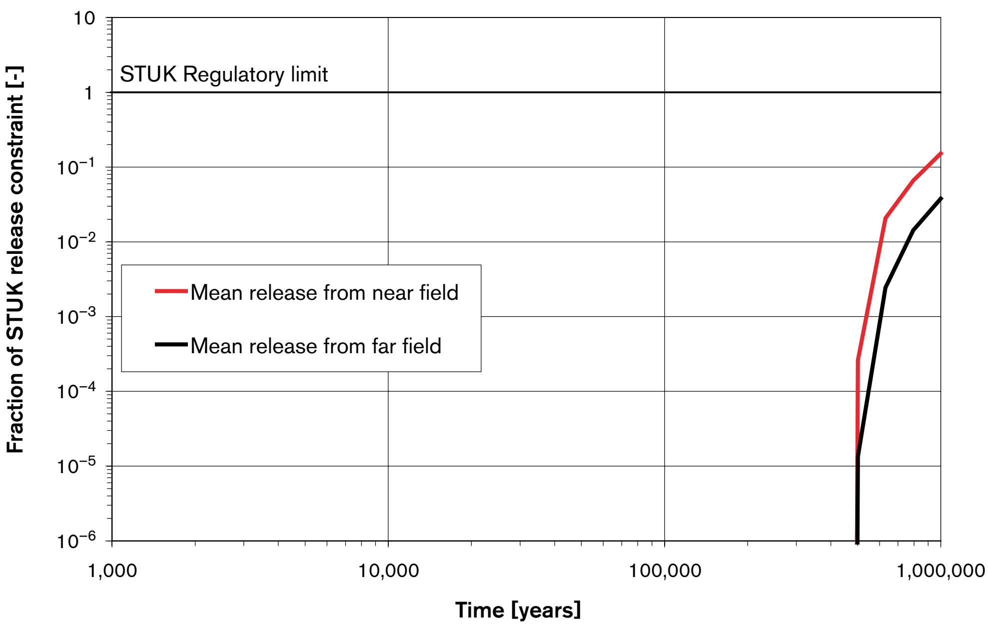


Figure 10-45. *Releases as a fraction of the activity release constraint index adopted by the Finnish regulator.*

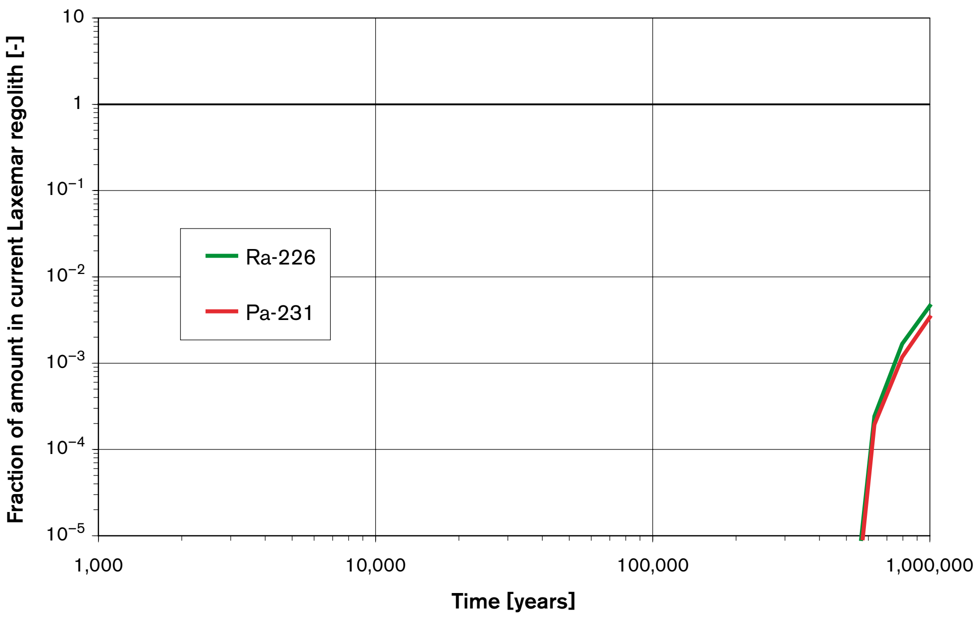


Figure 10-46. *Accumulated release of Ra-226 and Pa-231 as a fraction of the total contents of the same nuclides in the regolith above the repository.*

10.6.8 Cases to illustrate key uncertainties identified in the reference evolution

Several key uncertainties that were addressed for the pinhole case are not relevant for the advection/corrosion case. This applies to the effect of neglecting spalling, since spalling is irrelevant when advection is the active transport mechanism, and to different properties of the EDZ and the deposition tunnels, since the fracture intersecting the deposition hole with advective conditions renders all other exit paths from the near field insignificant.

Alternative interpretations of the Forsmark site are not relevant for the base case that assumes implementation of the FPC criterion; this case yields failures only for the semi-correlated DFN model. (The Forsmark CPM model does not lead to corrosion failures for cases considered in SR-Can.)

Sensitivity to deposition hole acceptance/rejection criteria

Figure 10-47 shows the sensitivity of the calculated doses for the buffer advection case to different deposition hole acceptance/rejection criteria. Results are given for both the fully correlated DFN model and the semi-correlated model. The base case (thick black line) assumes that the FPC criterion has been implemented. A no rejection case and different fracture transmissivity criteria are also tested. As already noted in Table 9-6, the Extended FPC, see section 9.4.5, has not been tried in the hydrogeological modelling. Application of the Extended FPC would be potentially powerful, since this criterion would reject deposition holes intersected by long gently dipping fractures.

Note that for the fully correlated DFN model, no canisters fail when the FPC criterion is applied, as mentioned above. Note also that imposing the criterion that the fracture transmissivity must not exceed 10^{-6} m^2/s does not improve the situation compared with the case without rejection.

For the semi-correlated case, the FPC criterion improves the situation considerably compared with the no rejection case.

In the further discussion of deposition hole acceptance criteria in this report and for the future development of more definitive criteria, it is, therefore, concluded that the advection/corrosion case could be a relevant test when evaluating the impact of deposition hole rejection criteria.

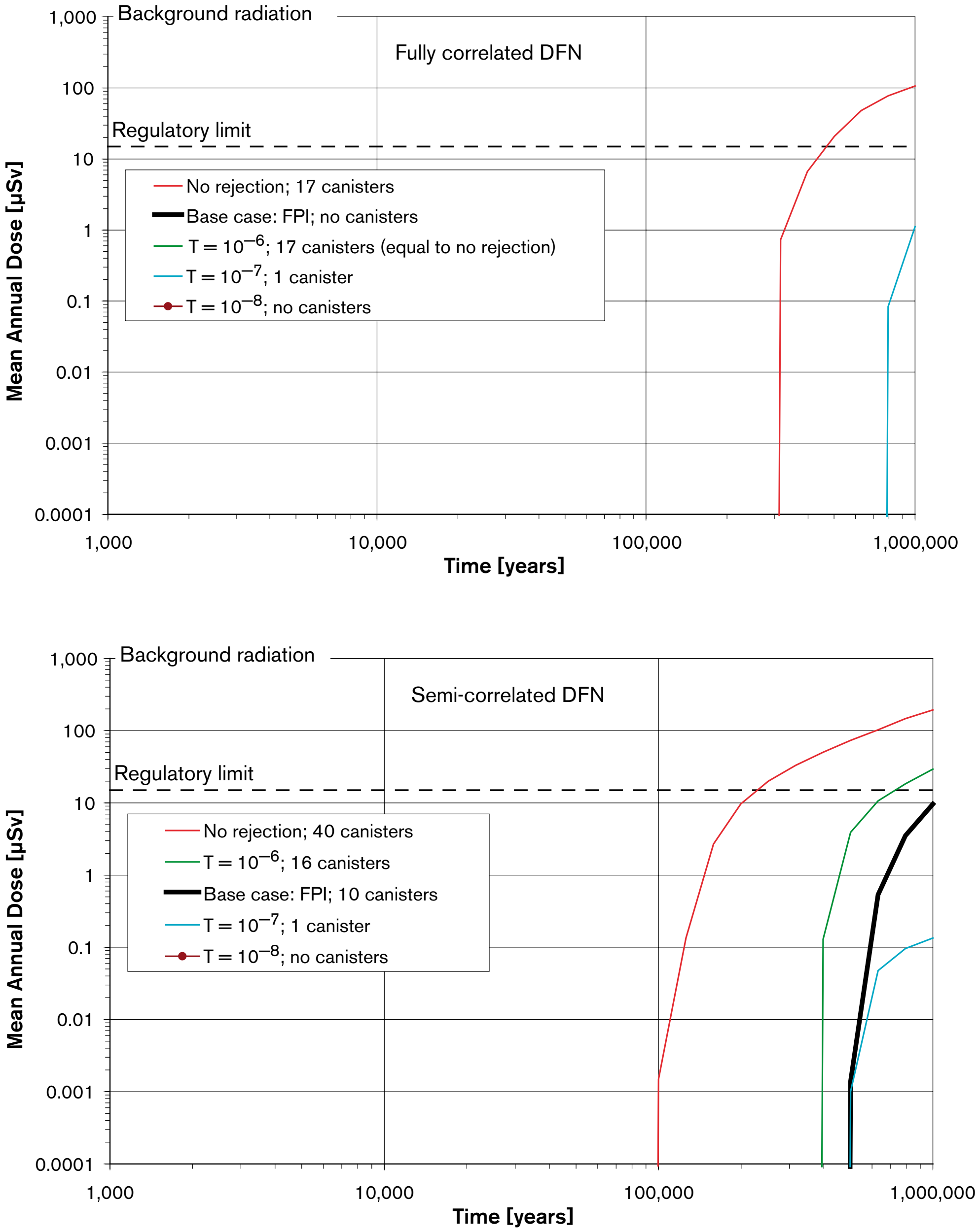


Figure 10-47. *Sensitivity to deposition hole rejection criteria for the two DFN interpretations of the Forsmark site. The number of failed canisters, out of the total of 6,000, is also indicated in each case. 1,000 realisations of the analytic model for each case.*

10.6.9 Geosphere transmission

Using the method described in section 10.5.9, geosphere transmission was calculated for the advection/corrosion failure mode. The result for Forsmark is shown in Figure 10-48. As expected, the transmissions are considerably higher for the fraction of deposition holes considered here, i.e. those with the highest flow rates. Some data for these deposition holes of relevance for the transmission calculation are presented in Table 10-11.

10.6.10 Issues related to the probabilistic nature of the calculations

Convergence

The transport model for the advection case is much simpler than that for the pinhole case. The only input variable to which the result is sensitive is the fuel dissolution rate. This also means that convergence is reached after many fewer realisations than for the pinhole case. Repeating calculations with 1,000 realisations and Latin Hypercube Sampling (LHS) yield virtually indistinguishable results.

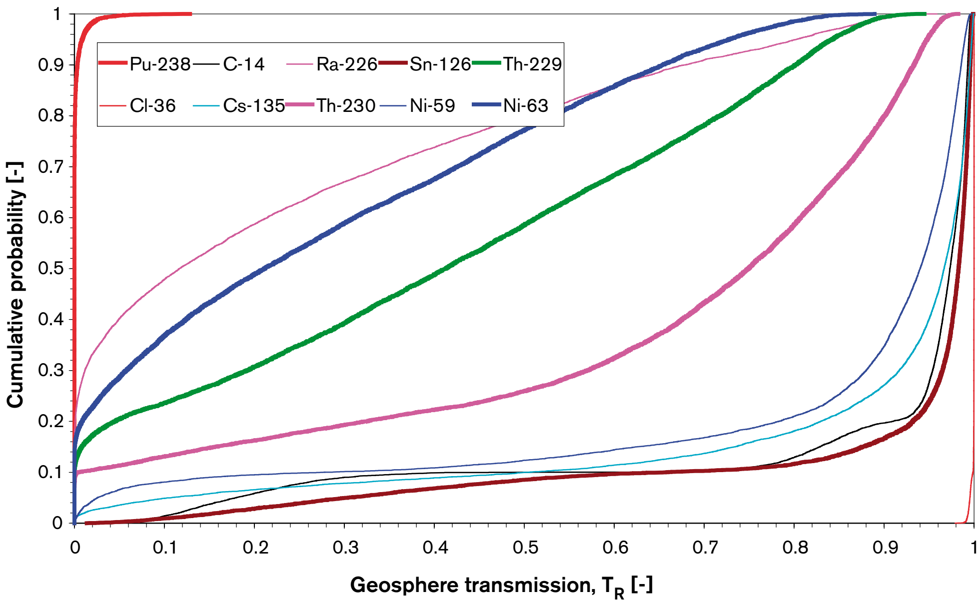


Figure 10-48. *Geosphere transmission distributions, T_R, for a selection of radionuclides, calculated probabilistically for the input distributions used in the Forsmark advection/corrosion base case.*

1,000 realisations and LHS were therefore used for all probabilistic calculations for the buffer advection case.

Risk dilution

In all probabilistic advection/corrosion cases, a fixed number of canisters, depending on the case studied, was assumed to fail at a fixed set of times. In e.g. the probabilistic base case for Forsmark, in each realisation 10 canisters are assumed to fail at the 10 fixed points in time calculated with the corrosion model described in section 9.4.9. Thus, this factor cannot give rise to risk dilution. Risk dilution could possibly be caused by the assumed triangular distribution of the delay times between the failure of the copper canister and cast iron insert. A probabilistic case where this delay time was fixed at 10,000 years has, therefore, been calculated, see Figure 10-49. As seen in the figure, both the near field and the geosphere releases are only marginally different from the base case, leading to the conclusion that the risk dilution caused by the probabilistic delay time is of minor importance.

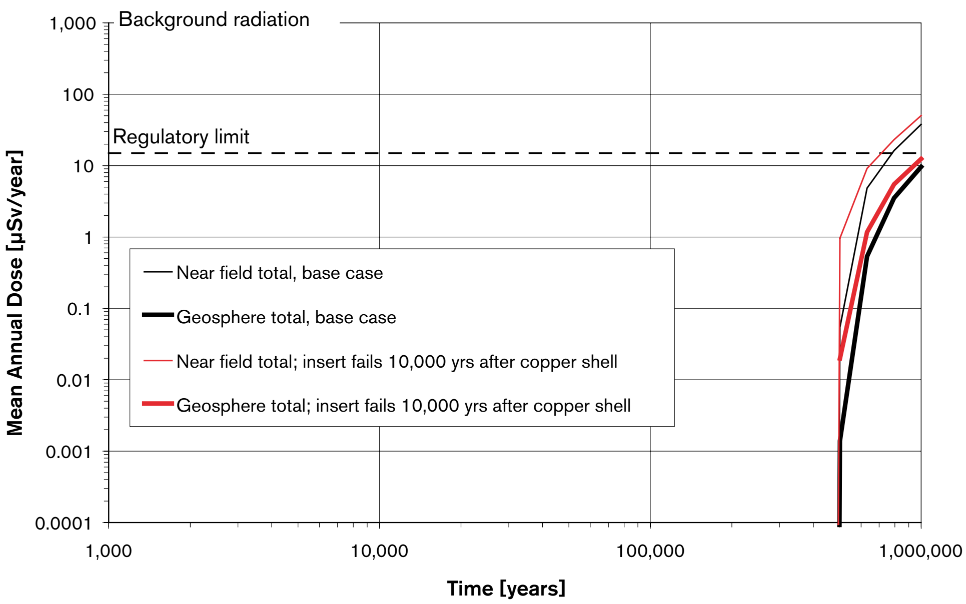


Figure 10-49. *Case to illustrate risk dilution. Black lines: Base case calculation with triangularly distributed delay between failure of copper shell and cast iron insert (1,000, 100,000, 100,000) years. Red lines: Fixed delay time of 10,000 years.*

10.7 The shear movement failure mode

Canister failure due to rock shear was demonstrated to have a low probability in the reference evolution. The only identified cause for this failure mode is the event of large earthquakes in the vicinity of the repository, see further section 9.4.5.

Pessimistic estimates of the extent of this failure mode in section 9.4.5 indicate that the probability that one out of the 6,000 canisters fails at Forsmark during the initial 120,000 year glacial cycle is $1.4 \cdot 10^{-2}$. The corresponding value at Laxemar is $7.7 \cdot 10^{-3}$. In one million years, the corresponding probabilities are $1.17 \cdot 10^{-1}$ and $6.45 \cdot 10^{-2}$, respectively (Table 9-19).

A calculation case can be formulated, based partially on the analyses carried out in section 9.4.5. The following data and assumptions are used.

- In the affected deposition holes the faulting is supposed to be so large that it causes massive failure of the canister, i.e. there will be no delay between failure and the onset of radionuclide transport and no credit from limited transport resistance in the canister.
- The shear movement will not affect the buffer to the extent that its protection against advective flow will be impaired, but the effective amount of buffer between canister and the shearing fracture is assumed to be reduced from 35 cm to 20 cm. In section 9.4.5, canister failures are cautiously assumed to occur for shear movements exceeding 10 cm in fractures intersecting deposition holes. The reduction in buffer thickness by 15 cm is selected in relation to this criterion.
- The canister failure location is assumed to fully coincide with the location of the shearing fracture. Furthermore, the shear is assumed to increase the fracture transmissivity significantly. The Q_{eq} value for the intersecting fracture is, therefore, assumed to be sufficiently high (1 m^3/yr) that it does not contribute to the transport resistance in the near field.
- The shearing fracture is likely to be among the larger in the modelled fracture network and its properties after shearing are difficult to assess. Therefore, no credit for radionuclide retention in the geosphere is taken.

All other data and assumptions are handled probabilistically as in the base case.

Figure 10-50 shows the result of a calculation where the failure of one canister at 100,000 years is postulated. The peak mean dose is almost three orders of magnitude higher than that of the base case. It is noteworthy that the consequences are very similar to those calculated deterministically for the advection/corrosion failure, see Figure 10-40. This means that if failure due to a shear movement is followed by buffer erosion, the consequences will not increase compared with the case where the buffer remains intact after the shearing.

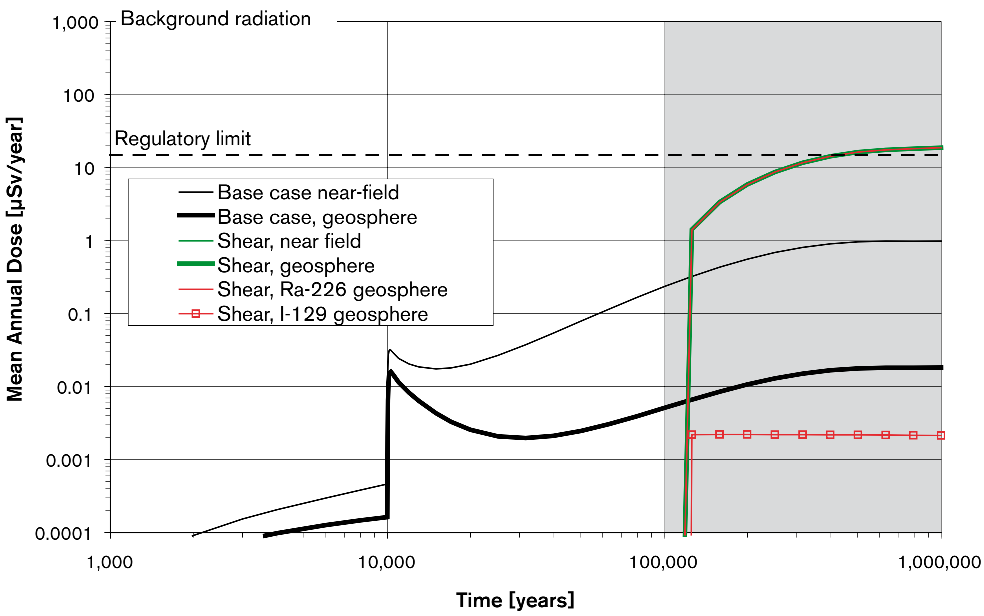


Figure 10-50. *Probabilistic results of a calculation postulating failure of one canister due to rock shear at 100,000 years. 10,000 realisations, analytic model.*

Figure 10-51 shows a probabilistic evaluation of rock shear failures using the assumptions on probability for this event from the reference evolution cited above, i.e. the probability of one out of the 6,000 canisters failing in one million years is 0.117 and 0.0645 for Forsmark and Laxemar, respectively. The doses are completely dominated by releases of Ra-226 after about 30,000 years. Before that, releases of Nb-94 dominate.

A uniform distribution of failure times for a single canister between zero and one million years is thus assumed and the results for Forsmark and Laxemar are multiplied by 0.117 and 0.0645, respectively, to account for the probability. Note that the only other site-specific data used in this case are the LDF factors. The LDF factor for Ra-226 is about 5 times higher for Laxemar than for Forsmark, leading to a slightly higher dose for Laxemar despite the lower failure probability for this site.

The probabilistic case for Forsmark has been calculated also with the numerical models, yielding an almost identical result, see last section of Appendix B.

As for the cases illustrating advection/corrosion failure, the above case represents a situation that is a direct consequence of the analysis of the reference evolution. It thus represents a contribution to the calculated risks associated with releases from the repository. This is further addressed in chapter 12.

10.7.1 Issues related to the probabilistic nature of the calculations

Risk dilution

Risk dilution for the shear movement canister failure mode needs to be considered, since canisters fail at probabilistically determined times.

An illustration is obtained by comparing the results in Figure 10-50 (postulated, deterministic failure time) with those in Figure 10-51 (distribution of failure times). If the result in Figure 10-50 is multiplied by the overall probability of the event occurring during the assessment period, i.e. 0.117, then the dose at one million years is very close to that obtained at one million years in Figure 10-51.

This is because the consequences are determined by in-growth of Ra-226 and thus in general occur long after the failure time.

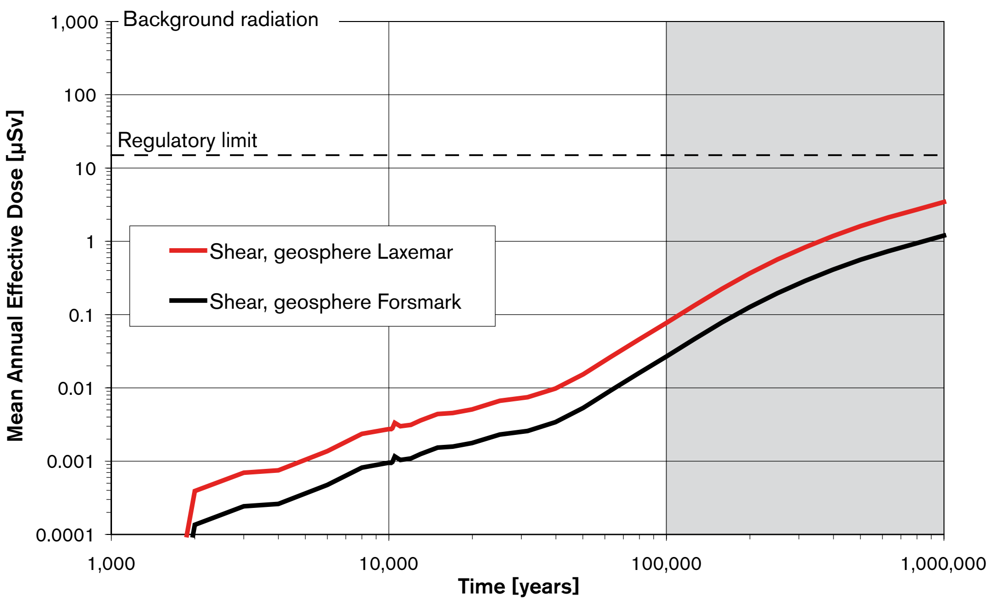


Figure 10-51. *Probabilistically calculated consequences of shear failure at Forsmark and Laxemar. Analytic model, 10,000 realisations.*

10.8 The isostatic load failure mode

This failure could occur as a consequence of the increased isostatic pressure due to a glacial overburden. The analysis of the reference evolution in chapter 9 implies that the likelihood of this failure mode is negligible. For this failure mode, the canister (both the cast iron insert and the copper shell) is bypassed, whereas the buffer and the geosphere are assumed to have intact retention properties. It thus resembles the final state of the pinhole case, i.e. its state after the occurrence of the large failure. Since that case is thoroughly treated in section 10.5, the general development of the isostatic collapse case after failure is not further described here.

10.8.1 Calculation cases

The consequences of a *postulated* failure due to isostatic collapse 10,000 and 100,000 years after repository closure is shown in Figure 10-52. Since both global causes (glacial load) and local causes (deficient material properties, higher than intended buffer density) for this failure mode can be envisaged, cases where a single canister fails and where all canisters fail are shown.

As expected, the results for a singe canister resemble those for the probabilistic growing pinhole failure base case, when the large defect has developed. The consequences of the hypothetical case of all canisters failing are simply 6,000 times higher than those for the single canister. It is interesting to note that the hypothetical case with all canisters failing, i.e. where the isolating function is assumed to be completely lost, yields consequences substantially less than background radiation. This type of bounding case is further reported in section 10.10.

10.9 Radionuclide transport in the gas phase

Radionuclide transport in the gas phase, described by the processes Bu24, BfT22 and Ge25 for the buffer, the deposition tunnel backfill and the geosphere, is addressed in this section.

Gas transport through the buffer is described in section 10.5.2 as part of the treatment of failure mode 1. The formation of a gas phase is not possible in failure mode 2 (see section 10.1), since there is no buffer that can contain the gas in that case. The following description is valid for failure modes 1, 3 and 4.

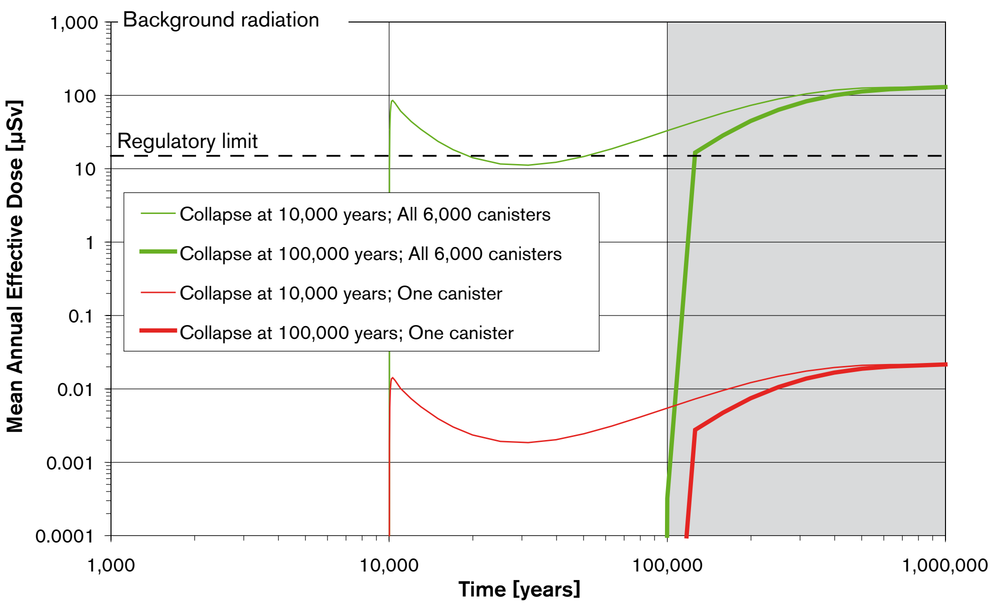


Figure 10-52. *Postulated failure of one and of all canisters at 10,000 years and at 100,000 years. The failed canisters are assumed to exhibit no resistance to radionuclide transport. All other data as for the base case for Forsmark. 10,000 realisations, analytic calculation.*

The sealing properties of the buffer make it possible for a gas pressure to build up and a pulse of hydrogen gas to be released from a defective canister due to corrosion of the iron insert. Some radionuclides could potentially enter the gas phase and thereby be transported to the surface much more rapidly than would be the case for the aqueous pathway. In practice, only C-14 and Rn-222 are likely to enter the gas phase to any significant extent.

It is assumed that if gas production exceeds the ability of the surrounding groundwater to take it into solution and transport it away from the container that a pressure will build up within and adjacent to the container. Based on experimental evidence /Harrington and Horseman 2003/, the bentonite is assumed to ultimately open by fracturing and release gas when the internal pressure exceeds 20 MPa. A rapid outflow would be expected until the pressure fell to values below ~ 10 MPa when the buffer would seal and further gas transport would be by diffusion (however, see also below). This means that half of the gas inside the canister would be released instantaneously together with the radionuclides contained in that amount of gas. Neither the buffer nor the geosphere is expected to significantly delay the transport to the biosphere.

After the initial breakthrough pulse, the pathway is expected to stay open as long a there is a gas production in the canister. After the breakthrough pulse, the gas is expected to be released at the same rate as it is produced by corrosion. The buffer will only close if the gas production falls to levels where the gas can dissolve and diffuse away.

Due to the uncertainties of the chemical form of carbon in the spent fuel, it is pessimistically assumed that the entire inventory of C-14 can enter the gaseous phase. The full inventory of Rn-222 is also assumed to be in the gaseous phase.

The time for gas breakthrough is determined by the failure time of the copper shell and the corrosion rate of the canister insert (see section 10.5.2). At that time, half of the inventory of C-14 and Rn-222 is taken to be released immediately to the biosphere. The remaining gaseous inventory (and the Rn-222 that is produced) is then taken to be released together with the gas that is produced continuously. However, this release is neglected, since it will be insignificant in comparison with the pulse release. If the release occurs in the first 10,000 years (unlikely) the release of C-14 would be ~ 10 GBq. A release of Rn-222 would be about 25 GBq if the release occurred after 100,000 years.

In /SKB 2006hi/ the calculated exposures from pulse releases of C-14 and Rn-222 are presented. C-14 may be released as methane (CH_4) or carbon dioxide (CO_2). It is assumed that if C-14 is released as methane from the repository, it will be oxidised to carbon dioxide by soil organisms. Radon is a noble gas and will not undergo chemical transformations. Two exposure cases are considered, one outdoors where radionuclides can be inhaled or consumed via uptake in plants in an area of 10,000 m^2, subject to a wind speed of 2 m/s and a mixing height of 20 m, the other inhalation of radionuclides indoors in a house with a volume of 1,000 m^3 and a ventilation rate of 2 h^{-1}. For C-14, exposure may occur via inhalation or ingestion, for Rn-222 only inhalation of Rn-222 and its radioactive daughter products needs to be taken into account. A summary of the results is given in Table 10-13.

If the gas pressure is built up during a period of glaciation, the hydrostatic pressure from the ice has to be added to the gas breakthrough pressure. This may lead to internal pressures of ~ 50 MPa inside the canister. If the retreat of the ice is rapid, this could lead to pressure drops of around 40 MPa and consequently 80% of the gaseous inventory would be instantly released.

The highest dose from a gas pulse of Rn-222 occurs in buildings. It is below the regulatory limits for an annual average life time risk for a repository, and it is considerably lower than the consequences of today limits of 200 Bq/m^3 for radon in buildings in Sweden, which gives about 2 mSv/y.

Table 10-13. Calculated annual mean life time risk from pulse releases of C-14 and Rn-222 /SKB 2006hi/.

Pathway	C-14 (10 GBq release)	Rn-222 (25 GBq release)
Ingestion	0.036 μSv/y	–
Inhalation outdoors	$4.4 \cdot 10^{-5}$ μSv/y	0.22 μSv/y
Inhalation indoors	0.0028 μSv/y	7.2 μSv/y

10.10 Additional cases to illustrate barrier functions

10.10.1 Introduction

According to SKIFS 2002:1, the safety assessment should "…include sequences of events and conditions that are selected and studied independently of probabilities in order to, inter alia, illustrate the significance of individual barriers and barrier functions."

SSI's general guidance state the following: "For repositories primarily based on isolation of the spent nuclear fuel or nuclear waste, an analysis of a conceivable loss, during the first thousand years after closure, of one or more barrier functions of key importance for the protective capability should be made separately from the risk analysis. The intention of this analysis should be to clarify how the different barriers contribute to the protective capability of the repository."

These requirements are a convenient starting point for the formulation of cases to illustrate barrier functions. In general, no losses of key functions were assessed to occur during the initial thousand years in the reference evolution, chapter 9. These cases are thus purely illustrative of the safety functions of the repository. As there is no particular time during the first thousand years that is more likely for the loss to occur, the cases are based on an initial loss, i.e. barrier defects occurring at deposition.

Some conclusions regarding loss of safety functions can be drawn from the analyses already presented. In order to provide an explicit treatment, the following cases of barrier deficiencies are postulated:

- An initial, large opening in the copper shell *for all canisters.*
- An initial absence of enough buffer to cause advective conditions in the deposition hole *for all deposition holes*.
- A combination of the above two, i.e. an initial large opening in all canisters and advective conditions due to loss of buffer *for all deposition holes*.

A loss of the radionuclide retention capability of the rock is combined with each of the three cases, yielding a total of six release situations.

The analyses are presented in two steps: i) a brief discussion of the general evolution of the system for the postulated, altered conditions and ii) a simplified radionuclide transport and dose calculation for the situation resulting as a consequence of the general evolution. The transport and dose analyses are probabilistic, since it is desirable to take the spatial variability of the properties of the deposition holes into account when evaluating the role of the geosphere.

The semi-correlated hydrogeological model of the Forsmark site has been used for these stylised calculations. It was chosen since it gives the highest consequences of the three conceptual hydrology models for Forsmark. This choice is adequate when using the results to put bounds on possible consequences of these postulated failures.

In addition to the barrier functions described above, the dissolution rate of the fuel matrix and the elemental solubilities may be important factors that limit the release of radionuclides. To illustrate the effects of these factors, the study could, in future assessments, be extended to include calculation cases with instant dissolution and unlimited elemental solubilities. These remaining cases could also be combined with the ones above.

10.10.2 Initial, large opening in the copper shell

Definition of defect

An initial opening in the copper shell of the same size as the large opening eventually resulting in the pinhole failure case, (Table 10-3), is postulated for every canister. The defect is thus so large that there is no transport resistance between the canister interior and the surrounding buffer.

General evolution

The general evolution of the near field for this case is similar to that of the isostatic collapse case. There is, however, an important difference: For the isostatic collapse case, it is assumed that both the cast iron insert and the copper shell are penetrated when the failure due to over-pressure occurs. For a postulated, initial large failure of the copper shell, it remains to decide the failure time of the insert. The situation is similar to that for the canister failure due to corrosion under advective conditions in the deposition hole analysed in section 10.6. There, the time for penetration of the cast iron insert was assumed to be triangularly distributed on (10^3, 10^5, 10^5) years, see section 10.6.2. The same distribution is used here.

Note that, in the reference evolution, a considerable fraction of the deposition holes are affected by buffer erosion to the extent that advective conditions occur in the hole, see Table 9-22. For the stylised case considered here, no such erosion is, however, assumed, in order to more clearly demonstrate the role of the canister if all other barriers are intact. Combinations of canister and buffer defects are analysed in section 10.10.4.

Consequence calculation

The calculation case is similar to the pinhole failure probabilistic case for the semi-correlated DFN model of Forsmark, multiplied by the number of canisters in the repository. Here, however, the time for onset of the release from the large failure is triangularly distributed between 1,000 and 100,000 years, rather than being fixed at 10,000 years as in the pinhole case.

Ten thousand realisations were calculated with the analytic model described in section 10.4.4. Releases from the geosphere were converted to doses using the LDF values for Forsmark. The effect of neglecting radionuclide retention in the geosphere was evaluated by applying the LDF to the releases from the near field. The results are given in section 10.10.5.

Variant: Large opening in shell and insert; "lost canister"

A case where not only the copper shell but also the cast iron insert is assumed to be initially defective has also been calculated. This is identical to the case discussed above, but where the onset of radionuclide transport is set to 1,000 years to account for the time required to saturate the buffer, to fill the canister with water and to penetrate the fuel cladding.

10.10.3 Initial absence of buffer

Definition of defect

An initial absence of enough buffer to cause advective conditions in the deposition hole is postulated for all deposition holes.

General evolution

A similar case to this has been analysed in the reference evolution, namely the situation where loss of buffer due to erosion/colloid release occurs due to exposure of glacial melt waters and subsequently leads to enhanced canister corrosion. There is, however, an important difference in that the buffer loss is now assumed to occur initially. For most of the deposition holes, the groundwater flow is not sufficient to cause canister failure during the one million year assessment period. In fact, for the Forsmark semi-correlated case, ten out of the 6,000 canisters fail during the assessment period, irrespective of whether an initial loss is assumed or if the loss over time is calculated with the buffer erosion model, see section 9.4.9, sub-heading 'Canister corrosion for a partially eroded buffer'. This case is thus almost identical to the advection/corrosion base case analysed in section 10.6.5. The only difference is the somewhat earlier failure times of the ten canisters, since the time for buffer erosion to cause advective conditions is not included. As pointed out in section 9.4.9, this latter time is probably short in comparison to the time required for the subsequent corrosion failure of the copper shell.

Consequence calculation

The calculation case is similar to the advection/corrosion failure probabilistic case for the semi-correlated DFN model of Forsmark, but with the time to onset of advective conditions set to zero.

Ten thousand realisations were calculated with the analytic model described in sections 10.6.3 and 10.6.5. Releases from the geosphere were converted to doses using the LDF values for Forsmark. The effect of neglecting radionuclide retention in the geosphere was evaluated by applying the LDF values to the releases from the near field. The results are given in section 10.10.5.

10.10.4 Combination of canister and buffer losses

Definition of defect

The copper shell and the cast iron insert are assumed to be initially defective, as described in section 10.10.2. The buffer is assumed to be initially defective as described in section 10.10.3.

General evolution

The time of onset of radionuclide transport is set to 1,000 years to account for the time required to fill the void in the deposition hole and the canister with water and to penetrate the fuel cladding. Thereafter, advective conditions are assumed in all deposition holes. No detailed evaluation of concentration limits has, however, been performed for this case. Rather, it is assumed that the advective flow is sufficiently high to dissolve all radionuclides released from the fuel. This is partly justified by the more detailed evaluation for the poorly soluble element thorium in section 10.6.5, where it was demonstrated that the high flow rates considered in that case are about two orders of magnitude too high to permit precipitation of thorium.

Consequence calculation

The same model as in the "no buffer" case is used and applied to all deposition holes.

10.10.5 Results and discussion

The results of the cases defined above are given in Figure 10-53.

No copper shells

This case is similar to the pinhole case for the semi-correlated hydrogeological DFN model for Forsmark, but with all 6,000 canisters initially having a large defect, rather than one having a growing pinhole defect and the remaining canisters being intact. The consequences at the end of the assessment period are close to 6,000 times the corresponding consequences for the pinhole case. The doses are dominated by in-growing Ra-226.

The primary safety function is lost in this case and this yields considerable consequences. It is, though, noteworthy that the calculated consequences for this stylised case are below those caused by background radiation. If geosphere retention is also neglected, the consequences increase by more than an order of magnitude.

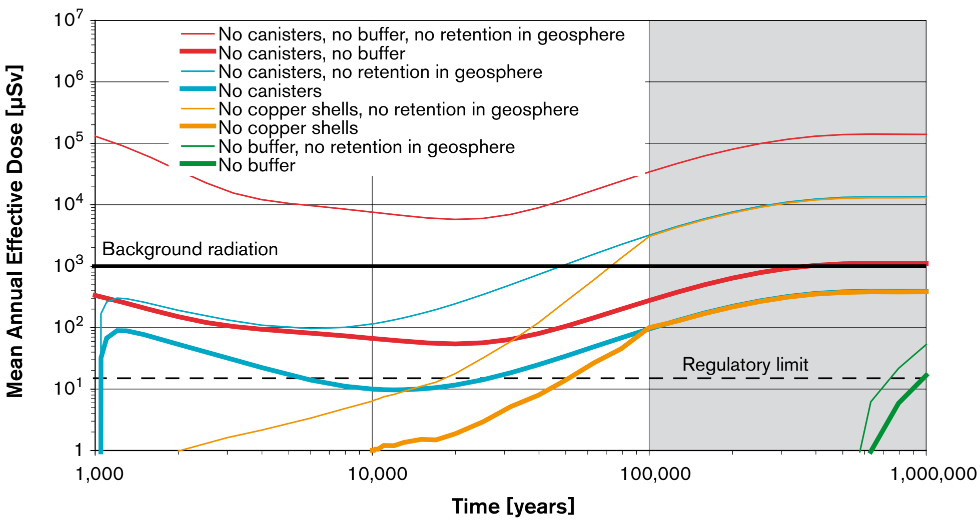


Figure 10-53. *Results of stylised cases to illustrate barrier functions. "No canisters" mean that both the copper shell and the cast iron insert are initially defective.*

No copper shells and no cast iron inserts (no canisters)

This case is similar to the case with no copper shells above, but with the time for the onset of radionuclide releases at 1,000 years. After 100,000 years, the two cases are identical since all the inserts in the first case are then assumed to be penetrated.

No buffer

This case is almost identical to the advection/corrosion base case, using the Forsmark semi-correlated hydrogeological DFN model. As mentioned above, canister failures only occur in the few (ten for this particular hydrogeological model) deposition holes where the advective flow provides canister corroding agents to the extent that failures due to corrosion occur. The doses at the end of the assessment period are about two orders of magnitude lower than background radiation and increase by less than an order of magnitude if geosphere retention is neglected.

It is noteworthy that an initial deficit of buffer in all deposition holes yields almost identical consequences to the base case, where the extent of buffer erosion is that suggested by the analysis in the reference evolution.

No canisters and no buffer

In this case, advective conditions are assumed in all deposition holes and all canisters (both copper shell and cast iron insert) are assumed to be defective. Hence, two of the key barriers are assumed to be lost in all deposition holes. Only the fuel dissolution and geosphere retention are limiting the consequences. The consequences in this case are comparable with those of the background radiation. The results also demonstrate that the geosphere retention plays a more significant role in this case; neglect of geosphere retention increases the doses by about two orders of magnitude.

This is a significant result. Although all canisters and all buffer is assumed to be initially failed, the consequences are not above background. Furthermore, the calculated doses will increase only slightly with time beyond one million years as long as the geosphere is stable and the biosphere is similar to that during an interglacial period. This is because all canisters are already failed and the only factor leading to increased releases is the on-going fuel dissolution.

Conclusions

These analyses demonstrate the multi-barrier character of the KBS-3 system, which may be less evident from the previous analyses. For example, with intact canister and buffer properties, the rock appears relatively unimportant, since most nuclides are retained already in these barriers. However, for the unrealistic case of complete initial failure of the canister and buffer barrier, Figure 10-53 clearly illustrates the importance of the rock. Similarly, unrealistically omitting the buffer, while canister and rock are kept suggests that the buffer has a minor impact, but the buffer alone is sufficient to keep doses below those from background radiation for almost 100,000 years.

In conclusion, it has been demonstrated that completely unrealistic, illustrative assumptions on early failures of even all canisters and buffer leads to long-term consequences that are comparable with natural background radiation.

It should also be remembered that the LDF values used to convert the releases to doses are constructed such that they capture the worst exposure situations during an interglacial period. During the overwhelming part of the one million year assessment period, the dose conversion factors are expected to be lower. More detailed handling of the precipitation and immobilisation phenomena could also lead to more favourable outcomes of the bounding cases presented above.

10.11 Conclusions regarding approach to sensitivity analyses

Radionuclide transport and dose calculations were performed for four reference canister failure modes: the initial, growing pinhole defect; failure due to copper corrosion for an eroded buffer; failure due to shear movement and failure due to isostatic collapse.

Of these, two were identified as possibly occurring according to the reference evolution in chapter 9 and need thus to be considered in a risk summation. These are failure due to copper corrosion for an eroded buffer, the consequences of which are shown in section 10.6.5, Figure 10-42 and Figure 10-43 for Forsmark and Laxemar, respectively, and failure due to shear movement, Figure 10-51 in section 10.7. The remaining two cases, in particular the growing pinhole defect, are included as illustrations and to learn about the retarding function of the system.

Uncertainties for the four cases have been evaluated probabilistically to capture spatial variability and also lack-of-understanding where it has been possible to define a probability distribution. Probabilistic input data are justified in the **Data report**. A number of deterministic cases have also been analysed, essentially to study the impact of uncertainties that have not been quantified.

Methods for sensitivity analysis of probabilistic results of the type emerging from the calculations of the growing pinhole defect were presented in the SR-Can Interim report /SKB 2004a section 12.4.5/. These methods are applicable also to the results of the probabilistic calculations in this report. Such sensitivity analyses have not been repeated.

Furthermore, there are a number of uncertainties that are not included probabilistically, but rather as different conceptualisations of the base case calculation of the growing pinhole failure. These concern e.g. the different hydrogeological interpretations of the site, the effect of spalling, effects of an extensive excavation damage zone and a deteriorated deposition tunnel backfill and the effect of co-precipitation of radium in the canister. These are addressed in section 10.5.7 and it is demonstrated that several of these factors could affect the result significantly, as summarised in section 10.5.10, subheading "Uncertainty related to lack of understanding vs natural variability". These analyses form an important complement to the first type of sensitivity analysis that aimed at identifying important parameters within a particular conceptualisation. For drawing conclusions, e.g. in terms of urgent R&D issues to be pursued, the sensitivity to different conceptualisations is often more important.

Of the four failure modes considered in this chapter, the growing pinhole case contains most parameters and, from that point of view, requires the most elaborated sensitivity discussion. However, it is a hypothetical case that is not assessed to contribute to the risk summation in section 12.12. The failure modes that contribute to risk, the advection/corrosion failure and the shear movement failure, contain a smaller number of uncertain parameters when analysed probabilistically. They are, however, associated with considerable conceptual uncertainties that are addressed through a set of calculation cases addressing in particular their causes, rather than their consequences. Such analyses are found in the reference evolution in chapter 9 and further in the scenario analyses in chapter 12.

In conclusion, the methods for sensitivity analyses provided in the SR-Can Interim report are deemed adequate for analysing the effect of input data uncertainties on the probabilistic calculation result, but the results of the many calculation cases that address conceptual uncertainty are often more important for deriving conclusions and providing feedback from the safety assessment.

11 Selection of scenarios

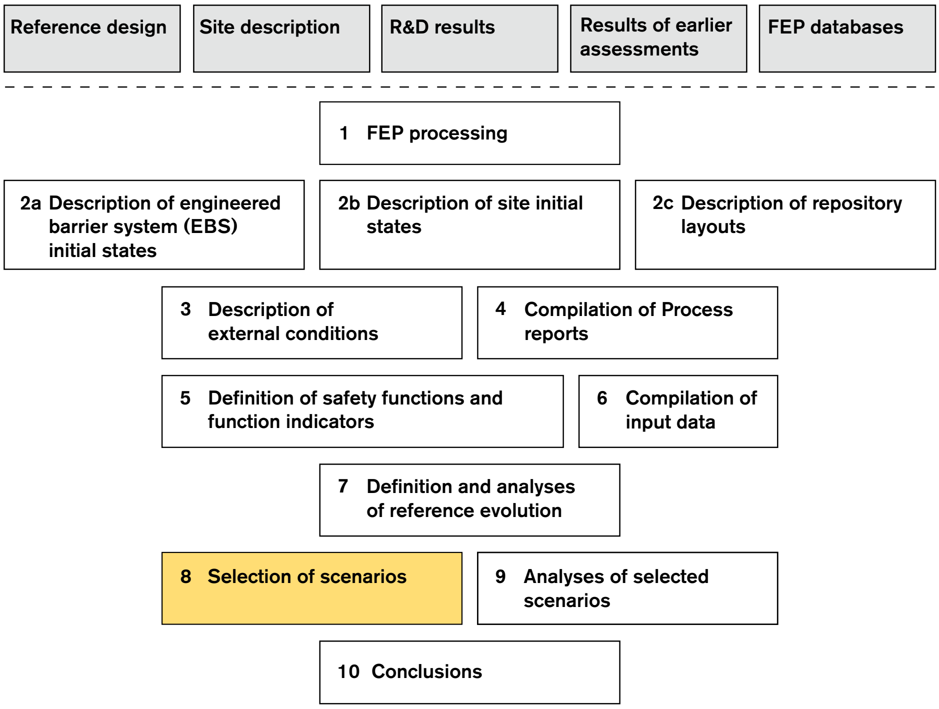


Figure 11-1. *The SR-Can methodology in ten steps (section 2.2), with the present step highlighted.*

11.1 Introduction

As mentioned in section 2.7.3, a key feature in managing uncertainties in the future evolution of the repository system is the reduction of the number of possible evolutions to analyse by selecting a set of representative scenarios.

The selection focuses on addressing the safety relevant aspects of the evolution expressed at a high level by the safety functions isolation and retardation which are further characterised by reference to safety function indicators in chapter 7.

Guiding principles in the selection of scenarios is that they should be mutually exclusive and that, together, they should cover all reasonable future evolutions. A main reason for this is that it should be possible to logically calculate the risk associated with the presence of the repository as a probability-weighted sum of risk contributions from the set of scenarios, as discussed further in section 2.9.2.

This chapter discusses regulatory requirements in the selection of scenarios in section 11.2. Thereafter, a methodology for the selection of scenarios is presented in sections 11.3 and 11.4. A discussion on uncertainties in relation to scenario selection is given in section 11.5.

11.2 Regulatory requirements and recommendations

There are several issues concerning applicable regulations that have to be taken into account in the selection of scenarios. The quantitative criterion for repository safety in Swedish regulations is a risk limit and from the analyses of the defined scenarios it must therefore be possible to draw conclusions regarding risk.

SKI's regulations SKIFS 2002:1 require that scenarios be used to describe future potential evolutions of the repository and that among these, there should be a main scenario that takes into account the most likely changes within the repository and its surroundings.

SKI's General Recommendations concerning SKIFS 2002:1 describes a scenario in the safety assessment as comprising "a description of how a given combination of external and internal conditions affect repository performance".

The General Recommendations describe three types of scenarios: the main scenario, which includes the expected evolution of the repository system; less probable scenarios, which include alternative sequences of events to the main scenario and also the effects of additional events; and residual scenarios, which evaluate specific events and conditions to illustrate the function of individual barriers. For these categories SKI's Recommendations state the following:

"*The main scenario should be based on the probable evolution of external conditions and realistic, or where justified, pessimistic assumptions with respect to the internal conditions. It should comprise future external events which have a significant probability of occurrence or which cannot be shown to have a low probability of occurrence during the time covered in the safety assessment. Furthermore, it should be based, as far as possible, on credible assumptions with respect to internal conditions, including substantiated assumptions concerning the occurrence of manufacturing defects and other imperfections, and which allow for an analysis of the repository barrier functions (it is, for example, not sufficient to always base the analysis on leaktight waste containers, even if this can be shown to be the most probable case). The main scenario should be used as the starting point for an analysis of the impact of uncertainties (see below), which means that the analysis of the main scenario also includes a number of calculation cases.*

Less probable scenarios should be prepared for the evaluation of scenario uncertainty (see also below). This includes variations on the main scenario with alternative sequences of events as well as scenarios that take into account the impact of future human activities such as damage inflicted on barriers. (Damage to humans intruding into the repository is illustrated by residual scenarios, see below). The analysis of less probable scenarios should include analyses of such uncertainties that are not evaluated within the framework of the main scenario.

Residual scenarios should include sequences of events and conditions that are selected and studied independently of probabilities in order to, inter alia, illustrate the significance of individual barriers and barrier functions. The residual scenarios should also include cases to illustrate damage to humans intruding into the repository as well as cases to illustrate the consequences of an unclosed repository that is not monitored."

Regarding scenario probabilities, the SKI recommendations state: "*The probabilities that the scenarios and calculation cases will actually occur should be estimated as far as possible in order to calculate risk.*"

SSI's general guidance on application of SSI's regulations defines a scenario as a "*description of the development of the repository given an initial state and specified conditions in the environment and their development*".

Regarding the choice of scenarios, SSI's general guidance states the following:

"*The assessment of the protective capability of the repository and the environmental consequences should be based on a set of scenarios that together illustrate the most important courses of development of the repository, its surroundings and the biosphere.*

Taking into consideration the great uncertainties associated with the assumptions on climate evolution in a remote future and to facilitate the interpretation of the risk to be calculated, the risk analysis should be simplified to include a few possible climate evolutions.

A realistic set of biosphere conditions should be associated with each climate evolution. The different climate evolutions should be selected so that they together illustrate the most important and reasonably foreseeable sequences of future climate states and their impact on the protective capability of the repository and the environmental consequences."

"*The risk from the repository should be calculated for each assumed climate evolution by summing the risk contributions from a number of scenarios that together illustrate how the more or less probable courses of development in the repository and the surrounding rock affects the repository's protective capability and environmental consequences. The calculated risk should be reported and evaluated in relation to the criterion of the regulations for individual risk, separately for each climate evolution.*"

SSI's General Guidance states: "*A number of scenarios for inadvertent human impact on the repository should be presented. The scenarios should include a case of direct intrusion in connection with drilling in the repository and some examples of other activities that indirectly lead to a deterioration in the protective capability of the repository, for example by changing groundwater chemistry or the hydrological conditions in the repository or its surroundings. The selection of intrusion scenarios should be based on present living habits and technical prerequisites and take into consideration the repository's properties.*

The consequences of the disturbance of the repository's protective capability should be illustrated by calculations of the doses for individuals in the most exposed group, and reported separately apart from the risk analysis for the undisturbed repository. The results should be used to illustrate conceivable countermeasures and to provide a basis for the application of best available technique".

SSI's General Guidance states the following: "*An account need not be given of the direct consequences for the individuals intruding into the repository.*" It is noted that this is contrary to SKI:s view, where these situations are included among the residual scenarios.

SSI's guidance also mention "special scenarios": "*... an analysis of a conceivable loss, during the first thousand years after closure, of one or more barrier functions of key importance for the protective capability should be made separately from the risk analysis. The intention of this analysis should be to clarify how the different barriers contribute to the protective capability of the repository.*"

11.3 Method for scenario selection

Given the regulatory requirements and the general considerations discussed in the previous section, a method for the selection of scenarios in five steps has been developed as explained below.

1. Definition of the main scenario

A main scenario is defined, according to the SKIFS 2002:1. The main scenario is split into two variants, based on the two variants analysed in chapter 9.

A base variant is defined based on the results of the analysis of the base variant of the repository evolution presented in chapter 9. It thus builds on the reference initial state described in chapter 4, the handling of processes established in the Process reports and summarised in chapter 6, and on a repetition of the last glacial cycle. There are however a number of issues where alternative developments/interpretations are discussed in the analysis of the reference evolution in chapter 9 and for which a clear decision on the handling in the main scenario is required in order to obtain an unambiguous definition of it. These include alternative interpretations of the hydraulic understanding of the site and the handling of earthquakes of sufficiently large magnitude to potentially cause canister damage, which was demonstrated to be a low probability event.

An additional "greenhouse" variant of the main scenario is defined as a means of addressing the requirement in SSI's general guidance of analysing alternative climate evolutions. This is identical to the base variant except that the external conditions are assumed to be consistent with effects of increased greenhouse warming. This variant of the main scenario is thus based on the analysis of the greenhouse variant in section 9.6 of chapter 9.

SSI uses "climate evolutions" as a hierarchical level above the scenarios. In order to not complicate the description further, the different types of climate evolution mentioned in SSI's general guidance are handled as variants of the main scenario.

The main scenario is defined in detail in section 12.2.1, chapter 12. Its consequences is analysed in section 12.2.

2. Selection of additional scenarios based on potential loss of safety functions

A main factor governing scenario selection is the concern that the intended safety functions (chapter 7) of the repository should be upheld. Therefore, the safety functions are used to structure the selection of additional scenarios. This is the main approach for addressing the issue of *less probable scenarios*, in SKIFS 2002:1.

Three distinct canister failure modes, due to corrosion, isostatic over pressure and shear movement, respectively, each generate a scenario. Three 'failed' states of the buffer; advective, frozen and transformed, are also considered as scenarios. The canister scenarios are systematically combined with the buffer scenarios.

For each selected scenario, uncertainties related to initial state factors, processes and external conditions that are not covered in the main scenario are considered. In e.g. the case of canister failure due to isostatic overpressure, inadequacies in the manufacturing of the load-bearing canister insert, higher than reference buffer swelling pressures and extreme ice sheets yielding high groundwater pressures are considered.

The FEP chart, see section 7.6, aids in ensuring that all conceivable routes to deficiencies in system performance are captured. Systematic analyses of initial state factors, long-term processes and external conditions possibly contributing to each of these scenarios are made. The results of the analysis of the main scenario, with all the coupled FEPs and uncertainties considered there, is an important starting point for this assessment.

Based on this information, an assessment of whether each scenario is to be considered as "less likely" or "residual" is made. In the former case, the likelihood of the scenario is also assessed, to the extent that this is possible.

The consequences of the scenario for isolation and retardation are assessed, in general, through modifications to calculations used in analysing the main scenario.

These scenarios also cover many of the residual scenarios required by SKI's regulations and SSI's general guidance to analyse *the significance of barriers and barrier functions*. However, a more clear-cut analysis of the latter cases was presented in section 10.10.

The selection of additional scenarios is described in detail in section 11.4.

The analyses of the selected additional scenarios are described in chapter 12, from section 12.8 onward.

3. Scenarios related to future human actions

A set of scenarios related to future human actions was also defined and analysed. Human intrusion scenarios resulting in a degradation of system performance, are to be considered as "less likely scenarios" according to SKI's regulations, but not included in the risk summation according to SSI's general guidance. SKI requires residual scenarios to illustrate *damage to humans intruding into the repository* and cases to illustrate the consequences of an *unclosed repository that is not monitored*.

The selection and consequence analyses of scenarios related to future human actions for a sealed repository are reported in section 12.10. After elaborate FEP analysis, two cases are selected for consequence assessments, see Table 11-1 and section 12.10.

Scenarios relating to unsealed repositories are, due to time constraints, not analysed in SR-Can. To some extent, these cases are covered by the bounding calculations reported in section 10.10.

4. Other residual scenarios, etc

Any other scenarios that are, for any reason, considered as necessary in order to obtain an adequate set of scenarios are also defined. These could include scenarios directly identified in the FEP analysis but not according to the criteria above.

No such issues have been identified in SR-Can. There are, therefore, no residual scenarios in addition to those defined according to the procedure described in steps 2 and 3 above. However, a number of bounding cases have been calculated, see section 10.10. These can be seen as additional scenarios defined in order to illustrate barrier functions.

5. Combination of scenarios

For the scenario selection to be comprehensive, combinations of the scenarios and variants must be considered. This is done when all the variants and residual scenarios have been selected and analysed. The number of possible combinations could become large, even considering that mutually exclusive scenarios should not be combined, and a practical approach for handling this situation has to be adopted. The problem is further complicated by the fact that each variant may be investigated through a number of calculation cases.

Related to the issue of combination of scenarios is that of different event sequences. The sequence in which different events or aspects of the evolution occur may be important for the evolution of the repository. This is explicitly addressed within each scenario.

The evaluation of combinations is described in section 12.11.

11.4 Scenarios derived from safety function indicators; selection and structure for analysis

11.4.1 Selection of additional scenarios

Uncertainties not covered by the main scenario

As discussed above, the main scenario is based on the reference evolution. The main scenario is defined in detail and analysed in section 12.2 and covers the evolution of the repository system for a *realistic* initial state of the repository and for an example of a *credible* evolution of external conditions over the assessment period.

However, as implied by the terms "realistic" and "credible", significantly different conditions and hence different repository evolutions cannot be ruled out. There are uncertainties regarding the initial state, the processes governing the evolution and the external conditions. Not all these uncertainties are covered in the main scenario and they need to be explored in a set of additional scenarios. The evaluation of uncertainties explores whether more extreme initial state and external conditions need to be included in the analyses, and if uncertainties related to the handling of processes warrant further analyses.

Approach to selection of additional scenarios

A structured selection approach is required in order to obtain a set of additional scenarios that can be argued to be comprehensive. The purpose of the scenarios is to aid in a critical evaluation of repository safety and it is, therefore, natural to use the safety functions and the safety function indicators discussed in chapter 7 when seeking a structure for scenario selection.

The approach taken in SR-Can is to use the safety functions with their indicators and indicator criteria as expressed in Figure 9-2 to define a set of scenarios that are distinguished by their different status of the safety functions. The scenarios thus consider cases where the possibilities of partially or completely loosing one or several of the safety functions are evaluated. Examples are scenarios where canisters fail due to corrosion, isostatic overpressure or shear movements. The scenarios are defined without consideration of their likelihood.

In the analyses of the selected scenarios, all conceivable routes to the loss of the safety function that defines the scenario are critically examined, in order to evaluate the likelihood of the scenario, its consequences and its potential contribution to the risk summation for the repository. From the understanding of the functioning of the repository system, this examination is focussed on the factors contributing to the particular safety function, thus focussing the evaluation of each scenario on a limited set of uncertain factors. The FEP chart, Figure 7-3, is an aid when identifying such factors. Another important basis for the evaluation is the analysis of the reference evolution, where all the factors covered in the FEP chart are analysed for reference conditions.

The approach taken when selecting scenarios is thus to ask the question: What characterises a failed repository? The answer to that question is a list of states where one or several safety functions are not upheld, e.g. a situation where advection is the dominant transport mechanism in the buffer. The analyses of the so selected scenarios then focus on identifying and quantifying all conceivable routes to these failed states. The goal, for each scenario, is to either dismiss it, since no credible such route can be identified, or to assess its likelihood and consequences so that it can be included in the risk summation for the repository.

Elaboration of list of safety functions for the scenario selection

The primary safety function of a KBS-3 repository is isolation. Therefore, an obvious step when selecting scenarios based on safety functions is to select three *canister scenarios* based on the three safety functions directly related to canister isolation, i.e. scenarios characterised by (Figure 9-2)

- Canister failure due to corrosion, safety function C1.
- Canister failure due to isostatic pressure, safety function C2.
- Canister failure due shear movement, safety function C3.

For the further selection of scenarios, the list of safety functions requires some elaboration, since many of the safety functions are overlapping or inter-connected. The buffer safety function 'limit advective transport' is e.g. connected to the canister safety function 'provide corrosion barrier' in that corrosion is strongly enhanced if advective conditions prevail in the buffer. A comprehensive evaluation of the canister corrosion scenario must thus encompass also an evaluation of advection in the buffer. In general, each of the above three scenarios related to canister failure needs to be combined with relevant states of the buffer in order to obtain a comprehensive evaluation.

Derivation of critical buffer states

From the safety functions, four buffer states related to safety can be derived:

- A basic state is the *intact buffer*, where all buffer safety functions are upheld.
- Another state directly derivable from the safety functions is the buffer with advective conditions, relating to loss of the safety functions Bu1a or Bu1b. A special case of advective conditions occurs when the buffer is not able to keep the canister in its intended vertical position so that, in the most extreme case, the canister has sunk to the bottom of the deposition hole. The buffer diffusion barrier is then lost and the mass transfer between the groundwater and the canister is controlled by advection in the surrounding rock and possibly also in the buffer. This relates to the function indicator Bu6.
- Another state needing consideration is the *transformed buffer*. This is related to the buffer function Bu5 that concerns the maximum temperature of the buffer. There are, however, a number of additional potential causes for, or routes to, buffer transformation that also need to be considered in order to fully evaluate this buffer state.
- Finally, a *frozen buffer* must be considered, relating to the function indicator Bu7.

These are four distinct buffer states that emerge from the list of safety function indicators, and also from the general understanding of the role of the buffer and its evolution over time in a KBS-3 repository. Three buffer safety functions are not included in the above account. These are the functions Bu2, Bu3 and Bu4 which are related to the buffer's ability to filter colloids, to eliminate microbes and to damp rock shear, respectively. These safety functions are related to the buffer density and swelling pressure but not to distinct physical states of the buffer. They are considered in the appropriate scenarios as indicated in Figure 11-2 below.

11.4.2 Structure for analysis of the additional scenarios

Approach

The analysis of the additional scenarios uses the main scenario as a point of departure. The analysis of each of the scenarios then focuses on an evaluation of possible uncertainties of relevance to the particular scenario, specifically uncertainties that are not addressed in the analysis of the main scenario. These uncertainties may be related to the initial state of the repository, to processes governing repository evolution or to external influences.

For example, in the analysis of the buffer advection scenario, the following issues are among those addressed:

- Could the initial density of the buffer – density being a critical factor for the occurrence of buffer advection – for any reason be lower than the reference initial density assumed in the main scenario?
- Are there remaining conceptual uncertainties related to the buffer colloid release/erosion process (leading to loss of density) that are not addressed by the models used to quantify this process in the main scenario?

- Could the groundwater composition and flow be less favourable for the arising of buffer advection than what follows from the reference external conditions, a repetition of the Weichselian glacial cycle, in the main scenario?

Combination of scenarios related to buffer functions and canister functions

Each of the three failed buffer states is evaluated as a separate scenario, critically examining all identified routes to them, as described under the previous sub-heading. Their consequences in terms of canister failures and release of radionuclides are, however, not evaluated until they are combined with the three canister scenarios defined above. By this procedure, much of the issue of combining scenarios is handled. Figure 11-2 shows schematically how the scenario analysis based on safety functions is carried out. Note that, if the analysis of a particular buffer scenario comes to the conclusion that it is to be considered as residual, then it is not propagated to the canister scenarios defined above.

The safety functions related to the rock are evaluated *within* each of these combinations through the consideration also of uncertainties related to geosphere and external conditions when evaluating both the buffer states and the canister failure modes (see buffer advection example above). This is necessary since e.g. the potential occurrence of advective conditions in the buffer is directly related to the groundwater composition through the safety function R1c (groundwater minimum ionic strength) and the occurrence of canister failures due to rock shear is directly related to rock movements through the safety function R3a, see further Figure 11-2.

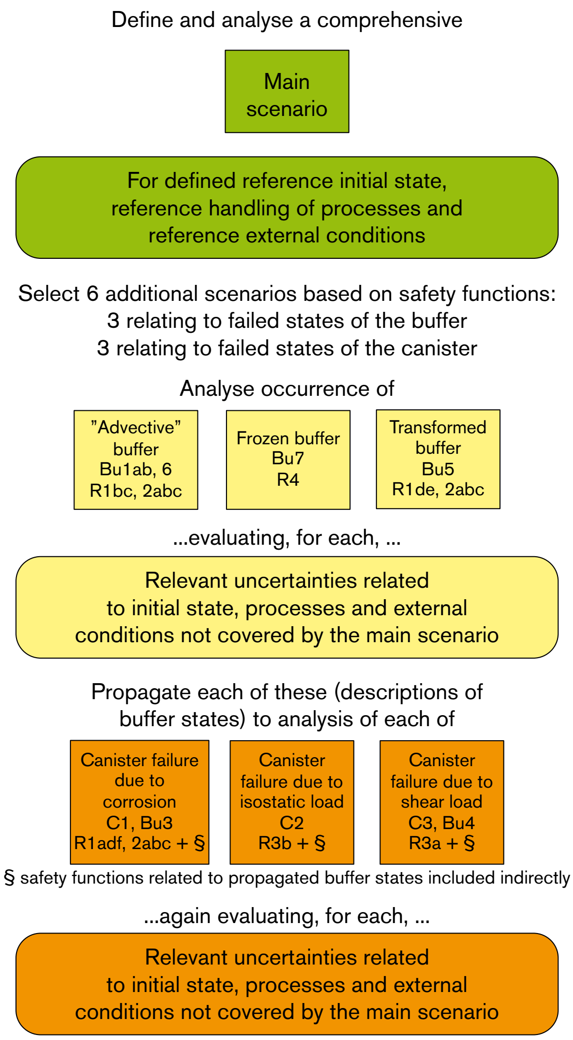


Figure 11-2. *The main components of the scenario selection and analysis procedure where safety functions of the canister and the buffer are used to derive the additional scenarios (yellow and orange squares). The safety function indicators of relevance in each scenario are given with the same nomenclature as in Figure 9-2.*

Approach to retardation

The approach presented so far concerns direct failure modes of the canister, and how the buffer safety functions relates to these failure modes, i.e. it is related to the primary safety function of the repository. The approach taken to evaluate also the secondary safety function, retardation, is to determine, for each of the canister failure modes, uncertainties related to retardation. This approach is strongly motivated by the fact that each canister failure mode has distinct consequences for retardation, thus requiring a specific evaluation of uncertainties related to this characteristic.

Within each scenario, uncertainties related to the relevant aspects, for that particular scenario, of retardation properties of the fuel, the canister, the buffer, the deposition tunnel backfill and the geosphere are evaluated. Many of the uncertainty issues overlap with those relevant for isolation. For example, advective conditions in the buffer are relevant for both isolation, through the inward transport of canister corroding agents, and for retardation, in relation to the outward transport of radionuclides.

Classification as 'less likely' or 'residual'

A key point in the evaluation of the scenarios is to arrive at an assessment of whether there is any appreciable probability of the scenario occurring. If this is the case, the scenario is classified as "less likely" and included in the risk summation, otherwise it is defined as "residual".

There is no numerical limit to the probability below which a scenario is considered as residual in SR-Can. The approach taken is that if it can be argued that a scenario is not physically reasonable, given cautious evaluations of current knowledge of e.g. barrier properties, processes and effects of future climate changes, then the scenario is considered as residual.

A more precise definition, covering all possible situations, is not seen as possible or meaningful to formulate; the reader is referred to the implementation in chapter 12 for detailed applications of the approach.

Common causes affecting several scenarios, combination of scenarios

As mentioned above, through the combination of buffer- and canister-related scenarios, much of the issue of combining scenarios is handled. There are, however, some additional considerations regarding scenario combinations.

Combinations of the canister failure scenarios need to be considered. Are the identified failure modes independent, so that their risk contributions can be added, i.e. are their causes independent? Furthermore, is the response to a particular failure cause independent of whether another cause is acting simultaneously? The combination of isostatic load and loads caused by a shear movement on a canister illustrates both these issues: Is the likelihood of an earthquake independent of whether a major ice sheet, potentially generating high groundwater pressures, exists above the repository? If these two load situations can exist simultaneously, is the canister response to an earthquake-induced shear movement independent of the existence of an isostatic overpressure?

Also combinations of the buffer states need to be considered in a similar way. The freezing temperature of the buffer is e.g. dependent on the buffer density which is lowered when advective conditions prevail in the buffer.

When the analyses described in Figure 11-2 were completed, the issue of combinations was revisited through a structured approach aiming at a comprehensive treatment of scenario combinations, see further section 12.11.

Risk summation

The risk contributions from each of the scenarios, including that of the main scenario, form the basis for a risk summation, when the scenario analyses are completed.

Risk contributions from scenarios that are independent are added, if combinations do not lead to higher consequences than the individual scenarios. If combinations may lead to higher consequences, the likelihood and consequence of such combinations are also assessed.

Scenarios with common causes, but for which the consequences do not affect each other can be handled individually.

In the summation, it is also observed whether some sub-sets of the scenarios are mutually exclusive, in which case the total consequence of the sub-set cannot exceed that of the scenario with the highest consequence in the sub-set. This is a way of bounding the risk from a set of mutually exclusive scenarios (or cases within a scenario) if the basis for apportioning probabilities among the members of the set is limited.

Relation to main scenario

For several safety function indicators, criteria exist such that if the criterion is fulfilled, a certain phenomenon, negatively impacting safety, is excluded. Freezing of the buffer is e.g. excluded if the buffer temperature is above −5°C. If the criterion was assessed to be fulfilled in the main scenario, then the evaluation focuses on conceivable routes, beyond those covered by the main scenario, to a violation of the criterion. Guided by the FEP chart, uncertainties related to initial state and external conditions as well as conceptual uncertainties associated with processes are explored.

If the indicator is not associated with a criterion, or if the criterion was assessed to be violated in the main scenario, then it is evaluated if the value of the safety function indicator could be less favourable for safety than is the case in the main scenario. Again, uncertainties related to initial state, external conditions and processes are explored.

11.4.3 Template for assessment of scenarios based on safety function indicators

A common template is followed in the analysis of all scenarios derived from safety function indicators. The template is given below, and, for each heading, a brief description of the information that can be expected under it is given. Minor modifications of the structure for a specific scenario are made as appropriate, but the contents given below are always covered.

Safety function indicator(s) considered

The safety function indicator under consideration is stated. If the scenario concerns a safety function indicator for which a criterion of adequate safety function has been determined, it is stated that this criterion is assumed to be violated. The degree to which it is violated is specified as the analysis continues.

It is clarified whether the indicator affects isolation and/or retardation.

In some cases, several safety function indicators are evaluated within the same scenario, since they all indicate circumstances that are relevant to a common safety function. If this is the case, all involved indicators and their dependencies are explained. The indicator "buffer hydraulic conductivity" is e.g. related to the indicators "buffer swelling pressure", "minimum ionic strength of groundwater", "limited salinity" and "backfill compressibility".

Treatment of this issue in the main scenario

The treatment in the main scenario is described briefly.

Qualitative description of routes to this situation

Based on the FEP chart, the factors contributing to the possible occurrence of the scenario are presented. The presentation results in a listing of i) initial state factors, ii) processes and iii) external conditions to be considered.

Quantitative assessment of routes to this situation

A critical evaluation of the analysis of the main scenario is carried out, in order to exhaustively evaluate all conceivable routes to the situation characterising the scenario. Uncertainties possibly remaining after the treatment in the main scenario are addressed. For example, initial state conditions not covered by the reference initial state are addressed as are external conditions not covered by the reference external evolution in the main scenario. Conceptual uncertainties related to the processes involved are discussed.

An analysis of the importance of the sequence in which different processes or events occur is made.

Unless overridden by assumptions related to this particular scenario, the scenario is analysed for both the reference glacial cycle and the greenhouse variant, to satisfy SSI's requirement that each scenario is to be analysed for several alternative climate evolutions.

Categorisation as "less probable" or "residual" scenario

Based on an assessment of plausibility of the routes to the situation, the scenario is characterised as either a "less probable" scenario if its occurrence can not be ruled out or otherwise as a "residual" scenario. In the former case, the consequences of the scenario are included in the risk summation for the repository, which means that an assessment of the likelihood of the scenario's occurrence is made. In some cases it is relevant to consider both the probability that a single deposition hole is affected and the probability of all (or many) holes being affected. In the "residual scenario" case, the consequences of the scenario are not included in the risk summation for the repository.

Quantitative consequence analysis/discussion – isolation and retardation

The consequences of violating the safety function indicator(s) in question are quantified for a *postulated* violation. Consequences for i) isolation and ii) retardation are considered. Depending on the case, it may be relevant to consider consequences for a single canister or for all canisters in the repository. Simple, bounding estimates are used in some cases.

Conclusions

Brief conclusions, based on the results under the previous headings, are drawn.

11.5 Handling of uncertainties within scenarios

This section summarises how different types of uncertainties are handled in the selected scenarios.

As mentioned in section 2.7, uncertainties can be broadly categorised as system uncertainty, conceptual/model uncertainty and data uncertainty. It needs to be assured that all these uncertainties are appropriately handled in the assessment. Since the distinction between the main scenario and additional scenarios, and also in the applicable regulations, is largely related to uncertainties and the likelihood of occurrence of relevant phenomena, the overall strategy for handling of uncertainties is closely related to the selection of scenarios.

The general discussion on handling of uncertainties in section 2.7 is further developed below, based on the process of scenario selection.

11.5.1 The main scenario

As mentioned above, the main scenario is based on the reference evolution analysed in chapter 9 and thus covers a reference initial state, based on a realistic description of the repository system immediately after closure and a realistic description of the site(s) with uncertainties, based on the results of site investigations and subsequent site descriptive modelling. Furthermore, all processes identified as relevant for long-term safety are addressed in the main scenario, in accordance with documentation in the process reports. The main scenario also covers reference external conditions, essentially a repetition of the last glacial cycle and, in a variant, a case with an extended temperate climate assumed to be due to an increased greenhouse effect. Future human actions, like drilling or other use of or influences on the host rock are, by definition, not included in the main scenario.

The following is a brief account of how the three classes of uncertainty defined in section 2.7.1 are addressed in the main scenario.

General evolution

System uncertainty, FEPs included: *All identified internal processes are considered* and included in accordance with prescriptions developed in the **Process reports** and summarised in Table 6-2 through Table 6-6. External conditions are included as a base variant in the form of a model reconstruction of the last glacial cycle, the Weichselian, and in a more stylised greenhouse variant of the main scenario. This means that *all external, climate related processes/phenomena are considered* in the main scenario. The extent to which the processes and phenomena are addressed is, however, limited to the the range covered by the two variants, meaning that e.g. more extreme glacial loads than those in the reference evolution are not considered. FHA FEPs are by definition excluded from the main scenario, as are FEPs related to altered initial states like an abandoned unfilled repository.

Conceptual uncertainty: Models are selected, taking into consideration conceptual uncertainty, according to prescriptions in the **Process reports** (summarised in Table 6-2 through Table 6-6) and the **Climate report**. In many cases, conceptual uncertainties are handled pessimistically. They may also be addressed by formulating variant representations, as in the case for groundwater flow models. These models constitute the reference conceptual models for the repository evolution in SR-Can. They are summarised in the **Model summary report**.

Data uncertainty: Input data for modelling, with uncertainties, are taken from the **Data report** for many of the calculations related to the general evolution in the main scenario. Reference initial state data are used in accordance with the definition of the main scenario. This means that those uncertainties regarding manufacturing flaws and deficiencies that are not covered by the reference initial state are not included in the main scenario.

Radiological consequences

System uncertainty, FEPs included: All FEPs considered in the general evolution are included indirectly, since data for the consequence calculations are derived from the result of the analysis of the system evolution. All FEPs directly related to radionuclide transport in the engineered barriers and in the geosphere are included in accordance with prescriptions in the **Process reports** (summarised in Table 6-2 through Table 6-6). The biosphere models are discussed in /SKB 2006hi, Avila 2006, Avila et al. 2006/, but not fully considered in this framework.

Conceptual uncertainty: Models for radionuclide transport are selected, taking into consideration conceptual uncertainty, according to prescriptions in the **Process reports** (summarised in Table 6-2 through Table 6-6). In many cases, conceptual uncertainties are handled pessimistically. They may also be addressed by formulating variant representations, as is the case for groundwater flow models. These models constitute the reference conceptual models for the radiological consequence calculations in SR-Can. They are summarised in the **Model summary report**.

Conceptual uncertainties for the biosphere models are discussed in /SKB 2006hi, Avila et al. 2006/.

Data uncertainty: All data for the consequence calculations are given in the **Data report**. In most cases, input data uncertainties, frequently also those originating from conceptual uncertainties, are quantified in the form of a set of input data distributions. Correlations between these distributions are considered and included as appropriate. Uncertanity of input data to the biosphere modelling is considered in /SKB 2006hi, Avila 2006, Avila et al. 2006/.

11.5.2 Additional scenarios based on potential loss of safety functions

A main purpose of the selection and analysis of a number of additional scenarios based on the potential loss of safety functions is to evaluate the effect of uncertainties not covered in the main scenario and, if appropriate, to include additional scenarios in the overall risk summation if this additional uncertainty analysis so requires.

In each of these additional scenarios, the handling of relevant aspects in the main scenario is revisited and system, conceptual and data uncertainties are revisited and extended or modified, as appropriate.

General evolution

System uncertainty, FEPs included: All relevant FEPs potentially affecting the safety function under consideration are included, based on the FEP chart and the SR-Can FEP catalogue.

Conceptual uncertainty: Conceptual uncertainty beyond that covered by the reference conceptual models used in the main scenario is considered.

Data uncertainty: Input data beyond those used in the main scenario are considered, i.e. initial state conditions beyond the reference initial state and external conditions beyond those covered by the two variants of the main scenario.

As only those aspects of the general evolution relevant for the safety function(s) under consideration are considered, the analysis of the general evolution is much less extensive than that in the main scenario.

Radiological consequences

The radiological consequences for these additional scenarios are generally calculated through modifications to the calculation cases in the main scenario. The alterations made are based on the conclusions from the analysis of the general evolution for the altered situation, if this evolution implies canister failures.

If the altered evolution does not imply canister failures, then failures related to the safety function under consideration are postulated and the scenario is classified as a residual scenario. The consequence calculations for such cases often provide bounding estimates e.g. in a case where all canisters are assumed to fail at a specific time.

11.5.3 FHA and other stylised scenarios

FHA scenarios obviously include FHA FEPs that are, by definition, not included in the main scenario. The aspects of the general evolution that are not affected by the FHA FEPs are assumed to develop as in the main scenario, meaning that conceptual and data uncertainty for these aspects are handled as in the main scenario. Aspects related to the FHA FEPs are handled in a stylised manner that gives a reasonable coverage of uncertainties.

Other stylised scenarios such as the case of an open, abandoned repository are treated similarly.

11.6 Summary of scenario selection

Table 11-1 summarises the result of the scenario selection carried out as described in this chapter.

The main scenario, which is closely related to the reference evolution described in chapter 9, forms the basis for selection of additional scenarios.

The safety functions are used as a basis for the selection of additional scenarios. These comprise three buffer scenarios, representing ‘failed’ states of the buffer and three canister scenarios, representing distinct canister failure modes. The buffer scenarios are analysed first and each buffer state is then considered in the analyses of the canister failure modes. Should, however, the analyses of any of the buffer states lead to the conclusion that it can be ruled out, that state is not necessarily propagated.

Scenarios related to future human actions and other scenarios analysed e.g. in order to understand barrier functions are included as necessary if not covered by the results of the already analysed scenarios.

Table 11-1. Result of scenario selection. Green cells denote conditions for the base variant of the main scenario, red cells denote deviations from those conditions.

Main scenario				
Name	**Initial state EBS**	**Initial state Site**	**Process handling**	**Handling of external conditions**
Base variant	Reference ± tolerances	Site descriptive model version 1.2 (with variants/uncertainties)	According to Process Reports	Reference climate (repetitions of Weichselian glacial cycle) No future human actions (FHA)
Greenhouse variant	Reference ± tolerances	Site descriptive model version 1.2 (with variants/uncertainties)	According to Process Reports	Extended warm period No future human actions (FHA)
Additional scenarios based on potential loss of safety functions ("less probable" or "residual" based on outcome of analysis)				
Name	**Initial state EBS**	**Initial state Site**	**Process handling**	**Handling of external conditions**
Buffer advection	Scrutinise uncertainties of relevant initial state factors, internal processes and external conditions possibly leading to violation of safety function indicator under consideration. Analysis of main scenario used as starting point.			
Buffer freezing	See above			
Buffer transformation	See above			
	Consider each of above three buffer states + intact buffer when analysing below three canister scenarios.			
Canister failure due to isostatic load	Scrutinise uncertainties of relevant initial state factors, internal processes and external conditions possibly leading to violation of safety function indicator under consideration. Analysis of main scenario used as starting point.			
Canister failure due to shear movement	See above			
Canister failure due to corrosion	See above			
Scenarios related to future human actions				
Name	**Initial state EBS**	**Initial state Site**	**Process handling**	**Handling of external conditions**
Boring intrusion	As base variant of main scenario	As base variant of main scenario	As base variant of main scenario, except processes affected by boring	Reference climate + boring
Additional intrusion cases, e.g. nearby rock facility	As base variant of main scenario	As base variant of main scenario	As base variant of main scenario, except processes affected by intrusion	Reference climate + intrusion activity
Unsealed repository (not analysed in SR-Can)	As base variant of main scenario, but insufficient sealing	As base variant of main scenario	As base variant of main scenario, modified according to initial state	Reference climate

12 Analyses of selected scenarios

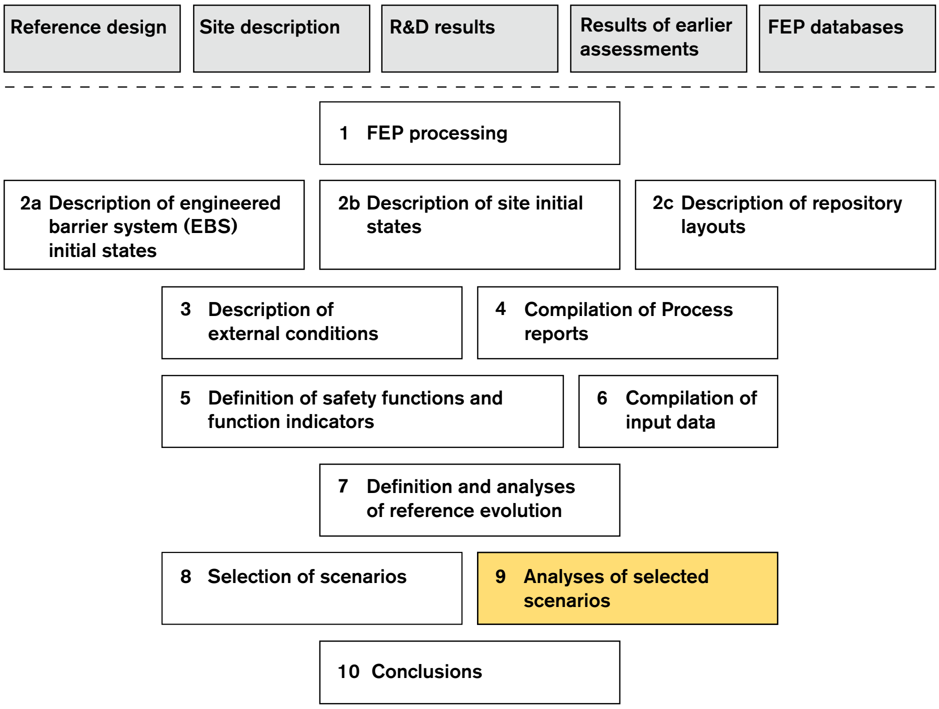


Figure 12-1. *The SR-Can methodology in ten steps (section 2.2), with the present step highlighted.*

12.1 Introduction

This chapter deals with the analyses of the scenarios selected in chapter 11, i.e. the analyses of the following scenarios.

- The main scenario, section 12.2.
- Scenarios derived from safety function indicators, section 12.3 through 12.9. The three buffer scenarios are treated in sections 12.3 to 12.5 and then propagated to the three canister scenarios analysed in section 12.7 to 12.9. Dose consequence calculations are done for the canister scenarios, where the results of the buffer scenario analyses are taken into account.
- FHA scenarios, section 12.10.

It also provides an analysis of possible combinations of the above scenarios in section 12.11 and a risk summation in section 12.12.

12.2 The main scenario

12.2.1 Definition of the main scenario

The main scenario is strongly linked to the analysis of the reference evolution described in chapter 9. The definition of the main scenario thus has large overlaps with the detailed prerequisites given for the general evolution in section 9.1.1. These are not repeated here. The aim of that description is to present a reasonable evolution of the repository system, and that is also the aim with the main scenario. Therefore, most of the developments and results described in chapter 9 apply to the main scenario. As for the reference evolution, there are two variants of the main scenario; the Weichselian variant and the greenhouse variant. As mentioned above, there are, however, a few issues that need to be further specified in order to obtain an unambiguous definition of the main scenario.

Hydraulic model interpretations of the sites

Several hydraulic model interpretations of the two sites are presented and analysed in chapter 9, basically as a result of an analysis of uncertainties propagated from the site descriptive models.

For the Forsmark site, a multi component Continuum Porous Medium model, CPM, and two variants of a discrete fracture network model, DFN, were considered, see section 9.3.6. The variants are distinguished by their different assumptions regarding the correlation between fracture sizes and fracture transmissivities; i) perfectly correlated and ii) semi-correlated. Clearly, the CPM model could be judged unrealistic, since it is only discrete fractures that may possibly be transmissive. On the other hand, the current hydrogeological DFN-model may overestimate the connectivity of this fracture system. The CPM model is thus judged to be a fair representation of the spectrum of possible interpretations of current hydraulic data that indeed show very low – if any – transmissivity at depth. Based on the information in SDM version 1.2 of the Forsmark site, it is not possible to rule out any of these three representations as unlikely, or to state that any of them is a distinctly more plausible representation of the site than the others.

It should be noted that only a certain range of fracture sizes are considered in the DFN models, from a few metres up to 1,000 m and it is the correlation for this limited set that is of interest when evaluating the representativeness of the DFN variants.

As also demonstrated in chapter 9, the different hydraulic variants of the Forsmark site have radically different consequences in terms of canister failures and hence safety.

For the Laxemar site, only a semi-correlated DFN model is considered in SR-Can and it is repeated that the confidence in the Laxemar site descriptive model is limited and that recent data from the site suggest that, in particular, its hydraulic properties are more favourable than suggested by the site descriptive model version 1.2.

Thermally induced spalling

For the reference evolution, equivalent flow rates are calculated both with and without the effects of thermally induced spalling at deposition holes. Since a conclusion from the thermo-mechanical analyses of the reference evolution is that thermally induced spalling cannot be ruled out for any deposition hole, such spalling is assumed in the evaluation of the main scenario.

Major earthquakes

The likelihood of canister failures due to major earthquakes is analysed in chapter 9, section 9.4.5. It is concluded that the likelihood of one of the 6,000 canisters in the repository experiencing such a failure is of the order of a few percent in one million years. This failure mode is, therefore, excluded from the main scenario and considered in a less likely scenario in accordance with the definitions suggested by SKI's regulations.

Canister failures

The canister failures to be further analysed in the main scenario can now be specified, based on the specifications above and on the results of the analysis of the reference evolution in chapter 9.

As for the reference evolution, canister failures due to isostatic load are ruled out for both variants of the main scenario. Additional uncertainties regarding this failure mode are addressed in a dedicated scenario, see section 12.8.

Canister failures due to shear movement are also ruled out for both variants, since the probability is sufficiently low to treat this failure mode in a less likely scenario. This is done in section 12.9.

Canister failures due to corrosion do not occur in the main scenario except for cases where advective conditions prevail in the buffer. For Forsmark, the results from section 9.4.9 are used to define the failure rates. For Forsmark, this means that for the CPM and the perfectly correlated DFN models, no failures occur during the one million year assessment period. For the semi-correlated DFN model, no failure occurs during the initial 100,000 years and 10 canisters fail between 100,000 and 1,000,000 years. For Laxemar, no failures occur during the initial 100,000 years and 50 canisters fail between 100,000 and 1,000,000 years.

As these failures occur sufficiently far into the future for the differences between the two variants to be small, it is not meaningful to distinguish between the Weichselian variant and the greenhouse variant. If anything, the greenhouse variant should be somewhat more beneficial since the first glacial episode occurs later, but it is not meaningful to quantify the difference based on available knowledge. For that reason, only the Weichselian variant is considered.

Hence, the only failure mode considered in the main scenario is that of failures due to corrosion for advective conditions in the buffer.

12.2.2 Risk assessment for the main scenario

The general evolution of the repository system for the main scenario is analysed in chapter 9 and is not repeated here. Radionuclide transport and dose consequences for failure modes related to the general evolution are analysed in chapter 10, irrespective of whether they were deemed probable or not, and those results are now used to assess the risk contribution for the main scenario.

As stated above, the only failure mode occurring in the Weichselian variant of the main scenario is that of corrosion failure following buffer erosion leading to advective conditions in the buffer.

For the Forsmark site, three hydraulic interpretations, the CPM model and the perfectly correlated and the semi-correlated DFN models, of the site are considered in the main scenario. Only the semi-correlated DFN case yields releases due to advection/corrosion failures during the one million year assessment period, see section 10.6, Figure 10-42.

For Laxemar, the only hydraulic interpretation yields releases according to Figure 10-43.

The main scenario has a high probability, and a more detailed discussion of probabilities is given in conjunction with the risk summation in section 12.12.

12.3 Buffer advection

12.3.1 Introduction

Bounding cases

For the reference evolution, some tens of canisters are calculated to fail during the one million year assessment period due to buffer colloid release/erosion leading to buffer advection and hence enhanced corrosion, see section 9.4.9. There, it is also demonstrated that the consequences are about the same if *advection is assumed initially in all deposition positions*.

This result is important for the treatment of the buffer advection scenario. Irrespective of the outcome of the complex interplay of a number of uncertain factors influencing the occurrence of buffer advection, the consequences in terms of canister failures are always bounded by the case where advection is assumed for all canisters throughout the assessment period, and these failure rates are almost identical to those for the reference evolution where only a small fraction of the deposition holes are affected by advective conditions in the buffer. The reason for this simplifying circumstance is that the time taken to erode the buffer to the extent that advection occurs is considerably shorter than that required to cause corrosion failure once the advective conditions are established.

Three important cases can therefore be envisaged before this scenario is analysed:

1. A case where advective conditions occur in every deposition hole throughout the assessment period.
2. A case where advective conditions occur to the extent given by the reference evolution treated in chapter 9.
3. A case where diffusive conditions are preserved in every deposition hole throughout the assessment period.

These three cases, two of which are bounding, are used as a background for the discussion below.

As mentioned in the reference evolution, the buffer colloid release/erosion process is poorly understood and leads already in the reference evolution to loss of buffer mass to the extent that advection cannot be ruled out for a considerable fraction of the deposition holes during the first glacial cycle, at least for the most unfavourable hydrogeological model. In a one million year perspective, case 1 is therefore not vastly different from the reference evolution case 2, in particular since advective conditions in the buffer are tolerated by the canister throughout the assessment period for the majority of deposition holes and for around 100,000 years for all holes, according to the calculations in chapter 9. The three cases can, therefore, be said to reasonably reflect the current uncertain knowledge of the extent of buffer colloid release/erosion. They are however encompassing in the sense that it is difficult to conceive of a worse situation than case 1 or a more favourable situation than case 3.

Safety function indicator(s) considered

A central safety function of the buffer is to prevent advective transport of species between the groundwater and the canister, (safety function indicators Bu1a and b) ensuring that diffusion is the dominant mechanism of transport. In order to maintain this safety function, the buffer must have a sufficiently low hydraulic conductivity. A prerequisite for an appropriate and homogeneous hydraulic conductivity is also a certain minimum buffer swelling pressure, which ensures tightness and self-healing of the material.

In this scenario, conceivable routes to a violation of the buffer hydraulic conductivity criterion are examined. Basically, there are two routes to a situation where advection could be an important mechanism for transport in the buffer:

1. A drop in dry density caused by loss of buffer material which would give a hydraulic conductivity sufficiently high for advection to dominate over diffusion, or too low a swelling pressure to maintain the self-sealing ability.
2. Transformation of the montmorillonite in the buffer to another mineral with different hydraulic properties.

The results of these routes could lead to either:

1. *High conductivity case:* A case where so much buffer material is lost that water is allowed to flow through the buffer.
2. *Fracture case:* A case where the buffer has lost its sealing properties and a conductive fracture is formed in it.

For an intact canister, advection concerns the transport of corroding agents to the canister. For a potentially defective canister, transport of radionuclides to the groundwater is affected.

A number of factors influence, directly or indirectly, the buffer hydraulic conductivity. The hydraulic conductivity is directly influenced by the buffer density, and the type of cations in the buffer. These factors also influence the buffer swelling pressure. The swelling pressure is further influenced by the ionic strength of the surrounding groundwater.

There are a number of safety function indicators that can be seen as "sub-indicators" to the "master" indicator buffer hydraulic conductivity. These are all used to evaluate this scenario:

- PSw > 1 MPa.
- Minimum content of divalent cations in the groundwater.
- Limited groundwater salinity.

A maximum temperature of 100°C can also be seen as a sub-indicator for this scenario. However, the consequences of this are evaluated in section 12.5.

A special case of this scenario is the effect of a sinking canister. This is dealt with in section 12.3.4.

Treatment of this issue in the main scenario

In the main scenario, advection as a transport mechanism in the buffer is assumed to the extent suggested by the results of calculations for the reference evolution in section 9.4.8.

Qualitative description of routes to buffer advection (including initial state aspects and external conditions)

As mentioned, the buffer density plays a key role for the buffer's ability to prevent advection. The density may decrease due to erosion induced by piping as the buffer saturates, through buffer expansion into the deposition tunnel as a saturated buffer swells or through erosion caused by dilute groundwater for glacial conditions. Buffer expansion into the deposition tunnel will be counteracted by the tunnel backfill material, meaning that factors affecting the density and compressibility of the backfill material could also indirectly influence buffer hydraulic conductivity.

Of these factors, colloid release/erosion caused by dilute glacial groundwater has by far the highest impact on density in the reference evolution and it is the only factor that causes any considerable alteration of buffer density over the one million year assessment period in that evolution.

The overall conclusion from the analysis of the reference evolution is, therefore, that the buffer is expected to function as intended until intruded by dilute glacial groundwater, after which there is little confidence that advection is prevented in many of the deposition holes. After several glaciations, there is little confidence that advection is prevented in any deposition holes. Thus, the main consideration is corrosion rates post-glaciation in the full set of deposition holes.

Initial state factors involved

- Buffer density (amount of dry mass deposited).
- Backfill density (amount of dry mass deposited above the deposition hole).
- Type of buffer material used (This is not an uncertain factor, but the evolution will, in some respects, be different for e.g. the two materials considered in SR-Can).

Processes involved

A number of different processes could lead to a drop in buffer density:

- Piping/erosion during the early stage.
- Swelling/expansion into the backfill.
- Colloid release (safety function indicator ionic strength).

For a given density, the hydraulic conductivity and swelling pressure will be determined by the following processes:

- Ion exchange.
- Osmosis.

The hydraulic conductivity and swelling pressure of the buffer will also be determined by the process montmorillonite transformation.

External conditions involved

- Geosphere conditions yielding very high or very low ionic strengths of groundwater.
- Geosphere conditions leading to increased flow.

There are thus a large number of factors that need to be considered in the buffer advection scenario.

12.3.2 Quantitative assessment of routes to buffer advection

In the reference evolution and hence the main scenario, the reference buffer and backfill densities are addressed, as are reasonably high and low ionic strengths and durations of such conditions for a glacial cycle. The possibility for the transformation of the montmorillonite in the buffer is also evaluated.

Initially deposited dry buffer mass

As an extreme case of deviance during deposition one may consider the situation where one bentonite ring has been “forgotten”. This case is covered in the swelling calculations by /Börgesson and Hernelind 2006/ reported in the reference evolution, section 9.3.9.

The effect of a variation in the composition of the buffer material is not discussed in the reference evolution. It is expected that the defined delivery and quality control systems will ensure that all material will meet the specified requirements. These material requirements have not yet been fully defined. However, considering the very small difference in the important properties between the two reference materials in SR-Can at the target density (see section 4.2.5), it can be concluded that variation in the material composition will have a rather limited effect on buffer performance. The allowed variability of composition for the selected buffer material will be defined at time of purchase of the buffer. Under all circumstances this variability is expected to be small. The Deponit CA-N for example, which is a material mainly for landfill use (low tech application) has a guaranteed calcite content of 10 ± 2%.

The overall conclusion regarding initially deposited buffer dry mass is that except, in the case of a severe deficiency in procurement or quality control, the initial buffer mass and composition is expected to be well within the design specifications.

Initially deposited dry backfill mass

The expected uncertainties in the amount of initially deposited backfill are discussed in section 4.2.7. If less backfill is deposited this could potentially lead to buffer swelling into the deposition tunnel and a loss of buffer mass. However, as seen in Table 9-7, even a large deviation in backfill density will have a limited effect on the buffer density. There is no reason to believe that failures in the backfilling process ever will lead to significant contributions to the generation of advective conditions in the buffer.

Swelling

If the initial density of the tunnel backfill is lower than the design target, the buffer can expand into the backfill which in turn gives a lower average buffer density. This is discussed in the reference evolution and is thus included in the main scenario. Table 9-7 and Table 9-8 show the expansion of the buffer into the backfill for different combination of densities. According to calculations in the reference evolution, there is sufficient margin in backfill density to ensure acceptable performance for all reasonable combinations. Therefore, this issue is not further considered here.

Erosion caused by piping

Erosion caused by piping is discussed in the reference evolution in section 9.2.4. If the inflow of water to a deposition hole is higher than a specific value, assessed as 0.1 l/min, the buffer will not be able to seal and a channel (pipe) will be formed. The channel will most likely end in the deposition tunnel. As long as the tunnel is not sealed and the hydrostatic pressure is restored, there will be a flow in the pipe. The flow may erode the buffer and some material may be lost. The potential loss can be calculated from the flow rate, the concentration of bentonite that may be present in the water and the duration of gradient (the time it takes to restore the hydrostatic pressure). The inflow to each deposition hole can be measured and the holes can either be grouted or excluded if the inflow is found to be too high. Piping experiments /Börgesson and Sandén 2006/ have shown that the concentration of bentonite in eroding water is around 10 g/l. The value is dependent on water salinity, flow rate, test geometry and test duration. The uncertainty is about a factor of two up or down. The tunnel will be open during the deposition of the canisters and buffer, installation of the backfill and construction of the end plug. When the plug is constructed the hydrostatic pressure will be restored. The time for this to occur is dependent on the local hydraulic conditions in the tunnel. The key uncertainty is the time it takes to restore the hydraulic pressure in the tunnel. If all water is supplied through one single deposition hole and the tunnel is completely dry the erosion could go on for a long time. However, this type of situation is highly unlikely, since the tunnels and deposition holes will be well characterized.

Overall, the uncertainties in the parameters related to piping are rather limited and it is unlikely that the erosion from piping should be substantially higher than in the reference evolution.

Erosion of backfill

Erosion of backfill material during the operational phase could lead to a local loss of backfill density at the top of a deposition hole. This could, in turn, lead to and expansion of buffer material into the backfill and a loss of buffer density. However, as seen in Table 9-7 and Table 9-8 in section 9.3.9, large losses of material are needed before this process will have any importance for the buffer density. This issue is, therefore, not further considered here.

Colloid release

Buffer colloid formation and release during a glacial cycle is discussed in the reference evolution, section 9.4.8. Several uncertain aspects of the colloid release process are discussed in connection with the analysis of the reference evolution. These include the conceptual uncertainty of the Q_{eq}-based erosion model, behaviour of the selected buffer material, the duration of periods of low ionic strength groundwater and the groundwater flow rates during these periods. These uncertainties are the main reason for selecting the bounding cases for the buffer erosion scenario described in section 12.3.1.

Ion-exchange and osmosis

Figure 4-6 and Figure 4-8 show the swelling pressure and hydraulic conductivity for the two reference buffer materials as a function of dry density for different water salinities. Comparing the two materials gives a good indication on the effect of ion-exchange as well. MX-80 is Na-bentonite that was exposed to NaCl solutions, whereas Deponit CA-N is Ca-bentonite that was exposed to $CaCl_2$ solutions. Neither the exchangeable cation nor the salinity have any major effect on the buffer properties at the reference density. However, the effect of both processes becomes much stronger at lower densities. The effect of salinity becomes important for the swelling pressure at a dry density of ~ 1,400 kg/m^3. The ion-exchange characteristics are not important until the density drops to about 1,000 kg/m^3, but below that value the effect is very strong.

The groundwater composition, Ca/Na-ratio and total salinity, will determine how much buffer mass can be lost before advection starts to be important.

The effect of groundwater salinity will only be important if large amounts of buffer are lost, i.e. in combination with colloid release. The processes are mutually exclusive since colloid formation only occurs at low calcium concentrations but they could occur in sequence if the ground water composition is changing.

In conclusion, the uncertainties regarding the effects of increased salinities, including the differences between the two sites, are unimportant compared to the uncertainties in the colloid formation process.

Montmorillonite transformation

Transformation of the montmorillonite in the buffer to other minerals as an effect of elevated temperature is evaluated in the reference evolution and in the buffer transformation scenario (section 12.5).

Geosphere conditions

The properties of the buffer are dependent on the boundary conditions to the geosphere. Key parameters are:

- Flows and gradients during the construction phase. These will determine the magnitude of mass loss from piping/erosion.
- Ionic strength of the groundwater for all time scales. A low content of divalent ions in the groundwater will make it possible for the buffer to form a colloidal phase the can be transported away with the groundwater. A high ionic strength will affect the buffer hydromechanical properties, which may result in a higher hydraulic conductivity and a lower swelling pressure, in the case where some mass loss has occurred. The Ca/Na ratio will affect the ion-exchange capacity which can affect the buffer properties at very low densities.
- The groundwater flow will determine how much buffer mass can be transported away in the colloid formation case.

These factors are treated above under the issues where they cause effects.

Greenhouse variant

The occurrence of buffer advection is strongly linked to the presence of low ionic strength glacial groundwaters at repository depth. The delay of glacial conditions expected for the greenhouse variant would also delay the time when buffer erosion due to intrusion of glacial water might occur and thus delay and reduce any consequences of such en evolution. The issue is therefore not further treated for the greenhouse variant. The issue is therefore not further treated in SR-Can for the greenhouse variant. Further evaluations of the expected groundwater compositions for an extended temperate period will be performed within SR-Site.

12.3.3 Conclusions

Categorisation as "less probable" or "residual" scenario

All of the processes described above are included in the reference evolution and the main scenario except for the case with a "forgotten" buffer ring. The effect of high temperature transformations is also discussed in the high temperature scenario.

As evidenced by the above account, there are a number of uncertainties regarding the evolution of the buffer density. All conceivable initial states and subsequent developments are however, from the point of view of advection, which is the issue in this scenario, covered by the three cases outlined at the beginning of the analysis of this scenario, section 12.3.1. This analysis applies to the high conductivity case, see section 12.3.1.

For the fracture case, see section 12.3.1, no route leading to this situation has been identified and it is thus considered as a residual scenario. Canister corrosion for a fractured buffer can be illustrated with expressions given in /Neretnieks 2006a/. The life time of the canister is considerably longer for a fractured buffer than for an eroded buffer, for otherwise identical circumstances, see examples in /Neretnieks 2006a/. No additional such calculations cases have, due to time constraints, been performed in SR-Can.

Regarding event sequences, the evolution can certainly be affected by the order in which swelling, mass losses, intrusion of various types of groundwater, etc occurs. Again, however, these situations are bounded by the three cases considered.

Quantitative consequence analysis/discussion – isolation and retardation

Should transport in the buffer not be controlled by diffusion, corrosion of the canister could ultimately be controlled by advection of corroding agents in the groundwater. This is illustrated in the reference evolution and is also included in the main scenario. Further uncertainties regarding this situation are treated in the corrosion scenario, section 12.7, to which the three cases of buffer advection are propagated.

12.3.4 Special case of advective conditions: Canister sinking

Function indicator(s) considered

A central safety function of the buffer is to prevent advective transport of species between the groundwater and the canister. To ensure this, a certain buffer thickness is required. If the canister sinks or tilts in the deposition hole, this minimum thickness cannot be guaranteed. A swelling pressure of 200 kPa is needed to keep the canister in position in the deposition hole (Bu6). This function indicator assumes that the buffer consists of montmorillonite.

Treatment of this issue in the main scenario

Canister sinking is assessed not to occur in the reference case and hence is not included in the main scenario.

Qualitative description of routes to canister sinking

The swelling pressure could be reduced by:

1. Loss of buffer material;
2. A transformation of the montmorillonite to a non-expandable mineral;
3. A possible loss of swelling pressure due to high water pressures.

If sufficient buffer mass was lost to bring the average swelling pressure around the canister down to 200 kPa, advection would probably already be the dominant transport mechanism, hence 1. above is covered in the main scenario and in the general buffer advection scenario above. Transformation of the montmorillonite in the buffer is discussed in the transformation scenario, section 12.5. Loss of swelling pressure caused by high groundwater pressure is discussed and ruled out in reference evolution in section 9.4.8.

Quantitative assessment of routes to canister sinking

The routes to loss of swelling pressure are discussed in the scenarios mentioned above.

Categorisation as "less probable" or "residual" scenario

The effect of high water pressure on the swelling pressure was ruled out for all pressures expected in the repository evolution (section 9.4.8). This route to canister sinking does thus not give a contribution to the likelihood of the scenario.

The consequences of the loss of large amounts of buffer material are discussed in the reference evolution and further in the general buffer advection scenario above. Since considerably higher mass losses are required to cause canister sinking than are required for advective conditions, and since advective conditions is the safety related concern also in the case of canister sinking, the occurrence of canister sinking would not lead to consequences beyond those already quantified in section 12.3.3 above.

Conclusion

The only way the canister could sink to the bottom of the deposition hole is in the case of a large loss of buffer material. If this happens the diffusive barrier of the buffer is lost long before the canister starts to sink. Therefore, loss of the diffusive barrier caused by canister sinking does not have to be treated as a scenario on its own.

12.4 Buffer freezing

12.4.1 Introduction

Indicator criterion violated

This scenario concerns the criterion of minimum buffer temperature, namely that the temperature in the buffer should not fall below –5°C to avoid formation of ice in the buffer.

If the buffer minimum temperature criterion is violated, this could potentially affect both isolation and retardation. Isolation could be jeopardised through mechanical impact on the canister by a freezing buffer and the retardation potential may be impaired, in that it is uncertain what transport properties the buffer would have after thawing.

Treatment of buffer freezing in the main scenario

The possibility of buffer freezing was considered as unlikely and thus excluded from the main scenario. The main scenario is based on a plausible glacial cycle and indicates that it is unlikely for permafrost (0°C isotherm) to develop to greater depth than 250 m at Forsmark and 160 m at Laxemar. The freezing of buffer material requires temperatures of –5°C or lower, possibly also lower than –10°C /**Buffer and backfill process report**, section 2.2.2/. The possibility for the –5°C isotherm to reach repository depth in the main scenario is considerably smaller than that for the 0°C isotherm (Figure 9-74).

Qualitative description of routes to buffer freezing

The route to this scenario is permafrost development. A number of factors contributing to buffer freezing can be identified:

Initial state factors

- Thermal conductivity of bedrock.
- Heat capacity of bedrock.
- Geothermal heat flow.
- Hydraulic conductivity of bedrock.
- Porosity of bedrock.
- In principle also the heat output of the spent fuel, though this will be substantially diminished onthe timescales of interest.

Processes

- Heat conduction in bedrock.
- Heat conduction in buffer.
- Freezing of buffer.

External conditions

- Permafrost conditions leading to changes in temperature at ground surface.
- Glacial conditions leading to changes in temperature at ground surface.
- Submerged conditions leading to changes in temperature at ground surface.

12.4.2 Quantitative assessment of routes to buffer freezing

To investigate the climate conditions required to develop permafrost to repository depth, sensitivity tests on the evolution of permafrost for different constant temperatures was made. The simulations used the same model that was used for permafrost simulations in the main scenario. Site-specific data on physical-, thermal-, and hydrological bedrock properties were used /**Climate report**, section 3.4.4/. The calculations were made for two cases, with and without the heat contribution from a repository. The results show that, in cases of no heat from spent fuel, at Forsmark the ground temperature must be below –7°C for permafrost (0°C isotherm) to reach the repository depth of 400 m (Figure 12-2). If the ground temperature is –8°C it takes 26,000 years for the permafrost to develop to this depth. If heat from spent fuel is taken into account, it would instead take 80,000 years for the 0°C isotherm to reach a depth of 400 m. At Laxemar, the ground temperature must be below –13°C in order for the permafrost depth to reach the repository depth of 500 m if heat from spent fuel is not included. With a ground temperature of –16°C it takes 20,000 years for permafrost to reach repository depth. Including heat from the repository, it would take ~ 60,000 years for permafrost to reach repository depth (Figure 12-2).

Permafrost simulations were made also to investigate how much air temperatures need to be lowered in a *variable* climate for permafrost and sub-zero temperatures to develop to repository depth. The local temperature curve at ground level, used in the main permafrost scenario /**Climate report**, section 3.4.4/, was uniformly lowered until permafrost or the –5°C isotherm developed to, or just below, repository depth at both sites. The results show that at Forsmark the surface temperature curve of the last glacial cycle needs to be lowered by ~ 5°C in order for permafrost (0°C isotherm) to reach repository depth, see details in the **Climate report**, section 4.4.1. At Laxemar, the entire temperature curve of the last glacial cycle needs to be lowered by 12°C for permafrost to reach repository depth.

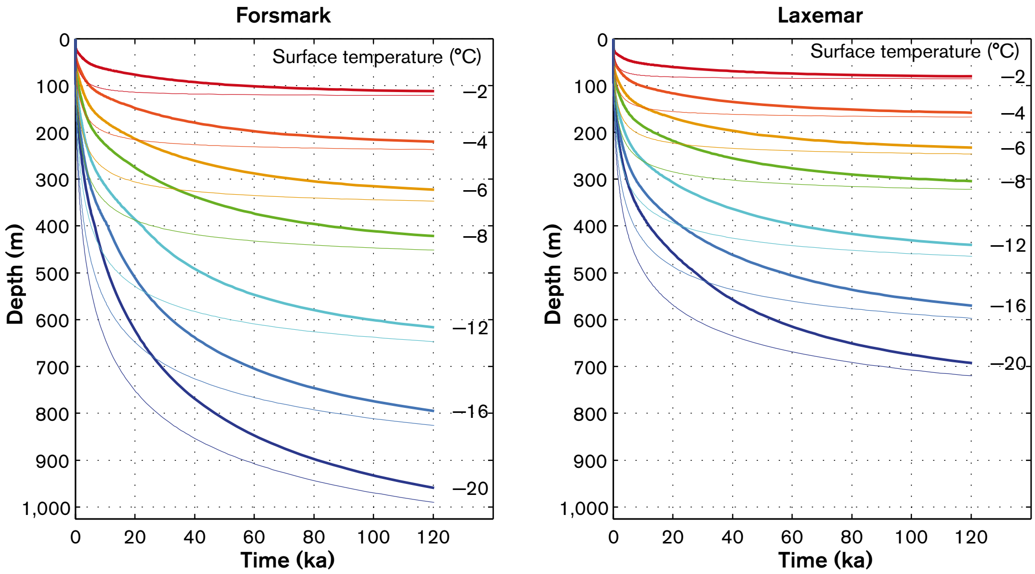


Figure 12-2. *Calculated evolution of permafrost depth (defined as the 0°C isotherm) at Forsmark and Laxemar for different constant ground surface temperatures. Calculations including heat contribution from the repository (6,000 canisters) are shown with bold lines, whereas calculations with no repository heat contribution are shown with thin lines.*

In order to make the –5°C isotherm reach repository depth at Forsmark and Laxemar, the regional temperature curves of the last glacial cycle would have to be lowered *more* that 10°C and 17°C, respectively (Figure 12-3).

Finally, glacial cycle simulations of development of permafrost and sub-zero temperature isotherms were made with climate and environmental conditions exceptionally favourable for permafrost growth. Air temperatures were assumed to fall according to the temperature curve of the reference glacial cycle, but in an extremely dry climate not supporting ice sheet growth over the sites. To favour permafrost growth further, the effects of protective snow cover and vegetation were excluded, and the sites were assumed to always remain above sea level. For further information on the setup of these simulations, see the **Climate report**, section 4.4.1. The maximum permafrost depth in these simulations is 400 m at Forsmark (Figure 12-4). At Forsmark, the –5°C and –10°C isotherms reach a maximum depth of 200 and 40 m respectively. For the corresponding case favouring permafrost growth at Laxemar, the maximum permafrost depth is 270 m (Figure 12-4). Here the –5°C and –10°C isotherms reach a maximum depth of 130 and 12 m respectively. As in the simulations in the main scenario, the greater permafrost depths at Forsmark are mainly due to different thermal bedrock characteristics.

The development of bedrock temperature at repository depth in this pessimistic glacial cycle simulation is seen in Figure 12-5. Without the heat contribution from the repository, the lowest temperature at repository depth is –0.71°C at Forsmark, and +6.1°C at Laxemar. If heat from the repository is included, the minimum temperature at repository depth increases by 0.65°C at Forsmark and 0.9°C at Laxemar. This pessimistic simulation was also used for additional sensitivity tests of the bedrock parameters most important for permafrost development, i.e. thermal diffusivity and geothermal heat flow. The test range was set according to the uncertainty derived from the site investigations, see further the **Climate report**, section 3.4.4. The minimum temperature at repository depth from these sensitivity analyses, with no heat contribution from spent fuel, is –1.8°C at Forsmark and +4.2°C at Laxemar. For details on the sensitivity tests, see further the **Climate report**, section 3.4.4.

The development of permafrost under exceptionally favourable conditions (Figure 12-4), with corresponding evolution of bedrock temperature at repository depth (Figure 12-5), have been chosen as extreme variants of the evolution of permafrost in the reference evolution.

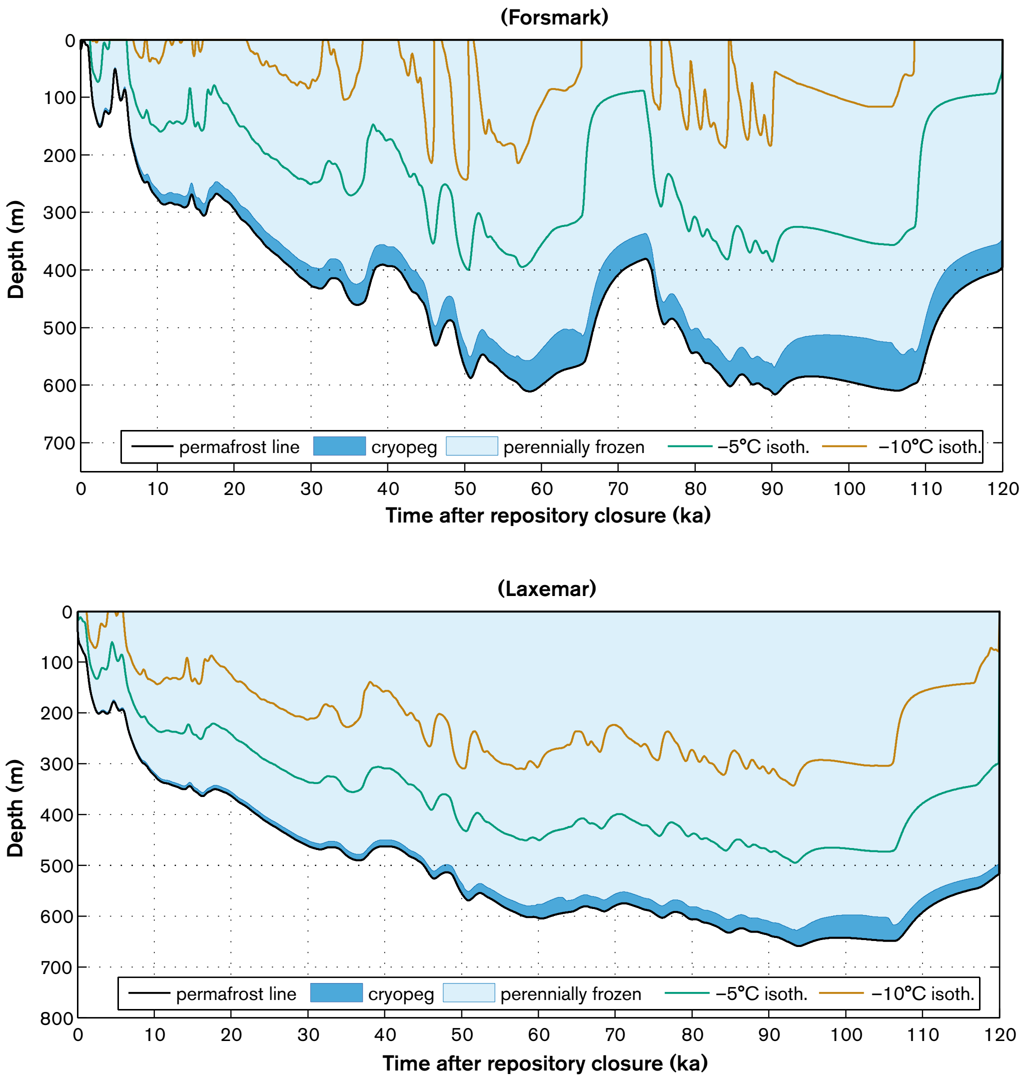


Figure 12-3. *Selected results of a series of sensitivity tests made to see how much the temperature curve of the last glacial cycle needs to be lowered in order to make the –5°C isotherm to reach repository depth. At Forsmark, reference scenario surface temperatures need to be decreased by 10.5° for the –5°C isotherm to reach repository depth, with the resulting permafrost evolution seen in the upper figure, whereas the corresponding value for Laxemar is 17.5°, giving results seen in the lower figure.*

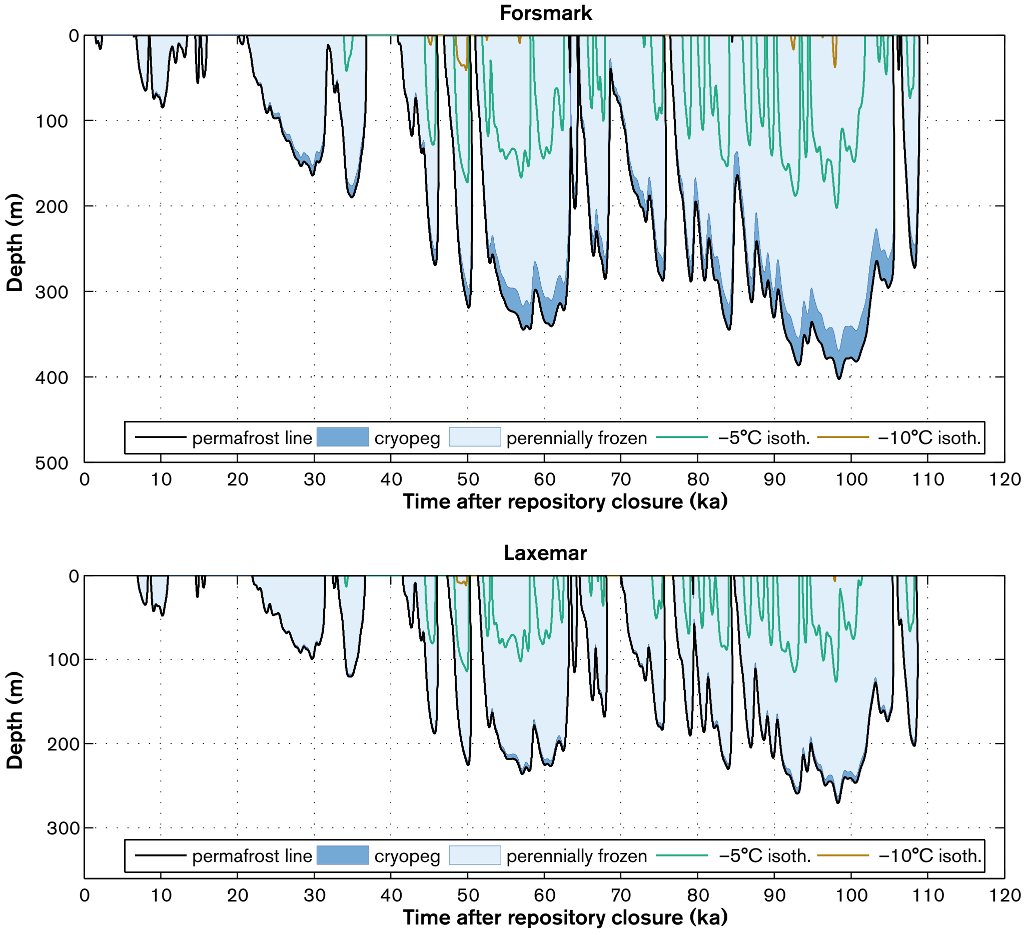


Figure 12-4. *Calculated permafrost (0°C isotherm) depth, frozen depth and depth of the –5°C and –10°C isotherms at Forsmark and Laxemar for environmental conditions exceptionally favourable for permafrost development.*

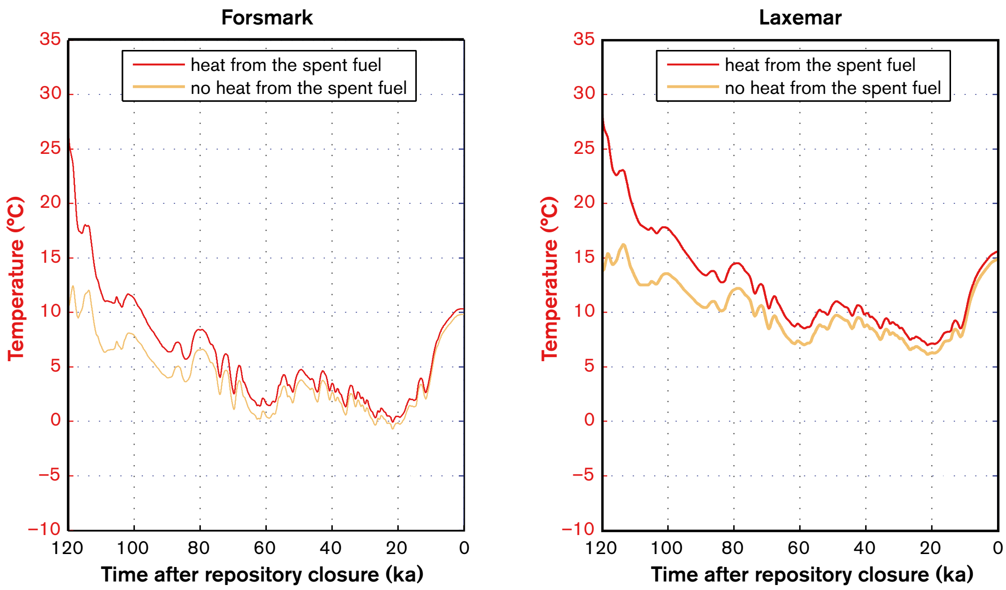


Figure 12-5. *Evolution of bedrock temperature at a repository depth of 400 m at Forsmark and 500 m at Laxemar, for environmental conditions exceptionally favourable for permafrost development. The temperature development both with and without the heat contribution from the repository is presented.*

Can climate get cold enough to cause buffer freezing?

Reconstructed late glacial climatic conditions for southern Sweden indicate that continental arctic conditions prevailed prior to ~ 15,000 years before present. At this time, mean July temperatures were around 10–12°C /Lemdahl 1988, Coope et al. 1998, Hohl 2005/, i.e. about 5 ± 2° colder than at present. The difference between the present warm interglacial temperatures and the *coldest* temperatures during the last glacial cycle as recorded in the GRIP ice core is in the order of 12°C, see Figure 12-6. Using an alternative way of interpreting ^{18}O values from the ice core in terms of air temperature, /Lang et al. 1999/ suggested that this cold event reflects a temperature change of 16°C, which several degrees more than in /Dansgaard et al. 1993/. However, according to all interpretations, this was a very short-lived climate event /cf Lang et al. 1999/. This exemplifies a typical feature of temperature climate archives namely that they show that climate is highly variable on both long and short time scales /IPCC 2001b chapter 2/, variability for example seen in the GRIP proxy temperature data (Figure 12-6). When severe cold conditions occur, these conditions do not persist for long periods of time. Such climate variability is observed also in frequency analysis of climate records /Moberg et al. 2005, Witt and Schumann 2005/.

How low could temperatures have been at Forsmark and Laxemar during the last glacial cycle? Current annual mean air temperature is ~ 5.5°C at Forsmark and ~ 6.5°C at Laxemar. Albeit transferred from Greenland conditions to regional conditions in Sweden in a rather simplistic way, air temperatures produced for the sites suggest that annual mean air temperatures during the coldest phases of the last glacial cycle may well have been around –11 to –12°C in the Forsmark and Laxemar regions, see Figure 12-7. However, considering the uncertainties in the transfer functions between ^{18}O and temperature, temperatures could have been several degrees lower. These values relate to air temperatures at ground level, whereas the mean annual temperature in the uppermost part of ground is 2–4°C higher, see **Climate report**, section 3.4.2. During the last glacial cycle, really low air temperatures only prevailed for restricted periods of time (Figure 12-6). This prevented permafrost to develop to great depths (Figure 9-74), and would do so also under even more extreme glacial cycle conditions (Figure 12-4).

If climate were to shift towards colder glacial cycles, it is unlikely that the variability within the climate system would cease. Very cold periods have been short lived in the past (Figure 12-6 and Figure 12-7), and nothing suggests that this would not be the case also during future glacial cycles. Variability is a characteristic feature of Earth's climate system. However, for a discussion on a less variable climate, see further below.

Assuming a similar climate variability as during the last glacial cycle, it requires a lowering of the entire last glacial cycle temperature curve by as much as 10.5°C in order to make the –5°C isotherm reach repository depth at Forsmark (Figure 12-3 upper). At Laxemar, the entire temperature curve

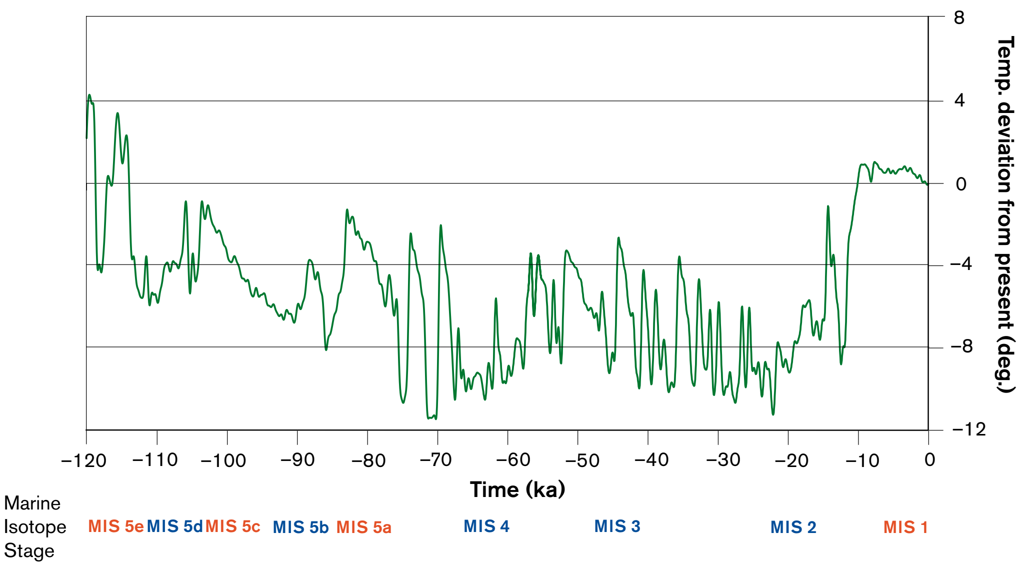


Figure 12-6. *GRIP proxy temperature curve /Dansgaard et al. 1993/. During the last glacial cycle, temperature was highly variable on both long and short time scales.*

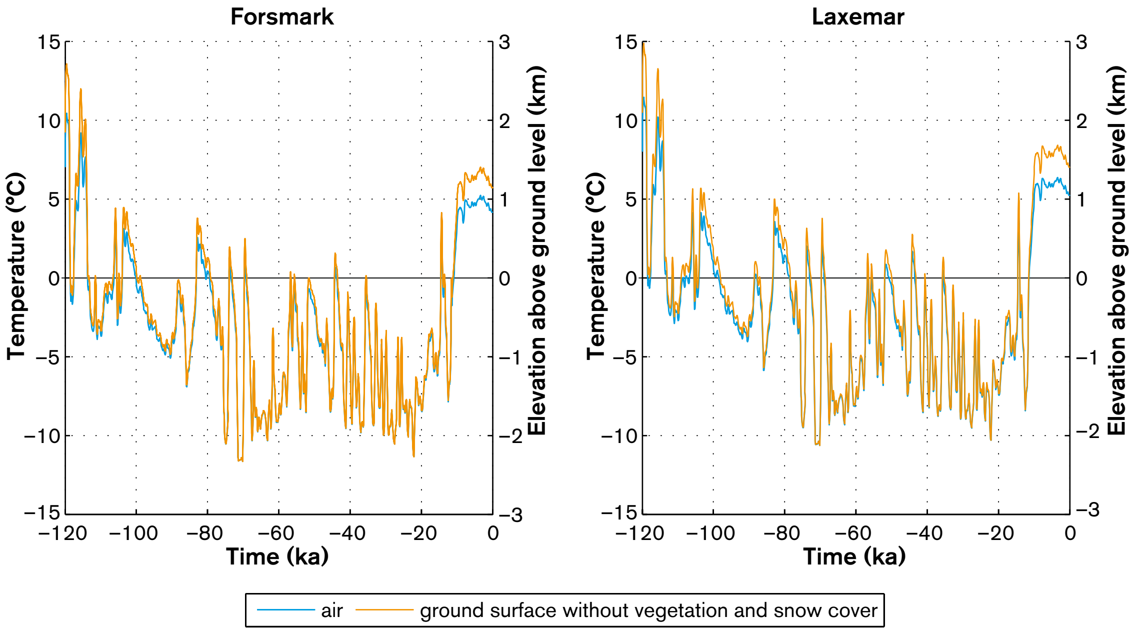


***Figure 12-7.** Evolution of air temperature and modelled ground surface temperature at Forsmark and Laxemar for the last glacial cycle, but without vegetation and snow cover.*

of the last glacial cycle would need to be lowered by 17.5° in order to make the –5°C isotherm reach repository depth (Figure 12-3 lower). A constant 10.5° lowering of last glacial cycle temperatures corresponds to an unrealistically large change in glacial climate conditions.

Furthermore, during the coldest phases of glacial cycles, Fennoscandia is covered by an ice sheet, and the glacial domain prevails at the candidate sites. Preliminary calculations using the ice-sheet model indicate that if the temperature falls by 9° an ice sheet will develop that covers the Forsmark region, and if temperatures fall by 10° an ice sheet covering both candidate sites will develop. When this happens, permafrost develops at a much lower rate or even decreases, see permafrost development under ice-covered conditions in the reference evolution, Figure 9-68, and details on permafrost growth rates in the **Climate report**, section 3.4.4. In association with major ice-sheet advances over the sites, these areas are also submerged for some time after deglaciation, which further prevents permafrost development. If future glacial cycles were to be colder than in the past, this would most likely produce larger ice sheets and longer periods of ice sheet coverage at the sites, reducing the depth of the permafrost and –5°C isotherm.

The effect of an unlikely future climate with considerably less glacial climate variability than during the past 2 million years can be determined by reference to the sensitivity test results in Figure 12-2. Here it is seen that if the ground temperature is –8°C at Forsmark, it would take 26,000 years for permafrost (0°C isotherm) to develop to repository depth without heat from spent fuel. If heat from spent fuel is present, it would take 80,000 years. At Laxemar, the ground temperature would need to be even lower for permafrost to reach repository depth. The –8°C ground temperature at Forsmark corresponds to an air temperature at ground level of –10 to –12°C. This is at least 15° colder than the present annual mean temperature at this site (5.5°C). Such low temperatures could possibly occur occasionally during a glacial cycle (Figure 12-6 and Figure 12-7), but really cold periods prevail for much shorter times than 26,000 years and 80,000 years (Figure 12-6). In addition, the annual mean air temperature would need to be *considerably* lower than –8°C for the –5°C isotherm to reach repository depth.

Based on the performed model studies, and what is known about past climate conditions and climate variability, the possibility that permafrost (0°C isotherm) reaches repository depth at Laxemar is ruled out. At Forsmark there is a small possibility that the 0°C isotherm could reach repository depth when adopting a pessimistic variant on permafrost development and heat generated from the spent fuel has declined (Figure 12-4). However, for buffer safety functions, the 0°C isotherm is not relevant, since ice formation in the buffer material requires temperatures of –5°C or lower /**Buffer and Backfill process report**, section 2.2.2/. The results in Figure 12-4 show that in the pessimistically chosen cold and dry scenario, the probability for the –5°C isotherm to reach repository depth at either of the sites is negligible. In this scenario, and without heat contribution from the repository, the lowest temperature at repository depth is –0.71°C at Forsmark, and +6.1°C at Laxemar. This demonstrates that not only in the base variant of the SR-Can main scenario, but also in colder variants favouring permafrost growth, the bedrock temperature at repository depth will not fall to such a degree that freezing of the buffer could take place at either of the two sites.

Freezing of the backfill in more shallow parts of the tunnel system will probably occur in the reference scenario during permafrost periods, as well as in the more pessimistic permafrost scenario. However, the consequences of this process are not evaluated within SR-Can. This issue will be analysed further in the SR-Site assessment.

12.4.3 Conclusions

Categorisation as "less probable" or "residual" scenario

This is considered as a residual scenario.

Quantitative consequence analysis/discussion – isolation and retardation

A bounding case would be one where all canisters are damaged due to freezing. This is similar to the situation where all canisters fail due to isostatic over-pressure, analysed in section 10.8. The case is, therefore, not further treated here.

Greenhouse variant

The occurrence of permafrost is delayed in the greenhouse variant. The delay would also delay the onset of possible buffer freezing and thus any consequences would also be delayed and reduced. Buffer freezing is, therefore, not further treated for the greenhouse variant.

12.4.4 Combination of buffer erosion and freezing

If groundwater were to freeze in cavities formed by buffer erosion, the associated volume expansion of the water would induce an additional pressure that possibly could affect the canister safety barrier. The following general approach was adopted to investigate the effects of this combined case:

- Calculations of freezing-induced pressures and freezing point temperatures in buffer erosion cavities were performed using various assumptions on compressibilities of any remaining buffer, shape of the erosion cavity, and surrounding ambient pressure (i.e. surrounding ground water pressure plus clay swelling pressure).
- The lowest temperature at repository depth for the two sites, resulting from the climate scenario exceptionally favourable for permafrost growth, was used to quantify relevant combinations of freezing-point temperatures and freezing-induced pressures. Considering the uncertainty range in geothermal heat flow, and from that assuming a low heat flow value, the lowest repository depth temperatures are –1.8°C and +4.2°C for the Forsmark and Laxemar sites, respectively, see the **Climate report**, section 3.4.4. This pessimistically also assumed no heat contribution from the spent fuel. Thus, the lowest temperature that needs to be considered can be approximated by –2°C.

A simple model was used to estimate the freezing point and pressure increase in a ring-shaped erosion cavity surrounding the canister, see Figure 12-8. In the calculations the compressibility of remaining clay was estimated from the swelling pressure of bentonite. It was also assumed that the erosion cavity was completely filled with ordinary compressible water, free from solutes and impurities. The effect of including these compressibilities is that they allow the freezing-induced expansion to occur at considerably higher temperatures than if the surroundings would have been incompressible. The compressibility of ice was also included, whereas the canister and the rock were assumed to be incompressible. Moreover, mean freezing temperatures for the erosion cavity as well as mean pressures for the erosion cavity and bentonite were assumed. For further details on the modelling, see the **Climate report**, section 4.4.1. In the analysis of the results, it was further assumed that collapse of the canister occurs when the surrounding pressure exceeds 90 MPa, see section 12.8.2.

The surrounding groundwater pressure may vary between the hydrostatic pressure, for completely unfrozen conditions, to a value up to the maximum freezing pressure for partially or fully frozen

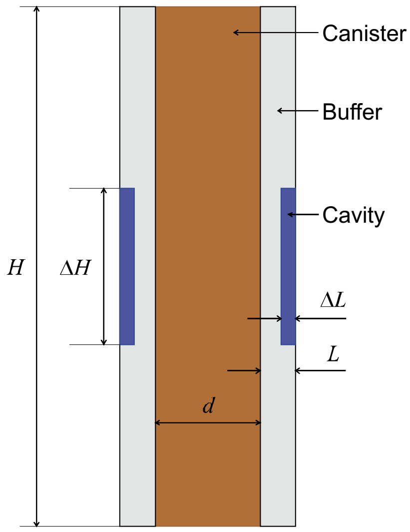


***Figure 12-8.** Geometry for calculations of freezing temperatures and freezing-induced pressures in buffer erosion cavities.*

groundwater conditions. The swelling pressure for an intact buffer with average reference density is 7.5–8 MPa for both MX-80 and Deponit CA-N, see section 4.2.8. 400 m of overlying rock mass at Forsmark contributes with a hydrostatic pressure of 4 MPa, resulting in a total ambient pressure of around 12 MPa. The full reference density interval for the clay corresponds to a swelling pressure up to 13 MPa, which would yield an ambient pressure of 17 MPa. However, for a certain freezing temperature and for ambient pressures lower than the maximum freezing pressure, the pressure increase from freezing is affected by the ambient pressure, including the swelling pressure, in such a way that the resulting total pressure is constant, see below.

Calculations of freezing temperatures and associated pressure increases were made for ambient pressures between 4 and 100 MPa. As an example, the results of the calculations for an ambient pressure of 10 MPa are shown in Figure 12-9. Examples of pressure increase and total pressure after freezing for various ambient pressures is presented in Table 12-1. For further results see the **Climate report**, section 4.4.1.

The theoretical knowledge and results of the modelling can be summarised as follows:

- Freezing of water in an erosion cavity at a given freezing temperature can increase the pressure from the ambient pressure to the maximum freezing pressure, i.e. the maximum pressure at which freezing can occur at that temperature. For a freezing temperature of –2°C, the maximum freezing pressure is about 26 MPa. For a freezing temperature of –2°C, the total pressure after freezing in the erosion cavity thus is between the ambient pressure and 26 MPa, depending on the size of the erosion cavity.
- The maximum freezing pressure for a certain freezing temperature is independent of the geometry and size of the erosion cavity.
- The pressure increase from freezing depends on the freezing temperature, the ambient pressure and the size or geometry of the erosion cavity. For certain combinations of freezing temperature and ambient pressure, complete freezing takes place and the resulting pressure increase grows with the size of the cavity. This occurs up to a certain point, at which the sum of the ambient pressure and the pressure increase equals the maximum freezing pressure. After that point, the freezing pressure is at its maximum and complete freezing can no longer take place.
- If the ambient pressure exceeds the maximum freezing pressure of 26 MPa, no freezing can occur at a temperature of –2°C, see also Table 12-1.

The above calculations describe cases with a simple cylindrical cavity in which water was allowed to freeze. Other cavity shapes than cylindrical, and their associated pressure distributions, have not been analyzed.

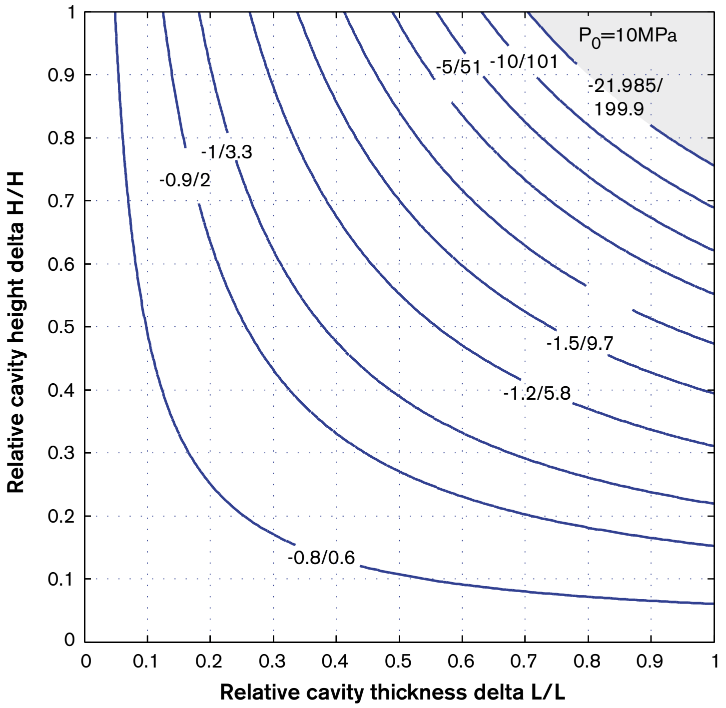


Figure 12-9. *Freezing point temperature (°C) and associated maximum pressure increase (MPa) in the erosion cavity, as a function of relative cavity thickness and height, at an ambient pressure of 10 MPa. In the figure, the first number is the freezing temperature and the second number is pressure (i.e. temp/pressure). The shaded area represents a region with very temperatures, below approximately –22°C.*

Table 12-1. Examples of pressure increase and total pressure after freezing in an erosion cavity for various ambient pressures at a freezing temperature of –2°C. The total pressure after freezing is independent of erosion cavity geometry and size.

Ambient pressure (sum of groundwater pressure and clay swelling pressure) (MPa)	Pressure increase from freezing (MPa)	Total pressure after freezing (maximum freezing pressure) (MPa)
4	22	26
5	21	26
10	16	26
20	6	26
26	0	26
50	0 (no freezing occurs)	50
100	0 (no freezing occurs)	100

Consequences in the reference scenario

The results from the permafrost simulations made show that, in the reference climate scenario, the above case does not affect the canister safety function. Not even the 0°C isotherm reaches repository depth at Forsmark in this scenario. Therefore, groundwater in erosion cavities does not freeze when a buffer erosion case is combined with a freezing case based on the reference climate scenario.

Consequences in the scenario with climate development favourable for permafrost growth

In the pessimistic climate development more favourable for permafrost growth, the 0°C isotherm reaches a depth of 400 m at Forsmark, see section 12.4.2. Therefore, freezing of groundwater in buffer erosion cavities can not be excluded at Forsmark when buffer erosion is combined with a freezing case based on the pessimistic climate development.

The results show that the pressure increase from freezing of ground water in erosion cavities, at an ambient pressure of 10 MPa and at a temperature of –2°C in a pessimistic climate scenario, is up to 16 MPa. Freezing at higher temperatures would yield lower pressures, see Figure 12-9, while other ambient pressures would not result in a total pressure higher than 26 MPa (Table 12-1). This total pressure is considerably lower than the maximum total pressures considered in the isostatic load scenario, see section 12.8.4. Since the isostatic load scenario does not result in canister failures, the same is concluded for this variant of the buffer freezing scenario.

If the maximum pressure from a very large ice sheet (28 MPa) (section 12.8.4) were to be directly and unrealistically combined with the total pressure associated with freezing of ground water in buffer erosion cavities from the pessimistic permafrost scenario (26 MPa), the resulting pressure would be 54 MPa. However, this case is not relevant since for ambient pressures greater than 26 MPa, the lowest bedrock temperature at repository depth in the permafrost scenario (–2°C) would not be low enough to freeze water in erosion cavities. In addition, the case of combined buffer erosion and freezing is of relevance only when permafrost is at its deepest in the climate scenario exceptionally favourable for permafrost growth. In order to produce this permafrost situation, it was assumed that the sites were situated above sea level, there were no protective snow or vegetation cover, and, above all, there was no ice sheet present at the sites at any time during the glacial cycle (section 12.4.2) i.e. a very pessimistically chosen cold and extraordinary dry climate scenario. The freezing-induced pressure in buffer cavities should, therefore, not be combined with the maximum pressure due to ice sheet load.

In the reference case, with an ice sheet present during the glacial cycle, the ice sheet may advance over pre-existing permafrost, but in this case the permafrost is far from reaching repository depth (section 9.4.3). In this case, no freezing of groundwater in eroded cavities would occur.

If there would be a transition from the combined buffer erosion with freezing case, described in this section, to a case when an ice sheet starts to form and eventually advance over the site, several other things of importance would also happen. This could be exemplified by a situation when the case exceptionally favourable for permafrost growth would be followed by the glacial cycle in the reference case. Firstly, this means that an increased winter precipitation is needed for the ice sheet growth. This implies that a snow cover would be present at the sites during winter, protecting the ground from winter temperatures, reducing the permafrost. Secondly, increased winter precipitation is associated with higher air temperatures at the sites /Moberg et al. 2006/, also reducing the permafrost depth. In addition, the growth process of the ice sheet, initiating in the Scandinavian mountain range, is slow. In the reference case it takes 50–60,000 years before the ice sheet reach the sites (Figure 9-67 and Figure 9-68) and the /**Climate report**, section 4.2.4/. Therefore, prior to ice sheet overriding at the sites, both a protective snow cover during winter and higher air temperatures would prevail for a considerable amount of time, allowing for a degradation of the permafrost that developed under the more extreme climate scenario. In this situation, the permafrost would degrade both from the surface, by warmer temperatures as such, and from the base, through the geothermal heat flux. In addition, freezing of ground water in erosion cavities under a higher ambient pressure from a large ice overburden, would result in a lower freezing-induced pressure in the erosion cavities, see Table 12-1, and as mentioned above, if the ambient pressure exceeds 26 MPa no freezing would occur at a temperature of –2°C. All in all, this means that also in this transient case, a possible freezing induced pressure in erosion cavities under exceptional permafrost conditions would not occur simultaneously as large ice loads from subsequent overriding of a thick ice sheet.

Conclusions

- Freezing of groundwater in buffer erosion cavities can be excluded when combining the buffer erosion case with a freezing case based on the reference climate scenario.
- Freezing of groundwater in buffer erosion cavities cannot be excluded when combining buffer erosion with a freezing case based on the pessimistic climate development more favourable for permafrost growth.
- For the latter pessimistic case, calculations for Forsmark using realistic assumptions on compressibilities of remaining clay, water, and ice, show that if freezing were to occur in erosion cavities, the total pressure at repository depth, including groundwater pressure, clay swelling pressure, and freezing-induced pressure, would be 26 MP, i.e. a total pressure considerably lower than the critical pressure for canister collapse.

- The freezing-induced pressure in buffer erosion cavities and large pressures from ice sheet load would not occur simultaneously.

12.5 Buffer transformation

Indicator criterion violated

This scenario concerns all conceivable routes to an alteration of the montmorillonite in the buffer material. This mainly concerns the function indicators on maximum buffer temperature and limited pH:

- the temperature in the buffer should not exceed 100°C,
- the pH of the groundwater should not exceed 11.

There may also be other processes that affect the stability of the montmorillonite. A *temperature gradient over the buffer* may cause transport of silica from the hot to the cold part. Presence of *metallic iron in contact with bentonite* could also alter the montmorillonite.

If the buffer material is transformed, this could possibly affect both isolation and retardation by affecting other function indicators. Isolation could be jeopardized indirectly through a lack of swelling pressure, which could lead to enhanced sulphide corrosion and create conditions suitable for microbially induced corrosion on the canister surface. Retardation could be affected by an increased hydraulic conductivity in the buffer and a loss of swelling pressure.

Treatment of routes to transformation in the main scenario

According to section 9.3.4 there are substantial margins to the 100°C function indicator even with account taken of uncertainties in the thermal conductivity in the rock. Based on this, temperatures above 100°C were not considered in the main scenario.

According to section 9.2.5, cement recipes with porewaters having pH $\leq$ 11 are assumed to be used in the repository. Based on this, alteration from high pH was not considered in the main scenario.

The movement of silica in the thermal gradient is discussed in section 9.3.10. The expected thermal gradients gave a very small redistribution of silica.

Contact between metallic iron and the buffer is only possible if there is a defect in the copper shell. This is not addressed in the reference evolution/main scenario.

Qualitative description of routes to buffer transformation

High temperature

This route to the transformation scenario can be due to:

1. A residual power in the canister, which is higher than the design value.
2. A misinterpretation of the thermal properties of the rock at the site.
3. A lower initial water content in the buffer than the design value.
4. A drying of the buffer, leading to a decreased thermal conductivity.

The only identified cause for route 4 is ventilation of the deposition hole for an extended period of time. There is no foreseen evolution of the near field that could lead to those conditions and drying of the buffer is not considered further.

High pH

High pH groundwaters in contact with the buffer could occur if the quality control systems for repository construction fails or malfunctions. The possible routes could either be a misjudgement of the pH from the cement used, or the use of a wrong cement mixture.

Thermal gradient

The thermal gradient is dependent on the thermal power from the canister and the thermal properties of the rock. However, the sensitivity to the parameters is small and the conclusions from the reference evolution are expected to be valid for all possible conditions.

Interaction with metallic iron

This process will occur if the canister insert gets in contact with the buffer material. Recent laboratory experiments under repository conditions have shown that reactions between montmorillonite and metallic iron in an oxygen-free environment may be relatively fast and in some cases also lead to a general breakdown of the montmorillonite structure /Lantenois et al. 2005/.

Another possibility would be if stray equipment or material containing iron or steel was left in a deposition hole during buffer emplacement. However, in SR-Can it is assumed that the QC system will ensure that the deposition holes will be cleaned before the buffer is deposited.

Quantitative consequence analysis/discussion – isolation and retardation

The effect of the thermal period on the buffer is described in section 9.3.10. The conclusion is that the expected temperature increase will have no significant effect on the buffer properties.

A buffer temperature exceeding the function indicator could lead to the following consequences.

- A transformation of the montmorillonite in the buffer to non-expandable minerals (illite). This would give a higher hydraulic conductivity and a decrease in swelling pressure.
- An accumulation of impurities in the buffer on the hot (or cold) side. This would be caused by temperature-dependent solubilities. This accumulation could potentially lead to clogging of the pore space and a change in the rheological and the hydraulic properties.

The transformation of montmorillonite to illite is calculated in section 9.3.10 and the results are shown in Figure 9-56. It is evident that even a temperature of 130°C for 1,000 years will have a very limited effect on the buffer. Figure 12-10 /Karnland and Birgersson 2006/ shows the swelling pressure of the MX-80 buffer material as a function of the dry density. The arrows in the figure indicate the swelling pressure for the reference density, a material with 30% transformation and a material with 50% conversion to illite. A conversion of 30% of the montmorillonite to illite would still give a swelling pressure above the 1 MPa function indicator. Figure 9-56 shows that a temperature of 170°C for a period of over 1,000 years is needed to get a degree of conversion of 30%. It is evident that the temperature under any reasonably postulated set of conditions will never be close to that value.

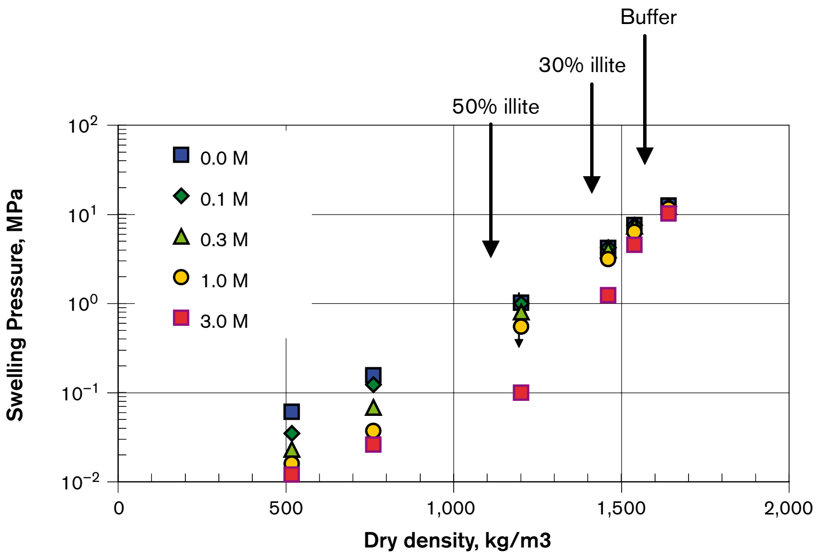


Figure 12-10. *Swelling pressure of MX-80 material in contact with pure water and NaCl solutions. Dots show measured values. Buffer indicates the swelling pressure of unaltered buffer material at KBS-3 target density, 30% illite indicates the pressure at the maximum acceptable transformation, and 50% illite illustrates the pressure at 50% illitization.*

An effect of steam on the properties of bentonite has been identified by /Couture 1985/ and is discussed by /Pusch 2000/ and /Karnland and Birgersson 2006/. There is an observed effect of vapour that could influence the maximum free swelling of the bentonite. However, the consequences on the long-term performance of the buffer will most likely be limited.

It is possible that the processes occurring at the canister/buffer interface are not fully understood. Changes in the properties of the buffer material close to the heater were observed in the Czech Mock-up Test /Pusch et al. 2005/ even though the temperature was limited to 90°C.

/Karnland and Birgersson 2006/ undertook a review of different kinetic models for smectite to illite conversion. Figure 12-11 shows the results from different models. The models of Cuadros /Cuadros and Linares 1996/ estimate a much faster alteration rate than the one used in SR-Can /Huang et al. 1993/. However, the Cuadros experimental work did not include specific determinations of all rate-determining constants and parameters, as was done by /Huang et al. 1993/. Cuadros, therefore, used natural analogues to adjust the model (Cuadros 5) in order to represent the conditions in nature, where bentonite persists over geological time scales.

There are two kinds of data uncertainties for this process.

1. Uncertainties in the temperature calculation. This is described in the section above.
2. Uncertainties in the data used in the alteration calculation /Karnland and Birgersson 2006/ and in the reactive transport calculation.

The potentially most critical data uncertainties are in the frequency factor and the activation energy in the kinetic expression for the alteration rate.

Based on the current understanding, a temperature increase in the buffer in the range described above will not have any significant effect on the swelling pressure and hydraulic conductivity function indicators.

High pH

If high pH groundwaters were to contact the buffer, some alteration or dissolution would be expected. The extent of the transformation is dependent on the actual pH of the water, the local hydrologic situation and the amount of cement producing the high pH (mass balance). However, in SR-Can it is assumed that the quality control systems will be sufficient to avoid the introduction of cements that could give rise to high pH waters in the repository.

Thermal gradient

The effect of the temperature gradient on the redistribution of impurities has been calculated by /Arcos et al. 2006/ and /Karnland and Birgersson 2006/. This process has been shown to have a very limited effect. The temperature gradient is only affected by the absolute temperature to a limited degree, and the dependence of this process on the temperature is, therefore, limited.

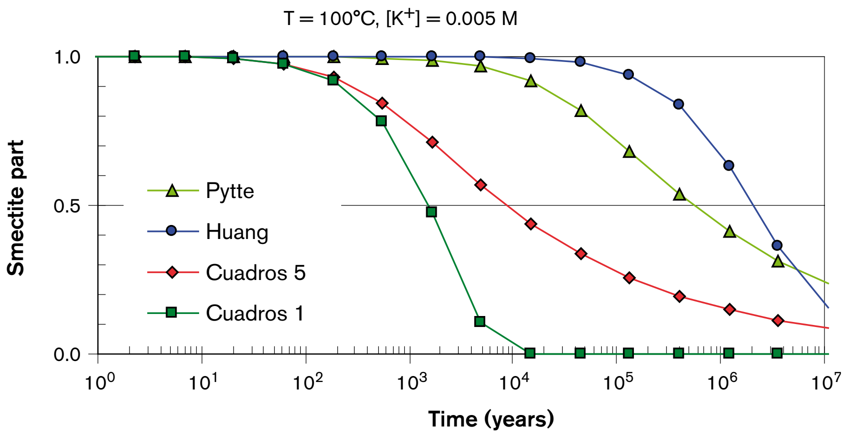


Figure 12-11. *Comparison of kinetic models for the smectite to illite transformation. Lines show the calculated remaining proportion of smectite versus time for a constant temperature of 100°C and a constant potassium concentration of 0.005 M.*

Interaction with metallic iron

The negative effects of metallic iron on bentonite are a recently identified issue. Currently, a mechanistic understanding is lacking and a quantitative model does not exist.

Summary

Since there still are some uncertainties on the effect of high temperatures on the long-term performance of the buffer, a case with an altered buffer zone next to the canister cannot be entirely excluded. The consequences of such a case would be a loss of swelling pressure next to the canister, and a correlated consolidation of this part due to the swelling pressure in the remaining buffer. However, a major part of the buffer has to be transformed in order for the buffer swelling pressure to fall below the pressure criterion of 1 MPa, which is most unlikely. If such a low pressure occurred, this would mean that it could be possible for sulphate-reducing bacteria to survive and sulphide corrosion to be enhanced.

The interaction between iron and buffer material is still under investigation. It is likely that only the region closest to the insert would be affected, assuming that there was any contact between the insert and the buffer, and the overall transport properties of the buffer would be maintained. However, today it cannot be excluded that the entire diffusion barrier could be lost. This, however, would have consequences only for retardation.

Greenhouse variant

There is nothing connected to the greenhouse variant (essentially 60,000 years before first permafrost) that would make buffer transformation worse. The climate on the surface has no bearing on any of the processes discussed in this section. The issue is therefore not further treated for the greenhouse variant.

Categorisation as "less probable" or "residual" scenario

High temperature, high pH and high temperature gradients are not expected to have any significant effect on buffer stability under any plausible conditions. Transformations of buffer material to an extent where the beneficial isolation and retardation properties are affected are, therefore, considered as a residual scenario.

If the buffer gets in contact with metal iron some alteration will occur. The extent of this is currently unknown. The process can only occur after copper canister failure. It is not relevant for failures when buffer is missing.

Conclusions

Processes that may alter or transform the montmorillonite, as described above, are not expected to have any significant effect on the important buffer properties, but since there are uncertainties over the combined effect of elevated temperatures and high pH, a case where the buffer next to canister is altered and the swelling pressure is lost to a level where bacteria can survive is appropriate to study. (This case is also relevant for evaluating the effects of silica transport /Karnland and Birgersson 2006/.) This case is treated as a residual scenario. A case for consequence assessment has, due to time constraints, not been analysed in SR-Can.

12.6 Conclusion from analyses of buffer scenarios

From the results of the analyses of the three buffer scenarios above, the following conclusions are drawn regarding propagation of buffer conditions to the analyses of canister scenarios.

- The buffer advection scenario is propagated as three cases to the canister scenarios: i) advective conditions in every deposition hole throughout the assessment period, ii) advective conditions according to the calculation results in the main scenario, iii) no advective conditions in any deposition hole at any part of the assessment period.
- The buffer freezing scenario is regarded as residual. It is, therefore, not propagated to the canister scenarios in SR-Can.

- The buffer transformation scenario is regarded as residual. It is, therefore, not propagated to the canister scenarios in SR-Can.

In addition to the buffer scenarios treating altered buffer states, also the case of an intact buffer needs to be considered, and this is covered by case *iii*) of buffer advection.

12.7 Canister failure due to corrosion

12.7.1 Introduction

Canister corrosion was evaluated for a number of situations in the reference evolution. As demonstrated in chapter 9, canister corrosion leads to failure only for advective conditions in the buffer, and for such conditions only in the most highly flowing deposition holes, in general after several hundreds of thousands of years.

The buffer conditions are thus crucial for the evaluation of the canister failure due to corrosion scenario. Based on the findings in the analyses of the buffer scenarios, the cases of intact buffer and of advective conditions in the buffer need to be propagated to this corrosion scenario. As described in the analysis of the buffer advection scenario, section 12.3, three cases for buffer advective conditions are propagated for further analyses.

Safety function indicator(s) considered

This scenario concerns the safety function C1, 'Provide corrosion barrier', that is directly related to the isolation potential of the canister.

This is one of the top-level safety functions, meaning that a number of sub-functions must be evaluated in order to fully assess the canister corrosion scenario. Several results from other scenarios, in particular regarding the buffer are, therefore, propagated to this scenario.

Treatment of canister corrosion in the main scenario

Canister failures due to corrosion occur in the main scenario, for the case of advective conditions in the buffer. For an intact buffer, the margins protecting against corrosion failures were demonstrated to be considerable.

The two tasks for this corrosion scenario are thus to i) evaluate whether all uncertainties for the corrosion case with advective conditions in the buffer are appropriately addressed in the main scenario and ii) whether for an intact buffer there are any remaining uncertainties that could challenge the conclusion that corrosion failures will not occur.

Qualitative description of routes to corrosion

Based on the FEP chart, Figure 7-3, a number of factors contributing to canister corrosion can be identified:

Initial state factors

- Initial minimum copper coverage.
- Buffer and backfill impurities.

Processes

- Copper corrosion.
- Buffer diffusion (for intact buffer).
- Buffer advection (for advective conditions in buffer).
- Microbial corrosion (for advective conditions in buffer).
- Groundwater flow.

- Groundwater concentrations of sulphide.
- Groundwater concentrations of methane (for advective conditions in buffer).
- The possibility of oxygen penetration.

External conditions

- Glacial conditions leading to enhanced groundwater flow.
- Glacial conditions leading to changed groundwater composition (oxygen, sulphide, methane).

12.7.2 Quantitative assessment of corrosion

Remaining uncertainties regarding each of the factors mentioned above are addressed below followed by corrosion calculations based on the additional uncertainties identified for an intact buffer and for a buffer in advective conditions.

Initial copper coverage

As mentioned in section 4.2.4, the initial copper coverage at the seals is assumed to be more than 40 mm for 99% of the canisters and between 35 and 40 mm for the remaining one percent. Other parts of the copper shell are assumed to have a thickness of 50 mm. For the corrosion analyses presented in this section, only a limited part of the canister surface is exposed to the corroding agent. For an eroded buffer where advection is the dominant transport process, a height of the canister corresponding to the thickness of the buffer around the canister, or 35 cm, is assumed to be corroded. For an intact buffer, where diffusion is the dominant transport process, the concentration profile in the buffer from species entering through a fracture in the deposition hole will have its maximum over an even smaller area. The probability that the area with (pessimistically) assumed reduced copper thicknesses around the seals will actually be exposed to corrosion is thus small. Therefore, the thickness is assumed to be 50 mm in the corrosion analyses. More sophisticated analyses could certainly be undertaken, but this is not seen as warranted in light of the considerable uncertainties associated with many other factors in the corrosion calculations, in comparison to the rather limited range of values of initial copper coverage discussed here. Furthermore, the results can readily be scaled to apply for other initial thicknesses than 50 mm. Similar arguments are presented in the discussion of the reference evolution, section 9.3.12.

Buffer and backfill impurities

The analysis of the reference evolution demonstrates that impurities initially present in the buffer and the backfill contribute negligibly to copper corrosion, see section 9.3.12. Mass balance considerations lead to the conclusion that corrosion depths from impurities are at most a few millimetres and furthermore that time intervals comparable to the one million year assessment period are required for all impurities to reach the canister. Considering that the impurity contents put a fundamental limit on the extent of corrosion caused by impurities, and that this extent is negligible, this issue is not further considered in this scenario. It is, however, noted that, say, a tenfold increase in impurity contents compared to that of the Milos buffer material would lead to a non-negligible effect on corrosion and that quality control procedures regarding impurities for the buffer and backfill materials need to be established.

Buffer diffusion

Buffer diffusion is neglected in the reference evolution and hence in the main scenario, see section 9.3.12. It has only been assumed that buffer is in place so that the Q_{eq}-concept is valid. If this is the case, then the buffer contribution to the transport resistance in the near field is negligible. As this factor is neglected already in the reference evolution, there is no reason to handle it any further in this corrosion scenario for the intact buffer. In the case of advective conditions in the buffer, buffer diffusion is, by definition, irrelevant.

Groundwater flow and glacial conditions leading to enhanced groundwater flow

The groundwater flow is one of the factors determining the equivalent flow rates around the deposition holes. In the reference evolution, conceptual uncertainties regarding groundwater flow for temperate conditions were evaluated by considering the three hydraulic interpretations of the Forsmark site resulting from the uncertainty analysis described in section 9.3.6. This aspect of groundwater flow is therefore not carried any further in the corrosion scenario.

Regarding groundwater flow for glacial conditions, four episodes of enhanced flow, based on a modelling reconstruction of the glacial episodes during the last glacial cycle are included in the reference evolution and the main scenario. Enhanced flow may occur when the front of a warm-based ice sheet is above the repository thus increasing the hydraulic gradients. The consequences for flow and hence corrosion depend on the magnitude of the gradient increase and on the duration of the altered situation. More extreme situations than that included in the reference evolution, referred to as case A in section 9.4.6, could be relevant to safety.

To address this, the stylised situation B, also described in section 9.4.6, is considered for one of the glacial cycles during the assessment period. This means that a 160-fold increase in groundwater flow over a period of 1,300 years is assumed. This implies an increase in equivalent flow rate, the entity of interest for corrosion in case of an intact buffer, of about 13, as the equivalent flow rate is directly proportional to the square root of the flow.

Intact buffer

For an intact buffer, the impact on corrosion for a case B episode is equivalent to that of $1{,}300\cdot\sqrt{160} \approx 17{,}000$ years of corrosion with unaltered flow. Over the one million year assessment period, or even over a 120,000 year glacial cycle, this has a negligible impact on the safety margins for corrosion for an intact buffer calculated for the reference evolution/main scenario in section 9.4.9. Furthermore, here, as for the reference evolution, the transport resistance offered by the buffer is neglected.

Advection in buffer

For a buffer with advective conditions, the impact on corrosion of a case B episode is equivalent to that of $1{,}300\cdot 160 \approx 208{,}000$ years of corrosion with unaltered flow. This is thus a 20% increase of the total impact over the one million year assessment period. This is taken into account in the formulation of cases for corrosion calculations below.

It is noted that this simple estimate disregards the fact that the corrosion rate will vary slower than linearly with the flow for very high flow rates, see further /Neretnieks 2006a/. Taking this into account could reduce the assessed increase in corrosion. Since the impact is, in any case, moderate, this detailed evaluation has not been pursued.

Groundwater concentrations of sulphide and methane

For an intact buffer, the concentration of sulphide in the groundwater is of importance, whereas when estimating effects for advective conditions in the buffer it is the sum of the concentrations of sulphide and methane that is of interest, since microbial sulphate reduction can take place in the deposition hole. For the reduction of sulphate to sulphide an electron donor is required. With methane as the electron donor, one mol of sulphate will be reduced by one mol of methane aided by microbial activity, see section 9.4.9.

For the reference evolution, it was assumed that the average groundwater sum concentration of sulphide and methane over a glacial cycle is 10^{-5} M, see section 9.4.7. This is regarded as a cautious assumption.

There is, however, a considerable spread in the observed sulphide concentrations at the sites. As explained in section 9.4.7, a considerable fraction of the observations are below the detection limit of $9\cdot 10^{-7}$ M, whereas a few observations are as high as $8\cdot 10^{-5}$ M. The data have been obtained over a number of years and with different measurement methods. Further analyses of the data are required before this spread in concentrations is fully understood. Pending the outcome of such efforts, a pessimistic case is formulated according to the following: The majority, 90% of the deposition holes, are cautiously assumed to experience a sum concentration of sulphide and methane of 10^{-5} M and for the remaining ten percent of the holes, the sum concentration is assumed to be 10^{-4} M (averaged over a glacial cycle). This is regarded as clearly more pessimistic than what is supported by the ensemble of present-day observations and by the understanding of the geochemical properties of the sites.

When assessing the impact for an intact buffer, the sulphide concentrations are, for simplicity, cautiously assumed to be equal to the sum concentration.

Intact buffer

For an intact buffer, this has, over the one million year assessment period consisting of eight glacial cycles, the effect of increasing the corrosion depths in the reference evolution by a factor of ten for the ten percent of the deposition holes assumed to experience sulphide concentrations of 10^{-4} M. For the reference evolution, the maximum corrosion depths were demonstrated to be around one millimetre for the deposition holes with the most extreme flow rates for the most pessimistic hydraulic interpretation of the site and including effects of spalling in the mass transfer calculation, see section 9.4.9. For this pessimistic case, even these deposition holes would not have corrosion depths exceeding around ten millimetres. Since the sulphide corrosion is by far the dominant corroding agent, it is concluded that no canister failures would occur in case of an intact buffer. It is also noted that any beneficial effects of the pore water chemistry in the buffer on sulphide concentrations have been disregarded.

Advection in the buffer

The increased sulphide concentrations for ten percent of the deposition holes are taken into account in the formulation of cases for corrosion calculations below.

Oxygen penetration

Penetration of oxygenated groundwater to the deposition holes could be a concern for situations with increased flow under the margin of an ice sheet. This effect was, however, ruled out both for type A and type B situations in section 9.4.7. Therefore, oxygen penetration is excluded from the corrosion scenario.

Stylised hypothetical cases of oxygen penetration have been analysed, as described in section 9.4.9.

Event sequences

The sequences of events that are considered in this scenario concern the succession of climate domains with their associated variations in groundwater flow and geochemical conditions. As averages over glacial cycles are used for these entities, justified by the fact that corrosion failures generally take several glacial cycles to develop, the detailed events sequences are of secondary importance for estimation of the number and timing of the resulting corrosion failures.

Quantitative consequence analysis/discussion – isolation and retardation

Intact buffer

For an intact buffer, the analysis of additional uncertainties did not result in any situations that challenge the conclusion from the reference evolution that there are considerable margins to canister failures. Type B situations of increased flow or pessimistic sulphide concentrations did not consume the margins to canister failure, even when combined with any of the hydrogeological models of the sites. Therefore, no additional corrosion calculations or analyses of radionuclide transport were carried out for the case of an intact buffer.

Advection in buffer

In the buffer advection scenario, section 12.3, three cases to be propagated to the corrosion scenario were identified.

1. A case where advective conditions occur in every deposition hole throughout the assessment period.

2. A case where advective conditions occur to the extent given by the reference evolution treated in chapter 9.
3. A case where diffusive conditions are preserved in every deposition hole throughout the assessment period.

The third case corresponds to an intact buffer and has been treated above. That case does not represent a situation with advective conditions in the buffer, but is included to represent the conceptual uncertainty regarding buffer colloid release/erosion. Further understanding of that process could lead to the exclusion of colloid release from future assessments. Furthermore, the uncertainty analyses of factors contributing to corrosion above have led to a number of situations that need to be evaluated quantitatively.

Figure 12-12 demonstrates the cases that have been formulated for the corrosion scenario. Uncertainties regarding geochemical conditions are represented by the red boxes to the left. For each of these, three hydrogeological models of the Forsmark site are included to cover uncertainties in the hydrological interpretation of the site (light blue boxes). The next branching represents the three cases of buffer advection propagated from the buffer advection scenario. Finally, the orange boxes to the right represent the number of failed canisters calculated for each of the situations.

As seen in Figure 12-12, most of the cases result in no canister failures. It is essentially only for the semi-correlated DFN model that failures occur; 10 for the cautious and 37 for the pessimistic geochemical conditions, during the one million year assessment period, assuming the SR-Can buffer erosion model. It is noteworthy that assuming initial advection in the buffer yields an almost identical result to that with the SR-Can erosion model. Figure 12-13 shows the corresponding result for Laxemar, but only for one hydrogeological model as alternatives have not been propagated to the safety assessment.

These two cases, denoted A and B in Figure 12-12, are propagated to radionuclide transport calculations. The same model as when quantifying buffer erosion for the reference evolution, see section 10.6, is used. Also the input data are the same as in section 10.6, except for the calculated failure times, that are obtained from the corrosion calculations presented above. The results are shown in Figure 12-14 and Figure 12-15 for Forsmark and Laxemar, respectively.

Cases A correspond to the base cases of the buffer advection/corrosion analyses and hence correspond to the reference evolution. Cases B represent the highest consequences when evaluating remaining uncertainties in this canister corrosion scenario. As seen in the figures, the most notable difference is the earlier onset in cases B, whereas the difference at the end of the assessment period is less than a factor of 2.

Uncertainties related to radionuclide transport and dose

Uncertainties regarding radionuclide transport for the advection/corrosion failure mode are discussed in section 10.6, for conditions related to the reference evolution. In the following, these uncertainties are considered again, for conditions related to the corrosion scenario.

- Fuel: The fuel dissolution rate is the most important controlling factor of the releases from the near field. Uncertainties relating to this factor are exhaustively handled in the analysis of the reference evolution, see further section 10.6.5.
- Canister and buffer: The shape of the eroded buffer volume in the corrosion model and the size of the corroded area of the canister surface are significant factors. These entities are difficult to assess and cautious assumptions have been made, see section 10.6.2. It is difficult to envisage cases that could be substantially worse, but it is also not possible to prove that the stylised cases are strictly pessimistic.
- Deposition tunnel backfill: This transport path is irrelevant for the canister corrosion scenario, since all failures occur due to relatively large and transmissive fractures intersecting deposition holes. These then also become the only relevant transport path from the near field.
- Geosphere: All geosphere uncertainties are bounded by the curve with doses from near-field releases, where geosphere retention is neglected. As seen in Figure 12-14 and Figure 12-15, the neglect of geosphere retention has a minor impact on the consequences. This is explained by the fact that only the deposition holes intersected by fractures with the highest flow rates and hence low geosphere retention yield corrosion failures.

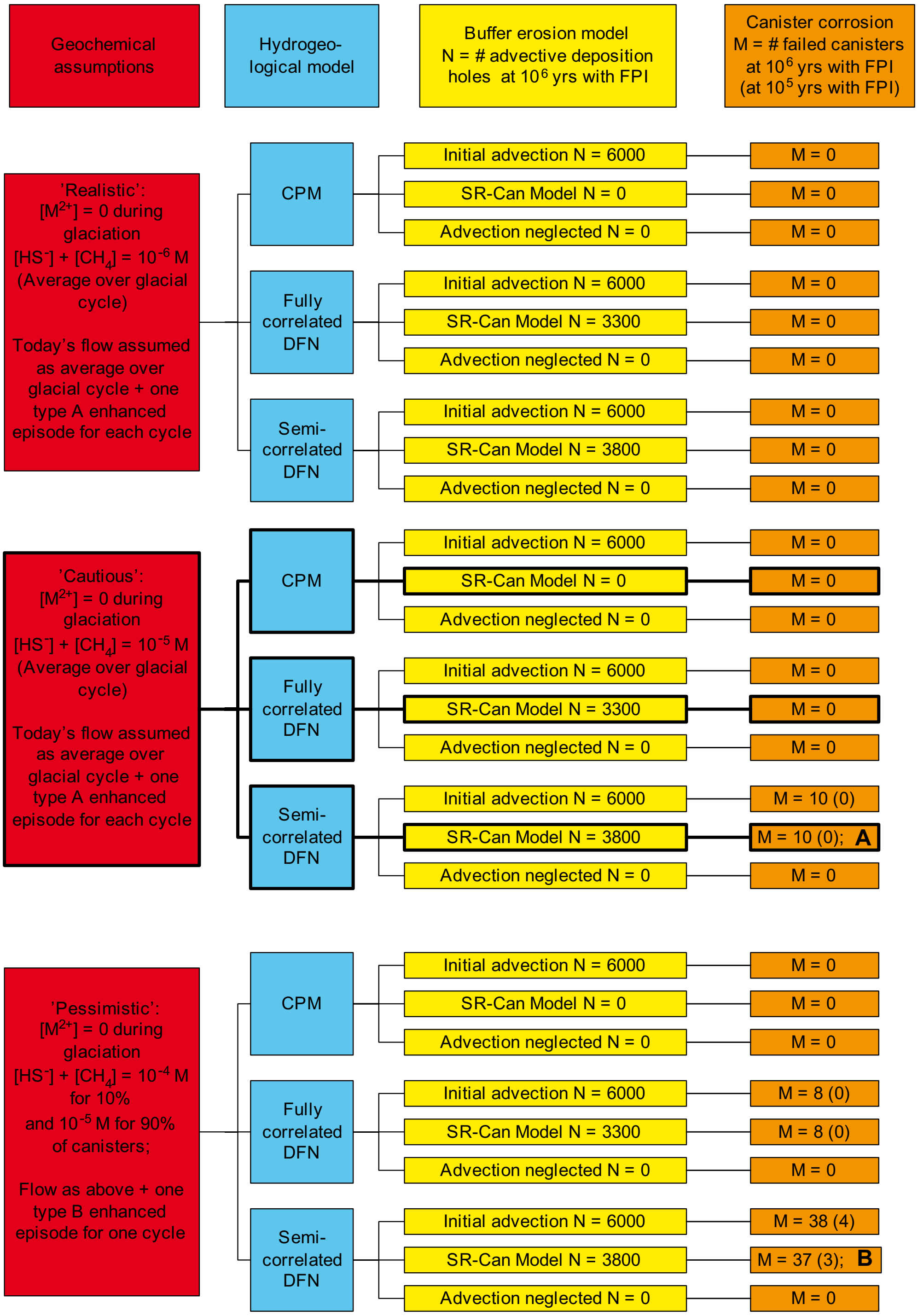


Figure 12-12. *Calculations for the buffer advection scenario for Forsmark organised as a tree structure. The boxes with thick, black frames represent cases covered by the main scenario. See main text for further explanation. Cases denoted A and B are propagated to radionuclide transport calculations.*

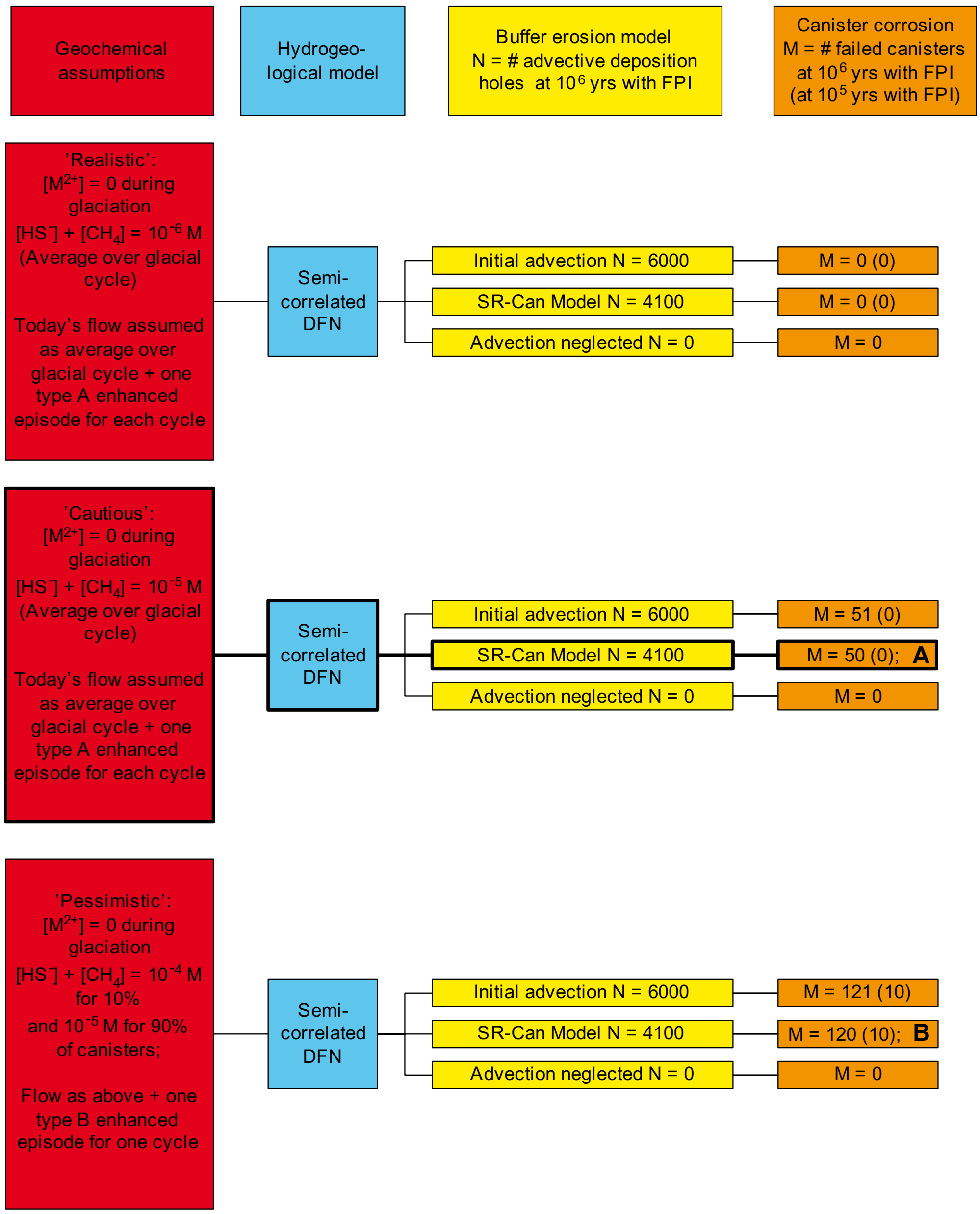


Figure 12-13. *Calculations for the buffer advection scenario for Laxemar organised as a tree structure. The boxes with thick, black frames represent cases covered by the main scenario. See main text for further explanation. Cases denoted A and B are propagated to radionuclide transport calculations.*

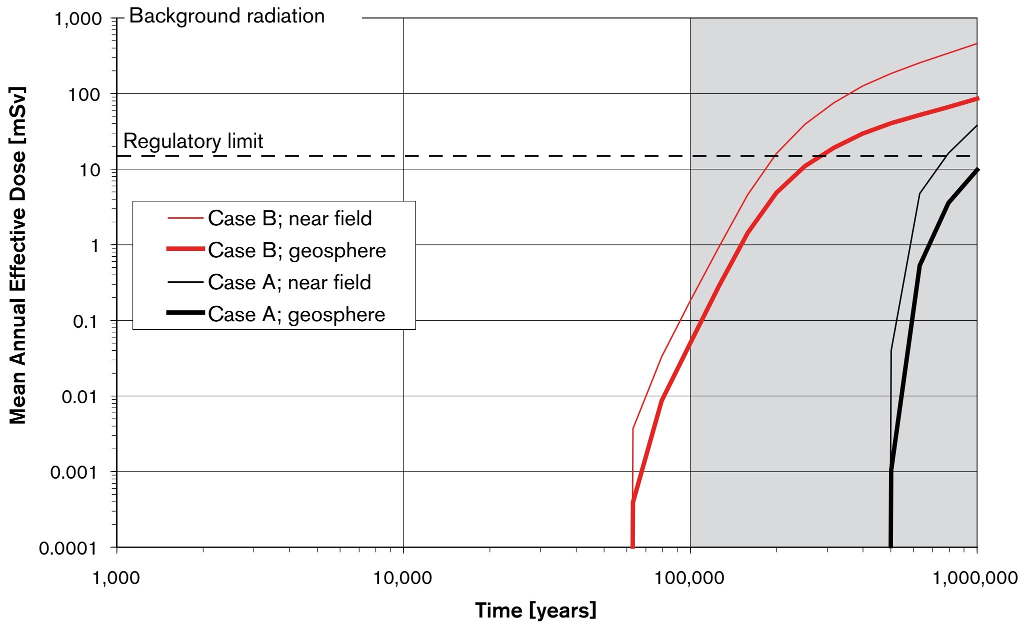


Figure 12-14. *Consequences for Forsmark for cases A and B in Figure 12-12. Analytic calculation, 10,000 realisations.*

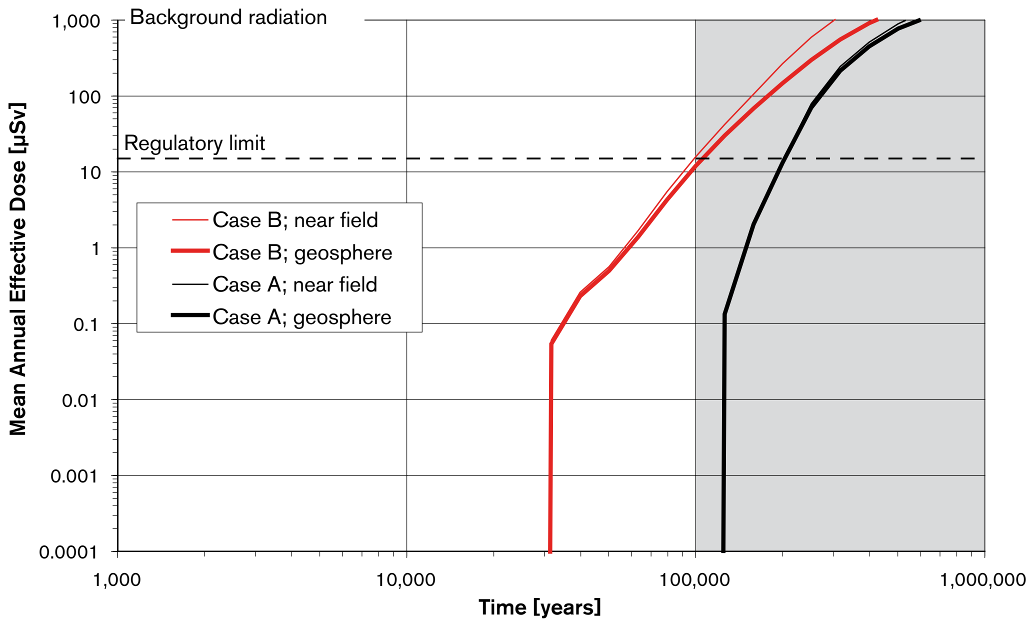


Figure 12-15. *Consequences for Laxemar for cases A and B in Figure 12-13. Note the minimal geosphere retention, i.e. the minimal difference between the near field and geosphere releases. Analytic calculation, 10,000 realisations.*

12.7.3 Conclusions

Categorisation as "less probable" or "residual" scenario

There is no basis for assigning probabilities to the set of corrosion cases. If it is assumed that all cases are equally likely, then the consequences in terms of number of failed canisters over one million years would be the average of the numbers in the orange boxes in Figure 12-12, i.e. around four failed canisters.

A pessimistic estimate is obtained if unit probability is assigned to the worst of the cases, i.e. 37 failed canisters in one million years for Forsmark and 150 for Laxemar. A more reasonable approach would be to consider the cautious case, yielding 10 failed canisters in one million years for Forsmark and 50 for Laxemar. Given the large uncertainties regarding several factors in the corrosion analyses, including those related to the evolution of the buffer, and the relatively small difference between the pessimistic case and the cautious case, it was decided to use the pessimistic case with unit probability as the contribution from the corrosion scenario in the risk summation. This is also motivated by the fact that some aspects of the modelling are stylised and difficult to assess.

Thus, case B in Figure 12-14, with unit probability, is propagated to the risk summation from the canister corrosion scenario.

Greenhouse variant

The above conclusions are valid also in relation to the greenhouse variant of the main scenario, since the additional uncertainties considered are related to more severe glacial conditions than in the reference evolution. Also, the alterations occur sufficiently far into the future that the distinction between the reference and greenhouse variants of the main scenario are of little significance, since the greenhouse variant postulates a warmer climate only for the initial 50,000 years of the first glacial cycle.

12.8 Canister failure due to isostatic load

12.8.1 Introduction

Safety function indicator(s) considered

This scenario concerns the safety function indicator isostatic load on the canister, safety function indicator C2. If the isostatic load exceeds the canister strength, the canister will collapse mechanically.

This safety function is directly related to isolation, as the isolation is assumed to be breached if the safety function indicator criterion is violated.

Treatment of this issue in the main scenario

Canister failure due to isostatic load was not included in the main scenario, since peak loads in the main scenario are well below the isostatic collapse load of the canister.

Propagated buffer conditions

According to section 12.6, three different buffer conditions are propagated to the canister scenarios. Two of these concern advective conditions in the buffer and the third is the intact buffer. Since advective conditions are related to an eroded buffer which has a lower swelling pressure than an intact buffer, such conditions are less likely to induce isostatic collapse.

Furthermore, in section 12.4.4, it was concluded that groundwater could possibly freeze in buffer erosion cavities for pessimistic assumptions of future climate conditions at the Forsmark site. It was, however, also concluded that if this were to happen, the resulting freezing-induced pressure would not be large enough to cause canister failures.

Based on these considerations, only the intact buffer is further treated in the analysis of potential canister failures due to isostatic load.

Qualitative description of routes to canister failure due to isostatic load (including initial state aspects and external conditions)

The evolution in this scenario is assumed to be identical to that of the reference glacial cycle variant of the main scenario, except for factors related to isostatic collapse of a canister.

According to the FEP chart, the possible violation of this criterion is a result of the relation between the mechanical strength of the canister, determined by the quality of the casting procedure, and the isostatic load on the canister which is in turn determined by the groundwater pressure, equal to the buffer pore water pressure, and the buffer swelling pressure.

The groundwater pressure is determined by repository depth for non-glacial conditions. For the Forsmark and Laxemar sites, this means pressures of around 4 and 5 MPa, respectively. For glacial conditions the alteration of the hydrostatic pressure due to the presence of the ice sheet is added. This pressure is, in the main scenario, assumed to correspond to the maximum ice thickness at the sites, as it cannot be significantly greater than this. At Forsmark, the additional hydrostatic pressure is 26 MPa and at Laxemar 22 MPa, see section 9.4.1.

The buffer swelling pressure is determined by the buffer density and chemical composition, including the species of adsorbed cation. In the main scenario, the maximum buffer swelling pressure, corresponding to an unaltered buffer of 2,050 kg/m^3 (the upper limit of the reference density interval), was determined to 13 MPa.

In summary, the following factors contribute to the possible occurrence of an isostatic collapse of the canister.

Initial state factors involved

- Canister strength.
- Buffer density.
- Repository depth (determining groundwater pressure if no glacial load).

Processes involved

- Buffer swelling.
- Buffer chemical alterations and density losses.
- Convergence of deposition hole.

External conditions involved

- Ice sheet thickness and hydrology.

An additional identified cause for increased isostatic loads would be freezing of the buffer. This is addressed in section 12.4.

These factors are discussed quantitatively in the following under the three headings canister strength, buffer swelling pressure and glacial load.

12.8.2 Canister strength

Both probabilistic and deterministic analyses of the canister strength have been performed. The probabilistic analysis was done in order to evaluate the consequences of the variability of the materials properties of the cast on the strength of the insert. For that study, a local collapse criterion was adopted. This means that only the overpressure at which the first local collapse event occurs was considered. At this point, there is no visible damage to the canister and, consequently, this event does not lead to any release. The total collapse of the insert and, as a consequence, the copper shell will occur at a much higher pressure. Since it is only after a total collapse that there will be any release, this collapse criterion has been adopted for SR-Can.

Probabilistic analyses of local collapse

The initial state of the canister insert determines its strength. Probabilistic analyses of canister inserts shows that for a base case with an overpressure of 44 MPa, the probability of failure is insignificant (~ $2\cdot10^{-9}$) for a BWR insert, which has less strength that the PWR version /Dillström 2005/. The result is sensitive to the eccentricity of the steel cassette with the channels for the spent fuel elements and the outer corner radius of the channel tubes. In the base case calculation, the cassette was assumed centred and the outer corner radius was 20 mm. Mechanical material properties of the insert were given as probabilistic input.

Crack growth and local plastic collapse were studied. The results showed that in all cases where crack growth occurred to a significant extent, local plastic collapse occurred at a smaller load. Therefore, only the latter is discussed in the following.

The probability of local plastic collapse of the insert was strongly dependent on i) the outer corner radius of the steel cassette tubes and ii) the eccentricity of the steel cassette.

The outer corner radius is determined by the specifications for the cassette tubes and will not change during the fabrication of the insert.

The cassette, however, can move out of its central position during the casting process. For a well-centred cassette, the onset value for local plastic collapse is at about 50 MPa For this pressure, the probability of local collapse is 10^{-4}. For an eccentricity of 5 mm, collapse starts between 45 and 50 MPa. For an eccentricity of 15 mm, the probability of local collapse is considerable (0.142) at a pressure of 40 MPa /Dillström 2005/.

Calculations and experimental tests of total collapse

The probabilistic analysis of collapse only considered the first local collapse; total collapse of the insert will occur at a much higher pressure. With a full collapse deterministic finite element analysis of the insert, the collapse pressure for the cast iron insert was calculated to be 104 MPa for a well-centred cassette. If the steel cassette and the copper corrosion barrier were also included in the calculation, the collapse pressure was calculated to be 130 MPa. The collapse pressures in calculations have also been confirmed in pressure tests of mock-up canisters /Nilsson et al. 2005/. Two mock-up canisters were pressure tested; the first one had an eccentricity of the steel cassette of about 10 mm whereas the second had no eccentricity. The first mock-up was pressurised to 130 MPa and showed large plastic deformations with residual radial deformation up to 20 mm. The second mock-up underwent plastic collapse at 139 MPa. In a study by Posiva, the failure pressure for a BWR insert with a 5 mm eccentricity of the internal cassette tubes was calculated to be 93 MPa /Ikonen 2005/.

These calculations and experimental studies indicate that a total collapse of the canister, leading to possible release of radionuclides will not occur until the external pressure has reached a level of 90 to 100 MPa.

Additional conceptual uncertainties related to the strength calculations

The statistical basis for the probabilistic analysis is rather limited. It was also found that one of the inserts from which the test specimens were taken obviously belonged to a different population from the other two inserts and it was, therefore, excluded from the analysis. The main reason for the difference was a high content of pearlite in that insert. This difference can be avoided with stricter specifications of the chemical composition for the cast iron.

In the calculations, idealised geometries and boundary conditions were applied. This limits the possible deformation modes. The consequences of this is considered negligible up to pressures of at least 60 MPa based on results from the ongoing more detailed analysis of acceptable discontinuities in the cast insert.

A simple bilinear elasto-plastic materials model was used for the cast iron. This model can be considered as conservative and the deviation from using a complete stress-strain curve is small up to 100 MPa.

In conclusion, no conceptual uncertainties that challenge the results discussed in the previous sub-sections have been identified.

Acceptance criterion for eccentricity

Based on the results from the probabilistic analysis, an eccentricity larger than 5 mm will not be accepted. This can be achieved by inspecting and measuring the insert after casting using laser technique. It should be pointed out, however, that the first mock-up insert had an eccentricity (10 mm) well above specification, but still did not undergo total plastic collapse until the expected maximum isostatic pressure had been exceeded by a factor of three.

Acceptance criteria for casting defects

Acceptance criteria for discontinuities in the castings are currently being developed based on the results from the probabilistic analysis. Awaiting those, the following observations can be made: i) The outer, peripheral region of the insert can be inspected with ultrasound using a pulse-echo technique. ii) The volumes between the fuel channels in the steel cassette can be inspected with ultrasound using transmission. Both these techniques were used for inspection of the canister inserts in the pressure tests.

A preliminary study of the influence of casting defects has been performed /Erixon and Kylberg 2006/. Three-dimensional deterministic calculations were performed for 1/8- and 1/4-segments of the canister insert. These calculations showed that a 15 mm deep cavity (half of the wall thickness between the fuel channels) with a cross-sectional area of 1 dm^2 only marginally affected the stability of the insert and that it would still withstand an outer pressure of 45 MPa. The same was the case for a cold lap through a segment. Even if the wall between the channels was totally missing over a 1 dm^2 area, the collapse pressure was only reduced by 10%.

In view of these preliminary results, it appears that the insert has a high damage tolerance and that only a combination of several unacceptable flaws will severely decrease the total collapse pressure. The probability of occurrence of such undetected multiple flaws is considered sufficiently low to be excluded from consideration in the safety analysis.

The ongoing, more detailed analysis of acceptable discontinuities in the cast insert will, however, show if this preliminary conclusion holds.

Conclusions

Total collapse, i.e. the criterion for canister failure, of the insert will not occur below 90 MPa according to both model calculations and laboratory tests.

Local collapse could occur at 45 MPa for preliminary values of the acceptance criteria for eccentricity and casting defects.

It is furthermore concluded that if the thickness of the cast iron wall of the canister insert were to be increased by 10 mm from the present value of 36 mm, these collapse loads are expected to increase considerably.

12.8.3 Buffer swelling pressure

Buffer initial density

The saturated density of the buffer under the reference conditions is 1,950–2,050 kg/m^3. The initial diameter of the deposition hole cannot reasonably be smaller than the reference value of 1.75 m since this is determined by the diameter of the boring machine.

The upper reference density limit of 2,050 kg/m^3 results in around 13 MPa swelling pressure according to Figure 4-6 and Figure 4-7. It is, furthermore, noted that a saturated clay density of 2,100 kg/m^3 yields both a calculated and experimentally observed swelling pressure of around 21 MPa.

A statistical analysis of buffer density based on data from variability observed between the 96 buffer blocks in the six deposition holes in the Prototype Repository in the Äspö Hard Rock Laboratory shows that the average buffer density for the deposition holes will be within a range of ± 28 kg/m^3 (for 5,999 of 6,000 holes in that analysis) /Birgersson and Johannesson 2006/. Thus, the expected range of densities is much narrower than the allowed variability of ± 50 kg/m^3.

The upper density limit of 2,050 kg/m^3 can therefore be seen as pessimistic. The variation of ± 50 kg/m^3 is, furthermore, seen as readily achievable given available techniques and quality control methods /Birgersson and Johannesson 2006/.

Buffer chemical alterations and density losses

The buffer swelling pressure is determined by the buffer density and chemical composition, including the species of adsorbed cation. All identified chemical changes (ion exchange, osmosis and mineral transformation, see section 4.2.8) of the buffer result in unaltered or decreased swelling pressure (possibly with the exception of a marginal effect for high density Ca bentonite). It is, therefore, pessimistically assumed that no such changes take place.

According to the FEP chart, the mechanisms through which buffer mass may be lost are piping, erosion or swelling into the deposition tunnel. It is pessimistically assumed that no buffer mass is lost over time due to these processes.

Conceptual uncertainties

No process has been identified that could increase the swelling of the buffer to a higher value than the original starting value. The pressure is expected to be as specified above or lower for all possible conditions.

Convergence of deposition holes

A possible issue is the convergence of deposition holes. No residual uncertainty has been identified that would challenge the conclusion from the main scenario, namely that convergence effects are negligible, see section 9.3.5.

12.8.4 Glacial load

Introduction

As mentioned in section 8.4.1, for glacial conditions an additional hydrostatic pressure related to the ice-sheet thickness is added to the hydrostatic pressure appropriate to ice-free conditions. The extremes regarding hydrostatic pressure in the glacial domain depend on the ice-sheet configuration and on its hydraulic systems. Under the Antarctic ice sheet, sub-glacial lakes have been observed. The hydrostatic pressure in these lakes is assumed to correspond to the ice overburden pressure. A hydro-thermo-mechanical balance is assumed where supply of basal melt water, re-freezing and ice deformation result in a hydrostatic equilibrium where the ice sheet rests, or floats, on the water surface /Pattyn et al. 2004/. As further justified below, it is reasonable to assume that also for the Fennoscandian ice sheet, the maximum ice-sheet thickness sets a limit to the maximum hydrostatic pressure that may occur at the bed.

Sensitivity to altered climate forcing

To investigate the maximum ice-sheet thickness that may occur in Fennoscandia, the ice-sheet model described in section 9.4.1 was run using a set of temperature evolutions where local annual air temperatures decreased linearly by 1°C per 2,000 years, from present-day temperatures down to various constant levels. In these sensitivity tests, temperatures were lowered between 4 and 16°C. Ice sheets only developed for temperature lowering cases of –7°C and colder (Figure 12-16). In all cases, the ice-sheet model simulated a total period of 100,000 years, after which approximate steady-state conditions were obtained with little further change in ice volume and area. The resulting maximum ice sheet thicknesses are shown in Figure 12-17.

As expected, the maximum ice-sheet thickness increases with colder climates (Figure 12-17 (black line)). However, the degree of increase in thickness with temperature lowering declines as colder cases are considered. For a temperature lowering of more than approximately 13°C, colder climates do not generate thicker ice sheets. This model result is in line with what is known of Antarctic ice-sheet variations, see below.

These simulated temperature cases are extreme as regards their prolonged duration. Variations in temperature of this magnitude have occurred in the past /Dansgaard et al. 1993/, but never of this extremely long duration without interruptions. The extreme nature of these sensitivity cases is reflected also in the resulting ice sheet configurations for the colder cases. Here, the ice sheet covers all of northern and central Europe, and extends southward all the way to the Alps. Geological observations of traces from Fennoscandian ice sheets show that such large ice configurations have never occurred, and can thus be considered unrealistic.

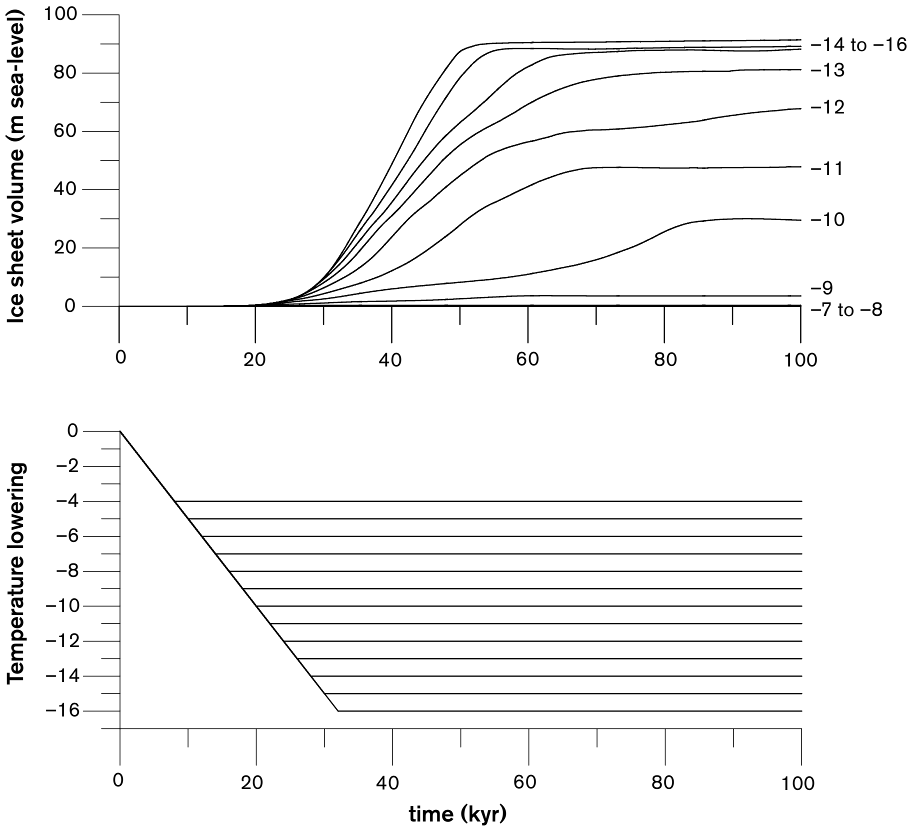


Figure 12-16. *Temperature lowering schemes and resulting development of ice-sheet volumes: The volume of the ice sheets is expressed as metres sea-level contribution.*

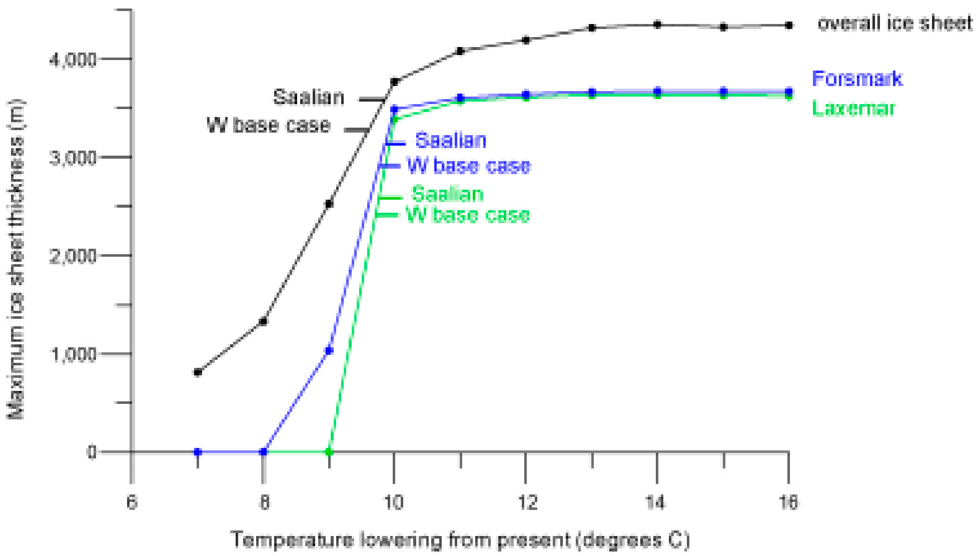


Figure 12-17. *Developed maximum ice-sheet thicknesses for the schematic climate evolutions in Figure 12-16. The three curves represent extracted maximum ice thicknesses for the Forsmark region (blue), Laxemar region (green), and overall largest ice-sheet thickness (black). The short lines marked W Base Case show the maximum ice thickness obtained in the Weichselian reference evolution, whereas short lines marked Saalian show the estimated maximum ice thickness for an ice sheet configuration supported by geological observations.*

The maximum ice thicknesses for Forsmark and Laxemar in the Weichselian reference case were 2,920 and 2,430 m, respectively, see Figure 12-17. In the sensitivity tests, the maximum ice-sheet thicknesses developed at Forsmark and Laxemar were 3,670 and 3,640 m, respectively. The uniform and high values of both sites reflect that they both have an interior location within these unrealistically large ice sheets. For more information on these simulations, see **Climate report**, section 4.4.2.

Estimate of maximum ice thickness at the sites during the past 2 million years

From geological information, it is known that the maximum ice extent of Pleistocene Fennoscandian ice sheets (i.e. those occurring the past ~ 2 million years) is larger than that of the Weichselian. This so-called Saalian ice sheet typically reached 100–200 km further south and 300–500 km further to the east than the Weichselian ice sheet /Svendsen et al. 1999/. Modelling of the Saalian ice sheet configuration showed that the maximum ice thickness of this largest ice sheet during the past 2 Ma supported by geological observations, is 3,130 m for the Forsmark region and 2,540 m for Laxemar, see Figure 12-17. Based on these results, the maximum expected ice sheet thickness is set to 3,200 m for Forsmark and 2,600 m for Laxemar.

From the results of the extreme cases in the sensitivity test, it is unlikely that the ice thickness at Forsmark and Laxemar could under any circumstance exceed 3,700 m. Both the Saalian estimates and the results of the sensitivity tests can be considered as high since it is unlikely that Fennoscandian ice sheets would, in reality, ever reach equilibrium size.

Estimate of maximum overall ice sheet thicknesses during the past 2 million years

In the climate cooling sensitivity tests, the maximum simulated *overall* thickness of the ice sheets is 4,360 m (Figure 12-17). This thickness occurs for the 13° cooling case and colder cases. This is 1,000 m more than the maximum ice thickness of the Weichselian reference case which is 3,300 m (Figure 12-17). Estimating the maximum thickness of the largest geologically feasible Pleistocene ice sheet in the same way as for Forsmark and Laxemar yields a maximum *overall* Saalian ice thickness of 3,600 m. The maximum expected overall ice thickness of the Fennoscandian ice sheet is, therefore, set to 3,600 m.

For comparison, the maximum ice sheet thickness occurring on Earth today is 4,500 m for parts of the East Antarctic ice sheet /Lythe et al. 2001/. The Greenland ice sheet has a maximum thickness of 3,400 m /Bamber et al. 2001/. In a colder glacial climate, the maximum ice thickness of the Antarctic ice sheet will probably not change significantly. In a colder climate, the marginal parts of the Antarctic ice sheet grow significantly, whereas, at the same time, more interior parts keep the same thickness or even gets thinner due to moisture starvation /Huybrechts 1990, Näslund et al. 2000/. It is, therefore, likely that the maximum thickness of the Antarctic ice sheet seen also over an entire glacial cycle is around 4,500 m. This value is close to the largest overall ice thickness obtained in the sensitivity test, 4,360 m (Figure 12-17). These results are also in line with a largest inferred thickness of the Laurentide ice sheet of 4,300 m /Tarasov and Peltier 2004/. These observations and results suggest that Pleistocene ice sheets up to date have not grown thicker than approximately 4,500 m, which gives a hypothetical upper limit for ice-sheet thickness.

Could hydrostatic pressure exceed ice overburden?

Hydrostatic pressures exceeding ice overburden can occur in some situations, for example in relation to jökulhlaups, i.e. large sudden outburst floods of glacial melt water from subglacial or supraglacial ice-dammed water reservoirs /Roberts et al. 2000/. In a few cases, higher pressures of non-jökulhlaup origin have been registered also in the ablation area of smaller glaciers. These high pressures are of artesian character, with the amount of pressure being ultimately determined by upglacier ice thickness and the presence of meltwater. This could possibly also occur in near-frontal parts of ice sheets /Roberts 2005/. However, during times of maximum ice thickness over Forsmark and Laxemar, during Last Glacial Maximum, these two sites are located within the ice sheet interior, far from the ablation area and the margin. For this ice-sheet configuration, surface melting is thus absent or negligible above and upstream of these sites, due to the high ice-surface elevation and associated low air temperatures. In addition, climate is at its coldest at this time during the glacial cycle, also precluding surface melt in these high-polar regions of the ice sheet. It is, therefore, reasonable to assume that hydrostatic pressures are dependent only on the local ice thickness during periods of maximum ice thickness, and not on ice thickness and surface melting *upstream* of the sites.

Conclusions

For the Weichselian reference case, the additional hydrostatic pressure related to ice thickness is 26 MPa for Forsmark and 22 MPa for Laxemar, Table 12-2. The *maximum* expected additional hydrostatic pressure, pessimistically derived from the largest ice-sheet configuration during the past 2 million years as supported by geological observations, is 28 MPa for Forsmark and 23 MPa for Laxemar. Maximum ice thicknesses of the more extreme and unrealistic ice-sheet configurations discussed above, with associated additional hydrostatic pressures, are also presented in Table 12-2.

12.8.5 Combined assessment

According to section 12.8.3, a maximum swelling pressure of 13 MPa could occur in the buffer.

The groundwater pressure is around 4 MPa at Forsmark for ice-free conditions. According to section 12.8.4, an additional ground water pressure of at most 28 MPa could occur as a result of a maximum glacial load supported by geological evidence.

This would give a maximum feasible isostatic load on the canister of 45 MPa at Forsmark. It is also noted that a simple addition of hydrostatic and swelling pressures is pessimistic.

According to section 12.8.2, local collapse cannot be ruled out for such a pressure, whereas the margin to total collapse (90 MPa), i.e. the criterion for canister failure, is considerable.

Overall, the following conclusions can be drawn.

- Total collapse is the relevant failure criterion since only this type of failure will lead to the release of radionuclides from the canister.
- There is ample margin to prevent canister failure due to isostatic load, even for the most extreme load situations.

Different event sequences

There are no different event sequences to consider in the discussion of this scenario, since pessimistic assumptions are made and maximum effects are sought for all involved factors. During the one million year assessment time, the canister will be subjected to some eight glaciations leading to repeated load cycles. The number of events is, however, far too low to have any effect on the mechanical stability of the cast iron insert.

Table 12-2. Maximum ice thickness and associated additional hydrostatic pressure for various Fennoscandian ice sheet configurations.

	Maximum ice thickness (m)	Hydrostatic pressure contribution (MPa)
Weichselian base case ice sheet		
Forsmark	2,920	26
Laxemar	2,430	22
Ice sheet overall	3,300	29
Largest Fennoscandian ice sheet during past 2 Ma supported by geological observations (Saalian)		
Forsmark	3,200	28
Laxemar	2,600	23
Ice sheet overall	3,600	32
Extreme ice sheets from climate sensitivity test		
Forsmark	3,670	32
Laxemar	3,640	32
Ice sheet overall	4,360	39
Maximum hypothetical		
	4,500	40

Combination of isostatic load and shear movement

See shear scenario, section 12.9, where it is concluded that the combined case can be excluded from consideration.

Greenhouse variant

The occurrence of high groundwater pressures is directly related to glacial conditions. The delay of glacial conditions expected for the greenhouse variant would thus be beneficial for repository safety in this respect. The issue is therefore not further treated for the greenhouse variant.

Categorisation as "less probable" or "residual" scenario

Based on the above assessment, this scenario, i.e. a canister failure due to isostatic load, is considered as "residual", meaning that its consequences are excluded from the risk summation.

The consequences in terms of radionuclide transport and annual effective dose of a *postulated* isostatic collapse are addressed in section 10.8.

12.9 Canister failure due to shear movement

12.9.1 Introduction

Safety function indicator(s) considered

This scenario primarily concerns the safety function indicator relating to shear loads on the canister. If the shear load exceeds the rupture limit of the cast iron insert, the canister is assumed to loose its isolation capacity (safety function indicator C3). A further consideration is the possibility of long-term creep effects in the copper shell.

Additional safety function indicators and criteria relevant to the evaluation of this failure mode are i) the requirement that rock shear movements at deposition holes should be less than 0.1 m (R3a) and ii) that the saturated buffer density must not exceed 2,050 kg/m^3 for the R3a criterion to be applicable (Bu4).

This safety function is directly related to isolation, as the isolation is assumed to be breached if the safety function indicator criterion is violated. Should this occur, also the retarding capacity of the system is affected, since the rock shear event affects the retarding properties of the buffer and the rock negatively.

Treatment of failure due to shear movement in the main scenario

The possibility of canister failure due to shear movement is of low probability and was, therefore, excluded from the main scenario, see section 12.2.1. This was based on the results of the analysis of the reference evolution reported in section 9.4.5.

The analysis below evaluates whether all uncertainties were appropriately considered in the main scenario.

Qualitative description of routes to failure due to shear movement

The evolution in this scenario is assumed to be identical to that of the base variant of the main scenario, except for factors related to a shear movement induced collapse of the canister.

As indicated in the FEP chart, the rupture limit of the cast iron insert is determined by the quality of the casting procedure. The shear stress on the canister, to which the rupture limit is to be compared, is determined by the movement of a fracture intersecting the deposition hole and the way in which this shear is propagated through the buffer. The buffer density affects this propagation, meaning that the buffer initial density must be evaluated. The rock shear movements are determined by the likelihood that the deposition hole is intersected by a fracture of a particular size, which, in turn, depends on the natural fracture structure of the host rock and the likelihood with which unsuitable fractures can be detected so that deposition holes intersected by these can be avoided.

Also the likelihood that earthquakes of a sufficient magnitude will occur during the assessment period needs to be evaluated.

In summary, the following factors contribute to the possible occurrence of a canister collapse due to shear.

Initial state factors involved

- Insert strength (casting quality).
- Copper shell tensile and creep ductilies.
- Buffer density.
- Buffer material properties.
- Fracture structure.
- Quality of deposition hole rejection.

Processes involved

- Canister: Deformation of copper canister; creep.
- Canister: Deformation of cast iron insert.
- Buffer: Swelling/mass redistribution.
- Buffer transformation.
- Geosphere: Reactivation of fractures as a consequence of earthquakes.

External conditions involved

- Earthquakes, in particular of post-glacial origin.

Propagated buffer conditions

According to section 12.6, three different buffer conditions are propagated to the canister scenarios. Two of these concern advective conditions in the buffer and the third is the intact buffer. Since advective conditions are related to an eroded buffer which has a lowered swelling pressure than an intact buffer, such conditions are of less concern when canister failures due to shearing are evaluated. Therefore, only the intact buffer is further treated in the analysis of canister failures due to shear movements. (In addition, the transformed buffer is discussed as a residual case below.)

12.9.2 Quantitative assessment of routes to shear failures

Insert strength (casting quality)

The failure criterion for the cast iron insert has been set to be a plastic strain, exceeding 7%. If plastic strain in any part of the insert exceeds that value, the canister will be considered as failed.

In the discussion in section 9.4.5, deterministic best estimate of the materials properties were used for the cast iron, i.e. variations in the casting quality were not considered, nor were possible casting defects considered. The effects of these factors on the stability of the insert during a shear movement are currently being studied in connection with the development of acceptance criteria for canister inserts and requirements on non-destructive examination of the insert. This will be further discussed in SR-Site.

Copper shell tensile and creep ductilities

The failure criteria for the copper shell has been set to be a plastic strain, exceeding 30% and a creep strain exceeding 10%. If plastic or creep strains in any part of the insert exceed those values, the copper shell will be considered as failed.

The tensile properties of the in the analysis a pessimistic low yield strength was used, which as a consequence over-estimates the plastic strain in the copper. Only a first attempt at including creep in the calculation has so far been made. This will be further elaborated in SR-Site.

Buffer density

As seen in section 12.8.3, the upper density limit of 2,050 kg/m^3 can be seen as pessimistic. The variation of ± 50 kg/m^3 is, furthermore, seen as readily achievable given available techniques and quality control methods /Birgersson and Johannesson 2006/.

Buffer material properties

The material model used for the buffer in the rock shear calculations is rather straight forward and simple with elastic-plastic deformations that do not consider that the clay is a porous material saturated with pore water since the shear rate is so fast that there is no redistribution of the water in the pores and subsequently no volume changes. The model for Na-bentonite is based on a large number of tests, while the model for Ca-bentonite is merely based on the general knowledge of the difference between these two bentonite types.

The assessment is, therefore, that there are no additional uncertainties regarding material properties or the material model that need to be addressed in this scenario.

Fracture structure

Uncertainties in the fracture description (DFN) were in the reference evolution, section 9.4.5, handled by calculating ε for alternative DFN model parameters for the Forsmark site, see Figure 9-83. As noted in the **Data report**, section 6.3, an appropriate evaluation of uncertainties of the coupled DFN parameters is not available for SR-Can. The approach used in section 9.4.5, to vary the parameter k_r, keeping the remaining parameters constant at best estimate values, is likely to yield a bound on the impact of DFN parameter uncertainties on ε.

Adequately quantified DFN uncertainties can readily be propagated to the calculations of ε. This will be possible when more elaborate evaluations of DFN uncertainties are at hand, for SR-Site. Regardless of scenario, the most critical parameter is the fracture intensity, especially for fractures with radii 75 m or greater. However, applying the FPC criteria (see below), lessens the impact of DFN uncertainties on the final estimate of affected canisters considerably /Munier 2006b/.

Quality of deposition hole rejection

The detection efficiency of the FPC criteria is covered in the reference evolution (section 9.4.5) and will not be treated further here.

Deformation of copper canister

The calculations in the reference evolution show that there is a substantial margin to failure of the copper canister for a 10 cm shear movement in both calcium and sodium bentonite buffers. As was mentioned in section 9.4.5, there are some remaining uncertainties regarding the behaviour of the canister lid and bottom and possible creep relaxation of stresses in the copper shell induced by the rock shear movement.

Only a first attempt at including creep in the calculation has so far been made. The finite element mesh used for the lid could have been too coarse to give at correct picture of the stresses. Work is in progress to address these conceptual uncertainties in SR-Site. It is at this time not clear if these uncertainties will lead to more or to less favourable results than those presented here.

Deformation of cast iron insert

Only deterministic analyses have so far been performed. These calculations show that there is a substantial margin to failure of the cast iron insert for a 10 cm shear movement in a sodium bentonite buffer. The maximum plastic strain was less than 1% in all calculated cases except one case where it amounted to 1.3%. For the case of calcium bentonite, the maximum plastic strains were higher, up to 5.4%. In many calculation cases, however, they were below 1% even with a calcium bentonite buffer. All these values are below or well below the specified ductility of the cast iron in the insert (7% plastic strain to failure).

As for the isostatic load case, the initial state of the canister insert is expected to determine its strength. The effects of the variability of the materials properties of the cast iron of the strength of the insert have not yet been investigated. The case is the same for possible excentric positioning of the cassette tubes for the fuel elements, which may have moved out of its central position during the casting process as well as the effects of other casting flaws, such as larger pores and cracks in the cast material.

In order to better understand the effects of these factors on the insert's stability under the load of a rock shear movement, a probabilistic analysis will be useful. Such a study will, therefore, be initiated in order to have these issues elucidated in SR-Site.

Swelling/mass redistribution

The uncertainties of the calculations do not primarily lie in the uncertainty of the material model or the critical parameters (mainly shear strength) but in the finite element model. The calculations suffer from the following main weaknesses:

1. The calculations do not take into account that there may be different strain rates in different parts of the buffer. However, this effect is not considered to be strong.
2. The element mesh, especially of the copper canister, may be too coarse to be able to detect stress concentrations, especially in the lid.

Another considerable uncertainty is the effect of long term geochemical transformations. The transformation to Ca-bentonite has been considered (see Table 9-13A and B). The effect of transformation to illite has also been investigated. The strength of natural illitic clay is only a tenth of the strength of MX-80, which clearly indicates that the effect on the canister of a rock shear is insignificant compared to when no transformation has taken place. The reason for the low strength is the low swelling pressure of the illite. The uncertainty lies in the question whether a transformed illite has the same properties as a natural illite, but the swelling pressure is certainly much lower.

A cementation of the buffer is not expected but if the buffer is partly cemented the properties may change radically. The properties of the cemented part will probably depend very much on the cementation process. An example of the consequences of a rock shear through a partly cemented buffer is analysed by /Börgesson and Hernelind 2006/. According to this calculation the effect of a rock shear on the canister when 8 cm of the buffer close to the canister has been cemented is that the maximum plastic strain in the copper and steel is increased somewhat but not more than for the case when the entire Na-bentonite was transformed to Ca-bentonite. However, that calculation is only an example since the properties of the cemented bentonite are not known.

A preliminary assessment is, therefore, that uncertainties regarding the mass redistribution modelling are covered in the reference evolution and that they need not be further addressed in this scenario. A renewed evaluation of the modelling will be made in the SR-Site assessment.

Earthquakes, in particular of post-glacial origin

While awaiting ongoing analyses, such as the impact of earthquakes larger than M6, the uncertainties linked to the likelihood of large earthquakes are judged to be reasonably well covered in the analysis in the reference evolution (section 9.4.5) and will therefore not be treated further here. It is, however, noted that additional analyses could lessen the impact of some of the cautious assumptions used for the analyses. For instance, it is not yet known if the prerequisites for seismic reactivation of faults can at all prevail at the candidate sites.

Reactivation of fractures as a consequence of earthquakes

The reactivation of fracture as a consequence of earthquakes is closely linked to the likelihood of earthquakes, see above. We therefore refer to the reference evolution, section 9.4.5.

Combination with isostatic load

As discussed in section 9.4.5, the stability of fractures in the rock is increased, rather than decreased, during periods of high isostatic load. This is a consequence of how stresses in the upper crust are expected to develop as a result of a typical future glacial cycle according to interpretations of preliminary analyses of large scale ice-crust-mantle interactions. More elaborate analyses based on alternative earth- and ice models are underway /Lund 2006/. These will give further perspectives on the stress development in the upper crust, but are not believed to change the general fault stability picture. This means that combined effects of high isotatic pressures and fracture shear movements do not have to be further considered.

Cumulative effects of several earthquakes

The induced slip on large fractures, as a response to an earthquake, might be less than the canister failure criterion due to the fracture's position, orientation, local stress field and other properties. However, it is possible that slip along a particular fracture accumulate to exceed the failure criterion as a response to repeated large earthquakes. In other words, the slip vectors on the fractures could be essentially identical for each seismic event. For this to happen several, large earthquakes need to occur along the same fault and the earthquake mechanism must be essentially identical for all events.

It is questionable if large earthquakes can be treated as independent events which is implied by the above reasoning. In fact, large earthquakes within a glacial cycle are most probably *dependent* events such that the release of elastic energy relaxes the fault so that another large earthquake along the same fault is less likely. Similarly, but on another scale, slip relaxes the fracture such that a repeated slip is less likely, and in particular slip of the same amount and orientation. Given the cautious assumptions discussed in 9.4.5, it is anticipated that repeated slip along a fracture, as outlined here, is of minor importance for the safety case.

Still, the cumulative effect of *multiple* glaciations must be treated as *independent* events. That is, we cannot account for stress released by earthquakes in previous glaciations. Again, the prerequisite for slip along a particular fracture, accumulated over several glaciations, is that the same fault reactivates as in the previous glaciation and that the fault mechanism is essentially identical. Again considering cautious assumptions as discussed in 9.4.5, the probability for this development is considered as remote.

We have therefore not, within SR-Can, evaluated such cases nor outlined any methodology to address this particular aspect. Nevertheless, this judgment must be tested by more elaborate analyses. Within the context of planned earthquake-related analysis efforts for SR Site, the issue of cumulative slip will be addressed.

12.9.3 Conclusions

Categorisation as "less probable" or "residual" scenario

Based on the above assessment, this scenario is considered as "less likely", meaning that its consequences are to be included in the risk summation.

The handling of uncertainties for this scenario was rather exhaustive in the reference evolution, see section 9.4.5. Several factors were treated pessimistically. The above analysis, however, demonstrates that there are some uncertainties, in particular relating to the mechanical properties of the canister, that have not yet been fully addressed. Further evaluations of these and of those handled in the reference evolution could lead to both a more and a less favourable result in SR-Site. Awaiting further assessments for SR-Site, probabilities of canister failures estimated in section 9.4.5 and used for the consequence calculations in section 10.7 are considered as a reasonable illustration of the risk contribution from the shear movement scenario.

The probabilistic results presented in section 10.7 are, therefore, for SR-Can, propagated to the risk summation in section 12.12.

Quantitative consequence analysis/discussion – isolation and retardation

The consequences of shear failures for the reference evolution were quantified in section 10.7, see Figure 10-51. These are propagated to the risk summation in section 12.12.

Uncertainties related to radionuclide transport and dose

Uncertainties regarding radionuclide transport for a failure due to shear movement were discussed in section 10.7, for conditions related to the reference evolution. In the following, these uncertainties are considered again, for conditions related to the shear movement scenario.

Fuel: Uncertainties relating to this factor are exhaustively handled in the analysis of the reference evolution, see further section 10.6.5.

Canister: No credit is taken for transport resistances in canister when the consequences of this failure mode are assessed.

Buffer: The reduction in buffer thickness assumed in the consequence calculations is larger than that corresponding to the rock shear movement required for canister failure. Uncertainties regarding other buffer properties are handled probabilistically as in the reference evolution. Therefore, no additional uncertainties relating to the buffer are addressed.

Deposition tunnel backfill: This transport path is irrelevant for the shear movement scenario, since all failures occur due to relatively large fractures intersecting deposition holes. These then also become the only relevant transport path from the near field.

Geosphere: No credit is taken for the retarding properties of the geosphere when the consequences of this failure mode are assessed.

12.10 Scenarios related to future human actions

12.10.1 Introduction

According to the scenario selection described in section 11.3 and Table 11-1, two main categories of scenarios related to future human actions, (FHA) were distinguished: scenarios related to a sealed repository and scenarios related to an unsealed or incompletely sealed repository. Only the former category is, due to time constraints, addressed in SR-Can.

The potential exposure to large quantities of the radiotoxic material is an inescapable consequence of the deposition of spent nuclear fuel in a final repository, and consequently intrusion into the repository needs to be considered in repository design and safety assessment. To reduce the probability of inadvertent intrusion and resulting exposure to the spent fuel, in line with ICRP recommendations /ICRP 1998/, the following countermeasures have been applied in the repository siting and design:

- The repository is to be located at a site not containing exploitable natural resources.
- The repository depth is selected to be substantially greater than the depth of interest for water supply and more generally occurring sub-surface facilities.
- The repository will be sealed.
- Measures will be taken to preserve institutional control and information on the repository for as long as possible.

12.10.2 Principles and method for managing FHA

Man is dependent on, and influences, the environment in which he lives. After closure of the repository, future generations should be able to utilize the repository site according to their needs without jeopardizing their health. In the case of a final repository of the KBS-3 type, there are, however, inevitably examples of activities that, if carried out carelessly or without knowledge of the repository, could result in exposure to radiotoxic elements. Examples of such activities are drilling of deep bore holes and construction of tunnels, shafts or rock caverns to great depth within the repository area. Globally occurring human activities such as the emission of greenhouse gases or pollution may also affect the repository. There is, therefore, an international consensus that future human activities shall be considered in safety assessments of deep geological repositories /OECD/NEA 1995, ICRP 1998/.

Human actions of concern are those with a potential impact on the repository's safety functions. The human actions can be divided into different categories e.g. "recent and ongoing" or "future"; "global" or "local" /Wilmot et al. 1999/ and "inadvertent" or "intentional" /OECD/NEA 1995, ICRP 1998/. Recent and ongoing, local, intentional activities are considered in the description of the local ecosystems (see sections 4.3 and 9.3.3). Mishaps can be regarded as local, inadvertent activities and the ones occurring during the excavation and operation phases are considered in the general handling of uncertainties in the main and additional scenarios. The global, recent and ongoing emission of greenhouse gases has no direct impact on the repository, but may affect the climate and is considered in the greenhouse variant of the main scenario, section 9.6. That leaves global pollution other than the emission of greenhouse gases and local, future activities for further analysis.

If people in the future for some reason deliberately enter the repository they are responsible for the consequences of their actions. Society today cannot protect future societies from their own actions if the latter are aware of the consequences /OECD/NEA 1995, ICRP 1998/. However, in developing a system for final disposal of spent fuel, as much consideration as possible should be given to future generations. These generally accepted principles are also expressed in the background comments to SSI's regulations /SSI FS 1998:1/.

Based on the above, the future human actions considered in this part of the safety assessment are restricted to global pollution and actions that:

- are carried out after the sealing of the repository,
- take place at or close to the repository site,
- are unintentional i.e. are carried out when the location of the repository is unknown, its purpose forgotten or the consequences of the action are unknown,
- impair the safety functions of the repository's barriers.

A problem when discussing future human actions is that the future of man and society cannot be predicted. On time spans of tens of years or more, the best we can do is to identify some important parameters or factors and combine them to explore possible outcomes. On time spans of hundreds of years and longer the future of man and society is, however, unpredictable and the uncertainties are indeterminate or unspecified, i.e. the outcome space is not known and cannot be described. It is for instance impossible to determine what scientific discoveries will be made the next 1,000 years. One commonly applied approach to handle this and to avoid speculation as to the future is to assume that the future conditions of society and technical practice are essentially the same as today /OECD/NEA 1995/. This provides a practical and comprehensible procedure to illustrate the potential hazards related to future human actions at the repository site which is applied in this assessment.

In the general guidance to their regulations SSI /SSI 2005/ recommends the inclusion of direct intrusion by means of drilling as well as examples of activities that indirectly may affect the safety functions in the safety assessment. They also recommend basing the future human activity scenarios on current habits and technical practise. Regarding the consequences, SSI considers that only doses due to the impaired repository need to be calculated. The consequences for the individuals performing the intrusion need not to be assessed.

In line with SSI's general guidance, future human actions and their impact on the repository are evaluated separately, and are not included in the main scenario or the risk summation.

Method

Human actions can affect the repository in different ways. The impact of the action on the repository as well as its consequences is the result of a combination of technical and societal factors. Examples of such factors are the level of technology and knowledge, existence of institutional control, infrastructure and settlement pattern and food supply system. For the purpose of providing as comprehensive a picture as possible of different human actions that may impact the deep repository as well as their background and purpose, the following systematics have been used /**FHA report**/:

A. Technical analysis:
   Identify human actions that may impact the safety functions of the repository and describe and justify the actions in technical terms.

B. Analysis of societal factors:
   Identify framework scenarios (framework conditions) that describe feasible societal contexts for future human actions that can affect the radiological safety of a deep repository.

C. Choice of representative cases:
   The results of the technical and societal analyses are put together and one or several illustrative cases of future human activities are chosen.

D. Scenario description and consequence analysis of the chosen cases.

The three first steps are reported in the **FHA report** and are mainly based on work carried out in conjunction with the safety assessment SR 97 /SKB 1999a/. Results from the development of the SKB FEP database, chapter 3, and a review of some relevant literature published after SR 97 are also considered. The last step is accounted for in sections 12.10.4 to 12.10.7 below.

12.10.3 Technical and societal background

Technical analysis

Step A – Technical analysis – was based on the results from a workshop carried out within the framework of SR 97 /Morén et al. 1998/. For SR-Can, the relevance of the results from the workshop regarding recent technical developments was reviewed based on consultation with technical experts within SKB. Furthermore, an audit against the NEA FEP database and linked national projects resulted in some minor amendments and the addition of the action "subsurface bomb or blast".

For SR 97 a group of engineers with good knowledge in the fields of geotechnics, geology, geohydrology, chemistry, systems analysis and risk analysis was selected to participate in a workshop. The purpose of the workshop was to make a list of human actions that could impact the repository and describe and explain these actions in technical terms. The list was required to be based on current technical practise and the human actions were defined as those that could impact the safety functions of the repository and be feasible and credible from a technical viewpoint.

The actions were divided into the categories human actions with thermal (T), hydraulic (H), mechanical (M) or chemical (C) impact. A human action was considered to belong to a specific category if variables or processes belonging to the category were affected and the purpose of the action was to utilize a resource and/or perform a task that could be said to belong to the category. It should be mentioned that most of the human actions will impact variables or processes belonging to more than one of the categories T, H, M or C, so the assignment was based on their principal impacts. The identified actions are presented in Table 12-3.

The list of human actions was audited based on the potential impact on the safety functions of the repository. The actions with the greatest influence on the performance and safety were identified. It was concluded that actions that include drilling and/or construction in rock are those with the greatest potential influence on the repository.

Table 12-3. Human actions that may impact repository safety.

Category	Action
Thermal impact	T1: Build heat store*
	T2: Build heat pump system*
	T3: Extract geothermal energy (geothermics)*
	T4: Build plant that generates heating/cooling on the surface above the repository
Hydrological impact	H1: Construct well*
	H2: Build dam
	H3: Change the course or extent of surface water bodies (streams, lakes, sea) and their connections with other surface water bodies
	H4: Build hydropower plant*
	H5: Build drainage system
	H6: Build infiltration system
	H7: Build irrigation system*
	H8: Change conditions for groundwater recharge by changes in land use
Mechanical impact	M1: Drill in the rock*
	M2: Build rock cavern, tunnel, shaft, etc*
	M3: Excavate open-cast mine or quarry*
	M4: Construct dump or landfill
	M5: Bomb or blast on the surface above the repository
	M6: Subsurface bomb or blast*
Chemical impact	C1: Store/dispose hazardous waste in the rock*
	C2: Construct sanitary landfill (refuse tip)
	C3: Acidify air, soil and bedrock
	C4: Sterilize soil
	C5: Cause accident resulting in chemical contamination

* Includes or may include drilling and/or construction of rock cavern.

The workshop also included some general technical or engineering discussions and conclusions. A technical assessment of the suitability of the repository site for the actions in Table 12-3 was that it is more favourable for building a heat store or heat pump plant than other places, due to the heat generated by the spent fuel. For the other actions, the repository site was considered to be equivalent to, or less favourable than, other places with similar bedrock. Since SR 97, sites for site investigations have been selected and regarding the ore potential, the site investigations and subsequent analyses have led to the conclusion that the candidate areas can be described as sterile from an ore viewpoint, see further section 4.3.

Other aspects of human actions at the repository site that were taken into account in the technical assessment were that:

- In order for an action to be carried out, someone must be willing to pay for it, or it must be expected to yield a profit that covers the costs of carrying it out.
- Both costs and potential profits are coupled to technological progress and overall societal evolution.
- The utilization time for man-made facilities that involve some kind of continuous operation may be from tens to hundreds of years.

Analysis of societal factors

Prevailing societal conditions are of importance both for the possible occurrence of inadvertent human actions impairing repository safety and for evaluation of their consequences. Important issues are why the disruptive action is being carried out and contemporary societal conditions such as general knowledge and regulations. These primarily humanistic and socio-economic questions were analysed at a workshop for SR 97 /**FHA report**, Morén et al. 1998, SKB 1999a/. Experts in the fields of cultural geography, history of science and technology and systems analysis participated in this workshop. So called framework scenarios that describe plausible societal contexts for future human actions with an influence on the radiological safety of the deep repository were formulated. The framework scenarios were developed by means of morphological field analysis /Morén et al. 1998, Ritchey 1997/, a group- and process-oriented interactive method for structuring and analyzing complex problem fields that are non-quantifiable, contain non-determinable uncertainties and require a judgmental approach.

From the study of societal aspects, it was concluded that it is difficult to imagine inadvertent intrusion, given a continuous development of society and knowledge. Owing to the long time horizon, however, it is not possible to rule out the possibility that the repository and its purpose will be forgotten, even if both society and knowledge make gradual progress. Nor is it possible to guarantee that institutional control over the repository site will be retained in a long time perspective. With a discontinuous development of society, where the development of society and technology contains a sudden, large change, it seems likely that knowledge will be lost and institutions will break down. It is also reasonable to assume that knowledge is lost if society degenerates.

12.10.4 Choice of representative cases

It is probable that the repository site will be used by people in the future. Human actions that influence radiological safety and are carried out without knowledge of the repository and/or its purpose cannot be ruled out. Actions that influence the isolation or the function indicators for isolation are the most severe, followed by actions that influence retardation or the function indicators for retardation. Changes in the biosphere may result in an increase in the doses to which human beings may be exposed if the isolation has been violated and there are leaking canisters in the repository.

A KBS-3 repository will be situated at 400–700 m depth in the rock, and at the candidate sites the suggested repository depth is 400 m at Forsmark and 500 m at Laxemar. One reason for the repository depth related to the KBS-3 method is the wish to locate the repository in an environment where the isolation of the fuel will be retained even in the event of extensive changes on the surface. Changes considered in the determination of the depth for a KBS-3 repository are natural changes and changes caused by man. Examples of natural changes are change of the repository's location in relation to the sea, and the presence of permafrost and ice sheets. These natural changes will also influence factors of importance for future human actions at the site e.g. settlement, society and man's opportunities to use the repository site.

Large uncertainties are associated with the development of technology and society. To avoid speculation, the NEA working group on assessment of future human actions suggested an approach based on present-day knowledge and experience /OECD/NEA 1995/. However, applying this approach literally or with consistency there would be no inadvertent human actions yielding radiological consequences. The current activities at the repository sites will not impact the safety. Drilling to great depth is solely performed to investigate the possibilities to locate a repository for spent nuclear fuel at the site. If this were to result in something hazardous, measures to avoid or minimize consequences for man and environment would be taken. There is another dilemma in the assessment of future human actions. In order to quantify the consequences, detailed descriptions of the human actions are required. Such descriptions will inevitably include speculations as to the course of actions which always can be questioned. However, both the technical and societal analyses can, even if they do not depict conditions that exist today, be said to be based on current practise and their results can be used for the selection of representative cases. When describing scenarios based on the selected cases, speculation is avoided by assuming the most severe among simplified and plausible alternatives.

All actions in Table 12-3 influence the migration of radionuclides in the biosphere. However, actions that are performed on or near the surface, down to a depth of a few tens of metres, are judged not to be able to directly affect the technical barriers and the isolation of the fuel. This applies to the actions T4, H2, H3, H4, H5, H6, H7, H8, M3, M4, C2, C3, C4 and C5 (though some of them could include drilling of relatively deep wells). Activities near the surface that belong to categories M and H are deemed to have less influence on the repository than natural changes in conjunction with future climate change. Of the actions that entail a chemical influence (C2–C5), acidification of air and land (C3) has been studied in most detail. In realistic cases of acidification by atmospheric sulphur and carbon dioxide, the environment at repository depth is not affected /Nebot and Bruno 1991, Wersin et al. 1994/. Soil layers and bedrock are judged to work efficiently as both filter and buffer against other chemical compounds as well.

Bombing or blasting on the ground surface above the repository (M5) cannot affect the isolation of the waste, except if blasting is done with a powerful nuclear weapon. Such an event implies a nuclear war and the consequences of the war and the blast itself would be much greater than the consequence of leakage from the repository. Sub-surface testing of nuclear bombs (M6) close to the repository may however violate the isolation in a similar way to an earthquake. The test would need to be carried out close to the deposited canisters. Testing of bombs could be combined with identified societal contexts to form a plausible scenario. However, tests of nuclear bombs require knowledge of nuclear fission and its associated risks and are carried out below the surface to avoid environmental impact. Since measurements are carried out in connections to the tests it is plausible that if a detectable leakage from the repository exists, it would be distinguished from the releases from the bomb and handled by a society performing sub-surface weapon tests.

Some of the actions in Table 12-3 can – besides influencing radionuclide transport – indirectly influence the isolation of the waste if they affect the geosphere's capability to provide favourable hydrological or chemical conditions. Such actions would have to be performed directly above or very close to the deep repository and include drilling and/or construction in the rock (M1, M2). These categories include actions that have to do with heat extraction (T1, T2, T3), well drilling (H1) and disposal of hazardous waste in the rock (C1). Hydropower plants (H5) and open-cast mines and quarries (M3) may also involve drilling or rock works at great depth. Before a rock facility is built, drilling is carried out to investigate the rock. What all of these cases share is therefore that – if present day technology is applied – they involve drilling in the rock.

Large rock facilities adjacent to the repository are deemed to be out of the question in a short time perspective, i.e. within a few hundred years, for several reasons. For example, the deep repository is itself a large rock facility – the only one of its kind in Sweden – that is very unlikely to be forgotten over such a short time span. Institutional control can be expected to endure on this timescale. The enumerated actions that encompass major rock works are less likely at the repository sites, based on current technology and economics. In a slightly longer time perspective, i.e. a few or several hundred years or more, it is difficult to predict how knowledge, technology and society will develop, and thereby how, where and why rock facilities will be built. Based on current practice, rock facilities at depth down to around 50 m may very well occur and actually do so at both candidate sites (the SFR facility at Forsmark and the Clab facility at Oskarshamn). In the far future, the potential ore resources to the south-west of the investigated area in Forsmark may be exploited.

Of the actions in Table 12-3, “Drill in the rock” is judged to be the only one that can directly lead to penetration of the copper canister and breach of waste isolation, while at the same time being inadvertent, technically possible, practically feasible and plausible. “Drill in the rock” is furthermore a conceivable action in the light of the results of the societal analysis. Even if it is possible to build a rock cavern, tunnel or shaft or to excavate an open-cast mine which leads to penetration of the copper canister, doing so without having investigated the rock in such a way that the repository is discovered, i.e. without knowledge of the repository, is not considered to be technically plausible. However the construction of a rock facility at shallow depth or a mine in the vicinity of the Forsmark site may occur in the future. The cases “Canister penetration by drilling” and “Rock facility in the vicinity of the repository” and “Mine in the vicinity of the Forsmark site” were, therefore, selected for further description and analysis.

12.10.5 Assessment of the drilling case

Purpose and execution of the drilling

Only drilling done without knowledge of the location and purpose of the repository is considered. Various countermeasures to reduce the likelihood of inadvertent intrusion into the repository have been discussed /OECD/NEA 1995, Eng et al. 1996/. When the repository is sealed the countermeasures then deemed to be most efficient will be implemented. Examples of such countermeasures are conservation of information in archives, marking the site and various types of institutional control, for example physical surveillance, ownership restrictions and restrictions on land use. All these countermeasures are assumed to have lost their preventive and warning effect at the time for the drilling.

As discussed in section 12.10.3, it is hard to imagine a societal evolution resulting in the loss of knowledge of the repository, its purpose and content in combination with preservation or development of knowledge, technology and society. It is likely that a society having the technical capability to drill to great depth also has the knowledge to analyse their findings and possibly will act to prevent harmful effects on man and the environment. In the drilling scenario, it is assumed that technology to drill to great depth is available, that the knowledge of the location and purpose of the repository is lost, that the intruders are incapable of analysing and understanding what they have found and that no societal regulations on drilling exist. It is assumed that an evolution rendering this situation will require some time. Countermeasures to prevent inadvertent intrusion are generally assumed to be preserved for between 100 and 500 years, whereas physical markers may be effective on a longer time perspective of up to a couple of thousand years /OECD/NEA 1995, Wilmot et al. 1999/. A KBS-3 repository is a large industrial establishment that will be under operation for several decades and this type of facility has been debated, investigated and analysed since the first nuclear power plants commenced operation in Sweden. It is plausible that it will take some time before the knowledge about the repository is lost and also for society and land owners to give up the control of activities such as drilling at the repository site. Based on this, it is assumed that the drilling will take place 300 years or longer after repository closure.

The technical practise is assumed to be similar to that at present. Today, drilling is done to sink wells, for the extraction of heat from the ground, and for exploratory purposes. Rock wells are normally drilled to a depth of between 50 and 100 m, but occasionally wells are drilled down to 130–150 m. Deeper wells are very uncommon. The reason is that it is expensive to drill and the probability of finding potable water in sufficient quantity declines with depth. The deeper wells are usually used to extract heat. Well drilling is generally done by percussion drilling. Today’s standard drill rigs are capable of drilling to a maximum depth of 200–250 m, but there is an ongoing development of equipment for percussion drilling down to 1,000 m depth (Nilsson 2006, SKB pers. comm.). However, this kind of drilling equipment is not capable of drilling through metal. Even if drilling to depths down to 500 m or more for the extraction of heat is performed today and may become more common in the near future, drilling to great depth is generally done for exploratory purposes, most often prospecting. It is, therefore, assumed that drilling through the repository is done for exploratory purposes.

Diamond (core) drilling is normally employed for exploratory drilling. The drill core is retrieved, placed in boxes and inspected by a geologist. Selected samples may be analysed more thoroughly. The cuttings (the pulverized rock mixed with the drill’s cooling water) are normally removed with water, which also cools the drill. The water with cuttings is usually spread on the ground around the borehole. When the drilling is finished, the cores are sent to core mapping and the borehole is abandoned. If the hole has passed a zone with high water flow, so that a great deal of water is brought up to the surface, the borehole may be filled in. This is generally only done if the flow entails a problem for local residents.

The direction of the borehole varies depending on the purpose and what is known about the rock volume to be investigated. In general the drill is inclined; the angle with the ground plane is usually 60–85°. If there are no known obstacles or underground facilities, the drillers always try to continue the drilling even if they run into problems. If the drill reaches the buffer and the canister these may very well be penetrated and the drilling continued and not stopped until the drill core is inspected, or the agreed depth is reached. If penetration of the backfilled deposition tunnel occurs, the water cooling the drill and bringing the cuttings to the surface will be glutted with fine-grained material. The usual procedure is then to try to flush the fine grained material away. If this does not succeed, which is plausible if trying to drill through the backfill, the borehole is frequently grouted and the drilling continued though the concrete (Nilsson 2006, SKB pers. comm.).

The drilling angle is assumed to be 85° as this will make the longest hole through the canister and bring most fuel to the surface. The cuttings are assumed to be spread on the ground, but the cores containing spent nuclear fuel are removed. It is assumed that the purpose of the drilling is to reach great depth and that the drill rig therefore is placed at a low point in the terrain. When the backfilled tunnel is reached the borehole is assumed to be grouted and the drilling continued. The buffer is assumed to be grouted as well, the drilling continued and the canister penetrated. When the drill core containing the canister and fuel is brought to the surface the anomalous situation is taken to be recognised and the drilling is stopped. The site and the borehole are abandoned without further measures. About a month later, a family moves to the site and operates a domestic production farm there. The abandoned borehole is used as a well by the family. The consequences for the repository and the annual effective doses to the family are assessed.

Function indicator(s) considered

The scenario affects the following function indicators:

- C1, Ensure isolation.
- B1, Avoid advective transport in buffer.
- B2, Ensure tightness, self sealing.
- B7, Prevent colloid transport through buffer.

Further B3, Avoid canister sinking may be affected if sufficiently much buffer material is lost. These function indicators all relate to isolation and retardation properties of the canister and buffer. If they are violated, the isolation of the canister as well as the diffusion- and colloid filter barriers could be lost.

Qualitative description of the consequences of unintentionally penetrating a canister when drilling

It is assumed that one canister has been penetrated by core drilling. The borehole above the penetrated canister is assumed to be grouted and the buffer's capability to prevent advective transport, self seal and prevent colloid transport are lost in the grouted area. Some buffer and backfill material is lost, but excluding the grouted parts both backfill and buffer are assumed to retain their safety functions. The water containing the cuttings from the drilling is brought the surface and spread on the ground on a circular area. The assumptions used in the consequence analysis can be summarised as follows:

- The canister is penetrated.
- The grouted borehole has left an open pipe from the penetrated canister to the surface.
- There may have been a drop in density in the buffer and backfill, but since the loss is assumed to be limited this is not further analysed.
- There is no delay for the radionuclide transport in the geosphere.
- The instant release fraction of the inventory, as well as the radionuclides in the cuttings are brought to the surface and spread on the ground.

Quantitative assessment of the radionuclide release and the dose consequences of a penetrated canister

Only doses to the family that settles on the site are considered. The dose originates from two sources. The abandoned borehole used as a well by the family and the cuttings containing the instant release fraction and the fuel particles spread on the ground. The engineered barriers have lost their safety functions and the geosphere most of its retarding capability. The important parameters in the assessment are summarised below.

Time of drilling: The time of drilling determines the radionuclide inventory left in the canister.

Time of settlement: The time the family settles on the site and starts using the borehole as a well and the contaminated soil for cultivation determine the content of radionuclides in the well and on the ground.

Amount of fuel brought to the surface: The amount of fuel and associated radionuclides brought to the surface will determine the dose from the cuttings spread on the ground.

Instant release fraction: Radionuclides not embedded in the fuel matrix will be immediately released. Certain elements may precipitate if their inventory is large and the water flow through the deposition hole is limited. However it is assumed that the instant release fractions are pumped to the surface during the drilling event.

Fuel alteration rate: The fuel alteration rate will directly determine the release of most radionuclides under most circumstances.

Water flow through deposition hole: The water flow through the deposition hole will determine the release rate of radionuclides. The flow rate may also control fuel matrix dissolution under some circumstances.

For the open borehole the properties of the waste form and the flow of water through the borehole will limit the release of radionuclides. The annual effective dose is determined by the capacity of the well and how the water is used. The annual effective dose for each radionuclide is calculated by multiplying the inventory at a given time by the fuel alteration rate and a biosphere conversion factor (see section 10.2). The water flow is used to check whether elemental solubility limits govern the release of some radionuclides and if the fuel matrix dissolution rate is limited by uranium solubility.

For the cuttings brought to the surface, the content of radionuclides, their availability for transfer to agricultural products and air and the time after the drilling that the site is utilized are the main parameters determining the annual effective dose. It is assumed that the family moves to the site one month after the drilling and that the radionuclides are instantaneously available for transfer to agricultural products and air. The calculated annual effective dose is that which an adult member of the family would be exposed to the first year at the site. The data used in the dose calculations are given in Table 12-4. The results from the calculations are shown in Figure 12-18 and Figure 12-19.

The results show that the dose from the crushed spent fuel and instant release fraction of the inventory left on the ground with the drilling cuttings is dominated by Sr-90. From the instant release fraction, other important radionuclides are Cs-137, Ni-63 and Nb-94 and from the cuttings with crushed spent fuel Am-241, Pu-239 and Pu-240. The doses from using the borehole as a well are dominated by the long-lived actinides. The plutonium isotopes 239, 240, 242 together with the uranium daughters Th-229 and Th-230 are the most important contributors.

Uncertainties

As discussed in section 12.10.3 both future societal conditions and technical practices are unknown. The dose calculations are based on the worst plausible situation given current habits and practise. There are a number of uncertainties in the assumed drilling case and these can be divided into uncertainties regarding the impact on the repository and uncertainties in the dose calculations.

Table 12-4. Data used in the calculation.

Parameter	Value/assumption	Comment/reference
Time of drilling	300 years after closure of the repository or later	–
Time the family settles at the site	One month after the drilling	/IAEA 2005/
Time the exposed individual spends in the middle of the contaminated area	365 h	1 hour per day every day of the year
Radionuclide inventory	12×BWR 38 MWd/kgU	**Initial state report, Data report** (section 3.1)
IRF	Included in the inventory left on the ground	–
Fuel alteration rate	10^{-7}/y	Mean value according to the **Data report** (section 3.3)
Water flow through deposition hole	1 m^3/y	Section 9.2.3
Dose conversion factor for the open borehole	Site-specific mean value for a well case	/Avila et al. 2006/ The water is used for drinking and irrigation of a garden farm
Dose conversion factors for contaminated ground	Different factors for external irradiation, inhalation and ingestion of food cultivated at the site	/Avila and Bergström 2006, IAEA 2005/
Radius of contaminated area	3 m	–
Thickness of contaminated soil layer	0.1 m	–
Borehole diameter	0.056 m	–
Core diameter	0.053 m	–
Portion of fuel in the cuttings	0.1	Set to the volume of the fuel in relation to the volume of the canister
Contaminated drilling length	5 m	Canister length divided by sine of the drilling angle
Dust concentration in the air	5 10^{-7} kg/m^3	/IAEA 2005/
Inhalation rate	1 m^3/h	/Avila and Bergström 2006/
Yearly intake of carbon	110 kgC/y	/Avila and Bergström 2006/
Productivity of contaminated area	0.15 kgC per m^2 and y	/SKB 2006hi/ Value used for landscape dose factors

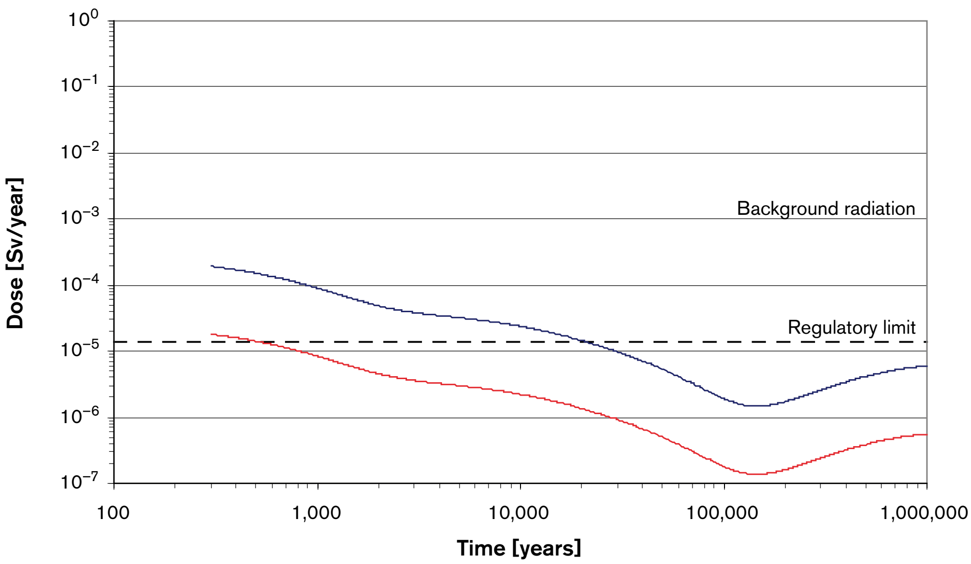


***Figure 12-18.** Calculated annual effective doses from using the borehole as a well for drinking water and irrigation at Forsmark (red line) and Laxemar (blue line).*

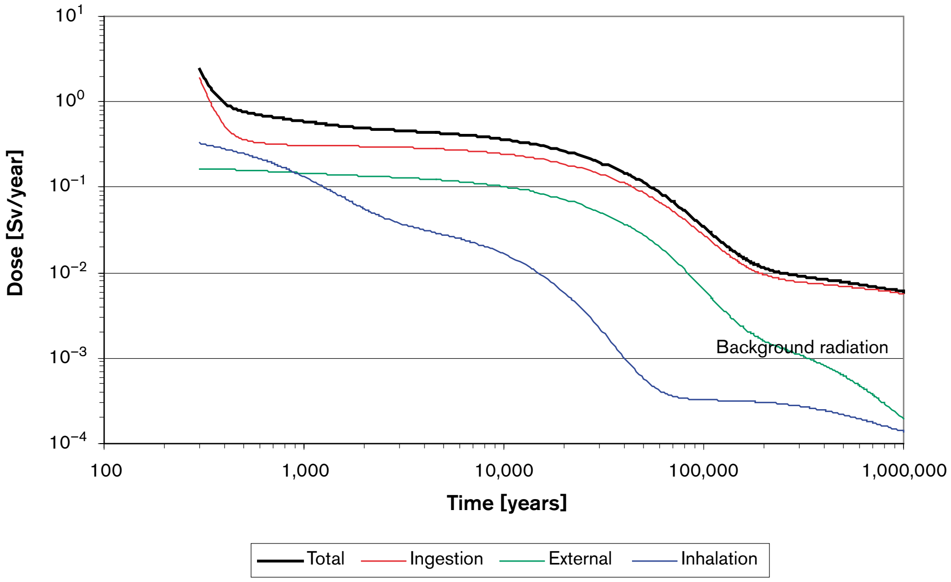


Figure 12-19. *Calculated annual effective doses from the cuttings left on the ground. The doses are those that an adult would get the first year after settlement if the person spends one hour per day in the middle of the assumed contaminated land area around the borehole and the contaminated area is used for domestic farming.*

Uncertainties regarding the assumed impact on the repository relate to:

- Buffer properties after the drilling event.
- Validity of the fuel alteration model under these circumstances.
- Validity of the use made of the instant release fraction.
- Direction of the flow through the bore hole.
- Flow rate through the deposition hole.

It is assumed that the buffer's function of preventing advective transport is lost. The borehole is assumed to penetrate both the deposition tunnel and deposition hole and the borehole is grouted and remains open. Based on current practise and the assumed drilling angle this would be a plausible situation. However, usually a smaller drilling angle is used and, if this was the case, it would be more probable that the borehole would only penetrate the buffer and canister and not the deposition tunnel. In such a case, it is probable that the borehole would not be grouted, that most of the buffer material would remain in the deposition hole and that there would be diffusion resistance in the buffer. This could lead to near-field transport properties similar to those of the main scenario and releases would be greatly reduced.

The fuel alteration model is based on the assumption that there will be reducing conditions and even a presence of a partial pressure of hydrogen. The cast iron insert is still available in this scenario, but the system has an open tube to the surface.

The instant release fraction used is based on the assumption that all nuclides in the metal parts of the fuel elements are immediately released to the water. If the buffer is still a diffusion barrier, this is acceptable since the time for transport through the buffer can be assumed to be much longer than the corrosion rate of the metal. However, if the buffer is lost this is not true and the instant release fraction used may lead to an overestimate of the inventory brought to the surface during drilling. Instead, a fraction of the radionuclides that are assumed to be immediately brought to the surface may be progressively released to the borehole and well, as the metal parts corrode.

Concerning flow direction, the assumption is that the borehole is used as a well and consequently the direction of the flow is in towards the borehole and then upward to the surface. If the borehole is not used as a well, the flow direction may be from the surface down. This would lead to longer geosphere transport and possibly some retardation due to sorption, and of course also to the release of the radionuclides into a different ecosystem. Possibly, this could also lead to a quick drawdown of oxygenated surface water with more rapid dissolution of the spent fuel as a consequence.

The flow through the deposition hole is set to 1 m^3/y. The calculated doses from using the borehole as a well are not very sensitive to this value. However, if the flow were much lower than this, the solubility limit of plutonium would control the maximum annual effective dose that could be received. If the flow was much higher the solubility of uranium would control the matrix dissolution.

Uncertainties regarding the calculated annual effective doses concern:

- The execution of the drilling.
- The time of the drilling.
- The time the family settles at the site.
- The availability in, and loss of radionuclides from, the contaminated soil.
- The use of the borehole and contaminated ground and the time the person spends in the contaminated area.

The assumed radius of the borehole and the drilling angel will affect the amount of radionuclides brought to the surface. The handling of the core and cuttings will affect their spreading and dilution in the biosphere. All these factors will affect the calculated doses from the cuttings left on the ground but not the doses from using the borehole as a well.

The time of the drilling was set to 300 years after deposition. This basically affects the radionuclide inventory, the earlier the drilling takes place the larger inventory of short-lived radionuclides and the higher the annual effective doses.

The shorter time between the drilling event and the time when the family settles at the site the more radionuclides will remain in the contaminated area on the ground and the larger inventory of short-lived radionuclides in the well-water.

The whole radionuclide inventory in the contaminated area is assumed to be instantaneously available for transfer to the agricultural production and air with contaminated dust. This assumption leads to a conservative value of the annual effective dose during the first year, since most likely only a fraction of the inventory will be available from the beginning. Further, it is assumed that there are no losses of radionuclides from the contaminated area other than by radioactive decay. However, in reality, other loss processes, such as leaching in percolating waters, are likely to be of importance. Note that the calculated annual effective dose from the radionuclides brought to the surface is valid only for the first year after the intrusion given these assumptions and that the land is assumed to be cultivated during that year.

It is not certain that the family finds the borehole and uses it as a well. Current practice is to place the pump just above the borehole for the well. Non-manual pumps are most often covered and some space is left around them to allow maintenance. Manual pumps require some space for pumping. The combination of using the borehole as a well and the small area (3 m radius) around it for cultivation therefore seems unlikely, but cannot be ruled out. The assumption that the person spends an hour per day right above the borehole in the middle of the contaminated, cultivated area also seems unrealistic. Based on current practice the most likely situation seems to be that the contaminated area will either be used for cultivation or the borehole will be used as a well and that an individual will only occasionally be situated in the middle of the contaminated area. Consequently, the person can be assumed to either receive the dose from agricultural products from the area or from using the borehole as a well and some fraction of the dose from direct exposure and inhalation of dust from the soil. The calculated annual effective doses are illustrations of possible consequences rather than estimations of what the consequences would be.

Conclusion

If a canister is penetrated and the safety functions of the buffer and backfill are lost and the borehole is used as a well for drinking and irrigation, the annual effective doses to representative members of critical groups will exceed the individual limit on annual effective dose for members of the public but not the annual effective dose due to background radiation. The calculated doses are, due to the greater capacity of the well and related dilution, an order of magnitude smaller at Forsmark than at Laxemar. Assuming the site-specific mean capacities of wells, at Forsmark the dose limit is only exceeded if the intrusion occurs during the first 500 years after closure, whereas, at Laxemar, the dose limit is exceeded if the intrusion occurs in the first 21,000 years after closure of the repository. If the instant release fraction and crushed material from the fuel elements is brought to the surface, the land is used for cultivation the same year as the intrusion occurs and a person spends time in the contaminated area, annual absorbed and effective doses may reach very high levels. The exposed person in the example given may be severely injured. The first 400 years after closure the yearly dose from the cuttings left on the ground is greater than 1 Sv. A dose of 1 Sv is the limit for suffering from radiation sickness some hours to days after exposure. After about 15,000 years the calculated dose from the cuttings on the ground is 0.3 Sv/year. Doses below 0.3 Sv give no observable symptoms but a risk to develop cancer of 1–2% /Upphed 1995/. One could expect that if the borehole is used as a well, the contaminated area immediately adjacent to the hole will be used for the pump and not for cultivation and vice versa if the contaminated area is used for cultivation no pump is placed on it.

12.10.6 Assessment of the rock cavity or tunnel case

Purpose and operation of the rock cavity or tunnel

As in the drilling case, it is assumed that location and purpose of the repository is forgotten and that the technical practise is similar to that used at the present. Further, it is assumed that the construction is initiated 300 years or longer after repository closure.

As discussed in section 12.10.3, there are several plausible reasons for constructing tunnels or rock cavities. Today, facilities are built below the surface to protect the activities or objects the underground facility is meant to accommodate from activities or conditions occurring at the surface or *vice versa*. Underground facilities can also be built if considered advantageous from an economic or resource consumption point of view. This can be due to high economic, ecological or cultural values of the land or due to climate conditions. For example, it can be beneficial from an economic point of view to accommodate an activity requiring an even temperature, e.g. cold or warm storage, below the surface.

The impact on the repository of the construction and operation of a tunnel or rock cavity at, or close to, the repository site will depend on the depth and size of the facility. The impact will also depend on the purpose of the facility i.e. the activities taking place there, the constructions made, the equipment used, the material stored etc. In relation to the assessment period of up to one million years, the operation of the facility can be assumed to go on for a short period, in the order of 100 years. Constructions and equipment may, however, be left in the facility after it is no longer in operation.

The larger and deeper the facility, the greater the potential impact on the repository. Today, existing and planned facilities constructed to repository depth of 400 m or deeper include mines, hard rock laboratories and deep geological repositories for radioactive material. These kinds of facilities are considered unrealistic at or close to the repository site. Mines are excluded, since sites including exploitable natural resources are excluded in the site selection. Hard rock laboratories and deep geological repositories are excluded, since it is probable that societies planning the construction of these kinds of facilities will discover and understand that the site is already used for a similar purpose and either construct their facility so that is does not intrude on the existing one or chose another site. For the other kinds of facilities mentioned in Table 12-3 the depth is generally as shallow as possible with regard to the geology and purpose of the facility. For the conditions prevailing at the candidate sites, a depth of 50 m is considered to be plausible. This is, for instance, the depth of the final repository for low-level waste (SFR) and the interim storage facility for spent fuel (Clab), both located close to the planned final repository for spent fuel.

The size of a tunnel or rock cavern depends on its purpose. Tunnels can have cross sections from about 4 up to 100–200 m^2 and caverns can have volumes from 10,000 to 100,000 m^3 or more. Here it is assumed that a tunnel is constructed at 50 m depth with a cross section of 100 m^2 and extending over the whole repository footprint along the centre line of the deposition areas. The justification of this assumption is that it is plausible in relation to current practice and does not underestimate the possible impact on the repository.

The purpose of the tunnel is not specified. However, for most purposes, tunnels are sealed to prevent water inflow and reinforced to avoid the fall of rocks. In many cases, the tunnel walls are lined with concrete. If the tunnel is used for final storage of something, it is assumed that measures are taken to prevent hazardous quantities of this unknown stored material to escape from the tunnel. The operational phase of the tunnel and the design working life of sealing and reinforcement is assumed to be a couple of hundred years. After operation, it is assumed that the tunnel is abandoned.

Function indicator(s) considered

This case concerns the function indicator

- R2, Provide favourable hydrologic and transport conditions.

During operation of the tunnel the hydraulic gradients in its vicinity are affected. Indirectly, if the impact on the hydrologic conditions is substantial, the function indicator, R1, Provide chemically favourable conditions, could be affected.

Assessment of the consequences of the construction of a tunnel above the repository

The analyses of the consequences of a rock facility in the vicinity of the repository are based on the analysis of the open repositories at Formark and Laxemar /Svensson 2005, 2006a/. The impact of a tunnel at shallow depth above the repository is assessed as limited. For the Forsmark site, where the upper part of the bedrock (down to about two hundred metres) is much more conductive than the lower part at 400 m depth, there is no reason to expect any influence of an open tunnel construction at 50 depth on the repository for spent nuclear fuel. In /Svensson 2005/ it is shown that the pressure disturbance of the open repository at 400 m depth is hardly noticed at 50 m depth. The high conductivity in the upper part of the bedrock would, in fact, place limitations on constructability and require extensive grouting. It is unlikely that any repository type of construction would be undertaken in such rock. Finally, it is noted that in the nearby SFR repository constructed at 50 m depth below the sea, there are no indications of inflow from depth but rather of inflow from above, i.e. inflow of sea water. It is thus concluded that a tunnel at 50 m depth, or any other shallow sub-surface facility, in Forsmark should imply no consequences for the repository at 400 m depth.

For Laxemar, the effects should also be very small if the observed depth trend in hydraulic conductivity is representative of real site conditions. Furthermore, the existence of highly conductive deformation zones close to the repository implies that very limited up-coning was observed in the open repository study /Svensson 2006a/. Thus, there is no reason to expect that an open tunnel at 50 m depth should result in up-coning felt at 500 m depth. In order to verify these preliminary hypotheses, numerical simulations may be needed. However, what can be stated with great certainty is that the possible increase in flow at repository depth due to a tunnel at 50 m depth is well below the increase implied by the analyzed glacial conditions, cf section 9.4.6, and likely also well within the ranges covered by the variants analysed for temperate conditions in section 9.3.6.

Conclusions

The above analyses indicate that the design consideration to locate the repository to a depth that allows utilization of the site for generally occurring future human activities is fulfilled at both candidate sites.

12.10.7 Assessment of the mine in the vicinity of the Forsmark site

Background to the mine case

The ore potential at the candidate sites has been analysed within the site investigations. The conclusion from the analyses is that the candidate areas can be described as sterile from an ore viewpoint. However, in an area south-west of the candidate area at Forsmark a felsitic to metavolcanic rock judged to have a potential for iron oxide mineralization has been identified, see further section 4.3. The mineral deposits have been assessed to be of no economic value. Nevertheless, as this judgement may be reconsidered in the future, the exploitation of this mineralization is addressed in SR-Can.

Since the mineralization is judged to be of no value, it is impossible to describe the design of a mine exploiting the mineralization based on current practice. It could be a quarry or a mine and the depth could be from tens to hundreds of metres or for mines a thousand metres or even deeper.

Function indicator(s) considered

This scenario relates to the function indicator:

- R2, Provide favourable hydrologic and transport conditions.

Indirectly, if the impact on the hydrologic conditions is substantial, the function indicator, R1, Provide chemically favourable conditions, could be affected. The mine would locally affect the function indicators fracture frequency and fracture transmissivity. During operation of the mine, the hydraulic gradients in its vicinity would be affected.

Assessment of the consequences of a mine in vicinity of the Forsmark candidate area

If a mine, or other sub-surface facility, were to be constructed in the vicinity of the Forsmark site, it may be assumed that the greatest influence on the repository for spent nuclear fuel would occur if the construction took place at the same depth and in close proximity to the repository for spent nuclear fuel. Based on the analyses of the open repository /Svensson 2005/, it is concluded that the influence of an underground construction at 400 to 500 m depth is limited. For Forsmark it is shown that the pressure disturbance of an open repository, grouted or un-grouted, is very limited around the repository. Any underground facility constructed only a few hundred metres away from the repository would thus likely not affect the repository. Based on the above, any facility constructed outside the tectonic lens would not affect the repository at all.

Conclusions

Exploitation of the potential ore resources in the vicinity of the Forsmark site would not impact the safety functions of the repository. The design consideration to locate the repository at a site without natural resources is considered to be fulfilled. If future generations decide to exploit the identified mineralisation, they can do so without being exposed to radiotoxic elements from the repository.

12.11 Summary and combinations of analysed scenarios

12.11.1 Summary of results of the analyses

In summary, the following conclusions were reached when the selected scenarios were analysed, as described above.

- The main scenario: Canister failures may occur due to advection/corrosion. These give the only risk contribution for the main scenario, and only for the semi-correlated hydrological DFN models for Forsmark and Laxemar.
- Buffer advection: This situation may occur in the main scenario. The additional analyses in section 12.3, considering conceptual uncertainties and additional interpretations of the hydraulic properties of the sites, suggest a considerable range in the possible extent of buffer advection. *These consequences were propagated to the canister corrosion scenario.*

  (Canister sinking to the bottom of the deposition holes was ruled out in the main scenario. In terms of consequences, canister sinking is a special case of buffer advection. The additional analyses in section 12.3.4 led to the conclusion that canister sinking, if it occurs, is preceded by advective conditions in the buffer due to buffer erosion. The consequences of a possible canister sinking are, therefore, covered by the general treatment of buffer advection.)
- Buffer freezing: Buffer freezing was ruled out in the main scenario, also for an eroded buffer. The additional analyses in section 12.4 led to the conclusion that freezing of an intact buffer should be considered as a residual scenario. In case of a partially eroded buffer, water could possibly freeze in erosion cavities for the most pessimistic climate scenarios analysed, but the mechanical consequences were not assessed to lead to canister failures. *The possibility of buffer freezing was, therefore, not propagated to the canister scenarios.*
- Buffer transformation: The analyses of a high buffer temperature, or other circumstances leading to the transformation of the buffer material in section 12.5 led to the conclusion that this should be considered as a residual scenario. *The possibility of buffer transformation was, therefore, not propagated to the canister scenarios.*

- Canister failure due to corrosion: This failure mode is included in the main scenario for both Forsmark and Laxemar, where it occurs for the case of advective transport through an eroded buffer. The additional analyses in section 12.7, with input from the buffer advection scenario, section 12.3, led to the conclusion that buffer advection is indeed the main potential cause of corrosion failures. Evaluating all the advective situations led to a wide range of potential consequences. *Uncertainties associated with many of the factors involved are large and cannot, based on current knowledge, be assigned probabilities. Therefore, the most pessimistic of the cases was propagated to the risk summation in section 12.12 below.*

Oxygen penetration to the canister positions was ruled out as a contributor to canister corrosion, based on the same considerations as in the reference evolution, section 9.4.7.

- Canister failure due to isostatic load: This failure mode was ruled out in the main scenario and the analysis in section 12.8 led to the conclusion that it should be considered as a residual scenario. This scenario is therefore not included in the risk summation in section 12.12.
- Canister failure due to shear movement: This failure mode was demonstrated to have a low probability in the context of the reference evolution, section 9.4.5, and was, therefore, excluded from consideration in the main scenario. Based on the additional analyses in section 12.9, it was considered as a less probable scenario. Its consequences were quantified, as those calculated for the reference evolution. *Consequences of canister failure due to shear movements are included in the risk summation, weighted by its low probability.*
- FHA scenarios: A number of scenarios related to future human actions have also been analysed, see section 12.10. *These are, by definition, not included in the risk summation.*

12.11.2 Combinations of analysed scenarios

Combinations of the analysed scenarios need to be considered. However, it is important to note that several such combinations have already been addressed, since, in the methodology for scenario analysis adopted, the buffer scenarios were analysed first. Results of those buffer scenarios that were not found to be residual were then propagated to the analyses of the canister scenarios. Table 12-5 gives a brief account of how the occurrence of these and other binary combinations of scenarios have been handled. As seen in the table, these combinations do not yield additional contributions to the risk summation. Higher order combinations were not considered in SR-Can.

The combination of the to two risk contributors requires particular attention. If the buffer is eroded, then the likelihood of failures due to shear movements is significantly reduced due to the reduced buffer stiffness, in particular near potentially shearing fracture. This combination is thus favourable for safety and it is pessimistic to neglect it. If a failure due to a shear movement occurs in a deposition hole with an intact buffer, the consequences are assessed to be very similar to those caused by a corrosion failure with an eroded buffer, illustrated by the two calculation cases in Figure 10-41 and Figure 10-50. Hence, this unlikely combination does not yield increased consequences compared with the case where the buffer is intact. It is, therefore, concluded that treating these two cases as separate terms that are added in the risk summation is justified.

12.12 Risk summation

The calculated risk as a function of time is an essential component of the compliance demonstration. This section contains a summation of the risk contributions from the analysed scenarios.

According to the previous sections of this chapter, radiological consequences may arise for the main scenario, and for the scenarios where canister failures due to copper corrosion and due to shear movements are analysed.

Table 12-5. Binary combinations of the six buffer and canister scenarios analysed. Green cells: Discarded combinations since at least one is residual. Yellow cells: Combination considered and discarded. Red cell: Combination propagated to risk summation.

	Buffer advection	Buffer freezing	Buffer transformation	Canister failure; corrosion	Canister failure; isostatic collapse	Canister failure; shear movement
Buffer advection						
Buffer freezing	Combined but not propagated to canister scenarios, see further section 12.4.4.					
Buffer transformation	Transformation residual, therefore not combined.	Both residual, therefore not combined.				
Canister failure; corrosion	Combined in section 12.7, propagated to risk summation.	Freezing residual, therefore not combined.	Transformation residual, therefore not combined.			
Canister failure; isostatic collapse	Isostatic residual. (Buffer erosion/advection favourable for avoiding isostatic collapse since reduced swelling pressure). Not combined.	Freezing residual, therefore not combined. (See also section 12.4.4.)	Both residual and transformation favourable for isostatic pressure, therefore not combined.	Isostatic residual. (Copper corrosion does not affect isostatic collapse since insert is load bearing.)		
Canister failure; shear movement	Not combined since a) Buffer erosion/advection favourable for avoiding shear collapse (reduced buffer stiffness, in particular near potentially shearing fracture). b) Shear movement failure followed by erosion/advection yields similar consequences as for intact buffer.	Freezing residual, therefore not combined.	Transformation residual, therefore not combined. (Altered buffer material properties studied as residual shear case, see section 12.9.2.)	Copper corrosion does not affect shear collapse since insert is load bearing.	Combined and ruled out in section 9.4.5, see also section 12.9.2.	

For the main scenario, the only failure mode that can not be excluded is due to copper corrosion following advective conditions in the buffer, see section 12.2.2. Uncertainties regarding this failure mode are further analysed in the copper corrosion scenario, leading to the conclusion that the consequences could be somewhat higher than in the main scenario, see section 12.7.3. In that section, it was not found meaningful to assign any probability less than one to the increased consequences, partly because these were not much higher than the consequences of the more probable cases analysed in the main scenario, partly because many of the uncertainties involved cannot be quantified at this stage. This means that, in the final risk summation, the higher consequences for the corrosion scenario, assigned a probability of one, replace those for the main scenario that were related to the same failure mode.

Consequences for canister failures due to shear movements, as given in section 12.9.3 are added to those for the corrosion scenario. It is noted that, through the use of LDF factors to transform releases to doses, it is implicitly assumed that the landscape to which the releases occur is always fully populated.

Thus, Figure 12-20 gives the calculated individual risk for the two sites, expressed in terms of risk, where the effective dose to risk conversion factor of 0.073 Sv^{-1} has been used in accordance with SSI's regulations (Appendix A).

It is obvious that the buffer colloid release/erosion process, that could occur when the buffer is exposed to glacial melt waters of low ionic strength is a main factor affecting the calculated risk for the two sites.

Long periods of glacial and submerged conditions are expected where no doses to humans occur since the site is not habitable, see Figure 9-66. This has not been taken into account in the risk summation. Rather, temperate conditions yielding the highest doses are assumed.

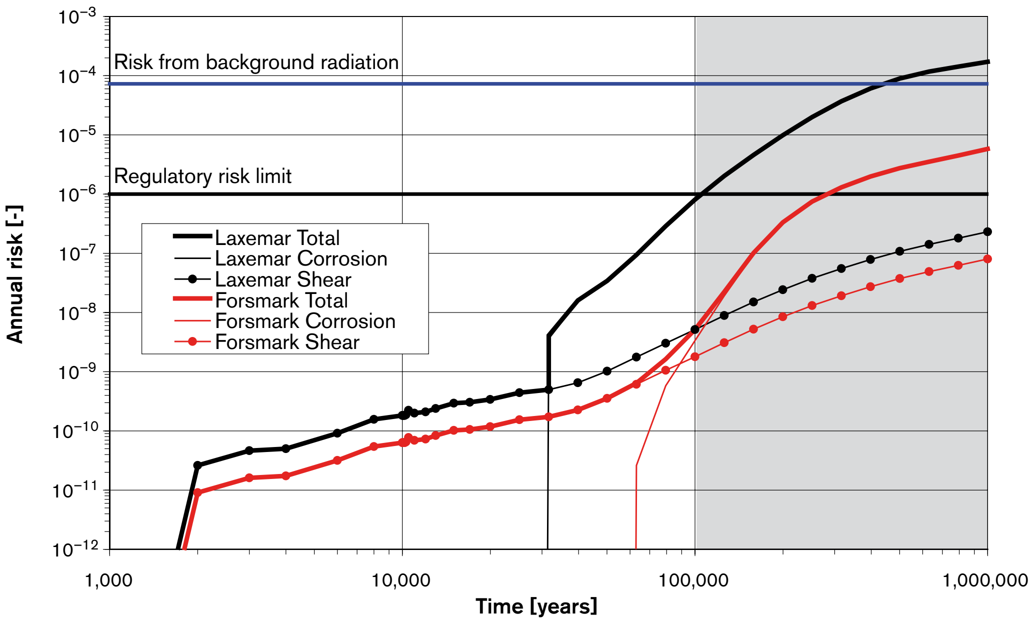


Figure 12-20. *Risk summation, expressed as annual individual risk for the two sites.*

13 Conclusions

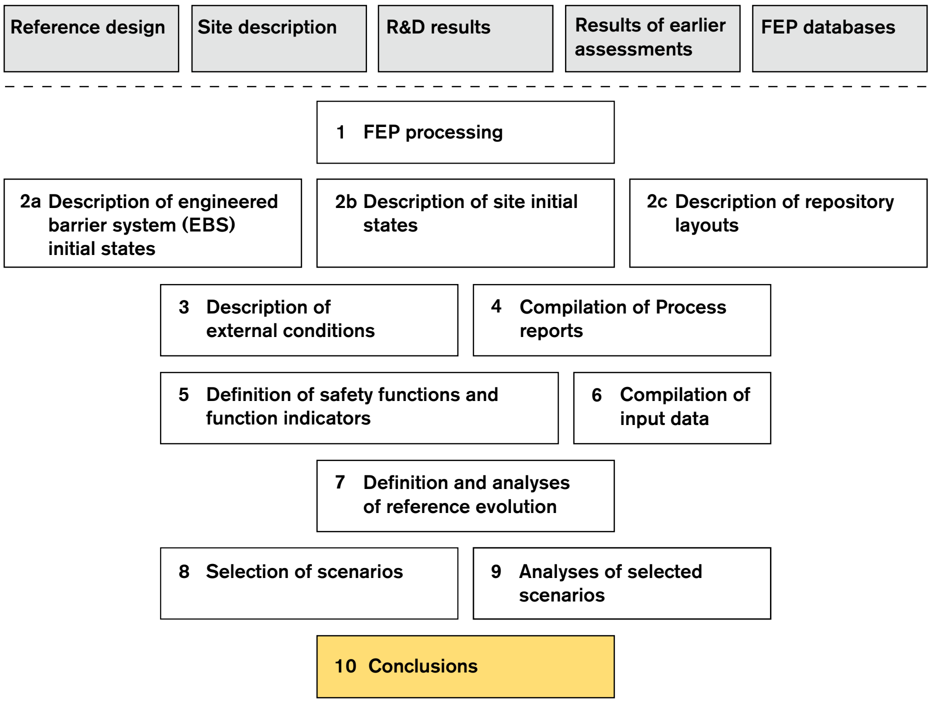


Figure 13-1. *The SR-Can methodology in ten steps (section 2.2), with the present step highlighted.*

13.1 Introduction

This chapter presents the conclusions from the SR-Can project. It is emphasised that the SR-Can assessment does not support a licence application, nor is it a direct input to any major decision in SKB's programme for the management of spent nuclear fuel. Rather, it is a preparatory step in the development of the SR-Site assessment, which will form an important part of the application for a final repository.

Two major roles for the presentation of the conclusions from the SR-Can project can be distinguished:

1. To provide a structure for the demonstration of compliance with applicable Swedish regulations and to provide a first version of such a demonstration for the Forsmark and Laxemar sites.
2. To provide feedback to the remaining work towards the licence application.

The first purpose is addressed in section 13.3 and the second in sections 13.5 through 13.9. Before the formal discussion of compliance-related issues and the detailed feedback, an overview of the results of the analyses is given in section 13.2 immediately below.

13.2 Overview of results

This section gives a summary of the most important findings in the SR-Can project. The conclusions are further discussed and substantiated in the following sections of this chapter.

13.2.1 Compliance with regulatory risk criterion

No canisters are assessed to fail during the initial temperate period, expected to last several thousand years

No canister failures are expected for either of the sites during the initial temperate period after deposition, estimated to last several thousand years. Furthermore, the evaluations of the canister sealing procedure undertaken so far, have led to the conclusion that all canisters will be tight at deposition.

A repository at Forsmark is assessed to comply with the regulatory risk criterion

The preliminary analyses carried out in SR-Can suggest that a KBS-3 repository at Forsmark will comply with the regulatory risk criterion issued by SSI.

Uncertainties in the hydrogeological interpretation and understanding of the Forsmark site are, however, considerable and, when propagated to various parts of the analyses, lead to a wide range of conclusions regarding e.g. buffer colloid release and water flow properties. A reduction of these uncertainties would allow more definite conclusions in future assessments. Even the most pessimistic interpretation of the Forsmark site is, however, assessed to comply with the regulatory risk criterion.

A repository at Laxemar is preliminarily assessed to comply with the regulatory risk criterion – but more representative data is required

The Laxemar site descriptive model version 1.2 is not sufficiently representative of the potential repository volume to allow definite conclusions regarding compliance. In particular, the hydraulic interpretation of the site is based on data partly obtained outside the candidate volume for the repository. Furthermore, recently obtained data indicate more favourable hydraulic properties than those on which the site model used in SR-Can is based.

However, it is noted that with the data used for Laxemar, the site is assessed to comply with the risk criterion and that use of more recent data would likely strengthen this conclusion.

13.2.2 Issues related to glacial conditions

In general, the most severe impact on the repository will occur during future glacial conditions. A number of conclusions regarding effects of such conditions can be drawn.

Freezing of an intact buffer is assessed as ruled out – even for very pessimistically chosen climate conditions

Freezing of an intact buffer is assessed as ruled out for both sites, even for the most pessimistic climate conditions considered. For a water-filled cavity in an eroded buffer, freezing is not entirely ruled out for the most pessimistically chosen climate development at Forsmark, but calculations demonstrate that the mechanical pressure on the canister is acceptable in such cases.

Canister failure due to isostatic load is assessed as ruled out – even for very pessimistically chosen climate conditions

Canister failure due to isostatic load is assessed as ruled out for both sites, also for the most severe future glacial conditions considered.

Oxygen penetration is preliminarily assessed as ruled out – even for very pessimistically chosen conditions

Oxygen penetration to repository depth for enhanced groundwater flows under an ice sheet, jeopardising the favourable reducing chemical conditions, is assessed as ruled out, based on the analyses carried out in SR-Can. This result is in agreement with conclusions from several earlier assessments. The modelling example is, however, stylised and simplified, meaning that additional analyses are warranted to increase confidence in the results. Such studies will be undertaken in SR-Site.

The risk contribution from earthquakes is assessed as small

Canister failures due to post-glacial earthquakes cannot be completely ruled out. The risk contribution from this failure mode is, however, small. The probabilistic analyses made imply that, on average, it would take considerably more than one million years for even one such canister failure to occur.

Loss of buffer may occur from exposure to glacial melt waters but the extent is uncertain – further studies are required

Substantial loss of buffer through buffer erosion/colloid release may occur as a result of intrusion of low ionic strength glacial melt waters in a 100,000 year perspective. The knowledge of the processes involved is uncertain and further research is being undertaken as a matter of priority. A status report will be given in SKB's RD&D-Programme 07 to be published in 2007.

Substantial loss of buffer may lead to canister failures in very long time perspectives

Loss of buffer mass, to the extent that advective conditions prevail in the buffer, which cannot be ruled out in a 100,000 year perspective, will lead to enhanced canister corrosion rates. In a one million year perspective, this may lead to failures of some tens of canisters for the pessimistic hydraulic interpretation of the Forsmark site, with cautious assumptions regarding sulphide concentrations and cautious assumptions regarding deposition hole acceptance rules.

A prolonged period of warm climate (increased greenhouse effect) before the next glacial period is assessed as primarily beneficial for repository safety

Since the processes that are potentially the most detrimental to repository safety are related to glacial conditions, a prolonged period of temperate climate is deemed as beneficial for safety. This concerns in particular the two main contributions to the calculated risk in SR-Can, namely *i*) potential buffer erosion with subsequent enhanced canister corrosion as a result of intrusion of glacial melt waters and *ii*) the occurrence of large earthquakes during deglaciation. Further evaluations of the geochemical evolution for a prolonged warm period are required in order to better substantiate the conclusion that the geochemical conditions would remain beneficial.

13.2.3 Other issues related to barrier performance and design

Crucial to avoid deposition positions intersected by large or highly water conductive fractures – further studies are required

The main risk contributors in SR-Can are related to the occurrence of large and/or highly transmissive fractures intersecting deposition holes. This applies to the buffer colloid release process and the impact of major earthquakes in the vicinity of the repository. These two phenomena are related to canister failures due to canister corrosion and to secondary rock shear movements, respectively. As also the retention in a large, highly transmissive fracture is small, such failures are in general associated with high consequences. Such fractures will be avoided when identified. The likelihood of occurrence of such fractures and the probability of unsuitable deposition holes remaining unidentified are, in many respects, uncertain and the results of the analysis are sensitive to these uncertainties. It is important to establish well-founded acceptance criteria for deposition holes as a basis for future assessments. This needs to be studied both by simulation of the effects of applying potential criteria and by exploring the practicability of applying the criteria.

The heat from the canister may fracture the rock in the deposition hole wall, which may enhance the in- and outward transport of dissolved substances – further studies are required

Thermally induced spalling around deposition holes may have a considerable impact on mass exchange between the flowing groundwater and the buffer as long as diffusion is the dominant transport mechanism in the buffer. If advective conditions prevail in the buffer, the effects of spalling are much less pronounced because it adds little to the already increased flow rate. There are uncertainties regarding the extent and the consequences of spalling and further studies are ongoing, see section 13.8.5.

The importance of the backfilled deposition tunnels as a transport path for radionuclides is limited

The importance of the backfilled deposition tunnel as a transport path for radionuclides is limited in comparison with fractures intersecting a deposition hole. Also, deterioration of the deposition tunnel backfill material has limited consequences in terms of radionuclide releases from the near field.

The importance of the excavation damaged zone in the rock around the deposition tunnels as a transport path for radionuclides is limited

The importance of the excavation damaged zone (EDZ) around deposition tunnels is limited in comparison to other transport routes for radionuclides, even for very pessimistic assumptions about the EDZ in relation to the reference excavation method.

Cautious excavation methods are still recommended for the deposition tunnels, because competing transport routes may be assessed as less important with additional data and because the conclusion regarding the EDZ is based on simplified, stylised modelling.

13.3 A first demonstration of compliance

13.3.1 Introduction

From applicable regulations from SKI and SSI and general recommendations and guidance associated with these regulations, a number of requirements on presentation of a compliance evaluation can be derived. The requirements are here categorised and addressed as follows:

- Account of calculated risk to individuals, section 13.3.2.
- Account of effects on the environment from release of radionuclides, section 13.3.3.
- Demonstration of use of best available technique, BAT, section 13.3.4.
- A discussion of confidence, section 13.3.5.
- Other, general requirements on the system, e.g. demonstration of a multi-barrier system, section 13.3.6.
- General requirements on the safety assessment (adequate handling of uncertainties, quality assurance, etc), section 13.3.7.

The above structure does not, however, address all aspects of the regulations. For a complete account of how the SR-Can report meets these requirements, the reader is referred to Appendix A, where the regulations are reproduced and where references are given to sections in this report where each issue is addressed.

13.3.2 Compliance with SSI's risk criterion

Regulatory requirements

The primary compliance criterion in Swedish regulations is SSI's risk criterion. An account of the calculated risk is therefore an essential component of a compliance demonstration *for the first 1,000 years*. This is also explicitly stated in SSI's general guidance, where a reporting of contributions to risk from each analysed scenario is also requested.

Also for *the initial glacial cycle*, a risk calculation is required. SSI states the following regarding this period in its general guidance:

"*Reporting should be based on a quantitative risk analysis in accordance with the guidelines to sections 5–7. Supplementary indicators of the repository's protective capability, such as barrier functions, flow of radionuclides and concentrations in the environment should be used to strengthen the confidence in the calculated risks. The given period of time of one hundred thousand years is approximate and should be selected in such a way that the effect of expected large climate changes, for instance, a glaciation cycle, on the protective capability of the repository and consequences to the surroundings can be illustrated.*"

Regarding *the time beyond the initial glacial cycle*, SSI states the following in its general guidance:

"*The risk analysis should illustrate the long-term development of the repository's barrier functions and the importance of major external disturbances on the repository such as earthquakes and glaciations. Taking into consideration the increasing uncertainties over time, the calculation of doses to people and the environment should be made in a simplified way with respect to climate development, biosphere conditions and exposure pathways. Climate development can simplified be described as a repetition of identical glaciation cycles.*

A strict quantitative comparison of calculated risk in relation to the criterion for individual risk in the regulations is not meaningful. The assessment of the protective capability of the repository should instead be based on reasoning on the calculated risk together with several supplementary indicators of the protective capability of the repository such as barrier functions, flows of radionuclides and concentrations in the environment. If the calculated risk exceeds the criterion of the regulations for individual risk or if there are other indications of substantial disruptions of the protective capability of the repository, the underlying causes of this should be reported on as well as possible measures to improve the protective capability of the repository."

Calculated individual risk in SR-Can

The calculated individual risks for repositories at Forsmark and Laxemar are presented and discussed in section 12.12. The risk summation is reproduced in Figure 13-2. Note that temperate conditions are assumed for the biosphere, whereas it is expected that the sites will be submerged or covered by ice during a considerable part of the one million year assessment time, yielding negligible risks for these periods. Also, several pessimistic assumptions have been made in order to not underestimate the risk, see further below.

Compliance for the first 1,000 years

As evidenced by the result shown in Figure 13-2, the assessed risk is zero for the initial 1,000 years. This is due to the fact that no canisters are assessed to fail during this period, either in the main scenario, building on the reference evolution described in chapter 9, or in any of the additional scenarios analysed in chapter 12. As all canisters are also assessed as tight at deposition, the conclusion is that there will be no failures and thus no releases of radionuclides during the initial 1,000 years. Hence the risk is zero for this period.

Compliance for the initial glacial cycle

For the initial glacial cycle, two risk contributions are identified: That from earthquakes and that from canister failures due to corrosion if the buffer has been eroded by glacial melt waters.

The probability of canister failures due to earthquakes for this period is very small and this probability is included in the risk estimate.

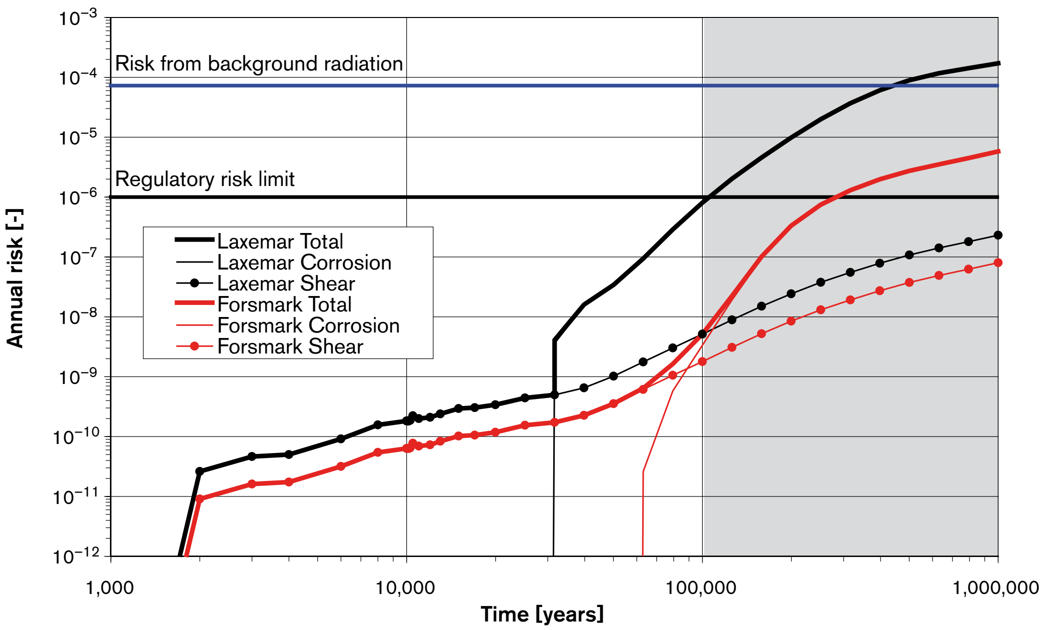


Figure 13-2. *Risk summation for the two sites. Temperate conditions are assumed for the biosphere, whereas it is expected that the sites will be submerged or covered by ice during a considerable part of the one million year assessment time, yielding negligible doses. Several other uncertainties are handled pessimistically.*

As concerns failures due to corrosion, a few canisters are calculated to fail during the initial glacial cycle at both sites. The total calculated risk up to 100,000 years is at most, i.e. after 100,000 years, close to regulatory limit at Laxemar and about two orders of magnitude below at Forsmark. As discussed in section 12.12, the risk is pessimistically based on that calculated for the canister corrosion scenario, where several uncertainties are handled pessimistically, due to insufficient understanding of groundwater flow and composition for glacial conditions and of the response of the buffer to glacial groundwaters. The risk calculated for Forsmark is based on a pessimistic interpretation of the current hydraulic situation. As also pointed out previously, the representativity of the Laxemar hydrogeological model is questionable. More recent site data from the candidate repository area indicate that the hydrogeological conditions are more favourable than those adopted in the model used in SR-Can. This would reduce the risk contribution from canister failures due to corrosion.

It is, thus, concluded that the calculated risks for the two sites comply with the regulatory requirements during the initial glacial cycle after closure.

As required by the regulations, to strengthen the confidence in the calculated risks, the barrier functions have been thoroughly evaluated for the initial glacial cycle, see chapter 9. As also suggested by SSI, flows of radionuclides have been determined, see below, and concentrations in the environment have been calculated in order to assess impacts on biota other than humans, see section 13.3.3.

Repository performance for the time beyond the initial glacial cycle

The same canister failure modes as for the initial glacial cycle, i.e. failures due to earthquakes and to corrosion for advective conditions in the buffer, contribute to individual risk during the period after the initial glacial cycle up to one million years after closure.

For Forsmark, the calculated risk contribution from earthquakes is more than one order of magnitude below the regulatory limit throughout the assessment period, whereas the contribution from corrosion failures is above the regulatory limit at the end of the one million year period.

For Laxemar, the contribution from earthquakes is similar to that for Forsmark, whereas that from corrosion failures exceeds the risk limit by about two orders of magnitude at the end of the assessment period.

As stated in SSI's general guidance, "*a strict quantitative comparison of calculated risk in relation to the criterion for individual risk in the regulations is not meaningful*" for this time period. Rather, the results are used as a basis for discussing how pessimistically handled uncertainties can be reduced and how the protective capability of the repository can be improved as suggested by the general guidance, see sections 13.3.4, 13.5 and 13.6.

It is important to note that the calculated risks, although exceeding the risk limit applicable for the initial 100,000 years, are considerably less than those due to the background radiation throughout the assessment period for Forsmark. For Laxemar, they are well below the background radiation for several hundred thousand years and become comparable to the background radiation only at the end of the one million year assessment period. Furthermore, as for the initial glacial cycle, a number of issues have been treated pessimistically and further knowledge may lead to a substantial reduction of these risk estimates in future assessments.

As required, the risk analysis does illustrate the long-term development of the repository's barrier functions and the importance of major external disturbances on the repository such as earthquakes and glaciations. Climate development has been represented, and dose calculations have been performed, in a simplified way, as suggested by SSI.

It is, thus, concluded that calculated risks for the time beyond the initial glacial cycle fulfil the regulatory requirements for this time period.

The time beyond one million years

For the time beyond one million years, no risk calculation is required. SKI's general recommendations suggest that an account of the evolution of radiotoxicity may be the only meaningful way of illustrating the further development of the repository. Such an account is given in Figure 2-3.

In general, it may be stated that there is no reason to suppose that the trends analysed for the one million year assessment period would not continue. This means that successively more canisters would fail due to the same causes as during the one million year assessment period. Any further quantification does, however, not appear meaningful, given the far distance into the future.

Alternative safety indicators

Two alternative safety indicators have been used in SR-Can: The release constraints issued by the Finnish regulator STUK and the naturally occurring contents of radionuclides in the biosphere above the repository, see sections 10.5.6 and 10.6.7.

The results of the analyses indicate that the release constraints are not exceeded and that the accumulated releases of radionuclides do not exceed the current contents of radionuclides in the biosphere above the repository for the reference evolution and thus the main scenario. The analysis can readily be extended to cover also other scenarios.

13.3.3 Effects on the environment from release of radionuclides

There is no release to the environment of radionuclides during the first 1,000 years, and thus no radiological effects on the environment.

For times beyond the initial 1,000 years, when canister failures may occur, an initial assessment of effects on the environment from releases of radionuclides has been completed, see sections 10.2.5, 10.5.5 and 10.6.6. The assessment is based on concentrations in the major substrates (soil and water) of different habitats obtained from the landscape model.

The conclusion is that the concentrations are several orders of magnitude below the screening limits suggested within the ERICA project for the pinhole failure mode base case. For the advection/corrosion base case, most radionuclides fall below the screening limit. However, for Ra-226 and the daughter nuclide Po-210 it exceeds the screening limits at the end of the assessment period. This requires more detailed assessments.

The results concern the reference evolution and thus the main scenario. The analysis can readily be extended to cover also other scenarios. It is, furthermore, noted that there is no clear indication in applicable regulations of the length of the time period for which doses to biota should be evaluated.

13.3.4 Optimisation and best available technique, BAT

Regulatory requirements

Regarding optimisation and best available technique, SSI's general guidance states the following:

"*The regulations require that optimisation must be performed and that best available technique should be taken into account. Optimisation and best available technique should be applied in parallel with a view to improving the protective capability of the repository.*

Measures for optimisation of a repository should be evaluated on the basis of calculated risks.

Application of best available technique in connection with final disposal means that the siting, design, construction, operation and closure of the repository and appurtenant system components should be carried out so as to prevent, limit and delay releases from both engineered and geological barriers as far as is reasonably possible. When striking balances between different measures, an overall assessment should be made of their impact on the protective capability of the repository.

In cases where considerable uncertainty is attached to the calculated risks, for instance, in analyses of the repository a long time after closure, or analyses made at an early stage of the development work with the repository system, greater weight should be placed on best available technique.

In the event of any conflicts between application of optimisation and best available technique, priority should be given to best available technique.

Experiences from recurrent risk analyses and the successive development work with the repository should be used in the application of optimisation and best available technique."

General issues regarding optimisation and best available technique

A general account of the use of best available technique (BAT) is a broad issue spanning from the selection of method for the management of nuclear waste to fine details of the selected method. Only a limited part of this broad issue can and should be addressed in the safety assessment of the preferred method. Here, the account of BAT is, therefore, confined to the KBS-3 method with vertical deposition, using copper/cast iron canisters, buffer and backfill. As is demonstrated below, it is, to some extent, possible to discuss e.g. the choice of materials and dimensions from the perspective of BAT, based on the results of the safety assessment. This role for the safety assessment regarding the contribution to the discussion of optimisation and BAT is also in agreement with the view expressed in SKI's and SSI's joint review of SKB's SR 97 assessment, section 3.3.6 of /SKI/SSI 2001/. The broader issue of BAT will be discussed in a dedicated document supporting SKB's application in 2009 for a final repository.

The issue of BAT is also closely related to that of feedback to repository design, as also stated in SSI's general guidance. For several issues discussed below, references to the more detailed accounts of feedback in subsequent sections are, therefore, made. As also acknowledged in the regulations, the development of a repository system is carried out in steps, with safety evaluations at appropriate points of the development. This means that the developer is not in a position to finally *claim* optimisation and use of BAT until much of the iterative development work has been finalised. At earlier stages, the discussion of optimisation and BAT is rather a framework for discussing feedback to remaining development needs. The discussion in SR-Can is to a considerable extent an example of the latter role for optimisation and BAT.

Related to the above, several aspects of the technique have not yet been established. For example, the results suggest that the number of failed canisters in a million year perspective depends sensitively on the choice of rejection criteria for deposition holes and the efficiency with which these criteria lead to avoidance of unsuitable positions. The establishing of such criteria is part of the remaining work in the field of BAT.

Optimisation or BAT?

In SSI's general guidance, optimisation is emphasised more for the initial period after closure. It is also stated that optimisation should be carried out with respect to calculated risks. As evidenced by the risk assessment discussed in section 13.3.2 above, the assessed risk is negligible for tens of thousands of years into the future, suggesting that optimisation is of limited relevance during this initial period that is emphasised in the regulations. However, as also mentioned in the regulations, the considerations of optimisation and BAT should be applied in parallel. In fact, it is often difficult to clearly distinguish the two. The discussion of BAT, when based on results from the safety assessment of the preferred method, is frequently 'reduced' to an account of optimisation of the selected solution, since there are in general no alternative techniques to choose between or analysed in the safety assessment. (The term "optimisation" is used in the same sense as in SSI FS 1998:1, i.e. "*keeping the radiation doses to mankind as low as reasonably achievable, economic and social factors taken into account*".)

In SSI's general guidance, it is noted that, for the time period between 100,000 years and one million years, the results of the risk calculation should be used to discuss measures to improve the protective capability of the repository if the risk limit is exceeded.

In the risk discussion in section 13.3, such situations do occur as a consequence of colloid release from the buffer leading to advective conditions in this barrier and subsequently to canister failures due to corrosion. This is also reflected in the discussion of BAT below. There are, however, considerable uncertainties associated with the fundamental understanding of, in particular, colloid release and any conclusions based on the results may thus change in future assessments.

The following is a first account of optimisation and BAT, for the canister, the buffer, the deposition tunnel backfill and the repository layout, based on the results obtained in SR-Can.

The canister

Canister strength

There are two aspects of canister strength that need to be addressed: resilience to a shear movement and to an isostatic load.

The results in SR-Can indicate that the expected shear movements give small contributions to the calculated risk with the current canister design, even with several pessimistic assumptions made about uncertain factors related to future earthquakes.

Isostatic loads, where global collapse is used as the failure criterion, give no contribution to the calculated risk in SR-Can, with the current canister design.

A stronger canister could always reduce the already small risk contribution associated with rock shear movements and further increase the safety margins for isostatic collapse. Considering the small gain in terms of risk reduction it is, however, considered unreasonable to take measures to increase the canister strength.

Further strength calculations and developments of design criteria are, however, required before a final assessment can be made. These requirements are discussed in section 13.5.1, as feedback to canister design.

Corrosion barrier

At Forsmark, the copper thickness is demonstrated to provide a corrosion barrier for 100,000 years and, for the large majority of deposition holes, also for one million years. A similar, preliminary, conclusion can be drawn for Laxemar, based on the site data used in SR-Can. As already pointed out, more recent data from the Laxemar site indicate better conditions than assumed in SR-Can.

Canister failure due to corrosion beyond the initial 120,000 year glacial cycle is, however, the main risk contributor in SR-Can. A thicker copper canister would reduce the calculated risk for this time period, but there are a number of uncertain factors not related to the canister that also influence the result. It is, therefore, premature to claim that the copper thickness is optimised.

The issue of a sufficient copper thickness is discussed in more depth in connection with the feedback to canister design in section 13.5.2.

The buffer

The main risk contribution for the time period beyond 100,000 years is strongly linked to the long-term evolution of the buffer and in particular the extent of colloid formation/erosion for intrusion of glacial melt water. This situation cannot be excluded for extended periods of time during a glacial cycle. Knowledge of the buffer colloid formation/erosion process is limited. A crude model has been used to assess the extent of this process. Better knowledge could lead to both higher and lower estimates of this extent. It is, however, important to note that a higher extent would have a very limited impact on the consequences reported since, if buffer erosion occurs to such a degree that advective conditions are created in the buffer, then it is the 50 mm copper canister thickness that determines the time required for canister failure with the model used in this assessment. However, it is possible that a better understanding of the process would allow neglect of buffer erosion in future assessments.

Relating to the issue of BAT, a thicker buffer would only improve the situation marginally. The time required to create advective conditions in the buffer would increase with the increased buffer mass loss required to create such conditions, but this time is overshadowed by the considerably longer time required to corrode the canister to the extent that a failure occurs. It is thus concluded that an increased buffer thickness would not improve the situation markedly. The main route for handling the issue of buffer erosion/colloid release appears to be an increased knowledge of the nature of the erosion process, so that better founded assessments of its potential occurrence and extent can be made in future assessments. It may also be possible to solve the issue by engineering measures. However, at present, no designs that may resolve the problem with colloid formation in a satisfactory way have been suggested.

Since it is difficult to claim that the groundwaters at the sites will fulfil the function indicator $\Sigma[M^{2+}]^{GW} > 10^{-3}$ M for glacial periods, it is also difficult to place reliance on buffer performance for longer timescales. In view of this, it is difficult to claim that the current buffer design is optimised or BAT for the Forsmark and Laxemar sites. On the other hand, no other material or design has been identified that would give better performance. Obviously, the buffer related issues identified in SR-Can need more attention before final decisions regarding the design of this system component can be made.

An increased buffer thickness will reduce the damage on the canister at a rock shear, but no calculations with larger buffer thickness have been done. As an average (but depending on the density and shear case) the effect of a doubled buffer thickness would then be a halving of the canister damage.

An increased buffer thickness will also increase the overall buffer mass, which would make the buffer more resistant to alteration and mass-loss processes (i.e. a smaller fraction of the total mass will be altered/lost). Still, it is not an unambiguous advantage since an increased thickness also would decrease the heat transfer capacity. An increased diameter would also increase the diffusional distance between the canister and the rock. However, this would also lead to a bigger deposition hole, which would increase the probability of intersection of a water conductive fracture.

Feedback on other performance aspects regarding the two buffer materials analysed in SR-Can is given in section 13.6.1.

The deposition tunnel backfill

All failure modes of the canister that have a non-negligible likelihood of occurrence are related to relatively large fractures intersecting deposition holes. The dominant transport pathway for radionuclides for these failure modes is via the intersecting fractures, meaning that releases through a potential excavation damaged zone or through the deposition tunnel backfill are of secondary importance.

It has, furthermore, been demonstrated that a considerably higher hydraulic conductivity in the deposition tunnel backfill only leads to marginally increased radionuclide releases in stylised cases where the releases through the deposition tunnel play a role, see section 10.5.7.

In SR-Can it has been demonstrated that a backfill consisting of Friedland clay at the given density will meet all requirements set on the tunnel backfill.

It can also be concluded that the safety of the repository system would not benefit significantly from improvements in deposition tunnel backfill materials or dimensions beyond the properties of the Friedland clay used as one of the reference materials in SR-Can.

The 30/70 mixture would also fulfil all safety function indicators as long as the design density is maintained. However, as stated in section 9.7, the mixture is considerably more sensitive to density variations than the Friedland material. It is clear that the Friedland Clay has several advantages compared to the 30/70 mixture, from the point of view of long-term performance. No technical or safety related area in which the mixture has any advantages has been identified.

Repository layout

Several issues regarding repository layout, like depth, selection of deposition areas, acceptance criteria for deposition holes and canister spacing are discussed in the feedback to repository design given in section 13.6. Several details of the layout remain to be determined, and can only be finalised based on data obtained during the underground excavation e.g. by applying deposition hole acceptance criteria, meaning that they can and will be further improved and that it is premature to claim that the current Forsmark and Laxemar layouts are optimised or that BAT is used.

It should also be recognised that further optimisation will be made before the SR-Site assessment.

13.3.5 Confidence discussion

As already mentioned, SR-Can is a preparatory step for the SR-Site assessment. The latter is intended to support an application for a final repository. It will thus support a major decision in SKB's programme for the management of spent nuclear fuel, and a statement on the confidence in the results obtained in SR-Site will have to be developed.

Below is a brief account of potential elements of such a statement and of the arguments for confidence in the results obtained that can be put forward for the SR-Can assessment:

- The engineered parts of the repository system are based on, to various extents, demonstrated technology and established quality assurance procedures to achieve the *initial state* of the system. This is systematically documented in the **Initial state report** and summarised in chapter 4. Examples of important aspects of the initial state of the engineered barriers include:
  a. The copper canister sealing quality.
  b. The cast iron insert casting quality.
  c. Buffer properties such as density and content of impurities.
  d. Backfill properties such as density and content of impurities.
  e. The quality of the excavation technique.
  f. The quality of the deposition technique.
- Confidence in the site-descriptive model and confidence in the understanding of the site is obtained by a systematic and quality assured programme for site investigations and site modelling. The confidence in the site model, assessed and documented in the site descriptive model reports, is limited to what is achievable for a model based on data from the initial phase of the site investigations. Key properties of the sites are documented in chapter 4.
- Confidence in the scientific understanding of the repository evolution is essentially built on decades of documented R&D efforts to understand repository evolution and safety leading to the understanding of key processes like corrosion and other potential canister failure causes, and of key phenomena controlling retardation. This knowledge is, in SR-Can, systematically documented in several reports in a format suitable for use in the safety assessment, see further chapters 5 and 6.
- The understanding of safety is built on a systematic identification of safety functions and criteria for the safety functions, see chapter 7.
- Repository evolution is analysed with a structured approach in several time frames, addressing in each of these the processes that have been identified as relevant and with the safety of the system, as expressed by the safety functions, as a focus, see chapters 9 and 10. Data uncertainties are documented according to a pre-established template, described in chapter 8. Quality assurance of models and modelling is achieved by following procedures documented in a **Model summary report**. The assessment is then broken down into a set of scenarios to exhaustively scrutinise all possible ways in which the identified safety functions could be impaired, see further chapters 11 and 12.
- As mentioned above, a QA plan, encompassing many of the routines followed in undertaking the steps described in the above points, has been established and partly implemented in SR-Can. This is part of the overall methodology followed in the assessment, as documented in chapter 2.

Completeness, comprehensiveness

Also relevant for the confidence discussion is the issue of completeness or comprehensiveness of the assessment. This issue may be formulated through the following questions:

1. Have all factors relevant for long-term safety been identified?
2. Have all identified factors been adequately treated in the assessment?

The following two points summarise the efforts made to ensure that all relevant factors have been identified, see also section 2.7.3, in particular the subheading 'System uncertainty':

- Decades of systematic and documented R&D, in international collaboration has been performed to achieve a sufficient knowledge of the repository system and its evolution. New phenomena have only rarely been identified in recent years, indicating that the scientific and technical foundation is mature. Several safety assessments have been performed throughout the years to obtain an integrated evaluation of the knowledge base and to provide feedback to the research programme.
- Systematic and documented studies of factors identified by other organisations have been made, e.g. by comparisons to internationally available FEP databases

The question of whether all identified issues have been adequately handled in the assessment is partly addressed in the confidence discussion above. A more complete answer is provided by the description of the methodology for the assessment described in chapter 2. Of particular relevance is the systematic handling of uncertainties described in section 2.7.3.

The above supports the claim that the SR-Can assessment is comprehensive, whereas completeness in a strict sense can never be proved. In this context it is, therefore, relevant to discuss possible consequences if completeness would not be achieved, for example if an important detrimental process would remain unidentified despite all efforts to ensure the opposite. In its most extreme form, such a discussion may take the form of the consequences of complete, early loss of safety functions. As evidenced by the section below, even very extreme and completely unrealistic assumptions regarding early barrier losses yield calculated doses that are comparable to those caused by the background radiation.

Based on the above reasoning, it is concluded that the SR-Can assessment is sufficiently comprehensive for its purposes.

13.3.6 Bounding cases, robustness

In section 10.10, a number of stylised, bounding cases illustrating complete, initial loss of important safety functions are analysed. The following illustrative and completely unrealistic cases were considered:

- An initial, large opening in the copper shell *for all canisters.*
- An initial absence of enough buffer to cause advective conditions in the deposition hole *for all deposition holes*.
- A combination of the above two, i.e. an initial large opening in all canisters and advective conditions due to loss of buffer *for all deposition holes*.

Several pessimistic assumptions, in addition to the completely fictitious losses of barrier functions, were made in the calculations of these cases.

The results reported in section 10.10.5 indicate that the calculated doses are below the natural background radiation also for very severe losses of safety functions. For example, an initial total loss of the canister and buffer in all deposition holes yields, for the Forsmark site, doses that are comparable to those caused by the background radiation.

The bounding analyses demonstrate the multi-barrier character of the KBS-3 system, which may be less evident from results of other analyses. For example, with intact canister and buffer properties the rock appears relatively unimportant, since most nuclides are retained already in these barriers. However, for the unrealistic case of complete initial failure of the canister and buffer barrier, the results in Figure 10-53 indicate that the rock reduces the doses by about two orders of magnitude, clearly illustrating the importance of the rock. Similarly, unrealistically omitting the buffer, while canister and rock are kept suggests that the buffer has a minor impact, but the buffer alone is sufficient to keep doses below those of the background radiation for almost 100,000 years.

13.3.7 Additional, general requirements on the safety assessment

Applicable regulations also bring up the issues of natural analogues, quality assurance and a systematic handling of uncertainties. These are briefly addressed below. A full account of how other details in the regulations are addressed is given in Appendix A.

Use of natural analogues

There is no general account of how natural analogues support the safety argumentation in SR-Can. Natural analogues sometimes provide useful information for the understanding of specific processes. In such cases, this information is given in the **Process reports**, under a dedicated heading. The reader is referred to these documents for a further account of how natural analogues support the SR-Can assessment.

The following is an example regarding copper corrosion taken from the **Fuel and canister process report**, section 3.5.4: /Milodowski et al. 2003/ present an analysis of the corrosion of native copper plates that have survived in a water-saturated clay environment for more than 176 million years. Although the native copper is affected by corrosion, the study shows that a significant proportion (30–80% of the original thickness) of the copper sheets is preserved in the saturated compacted clay environment of the Littleham Mudstone. Apart from the recent weathering effects due to exposure at outcrop, petrographical studies demonstrate that most of the observed corrosion and alteration of the native copper is geologically old (i.e. predating the main sediment compaction) and also occurred before the end of the Lower Jurassic. This demonstrates that the native copper can remain stable in a saturated and compacted clay environment for geological timescales well in excess of the timescales considered for performance assessment of a deep geologic repository for spent nuclear fuel.

Regarding the buffer, the existence of bentonite in nature is in itself the most valuable natural analogue for the buffer stability. As an example, the Wyoming bentonites (MX-80) has remained virtually unchanged since they were formed /Smellie 2001/.

Quality assurance

A quality assurance plan has been developed and partly implemented, as described in section 2.8. Several aspects, like the reviewing of central documents, quality assured FEP management and the following of pre-established templates when documenting essential information regarding e.g. process understanding and input data in the safety assessment have been fully implemented. A first version of a model summary report, compiling information regarding quality assurance of the models used, has also been produced.

The quality assurance plan will be slightly modified to fit the context of the SR-Site assessment, and will be fully implemented throughout that project.

Handling of uncertainties

A method for the systematic handling of uncertainties has been followed in SR-Can, see further sections 2.7 and 11.5 for a description of the method.

13.4 Design basis cases

13.4.1 Introduction

Regulatory requirements

The recommendations to SKIFS 2002:1 state the following: "*Based on scenarios that can be shown to be especially important from the standpoint of risk, a number of design basis cases should be identified. Together with other information, such as on manufacturing method and controllability, these cases should be used to substantiate the design basis such as requirements on barrier properties.*"

The role of the safety assessment

As stated in SKI:s recommendations, the purpose of identifying design basis cases is to provide input to the formulation of requirements on barrier properties. This process is *iterative* and contains several elements:

1. Establishing of a repository design, i.e. a barrier system *with a chosen set of properties*, see chapter 4 and the **Initial state report**.
2. Identification of the safety functions the system should fulfil over time, see chapter 7.
3. Identification of the external stresses the system will be subject to over time, potentially jeopardizing safety, summarised in chapter 3 and further substantiated in the **Climate report**, section 4.4.2.
4. A quantitative analysis of how the identified external stresses affect safety for the established design. This analysis is provided in chapters 9, 10 and 12. The external load situations occurring in the scenarios that are particularly important from the standpoint of risk, i.e. a set of design basis cases, are briefly summarised in section 13.4.2 below. These provide important input to the formulation of a design basis.
5. Conclusions regarding the sufficiency of the chosen set of properties or recommendations regarding possible improvements. This is provided in sections 13.5 and 13.6 below.
6. The derivation of modified requirements on barrier properties based on step 5, leading to a modified design for which the above steps can be repeated.

For a particular safety assessment, a certain repository design, step 1, is hence provided. Steps 2, 3, 4 and 5 essentially constitute the safety assessment. Step 6 is, however, not within the scope of the safety assessment, see further the sub-heading 'Integrated approach' below.

Scenarios

It is clear from the analyses in SR-Can that scenarios related to canister corrosion for an eroded buffer and to shear movements are most important from the standpoint of risk. As noted before, the corrosion scenario is dependent on the extent to which buffer erosion takes place and this is an uncertain factor. In addition to these most important scenarios from the standpoint of risk, some scenarios that did not contribute to risk, since the assumed design was sufficient to prevent canister failures, must be considered among the design basis cases. This concerns e.g. canister failures due to isostatic loads. Such failures did not contribute to risk, since the design was found sufficient to prevent them. The canister's resistance to isostatic loads is, nevertheless, an important component of the design basis.

Time scale

The design basis cases also depend on the time scale considered. The likelihoods of detrimental events like large earthquakes and major ice sheets increase with time. The detrimental effects of some continuous processes, like canister corrosion, also increase with time. SSI's risk criterion applies in a 100,000 year time scale and since the design basis cases are to be derived from scenarios that are important from the standpoint of risk, this could be taken as an indication that also the design basis should be developed for this time frame. However, the principle of best available technique, BAT, applies over the one million year assessment time. It does not seem reasonable to develop the design basis for the timescale of 100,000 years and then use the one million year time scale when the principle of BAT is applied. Therefore, the one million year time scale will be considered also when the design basis is developed.

Integrated approach

There is a considerable amount of information in SR-Can that can be used to further develop the design basis for a KBS-3 repository. There are, however, few, if any, load cases *on individual barriers* that can be directly derived from the analyses. For example, the isostatic load on the canister will depend not only on the external conditions like the size of a future glacial load, but also on the design of the buffer, that determines its maximum swelling pressure. The situation regarding shear movements on the canister is even more complex: This depends on external factors like probabilities of future large earthquakes, but also on the fracture statistics of the host rock at the site, layout rules adopted for the deposition areas and for individual deposition holes and the material properties of the buffer material.

The load on one barrier will thus depend on the design of other barriers, meaning that the design basis must be determined for the entire barrier system in an integrated manner. It also means that there are a range of different combinations of barrier properties that could provide a similar performance of the repository. The role of the safety assessment in this context is to provide input to the derivation of a design basis, in the form of external loads the barrier system should sustain, informed by the calculated risk. It is, however, beyond the scope of the safety assessment to derive these properties.

The following is a summary of the most important results, *concerning the external loads the barrier system will be exposed to*, that need to be considered when such a design basis is developed. It furthermore serves as an introduction to the more detailed discussion on feedback to canister and repository design in sections 13.5 and 13.6, respectively.

13.4.2 Summary of design basis cases

Canister; Isostatic load

The isostatic load on the canister depends on groundwater pressure and on the swelling pressure of the buffer. It is cautiously assumed that the sum of these two pressures determines the isostatic load.

The reference saturated density interval of the buffer, 1,950–2,050 kg/m^3, corresponds to swelling pressures up to 13 MPa.

The maximum isostatic pressure for the 100,000 year reference evolution were demonstrated to be 43 and 39 MPa, respectively, for the Forsmark and Laxemar sites, see section 9.4.9, sub-heading 'Canister failure due to hydrostatic pressure'. These maximum loads (sums of swelling pressure and hydrostatic pressure) are to be regarded as examples of what can be expected during a glacial cycle. Bounding estimates on maximum isostatic pressures indicate values up to 45 MPa, see section 12.8.4.

As discussed in section 12.8.2, total collapse is used as the criterion for canister failure as regards isostatic loads.

In summary, if the canister is emplaced in a buffer with a density in the range 1,950–2,050 kg/m^3, corresponding to swelling pressures up to 13 MPa, the canister should withstand an isostatic load of 45 MPa. Thereby, the isostatic collapse load scenario will remain a residual scenario, with no risk contribution.

Canister; Shear movements

Limited shear loads may occur as a consequence of uneven swelling of the buffer at early stages of the repository evolution. More severe shear movements may occur as a consequence of earthquakes that could induce secondary movements in fractures intersecting a deposition hole. The response of the canister to these latter loads depends on a number of factors:

- The rupture limit of the canister insert.
- The magnitude and location of the earthquake.
- The length over which the intersecting fracture is sheared.
- The angle of intersection of the fracture with the deposition hole.
- The velocity of the fracture shear movement.
- The buffer material properties, many of which depend strongly on the buffer density.

The combined effect of all these factors determines if a canister failure will occur. The analysis of the problem in the reference evolution, section 9.4.5, and further in the shear movement scenario, section 12.9, suggests the following:

- The copper canister and the cast iron insert should withstand a 10 cm shear movement at 1 m/s for buffer material properties of a 2,050 kg/m^3 Ca-bentonite, and for all locations and angles of the shearing fracture in the deposition hole.
- Then, if the site has similar properties to those analysed in SR-Can and if the selection rules of deposition holes are those applied in SR-Can, the contribution to calculated risk from earthquakes is limited, according to the results in SR-Can.

It is also noted that this risk contribution would dominate the total calculated risk if buffer erosion would be excluded, as may be the case when further analyses of the buffer erosion process have been completed.

Canister; Corrosion load

The only identified situation in which corrosion could lead to canister failures in SR-Can is that where the buffer is eroded, leading to advective conditions in the deposition hole, thus enhancing the corrosion rate from sulphide in the groundwater and possibly additional sulphide from sulphate reducing bacteria.

Considering the large uncertainties surrounding the buffer colloid release/erosion process, it would, however, be premature to draw firm conclusions regarding the corrosion load the canister should sustain. See further section 13.5.2.

Buffer

The buffer may be exposed to chemical loads like dilute and saline groundwaters:

- Groundwaters with concentrations of divalent cations well below 1 mM over extended periods of time can not be ruled out, according to the analyses in SR-Can. It is presently unclear how the selected buffer materials respond to such chemical loads.
- Groundwaters with chloride concentrations up to around 1 M occur in the scenarios analysed in SR-Can. This poses no threat to the buffer functions.

The buffer may also be exposed to isostatic pressures up to 45 MPa. The analyses in SR-Can show that the buffer materials analysed fulfil this requirement with a margin, see section 9.4.8, sub-heading Liquefaction.

Regarding shear movements, see the discussion of this issue for the canister above.

The occurrence of buffer freezing depends on the site-specific thermal properties of the host rock, repository depth, heat production within the repository, and future climate conditions. The minimum temperatures calculated in SR-Can are −0.7°C and +6.1°C for the Forsmark and Laxemar sites, respectively. This is considerably higher than the buffer freezing temperature, pessimistically assessed to be −5°C in SR-Can (function indicator criterion for buffer freezing).

13.5 Feedback to canister design and fabrication

13.5.1 Cast iron insert mechanical stability

Isostatic load

The present design has sufficient mechanical strength to resist the expected loads in the repository. The probabilistic analysis of the canister stability showed, however, a threshold-like behaviour in the response of the insert to increasing loads /Dillström 2005/. This threshold is above, but quite close to the maximum expected isostatic load during glaciations. A cassette of fuel channels that is not located at the centre of the insert will decrease the safety margin further. The failure criterion for the probabilistic analysis, however, was the first local plastic collapse (deformation) event. At this point, there is no visible damage to the canister and, consequently, this event does not lead to any release. Calculations as well as pressure tests of mock-up canisters showed that a total canister collapse would occur at much higher pressure. Releases of radionuclides would occur only after such a total collapse.

The volume between the fuel channels and the periphery of the insert can relatively readily be inspected with ultrasound. The volumes between different fuel channels, however, are more difficult to inspect. It may also be difficult to determine the size of possible defects in this region. Techniques for detecting and evaluating defects in the insert are currently being developed. This work includes the inspection of the volume between the fuel channels. It is coupled with damage tolerance analyses in order to develop acceptance criteria for defects in the insert and to define detection goals for the inspection. The current approach is to use ultrasonic inspection, but if the detection goals cannot be met in all parts of the insert, radiographic methods will have to be evaluated as a part of the inspection process of the insert.

If the possibility of larger defects cannot be ruled out by means of inspection, higher demands on the casting quality, i.e. the strength of the insert will be needed. It is, therefore, important that the reliability of the casting and inspection procedures are studied to confirm that there is sufficient confidence that inserts with a minimum of casting defects in the form of voids can be produced and appropriate inspection processes are available. If this is not the case further development of the casting process as well as inspection process will be needed.

Shear movement

The calculations presented in /Börgesson et al. 2004, Börgesson and Hernelind 2006/ indicate that the present design have sufficient mechanical strength to withstand a 10 cm shear movement with reasonable safety margins. The calculations were performed using actual materials data, but did not, as for the probabilistic analysis for the isostatic load, take into account the spread in the data that the industrial production of canister inserts will give rise to. A probabilistic analysis similar to that made for the isostatic load is, therefore, planned.

No casting flaws were considered in the calculations. Analyses of the consequences of such flaws are currently in progress for isostatic loads and they will be expanded to include also shear load (see above).

There are no indications so far that the design of the canister insert will have to be re-evaluated. This possibility, however, cannot be ruled out until the results from the ongoing and planned studies are evaluated.

13.5.2 Copper thickness

Considering the substantial uncertainties associated with the buffer colloid release process, the hydrogeological interpretations of the site and the, as yet, not established rejection criteria for deposition holes, it is premature to draw any firm conclusions regarding a sufficient copper thickness, other than that a 5 cm copper thickness provides a sufficient margin to achieve compliance with the regulatory risk criterion with these uncertainties taken into account.

The expected life time of the canister will, in the absence of a functioning buffer, also depend on factors such as sulphide content in the water and the extent of microbial production of sulphide. The large uncertainties associated with the long-term assessment of these factors further complicate the issue of determining a sufficient copper thickness.

Welding quality

A copper coverage of about 5 cm will be required in order to withstand the potential for increased corrosion attack caused by the loss of buffer density, resulting from colloid release after an intrusion of glacial melt water. As a consequence of this, the demands on the weld quality are high, particularly regarding the percentage of intact copper coverage in the weld. The efforts to characterise the weld quality must, therefore, continue together with further development of the methods and techniques for non-destructive evaluation.

13.6 Feedback to repository design

13.6.1 Buffer

Selection of buffer material

The long-term performance of the buffer depends critically on the extent to which colloid release will occur. As demonstrated in the analyses presented in this report, colloid release could jeopardise practically all buffer safety functions. There are, however, large uncertainties associated with the assessment of the extent of the release process and further knowledge could either confirm the problematic nature of this process or lead to the conclusion that it can be neglected. If massive colloid release cannot be ruled out, then the basic design and role of the buffer will likely have to be re-considered.

If, on the other hand, colloid release can be shown to be a manageable problem, then, based on the analyses carried out in SR-Can, both reference buffer materials, MX-80 and Deponit CA-N, are expected to fulfil all function indicators over the assessment period. There are however some differences that should be noted.

- Swelling properties: Both materials have roughly the same swelling properties at the design density. According to Figure 4-6 Deponit CA-N will lose the swelling pressure more rapidly with a decrease of density at higher salinities. This is mainly caused by the composition of the waters used in the tests. MX-80 in a calcium-rich solution would eventually show the same behaviour.
- Hydraulic conductivity: Both materials have roughly the same hydraulic properties at the design density. The changes in behaviour at lower densities are the same as for the swelling pressure.
- Piping properties: The difference in piping properties has not been evaluated. There are currently no data available for such a comparison.
- Colloid release properties: Deponit CA-N has a high content of divalent cations in the form of calcite and dolomite. This could potentially be a benefit for avoiding colloid release. Currently, the effect is not proven.
- Impurities: Deponit CA-N has a higher content of pyrite, which may corrode the canister. The total effect of this is relatively small. If found necessary, a maximum content can be specified at purchase if this material should be selected.
- Freezing properties: The difference in freezing properties has not been evaluated. There are currently no data available for such a comparison.

The buffer materials will also react differently to the chemical environment in the repository (section 4.2.8 and section 9.4.8).

Both the reference materials are from major bentonite suppliers. The quality control on the suppliers side can be expected to be equal.

With the exception of the colloid release process, the conclusion is that both materials will fulfil the function indicators, and the differences between them in a performance perspective are too small to make any ranking possible. Further studies of the colloid release process may, however, lead to a different conclusion in this respect.

It is important to note that material selection is only one part of making an adequate buffer. It is also important to have adequate quality control for the delivered material, and for manufacture and emplacement of the buffer blocks.

The findings in SR-Can will be used when establishing a buffer reference material on which the SR-Site assessment will be based. Further work with quality control issues will be carried out within SKB's repository engineering program. The colloid release process is studied within SKB's R&D programme as a matter of priority.

Buffer thickness

See discussion in section 13.3.4, sub-heading 'The buffer'.

13.6.2 Selection of deposition tunnel backfill material

It has been demonstrated that a backfill consisting of Friedland clay at the given density will meet all requirements set on the tunnel backfill. The 30/70 mixture will also meet all requirements as long as the design density is maintained.

The two reference backfill materials are compared in section 9.7. It is clear that the Friedland clay has several advantages compared to the 30/70 mixture, from the point of view of long-term performance. No area where the mixture has any advantages has been identified.

As for the buffer, it is important to have adequate quality control for the delivered material and for subsequent activities through to emplacement.

The findings in SR-Can will be used when establishing a deposition tunnel reference material on which the SR-Site assessment will be based. Further work with quality control issues will be carried out within SKB's repository engineering program.

13.6.3 Materials for grouting and shotcreting

It is noted that final recipes for cement-based grouting and shotcreting, assumed in SR-Can to have porewaters with pH $\leq$ 11, are not yet fully decided. Such recipes are being tested and optimised. The decision on what products to finally use as components of low-pH grouting and shotcreting during construction and operation will depend, among other things, on their availability on the open market at that time. Further work with this issue is carried out within SKB's repository engineering program.

13.6.4 Acceptance criteria for deposition holes

The analyses carried out within the SR-Can project clearly demonstrate the importance of defining appropriate acceptance (rejection) criteria for deposition holes. It is, however, relevant to note that the impact of these criteria on the layout is strongly related to the hydraulic properties of the site and the confidence with which these can be modelled, and to the, currently insufficient, understanding of the buffer colloid release process.

Avoiding intersection with large fractures

In order to ensure canister integrity during large earthquakes, it is necessary to apply a criterion such that deposition holes intersecting large fractures are avoided, see section 9.4.5. Application of the full perimeter intersection criteria (FPC or EFPC) suggests a high efficiency in reducing the number of deposition holes intersected by large fractures at the expense of a moderate increase in total deposition tunnel length. However, in order to fully avoid the issue of intersections by large fractures, it is also necessary to consider fractures intersecting several deposition holes, without intersecting the tunnel, the so called extended FPC criterion, EFPC, /Munier 2006b/. It is an expert opinion /Cosgrove et al. 2006/ that identification of these remaining long fractures in the deposition holes is fully possible, but that the specific criteria to apply would be site specific and can only be fully established by the detailed investigations that are possible to carry out during the construction phase. In fact, such geological/geophysical criteria would be correlated with criteria for avoiding high flow rates (see next subsection).

The FPC criterion will be used when the repository design for SR-Site is developed. Furthermore, additional studies are warranted for devising efficient means of applying the EFPC criterion, although the final specification of the approach to be adopted could only be established during the construction and detailed investigation phase.

Avoiding high flow rates

Large fractures and fractures with high flow rates intersecting deposition holes are common factors for many identified safety related issues. Flow in fractures intersecting deposition holes affects:

- piping,
- colloid release,
- effects of oxygen penetration,
- inflow of corrodants, potentially leading to canister failure, and
- outflow of radionuclides (in both cases in particular for eroded buffer).

High flow rates in deposition holes are also generally associated with low F-values in the geosphere.

The flow rate depends on the transmissivity of the intersecting fractures and how these fractures are connected with the fracture network. This means that there is generally a correlation between high flow rate and fracture size since long fractures have a much higher probability to be connected and since fracture transmissivity is correlated to fracture size, although the extent of this correlation is uncertain.

A flow rate criterion will be developed, and applied when the repository design for SR-Site is developed. Previous chapters show that applying the FPC criterion, as well as a criterion related to intersecting fracture transmissivity, is highly efficient in reducing the number of deposition holes with high flow rate, but this efficiency reduces dramatically for DFN-model variants with less correlation between fracture size and transmissivity. Furthermore, a simple transmissivity criterion would then also unnecessarily reject a large number of deposition holes with very low flow, just because they were intersected by very short highly transmissive fractures. This means that it is necessary to:

- further explore the possibilities for reaching firmer conclusions on correlations between fracture size and transmissivity (see further section 9.3.6), and
- devise a practically useful flow-rate related criterion that is less sensitive to the details of the hydraulic DFN-model.

It appears likely that a flow-rate criterion related to measured transmissivities in pilot holes drilled along the deposition tunnel or in individual deposition holes positions, or a flow-rate criterion related to measured inflows to deposition holes, would be a more efficient and better discriminating criterion. The measured flow would essentially test the combined transmissivity and connectivity of the fractures connected to the holes. Preliminary analyses by /Svensson 2006b/ suggest a very strong correlation between inflows to an open repository and subsequent flows after closure and resaturation.

Before adopting a flow-related acceptance criterion further evaluations are needed, as summarised below.

- The long-term stability of the measured transmissivity needs to be considered. Possibly a robust criterion would need not only to consider currently measured transmissivity (or flow), but also evidence of high flow in the past. /Cosgrove et al. 2006/ point out that if fractures of large magnitude have experienced high flows in the past, this would result in the walls of the fractures having been altered either physically or chemically and/or minerals having been deposited along the fractures. Such features are easily identified from tunnels by direct observation and can be detected in boreholes using geophysical techniques. This, could provide an additional, important criterion for identifying large fractures.

- The criterion needs to be tested, at least theoretically, in a numerical DFN-model exploring its implications for different assumptions on the correlation of flow with fracture size. Such analyses could build on the preliminary analyses by /Svensson 2006b/ discussed above.
- Its practical applicability needs also be considered, including assessing "skin-effects" and the effects of potential disturbances from grouting before measurements are conducted.

It is emphasised that the flow rate criterion will not be independent of the fracture size criterion, especially when there is a strong correlation between fracture size and transmissivity. As already noted, the FPC criterion alone is quite effective in removing high flow rate deposition holes for the fully correlated case, and application of the EFPC criterion should improve this effectiveness. Furthermore, /Cosgrove et al. 2006/ point out that there is generally a correlation between fracture size and evidence of strong fluid movement. When estimating the degree-of-utilisation, the correlation between the criteria should be considered, in order not to be overly pessimistic about the required space.

Deposition holes with initial spalling

As discussed in section 9.2.2, there may be a possibility of spalling in the deposition holes during their excavation, but spalling that takes place during the operational phase, in open deposition holes, does not have to be important for performance and safety. Detached rock fragments can be removed and cavities can be filled with, for instance, pieces of bentonite or with bentonite pellets before or during installation of the bentonite buffer. For the few instances in which this would not be possible, the holes will be discarded for deposition, with no safety consequence.

The need to avoid deposition holes with initial spalling is discussed in the Rock Engineering Design Basis report /SKB 2004b/ and this is also being considered as a reason for reducing the degree-of-utilisation. However, in order to take credit for this in the safety assessment, the procedures for handling initial spalling need further specification.

The modelling of the extent of initial spalling will be updated when the repository design for SR-Site is developed.

13.6.5 Measures regarding spalling

Mitigation of effects of spalling occurring prior to deposition

Procedures for handling deposition holes with initial spalling need further specification as already stated in section 13.6.4.

Reduction of the occurrence of thermally induced spalling

/Hökmark et al. 2006/ suggested that there is a possibility that pressures much smaller than the bentonite swelling pressure may be sufficient to suppress spalling, justifying this by reference to studies by /Cho et al. 2002/. Filling the buffer-rock clearance with bentonite pellets at the time of deposition would give such a small pressure. Even if that pressure were not sufficient to prevent initiation of brittle failures altogether, it would help stabilize the walls and limit the growth of failures. These issues will be studied when establishing the repository design for SR-Site.

13.6.6 Controlling the Excavation Damage Zone (EDZ)

The analyses in section 10.5.7, suggest that even an EDZ with up to one and a half order of magnitude higher conductivity than the surrounding rock would not imply any major problem with respect to safety. Some measures to control the excavation procedures so that they would not lead to a very extensive and transmissive EDZ are, nevertheless, needed. As discussed in section 9.2.2, it is reasonable to assume that, provided that proper excavation techniques and QA control are applied, the EDZ, if it develops at all, will be limited to a narrow zone (a few tens of cm thick) close to the tunnel and that it would not form a continuous path. More extensive fracturing would only occur with poor engineering and inadequate QA practices, including the possibility that the tunnel is excavated sub-parallel to a joint set so that the EDZ fractures link to the joint set. Evidently, such QA procedures need be developed before deposition tunnels are excavated. However, establishing such procedures is neither needed or appropriate prior to the underground excavation phase, since they would need to be adapted to the site-specific conditions experienced underground, as well as to the organization for construction and the actual construction equipments and methods.

13.6.7 Canister positions

Canister spacing

The thermal analyses, see section 9.3.4 demonstrate that the suggested layouts at both sites would fulfil the thermal requirements on peak buffer temperature by a large margin, even considering remaining uncertainties in the thermal data. Should, however, a more efficient (compact) design be suggested, the design must consider the uncertainty, spatial variability and scaling of thermal conductivity. More elaborate design rules than those used in layout D1 would then be needed. Furthermore, potential thermo-mechanical implications, i.e. thermal spalling, of such a compact design would need studying. Given the uncertainties on the conditions needed for initiating thermal spalling, it cannot be fully ruled out that its occurrence could be influenced by e.g. a less compact design or by reducing the initial residual power in the canister. However, the calculations performed for SR-Can do not suggest such measures to be practical, i.e. there would be a need for a very considerable reduction of the heat load to have a significant impact. This will be considered when the repository design for SR-Site is developed.

Deposition areas

Current design rules apply a respect distance of 100 m to deformation zones longer than 3 km. If this respect distance is achieved, there will be no risk of earthquake-related shearing of canisters as long as the deposition holes do not intersect fractures larger than 75 m radius, see section 9.4.5. However, the question arises whether there could be other reasons to set respect distances to deformation zones – or if there are other reasons to avoid certain potential deposition areas. This issue can be partly assessed from the results of the SR-Can analyses.

In the context of potential earthquake damage, a respect distance of 200 m to deformation zones longer than 3 km would relax the canister intersection requirement to fractures larger than 150 m radius, see section 9.4.5. This would reduce the probability of earthquake damage by a factor of 5, for the approximately 20% of the canisters removed from the 100–200 m band, if no action was taken to reject unsuitable canister positions. This relatively modest advantage needs to be weighted against the loss of available deposition areas if a 200 m respect distance was applied. Even with the 100 m respect distance, earthquake-related canister damage only makes a minor contribution to the total risk, see section 12.12, and an increase in the respect distance adopted cannot be justified.

Other factors are the hydraulic conditions and the related flows in deposition holes. These flows are very important to F-values, which are, in turn, moderately important to performance, as discussed at length in chapter 12.

The following observations arise from the hydrogeological modelling outlined in section 9.3.6.

- The Forsmark repository is located in a single rock unit within the tectonic lens. Hence the local properties are similar throughout the whole repository, and flows in deposition holes are also similar. Furthermore, flow and transport are strongly governed by the existing deformation zones and tends to be nearly vertical; hence discharge points also tend to be close to the repository footprint. Thus, the deposition hole positions closest to deformation zones tend to have lower F-values and higher flows, but the values are still generally acceptable.
- The Laxemar repository is located in hydraulic rock domains (HRD) with varying properties. In the modelling, the domains have been simplified into two domains with distinctively different properties, HRD(A) and HRD(D,E,M). Furthermore, some deposition holes are located within low confidence deformation zones that were not considered in the layout of the design. However, these deposition hole locations were excluded from consideration in the SR-Can analyses. HRD(A) has lower F-factors than HRD(D,E,M), due to the fact that the latter rock domain is more sparsely connected and hence has a lower effective permeability. The difference in connectivity also affects discharge points, such that discharge from HRD(A) is more disperse. The analysis can be refined to individual repository subareas and tunnels; however, no clear spatial pattern in the results can be defended due to the uncertainties in the current model.

Based on these findings, the following considerations arise.

- There will always be a possibility of existence of highly transmissive features not captured by a deterministic description. Such features cannot be fully accounted for in the design works, but rather by applying appropriate acceptance criteria for deposition holes, see section 13.6.4.

- Some rock mass volumes may be found to be generally more transmissive than others. Very transmissive volumes would be unsuitable, at least since the degree-of-utilisation would be very poor after applying flow-related acceptance criteria for deposition holes. At Forsmark, the considered volumes appear generally suitable for deposition. The understanding of the potential deposition volumes at Laxemar, based on version 1.2, is too poor to make any specific recommendations at this point, although more recent data suggest that at least southern Laxemar would be more suitable than assumed in the analyses presented herein.

In conclusion, there is no reason to reconsider the respect distances currently applied in the repository layout work, but there may be reasons to avoid certain rock domains if it is shown that these generally have too high a frequency of highly transmissive fractures.

13.6.8 Repository depth

There are several factors related to long-term safety that are influenced by repository depth and that need to be taken into consideration when the depth is determined. The following is a brief discussion of these issues for the two sites. The discussion is confined to depths between 400 and 700 m, since this is the interval of reference depths for the KBS-3 concept. However, it is noted that detailed analyses have, in many cases, only been carried out for the depth of 400 m, since this is the depth in the layout D1 for the Forsmark site in SR-Can. The corresponding depth for the Laxemar site is 500 m and it is repeated that the confidence in the results for Laxemar is low due to the preliminary nature of the site descriptive model used for Laxemar.

Design factors other than those of importance for long-term safety are not included in the discussion.

Salinity and upconing

Very high salinities may be detrimental for the long-term function of the buffer and the deposition tunnel backfill. In general, groundwater salinity increases with depth. Furthermore, during repository construction and operation, up-coning of deeper lying saline water is expected due to the drainage of the repository. The latter effect can though, to some extent, be prevented by appropriate grouting. Also, the altered flow situation during glacial conditions can lead to redistribution of groundwater in the bedrock thus exposing the repository to deeply lying saline waters.

The buffer and a backfill consisting of Friedland clay are likely to maintain their long-term properties for any salinity that can reasonably be expected during the assessment period of one million years, whereas the function of the deposition tunnel backfill consisting of a 30/70 mixture is slightly more vulnerable, possibly requiring detailed evaluation, both as regards the likelihood of e.g. loss of swelling pressure due to intrusion of saline water and the consequences this would have on the retarding function of the repository.

Lengths and transport resistances of hydraulic travel paths to and from the repository

The travel paths of solutes in the groundwater will increase with increasing depth, but the resulting impact would only be marginal, i.e. increasing depth by 100 m would only imply an increase in path length by about 25%. More importantly, the transport resistances offered by these paths would increase with depth if the hydraulic conductivity decreases with depth at the site, see further below.

Fracture frequency and fracture transmissivity

At Forsmark, analyses of fracture data, including those obtained after data freeze 1.2, indicate a large spatial variability in size, intensity and properties between different rock domains, but also within rock domain RFM029, see section 4.3.2. The fracturing in rock domain RFM029 is more intense in the upper part of the rock, but the fracture frequency shows no consistent depth dependence. Instead, it seems that the fracturing is affected by the proximity to deformation zones. This is indicated by the higher frequency of fractures close to the gently dipping deformation zone ZFMNE00A2 that outcrops in the target area, and very few fractures at larger depth below this zone. This overall picture is also consistent with hydraulic observations. Below the 300 m level and below zone ZFMNE00A2, the rock contains very few water-conducting fractures, but additional data, now being obtained in the Complete Site Investigation Programme, are needed to define the lateral extent of this low permeability zone. In summary, the chosen repository depth of 400 m is sufficient to reach the low fracture frequency and low permeability volumes of Forsmark, and there does not seem to be any advantage in going deeper.

At Laxemar, see section 4.3.3, fracture intensity is locally dependent on host rock lithology, fracture ages, degree of alteration, and presence of ductile or brittle deformation zones, whereas a simple depth dependence cannot be shown to be significant. There are several uncertainties in the DFN model and an updated DFN-model may distinguish between different rock domains and proximity to some of the deformation zones at Laxemar, but analyses of data obtained after data freeze 1.2 do not support a simple decrease with depth. In contrast, the hydrogeological model suggests depth dependence with a more conductive region in the upper 200 to 300 m of the rock, but the limited number of boreholes and the limited amount of data available for Laxemar 1.2 made this division uncertain. However, new data show a higher degree of lithological homogeneity and also distinctly lower hydraulic conductivity in the depth interval 300–700 m. In conclusion, neither the fracture frequency nor the frequency of transmissive fractures suggests that any other depth than the chosen 500 m would be preferable.

Groundwater pressure

Groundwater pressure, contributing to the isostatic load on the canister, increases with depth. However, compared with the buffer swelling pressure and hydrostatic pressures from a glacial overburden, the increased pressures are of marginal importance. An increased pressure will also increase the inflow to the repository during construction, unless this is counteracted by grouting – this is however mainly an issue for repository engineering.

Rock stresses

Rock stresses in general increase with depth. This is primarily an issue for the construction of the repository, but also affects the probability of thermal spalling. The probability of spalling of deposition holes and tunnels during construction and due to the thermal load after deposition will increase with increasing rock stresses but is also dependent of the strength of the rock. Current data suggest that problems with spalling would increase significantly by increasing the depths for the current designs.

As outlined in section 9.2.2, spalling of deposition holes during or after excavation would not occur at Forsmark, but the result is sensitive to uncertainty and variability of the in situ stress, the ratio between the spalling strength and the uniaxial compressive strength (UCS) of the rock, and to the uncertainty and variability in the UCS.

At Laxemar spalling in the deposition holes, during and after excavation, increases below a repository depth of 450 m. At 550 m depth the probability of spalling is approximately 20% whereas at a repository depth of 650 m the probability of spalling increases to approximately 60%, but the corresponding depth of spalling is limited. This means that there will be some likelihood of spalling in deposition holes at 500 m, even if the volume change may be so small that few, if any, deposition holes would need to be discarded for this reason, but the results are sensitive to the uncertainties in stress and rock mechanics properties.

For the analysed repository depths at both Forsmark and Laxemar, see section 9.3.5, the current modelling suggest there will be spalling in the deposition holes because of the thermal load, if there is no supporting bentonite swelling pressure. These results are sensitive to the uncertainties in stress and rock mechanics properties. On the other hand, thermal spalling may be a problem also for much smaller depths (and in situ stress levels) than in the current designs.

From a rock mechanics point of view an increase of repository depth from 400 m at Forsmark or from 500 m at Laxemar, would increase the probability of spalling both during excavation/operation and in the initial phase due to the thermal pulse. It could be argued that SR-Can already considers thermal spalling, implying that an increased effect at greater depth would not be an issue. On the other hand, the thermal spalling may enhance the mass transfer between buffer and rock, and means of reducing thermal spalling are beneficial, although not essential. Furthermore, increasing the depth would also imply spalling and other rock mechanics stability problems in other parts of the repository.

Initial temperature

The in situ temperature increases with depth, although the thermal gradient is relatively low in the considered depth range. This needs to be considered in the repository layout, when determining the necessary canister spacing that would ensure that the peak buffer temperature lies below stipulated limits. However, given that this is considered in the repository design, there are no other detrimental effects of the elevated in situ temperature with depth.

Freezing

Colder future climate may in principle ultimately lead to freezing of the buffer and the deposition tunnel backfill. This could in turn have detrimental effects on the canister and the near-field rock. The likelihood of freezing decreases with increasing depth. The analyses in SR-Can have, however, demonstrated that freezing of the buffer can be considered as a residual scenario, i.e. no reasonable way that this could occur has been identified for a depth of 400 m at Forsmark or 500 m at Laxemar. For an eroded buffer, the freezing point is higher than for an intact buffer. Freezing of water in an eroded buffer at repository depth at Laxemar is ruled out, whereas at Forsmark freezing of water in an eroded buffer is unlikely but cannot be fully ruled out. The effects are, however, not assessed to threaten the integrity of the canister. Freezing of the deposition tunnel backfill at 400 m depth at Forsmark, is unlikely, but cannot be fully ruled out. The impact of this on safety would, however, be considerably less severe than freezing of an intact buffer, since only the latter threatens canister integrity.

Surface erosion

Surface erosion of the host rock will occur, in particular by glacial erosion. This means that the repository depth will decrease somewhat for each glacial phase. The extent is uncertain, but is generally limited to a few metres or less per glacial cycle, when considering repository sites located in bedrock without major valleys and deformation zones. Therefore, erosion does not have to be considered when determining repository depth within the reference interval 400–700 m.

Inadvertent human intrusion

The probability of inadvertent human intrusion into the repository decreases with increasing depth. Intrusion may have consequences both for the intruders and for the long-term performance of the repository after the intrusion. Intrusion scenarios are evaluated separately from other scenarios in the safety assessment, in accordance with Swedish regulations. Therefore, it is not straight-forward to assign this factor an importance measure in a sense comparable to the other factors discussed here. In general, intrusion to several hundred metres is, though, considered unlikely in resource poor rock.

Other considerations

The repository depth must of course also be selected such that respect distances to deformation zones longer than 3 km are achieved. When the deformation zone model is updated during the CSI, this may imply minor adjustments of the now selected depths in order to optimally use the available volume.

Overall conclusion regarding the choice of repository depth at Forsmark

In conclusion, there is no reason for recommending a deeper location than –400 m at Forsmark. Updated layouts, however, need to ensure that the repository is located in the low permeable region at depth. This may require some minor adjustment of the depth. Furthermore, the ongoing revision of the deformation zone model may imply a need for a minor adjustment of the depth. However, a much deeper repository could imply unnecessary rock mechanics impacts, without providing any added safety for other aspects. These findings will be considered when the repository depth is established as part of the development of the repository design for SR-Site.

Overall conclusion regarding the choice of repository depth at Laxemar

The site descriptive model version 1.2 of Laxemar is less comprehensive than that of Forsmark, but the currently suggested repository depth of –500 m appears appropriate. There is no reason for a deeper repository, as this will increase the probability of spalling and also upconing of saline water. A shallower depth may be a possibility, but this would depend on the depth distribution of the hydraulic conductivity. Furthermore, the ongoing revision of the deformation zone model may imply a need for a minor adjustment of the depth. These findings will be considered when the repository depth is established as part of the development of the repository design for SR-Site.

13.7 Feedback to site investigations and site modelling

Previous chapters demonstrate that several site-specific conditions have a large impact on repository evolution and also – in some cases – on individual risk. Feedback to the continued site investigations can thus be given, considering the confidence and uncertainty in the version 1.2 site descriptive models, as outlined in section 4.3. It is generally found that the ongoing Complete Site Investigation (CSI) programme appears adequate, i.e. there is no real need for more data than already planned, but there is still important feedback that needs to be considered in the site descriptive modelling.

In this context, it is also noted that the main function of the geosphere is to provide chemically, mechanically, thermally and hydrologically favourable conditions for the buffer and the canister. The retardation properties of the geosphere are of secondary importance, illustrated by several examples showing that neglect of geosphere retardation leads to increases in releases/effective doses of typically no more than one order of magnitude. However, if extensive spalling occurs, causing deterioration in the retention properties of the buffer/rock interface, then geosphere retention can be more important. It is also noted that, in general, most sorbing nuclides decay to insignificance in the geosphere.

13.7.1 Existence and location of deformation zones larger than 3 km

In order to ensure mechanical stability of deposition holes, it is a necessary condition that deposition holes are located with appropriate respect distance to deformation zones with trace lengths longer than 3 km, see section 9.4.5. According to the site descriptive models, it is believed that most such zones have already been identified, but uncertainties remain. Especially, the Laxemar version 1.2 model contains considerable uncertainty in the detailed geometry and character of these zones. One major consequence of these current uncertainties is that the layout, which is based on the results of the initial site investigation, layout step D1, would likely need to be substantially altered when a less uncertain description is available.

Implication for site characterisation

The additional boreholes now being constructed in the CSI programmes at the sites, /SKB 2005d, 2006f/, are needed to more firmly define locations of the potentially suitable deposition volumes. Final verification of the location of deformation zones in relation to the layout, in order to ensure that respect distances are met, will be needed during the construction and detailed investigation phase.

Implications for site descriptive modelling

The site descriptive modelling approach used in version 1.2 is judged adequate to serve the needs of SR-Site.

13.7.2 Fracture statistical description – geological DFN-model

Mechanical stability of canisters also requires that deposition holes are not intersected by large fractures or deformation zones, see section 9.4.5. Furthermore, the occurrence of large fractures is also related to high flow rates in deposition holes and low transport resistance, although this depends on the correlation between the fracture size and fracture transmissivity. It should also be noted that the probability of adverse conditions at the canister depends on the acceptance criteria applied in relation to individual deposition holes, see section 13.6.4.

The DFN-models are quite uncertain at both sites, and in Laxemar version 1.2 there is also a lack of data from large parts of the potential deposition areas, but the suggested basis for accepting deposition holes using the FPC criteria is anticipated to be fairly robust to alternative DFN-models. It is of paramount importance to develop both geological and hydrological DFN models in which there is sufficient confidence. While the importance of representing large fractures correctly in site models is stressed, it is also noted that the likelihood of identifying and avoiding these structures determines their final impact on safety. Also, the extent of the buffer erosion process is poorly understood. If a basis for more favourable descriptions of this process can be obtained for future assessments, the impact of these large fractures could decrease considerably.

Implications for site characterisation

Compared with data freeze 1.2, more data are needed from the potential repository volumes as well as dedicated efforts in exploring the consistency between outcrop and drill core mapping. Such plans are presently being executed as a part of the ongoing CSI programme at the sites. The special efforts to map "minor deformation zones" and the dedicated "DFN-boreholes" at Laxemar should also be noted. While these data do not primarily cover the potential repository volume, they may still provide key input to the understanding of the fracturing at the site – and are therefore important for the overall understanding.

Further reduction of the uncertainties, if needed, would probably only be possible from the underground, detailed investigation phase. Presently, the overall strategies for detailed investigations during the construction phase are under development within SKB. Whatever strategies are expressed now, these will have to be adapted to the insights gained during tunnel excavation, regarding both the identification of any site-specific signature of large fractures/small deformation zones and the implications of identification of such signatures for the training of geologists for the required field work and detailed modelling.

Implications for site descriptive modelling

Efforts need also be spent on improving the strategy of DFN-modelling and this is also considered in the CSI phase of site investigations and site modelling. There are key assumptions made in current models that could be challenged and there seems to be room for making more thorough use of the available borehole information. It is especially important to provide robust estimates of the intensity and size distribution of large fractures and deformation zones (expressed as P_{32} and the k_r parameter in the currently assumed power-law distribution) and, in particular, further efforts should be spent on providing good support for the possible ranges of these parameters. In contrast, details of the orientation distribution of fractures are of much less importance.

Furthermore, the DFN-modelling needs better coordination with the related hydrogeological DFN-modelling. The models need to be mutually consistent and comprehensively exploit all available relevant information. However, as most fractures are not transmissive, the hydrogeological DFN-model will be a subset of the total fracture model. It is, therefore, important to maintain the distinction between the geological DFN and the hydrogeological DFN models.

As evidenced by several key results in this report, fractures with high flow rates intersecting deposition holes may cause substantial buffer erosion. Furthermore, the largest fractures intersecting deposition holes are associated with the highest risk of canister shear failures in the event of a large earthquake in a zone near the repository. It is thus important to have confidence in the high transmissivity/large size part of the DFN models. Also, these fractures are associated with low transport resistance in the geosphere, meaning that they are not only likely to be associated with canister failures, but also with high release rates should such failures occur.

13.7.3 Hydraulic properties of the repository volume

Groundwater flow at the deposition hole scale has a large impact on repository performance. Excessively high inflows during deposition could cause piping erosion, see section 9.2.4, although the condition could always be avoided by selecting deposition holes with sufficiently low inflow. After deposition, high groundwater flow affects the mass transfer between the buffer and the rock, see section 9.3.6, which in turn affects the potential for buffer erosion during glacial conditions, see section 9.4.8, and canister corrosion in case of buffer advection, see section 9.4.9. These evolutionary processes have large impact on the total risk, see section 12.12 and underlying analyses in chapter 10. High groundwater flow also affects the release of radionuclides for the case of an intact buffer.

According to the Forsmark SDM 1.2, the repository volume has a very low hydraulic conductivity. This means that most canister positions have very low flows, although potentially there will be some positions with higher flow and at least application of the FPC acceptance criterion appears to be necessary. However, the 1.2 model was based on very few data making the extrapolation in space uncertain.

At Laxemar, there are potentially more unsuitable positions, and the need for effective acceptance criteria is even greater. However, as already noted in section 4.3.3, the limited number of boreholes and small amounts of data available for Laxemar 1.2 makes the current hydraulic description of the repository volume highly uncertain.

At both sites, the flow at deposition hole scale, as well as the efficiency of the simple acceptance criteria tried, appears to be very sensitive to the selected conceptual model, e.g. CPM or DFN as well as to the details of the hydraulic DFN-model (fully correlated and semi-correlated), see section 9.3.6. It would be very helpful if these conceptual uncertainties could be reduced in order to propagate fewer models to the safety assessment. It is noted that the DFN models yield less favourable results both in terms of radionuclide release and transport in the geosphere. Possible fast paths for radionuclide transport are clearly better represented in the DFN than in the CPM models. These conceptual uncertainties are being addressed in the continued site descriptive modelling.

The hydraulic description also affects radionuclide retention, as well as the sensitivity to external changes of groundwater composition. A high transport resistance, F, is required to significantly retard sorbing radionuclides. At Forsmark, most deposition holes are connected to a high transport resistance, see e.g. Figure 9-29, and this only weakly depends on the conceptual model adopted as a basis. A similar conclusion can be drawn for Laxemar, even though the version 1.2 model suggests that there are more deposition holes that are connected to low transport resistance.

Implications for site characterisation

At Forsmark, more data from the repository volume, compared with those available for version 1.2, are needed to better confirm the extent of the low permeable volume. Such data have now been collected, or are being collected as a part of the CSI programme. The data appear to confirm the 1.2 conclusions and the ongoing characterisation programme appears adequate.

The Laxemar 1.2 site description of the repository volume is highly uncertain. However, and as already stated, new data that have become available after data freeze Laxemar 1.2, strongly support both a depth dependence of hydraulic conductivity and that the rock domains in southern Laxemar have lower hydraulic conductivity than in northern Laxemar. These data suggest that the hydraulic conductivity of the potential repository volume of Laxemar is lower than that assumed in SR-Can. These, and other planned hydraulic data from the ongoing CSI programme at Laxemar are needed before a firmer hydraulic model of the potential repository volumes at Laxemar can be supported.

Implications for site modelling

An updated hydrogeological site modelling strategy will be applied for the CSI modelling. The remaining site descriptive modelling should focus on the hydraulic DFN-modelling of the potential repository volumes. There is comparatively little need for a DFN-description outside these volumes. When there are multiple boreholes in the same HRD, being part of the repository volume, all boreholes should be used for the statistical fit rather than opting for a very accurate fit to a specific borehole. Furthermore, different size versus transmissivity variants should be tested, but with proper attention to the resulting scaling properties. The calibration must include fractures at the same scale as will be used in safety assessment application, i.e. sizes down to metre scale.

Some site-specific issues need careful assessment.

- At Formark, the extent of the low permeable volume needs a firmer confirmation. Within this volume it should be further assessed whether it can be described by a traditional DFN, or whether it is an extreme channelling system. The fracture size and transmissivity correlation also needs to be studied.
- At Laxemar, the prime issues concern the confidence in HRD distinctions and depth dependence as well as the fracture size transmissivity correlation.

Given the comparatively lower importance of the transport resistance, there is no special need to spend extensive resources in trying to further bound this estimate. Analysing the new hydraulic data from the CSI phase with the already used techniques – ranging from simple estimates based on the borehole data to upscaling using a DFN with various assumptions – appears to be fully appropriate for bounding the flow resistance estimates also for SR-Site.

13.7.4 Rock mechanics

High in situ stress in relation to the Uniaxial Compressive Strength (UCS) of the intact rock may result in spalling of deposition holes, both during construction and later, after deposition, due to the added thermal load. Spalling before deposition is possibly only a concern for engineering, its impact can be mitigated by e.g. only accepting holes with a limited amount of damage or by replacing the spalled material with bentonite pellets, whereas the thermal spalling may create a local zone of enhanced permeability and porosity close to the deposition holes, see section 9.3.5. A conductive spalled zone, also intersected by a conducting fracture, will enhance the mass transfer from and to the deposition hole, which affects both the potential releases (section 9.3.6) and the stability of the buffer during glaciation (section 9.4.8).

Thermal spalling is a possibility at both sites, considering the relatively high in situ stress levels observed at Forsmark and comparatively low UCS of the intact rock observed at Laxemar. However, uncertainty remains, both in relation to the stress levels and UCS.

Implications for site characterisation

Considering the high and uncertain stress levels that have been observed at Forsmark, further reduction of the uncertainties in stress and rock mechanics properties is needed. Although stress levels are generally lower at Laxemar, further reduction in uncertainty is needed given the apparently lower UCS. Especially at Laxemar, there is a need to obtain representative data from all important rock types in the potential repository volume. All these needs are already being addressed in the ongoing CSI programmes at the sites.

Implications for site modelling

The confidence in the stress and property modelling essentially depends on the quality and amount of input data. However, numerical stress modelling, as already tried at Laxemar, see section 4.3.3, is an important means of enhancing the confidence in extrapolating the sparse stress data. Such extended stress modelling is underway for both Forsmark and Laxemar.

The rock mechanics modelling should also, if possible, pay more attention to the 3D modelling of the UCS. In the CSI site modelling work there will be further attention to scaling and correlation to rock type. This may reduce uncertainties.

13.7.5 Thermal properties

Thermal conductivity and in situ temperature, determine, together with the repository layout, the buffer peak temperature. The thermal analyses, see section 9.3.4, demonstrate that the suggested layouts would fulfil the thermal requirements by a substantial margin, even considering remaining uncertainties in the thermal data. Should, however, a more efficient (compact) design be suggested, further reduction of uncertainties in the spatial variability and scaling of thermal conductivity would be necessary. Especially at Laxemar more representative data from the potential repository volume are needed. Such data are being obtained in the ongoing CSI programme.

13.7.6 Hydrogeochemistry

The chemical environment directly controls the evolution of the repository. The most important parameters are redox properties, salinity and ionic strength, which directly affect the canister and buffer safety functions. Other factors to consider are the groundwater content of potassium, sulphide and iron(II), as they might affect the chemical stability of the buffer and the canister.

Available hydrogeochemical data are clearly sufficient to prove that suitable conditions prevail at both sites today and also during the temperate period that should persist for the next few thousand years. More challenging is predicting the groundwater composition during a glacial cycle. As shown in section 9.4.7, upconing during glaciation will not result in excessively high salinity values, whereas intrusion of dilute glacial melt water, which may result in buffer erosion, cannot be excluded. Furthermore, for the case of an eroded buffer, the sulphide content becomes important, since excessively high values may lead to total corrosion of the copper canister (see section 9.4.9).

In order to enhance the confidence in these important predictions, and potentially also to be able to exclude the possibility of intruding dilute glacial melt water, more information is needed from the site descriptive hydrogeochemical models.

Implications for site characterisation

Additional hydrogeochemical data are required at both sites, compared with version 1.2. In order to have a full evaluation of the redox buffering capacity of the geosphere, more mineralogical data, i.e. Fe(II), pyrite and sulphide content of the rock and amount of fracture minerals in contact with the flowing water, are needed. Rock and fracture mineral data on "cation exchange capacity" would help improve the modelling of intruding dilute waters. Water sample data on sulphide, as well as hydrogen and methane, concentrations would improve the possibility of predicting the future sulphide content. More ^{36}Cl data would enable dating the occurrence of chloride – and thus potentially enhance the basis for the current mixing model. Additional samples of the water composition of the rock matrix and of helium contents of groundwaters would also be valuable, both as additional evidence for matrix diffusion and as input to assessing the long-term evolution of the groundwater composition. These issues are being addressed within the CSI programme.

Implications for site modelling

Whereas the hydrogeochemical modelling approaches are judged generally sufficient, further attention to the overall conceptual model is needed. Planned, focused efforts on the potential existence of a relatively shallow "process zone" capable of buffering the meteoric water with respect to redox and cation exchange seem highly appropriate. At Forsmark, there is also a specific need to find a definitive explanation for the high uranium content found at depth, see section 4.3.2.

Further integration with hydrogeology also appears useful, but the focus should be on determining whether the hydrogeochemical data sets any bounds on the "bulk properties" of the HCDs and HRDs at a regional scale. It is not appropriate to treat end-members from M3 as tracers in coupled modelling, as was done in some of the version 1.2 modelling. The quantitative analysis should rather predict the migration of some major species (Cl^-, O-18, H-3, and to a lesser extent Na and Ca, although they may be somewhat affected by reactions such as cation-exchange) and then assess water type distributions in discussion with experts on hydrogeochemistry.

13.7.7 Surface ecosystems

In SR-Can, site data have been collected and used as far possible in the biosphere models. Another major impact from the site investigations is the understanding of the development of the site and spatial connection and geometry of different objects. This gives also a logical and coherent connection to surface hydrology, which is the major transport and dilution factor at the surface. Furthermore, representation of the connection of surface waters, and near-surface and deep groundwaters has been facilitated by the spatial understanding of the site. The spatial and temporal understanding together with novel use of ecosystems models has established constraints on the potential human exploitation of the site, which in turn affects the size of, and annual effective dose associated with, for the most exposed groups. The landscape approach has also shown that various radionuclides are associated with different ecosystems and time periods for maximum annual individual effective doses, thus an integrated approach is more meaningful than trying to define a single critical ecosystem. It is emphasised that the approach adopted is cautious, as the LDF values adopted are maximum values that apply at different times and places, but which are treated as if they were additive.

Many of the data used are based on early studies of the sites and are associated with a lack in precision and limitations of coverage. These datasets are being improved in the ongoing program. A major review of data will be undertaken during the coming year and will inform SR-Site.

The major lack of data have been from the overburden, especially parameters like boulder frequency and extent of the various types of marine seafloor, thickness of regolith and dated stratigraphy. Many of the data have already been collected, but have not yet been analysed. For Laxemar, a direct succession from coast to mire/agriculture land was identified in the modelling and this needs to be confirmed using stratigraphic data.

Also lacking is retention data of elements in regolith and biota (e.g. Kd for soil, sediments and peat, soil to plant transfer factors, animal transfer coefficients). Most of the required samples have been collected and chemical analyses and reporting is in progress. The ecosystem modelling of elemental transfers is, when finalised, to be used as a complement to transfer factors. This is in particular necessary in order to satisfactorily handle radionuclides such as C-14, for which current radionuclide transport models are associated with large uncertainties.

These issues are being considered within the surface ecosystem site characterisation and modelling activities.

Implications for site characterisation

Process measurements (e.g productiviy of different ecosystems) and stoichiometric analysis of biota are necessary for future model versions.

For the regolith, the dated stratigraphy of sediments and mires is necessary in order to improve data on net sedimentation and understanding of the development of the sites. Revisiting raw data from sonar and depth soundings is required in order to estimate boulder frequency and size. Also, reinterpretations of field records and soundings are required in order to map soft and hard seafloors.

Further understanding is required of whether a direct succession from coast to mire/agriculture land at Laxemar occurred, and the potential occurrence of this phenomenon in Forsmark needs to be determined.

Finally, the descriptions and predictions of biosphere object properties need to be confirmed as far as possible by field observations.

Implications for site modelling

The site modelling needs to incorporate the stoichiometric analyses of regolith and biota in order to produce site-specific ranges of sorption estimates and bioconcentration factors. Furthermore, elemental concentration mass balances are required in order to obtain natural rates of transport and concentrations of elements.

The analysis of the coupling of deep groundwater with surface groundwater needs to be completed. Also, the terrestrial ecosystem models need to incorporate elemental fluxes and be completed.

13.8 Feedback to RD&D programme

The following is an account of issues that contribute to risk for which the basis for assessment can be improved through more R&D.

13.8.1 Radium co-precipitation

In section 10.5.7 it is concluded that there is a great potential of reducing the calculated releases of Ra-226 if co-precipitation effects can be taken into account. Each canister contains about 5 kg of barium and radium/barium co-precipitation is a well known process from contamination cleaning. However, this issue has not been addressed within the SKB programme to a level where full credit can be taken for the process in the assessment of the spent fuel behaviour. Since the process is well documented it may be possible to extract a quantitative understanding from studies of available literature.

13.8.2 Buffer erosion/colloid release

It is clear from the findings in SR-Can that colloid release from the buffer is one of the research areas which requires the greatest attention in future RD&D program. With current understanding severe, or total, losses of the buffer, a key element in the KBS-3 concept, cannot be ruled out.

Further investigations could be done in several areas:

- A critical evaluation of the CCC-values may yield lower values.
- The importance of Ca instead of Na in the exchange positions needs to be evaluated.
- The possibility to take credit for Ca (and Mg) containing impurities needs to be investigated.
- A model that describes the colloid release process in a correct way needs to be developed.
- The possibility for accessory minerals to form colloid filters needs to be evaluated.

An experimental test programme is implemented, and this may need to be extended. Further evaluations of the circumstances under which dilute glacial waters could reach repository depth are also required.

13.8.3 Equivalent flow rate at deposition holes

The mass transfer resistance between the bentonite and the flowing water in the fractures in the rock is one of the key features of the KBS-3 concept. The modelling concept has been used in all safety assessments since KBS-1. It has, however, never been experimentally verified. An experimental programme to test the assumption is desirable and will be undertaken.

13.8.4 Liquefaction

The loss of swelling pressure as a consequence of high hydrostatic pressure has recently been identified as a potential problem. However, an experimental programme to resolve this issue is ongoing and the results available already show that this issue is of no concern for the KBS-3 concept, see further section 12.3.4.

13.8.5 Spalling

A more firm understanding on under which conditions thermal spalling will occur, as well as the extent of the spalled zone would be of interest. In particular it would be of interest to determine if counter pressures much smaller than the bentonite swelling pressure may be sufficient to suppress spalling. This could imply that filling the buffer-rock clearance with bentonite pellets at the time of deposition would be sufficient for mitigating the spalling. The ongoing evaluation, including numerical modelling, of the Äspö Pillar Stability Experiment (APSE), see e.g. /Andersson and Eng 2005/ will provide important input to what conditions are needed for thermal spalling to occur and will be used in SR-Site.

It could also be considered whether in situ tests underground at the actual site and at repository depth would be a practical and useful means of assessing the actual, site-specific, potential for thermal spalling. Such tests could also explore the efficiency of mitigating measures, such as filling the buffer-rock clearance with bentonite pellets.

It is possible to estimate the consequences of spalling on the mass-transfer in the buffer rock interface. The treatment is found to be adequate for the purposes of SR-Can. An increased understanding of the extent of the spalling zone may facilitate a development also on the modelling side.

The model that describes the mass transfer in the buffer/damaged rock interface is being further refined and expected to be used in SR-Site.

13.8.6 Glacially induced stresses and earthquake simulations

The work in SR-Can has confirmed the need for simulations of the stress state at repository depth during a glacial cycle. In particular, the site-specific prerequisites for glacio-isostatic faulting need to be evaluated. Planned, but not yet initiated, simulation efforts are directed to addressing this particular aspect /Lund 2005/.

The simulations that defined the framework for incorporating respect distances /Munier and Hökmark 2004/ and their application, was based on earthquakes of magnitude 6. Although /Munier and Hökmark 2004/ argue that the stress drop rather than the magnitude is the determining factor in the simulation results, the validity of assumptions made in /Munier and Hökmark 2004/ need to be confirmed by simulations of earthquakes with larger magnitudes. Additionally, the treatment of multiple seismic events along one or several deformation zones, needs to be further evaluated.

The above issues will be addressed in SKB's RD&D programme or as part of the SR-Site assessment.

13.8.7 Effects of earthquakes on engineered barriers

The impact of a shear movement on a disposal canister has been modelled several times /Börgesson 1992, Börgesson et al. 2004, ongoing work/. It is questionable if further modelling would lead to a better understanding of the response of a canister to a shear movement. The planned probabilistic study will, though, provide information on how the variations of materials properties for the insert will affect the risk for failure.

A next step could be to perform a full scale experimental test, in analogy with the experimental test of failure under isostatic overpressure which proved useful and illustrative for understanding the canister's collapse behaviour. Such a test is being considered within SKB's R&D programme. If pursued, this would, however, not be completed in time for the SR-Site assessment.

13.8.8 DFN methodology

To our knowledge, the modelling techniques and the vast amount of multidisciplinary data which have been used for the modelling, are unique. Despite the identified shortcomings, the methodology of producing geological DFNs for granitic media is state-of-the-art and has contributed to advances within this particular field of the geosciences. The process of producing the DFN models have invoked a considerable R&D component as the DFN modellers have broken new grounds and, thereby, discovered new problems to solve. However, the methodology is, by the SDM version 1.2, fairly well settled and needs only adjustments that most probably can be handled within the SDM. Additionally, some methods have been developed but not yet invoked in the DFN modelling. Of the identified needs for methodology improvement, a stringent differentiation and quantification of variability and uncertainty is regarded as one of the most critical. In this context, a certain amount of R&D might be required. Though not a methodology issue *per se*, another critical issue of improvement is the integration between the hydrogeological and the geological DFNs.

The modelling relies upon assumptions, some of which are very hard to authenticate. More efforts need to be spent on evaluating the effect of altering key assumptions, within the framework of the uncertainty quantification. Of these, the assumptions of tectonic continuum (that the fracture size relation is assumed constant over all scales) is probably the most important to explore.

The above issues will be addressed in SKB's RD&D programme.

13.8.9 Biosphere

In addition to the continuous update of process knowledge, the R&D program for the biosphere needs to address several issues before the application in SR-Site. An extensive sensitivity study of the landscape to different combinations of biosphere objects at both sites is currently being carried out. This study is expected to give feedback to the R&D programme, to site investigations and to biosphere modelling as regards which ecosystems and parameters to be focussed on in order to improve knowledge and data.

A harmonisation of the models for agriculture land, mire and forest is required as part of the further development of terrestrial ecosystem models. Especially the material fluxes must be developed to a similar level as the marine models to allow appropriate modelling of elements like C-14. A plan for this will be presented in RD&D programme 2007.

Generic knowledge about permafrost ecosystems representative of expected permafrost conditions in Scandinavia is required to support assumptions in the landscape modelling of such conditions. Furthermore, the human exploitation of the landscape needs to be related to findings from the sites and the process of shore line succession immediately from sea to mire, with no intermediate lake, needs to be examined.

13.9 Conclusions regarding the safety assessment methodology

13.9.1 Methodology in ten steps

As outlined in section 2.2, and illustrated in Figure 2-1, the methodology used in the SR-Can assessment can be described in ten steps. These are repeated below and brief conclusions regarding further development needs and plans for the SR-Site assessment are given.

1. Identification of factors to consider (FEP processing)

   This step consists of identifying all the factors that need to be included in the analysis. Experience from earlier safety assessments and KBS-3 specific and international databases of relevant features, events and processes (FEPs) influencing long-term safety are utilised. An SKB FEP database is developed where the great majority of FEPs are classified as being either initial state FEPs, internal processes or external FEPs. Remaining FEPs are either related to assessment methodology in general or determined to be irrelevant for the KBS-3 concept. Based on the results of the FEP processing, an SR-Can FEP catalogue, containing FEPs to be handled in SR-Can, has been established. This step of FEP processing is further described in chapter 3 and fully documented in the SR-Can **FEP report**.

The SKB FEP database and the FEP catalogue developed for SR-Can will be updated as necessary for SR-Site. These products are regarded as mature, meaning that only minor modifications are foreseen. The comprehensive and time consuming audit against the NEA FEP database carried out within the SR-Can project lead to the identification of a few new FEPs. It is not seen as meaningful to repeat such an audit in the SR-Site assessment. The **FEP report** will be updated, based on experiences from the production of SR-Can.

2. Description of the initial state

   The initial state of the system is described, based on the design specifications of the KBS-3 repository, a descriptive model of the repository site and a site-specific layout of the repository. The initial state of the fuel and the engineered components is that immediately after deposition as described in the **Initial state report**. The initial state of the geosphere and the biosphere is that of the natural system prior to excavation, as described in the site descriptive models /SKB 2005c, 2006b/. The repository layouts adapted to the sites are provided in underground design reports for each site /Brantberger et al. 2006/ and /Janson et al. 2006/. See further chapter 4.

The **Initial state report**, describing the fuel and the engineered components will be updated, on essentially the same format as used in SR-Can.

Updated versions of the site descriptive models will be used as input to SR-Site. The handling of the updated site data is foreseen to be similar to that in SR-Can, i.e. a condensed version, focussing of safety relevant aspects, of the site description in the main report and a qualification of crucial data for the safety assessment in the **Data report**, as further elaborated in section 4.3.1.

The repository layouts will be updated to version D2, which will be used as input to SR-Site. The rules for deposition hole acceptance to be used in layout D2 will be developed based on the experiences from SR-Can.

3. Description of external conditions

   Factors related to external conditions are handled in the three categories "climate related issues", "large-scale geological processes and effects" and "future human actions". The handling of these factors is described in the **Climate report,** the **Geosphere process report**, and the **FHA report**, respectively. See further chapter 5.

The handling of external conditions will be described in updated versions of the mentioned reports. Regarding the handling of future human actions, only minor, if any, modification are foreseen.

4. Description of processes

   The identification of relevant processes is based on earlier assessments and FEP screening. All identified processes within the system boundary relevant to the long-term evolution of the system are described in dedicated **Process reports**. Short-term geosphere processes/alterations due to repository excavation are also described in these Process reports and are taken into account in the assessment. For each process, its general characteristics, the time frame in which it is important, the other processes to which it is coupled and how the process is handled in the safety assessment are documented. See further chapter 6.

The purpose of the **Process reports** is to provide a link between technical and scientific background reports describing general process knowledge and the safety assessment in that they condense the information in the background reports and focus on the needs of the safety assessment. As such, the process reports are seen as meaningful and they are, therefore, planned to be updated for the SR-Site assessment, using the same format as in SR-Can. For example, an update is foreseen regarding the understanding of the extent of buffer colloid release/erosion for dilute groundwaters, based on on-going experiments and other sources. Most of the material in the process reports is, however, seen as sufficiently mature to be reused in SR-Site.

The need for Process reports covering the additional system components "bottom plate in deposition hole", "plugs", "borehole seals" and "backfill of other repository cavities" that were not treated in SR-Can (see section 6.1.1) will be assessed in the planning of the SR-Site project.

The process tables and the assessment model flow charts (AMFs) introduced in chapter 6 are seen as useful tools for condensing information and providing overview. These will be updated for the SR-Site assessment.

5. Definition of safety functions, safety function indicators and safety function indicator criteria

   This step consists of an account of the safety functions of the system and of how they can be evaluated by means of a set of safety function indicators that are, in principle, measurable or calculable properties of the system. Criteria for the safety function indicators are provided. The process reports are important references for this step. A FEP chart is developed, showing how FEPs are related to the safety function indicators. The execution and results of this step are described in chapter 7.

This step constitutes an important foundation for the methodology used in SR-Can. It is planned to have a similar role in the SR-Site assessment. The set of safety functions, indicators and criteria may be revised, based on additional knowledge available for the SR-Site assessment.

The FEP chart introduced in chapter 7 is seen as a useful tool for providing an overview of the 'logic of safety' for the KBS-3 system. There is a partial overlap between the information contained in the AMF (see step 4 above) and that in the FEP chart, since the information from modelling activities is used when evaluating safety. It could be possible to join these tools, but that would likely require one FEP chart for each time period of the assessment. This will be further considered as the plans for SR-Site are developed.

6. Input data selection

   Data to be used in the quantification of repository evolution and in dose calculations are selected using a structured procedure. The process of selection and the data values adopted are reported in a dedicated **Data report**. Also, a template for discussion of input data uncertainties has been developed and applied. See further chapter 8.

The format for the presentation of input data and for the quantification of input data uncertainty used in the **Data report** is regarded as mature and planned to be essentially reused in SR-Site. The set of input data entities will be revised based on the results of SR-Can and additional information available for SR-Site. The **Data report** will be updated.

7. Definition and analysis of reference evolution

   A reference evolution, providing a description of a plausible evolution of the repository system, is defined and analysed. The isolating potential of the system over time is analysed in a first step, yielding a description of the general system evolution and an evaluation of the safety function indicators. If the evolution indicates breaching of isolation, the retarding potential of the repository and its environs is analysed and dose consequences are calculated for the long-term conditions identified in the first step. Also, some canister failure modes not resulting from the reference evolution are analysed in order to further elucidate the retarding properties of the system. Each process is handled in accordance with the plans outlined in the process reports. See further chapter 9 for the analysis of the general evolution and the isolating potential and chapter 10 for the analysis of the retarding potential.

The format used for the analysis of the general reference evolution in SR-Can consists of four time frames, each in which external conditions, the biosphere and the THMC evolution of the repository system is analysed, followed by evaluation of safety functions after each time frame. This format is seen as appropriate and is planned to be reused in SR-Site.

The format for the analysis of the retarding potential, subdivided into the different failure modes of the canister, is also seen as appropriate. Here, the method for the analysis of radionuclide transport and dose in the biosphere is novel and contains much of the elements of the methodology planned to be used in SR-Site.

Regarding the updated handling of some particular issues in the reference evolution, see section 13.8.

8. Selection of scenarios

   A set of scenarios for the assessment is selected. A comprehensive main scenario is defined in accordance with SKI's regulations SKIFS 2002:1. The main scenario is closely related to the reference evolution analysed in step 7. The selection of additional scenarios is focused on the safety functions of the repository and the safety function indicators defined in step 5 form an important basis for the selection. For each safety function, an assessment is made as to whether any reasonable situation where it is not maintained can be identified. If this is the case, the corresponding scenario is included in the risk evaluation for the repository, with the overall risk determined by a summation over such scenarios. The set of selected scenarios also includes e.g. scenarios explicitly mentioned in applicable regulations, such as human intrusion scenarios, and scenarios and variants to explore the roles of various components in the repository. See further chapter 11 for the scenario selection methodology and the application of the selection method.

The method for scenario selection based on safety functions is used for the first time in SR-Can. A main advantage with the method is that it addresses all identified safety related issues through a limited number of scenarios. This is obtained by focussing the selection directly on the safety functions, rather than by using all identified uncertainties that affect repository safety as the point of departure for the selection. These uncertainties are systematically addressed in the analysis of the selected scenarios.

The method was also found to be relatively straightforward to apply and explain, thereby promoting transparency of the safety case.

The same method is, therefore, intended for use in SR-Site.

9. Analysis of selected scenarios

   The main scenario is analysed essentially by referring to the reference evolution in step 7. An important result is a calculated risk contribution from the main scenario. The additional scenarios are analysed by focussing on the factors potentially leading to situations in which the safety function in question is not maintained. In most cases, these analyses are carried out by comparison with the evolution for the main scenario, meaning that they only encompass aspects of repository evolution for which the scenario in question differs from the main scenario. For these scenarios, as for the main scenario, a risk contribution is estimated. See further chapter 12.

The method used for the analyses of the selected scenarios was found to be adequate and essentially the same method is intended to be used in SR-Site.

Regarding estimates of scenario probabilities in order to determine risk contributions, these were often pessimistically determined. For example, since buffer erosion cannot be excluded based on present knowledge, it is assumed that substantial buffer erosion will occur for glacial conditions. Of the three hydrogeological model interpretations of the Forsmark site, the most pessimistic in terms of consequences of buffer erosion and subsequent canister corrosion and radionuclide release is selected, since there is no basis, in the current version 1.2 site descriptive models, for allocating probabilities to the hydrogeologial models. Also, for each hydrogeological model, three cases of long-term geochemical conditions are calculated. Again, there is currently no basis for partitioning probabilities between the three, and the most pessimistic was chosen when determining the risk contribution.

This approach is primarily motivated by lack of knowledge on which to base estimates of probabilities. Essentially the same approach is foreseen for SR-Site for issues where the knowledge base is insufficient. It is also noted that the knowledge regarding several of the above examples may have improved for SR-Site, allowing a less pessimistic treatment.

10. Conclusions

    This step includes integration of the results from the various scenario analyses, development of conclusions regarding safety in relation to regulatory criteria and feedback concerning design, continued site investigations and the R&D programme. See further chapter 13.

An essential part of the concluding chapter in SR-Can consists of a compliance discussion. This is SKB's first account of compliance with the relatively recent Swedish regulations in the area of deep geological disposal of radioactive waste. It reflects SKB's understanding of how compliance can be demonstrated. A similar format is foreseen for SR-Site.

13.9.2 Quality assurance

A QA-plan has been established and used in SR-Can, see sections 2.8 and 13.3.7. For the SR-Site assessment, this plan will be updated and adapted to the QA routines applicable in the larger project of which SR-Site will be a sub-project.

It is, furthermore, noted that a few models remain to be fully quality assured, e.g. the analytic models used in parallel with the fully quality assured numerical models for radionuclide transport calculations.

13.9.3 Expert judgements/expert elicitation

As mentioned in section 2.6, no expert elicitation panels are used in SR-Can. Presently, no plans exist for the inclusion of such formal approaches in SR-Site. If such procedures are to be used in SR-Site, it will be limited to one or a few issues of potentially high importance for safety, and for which a formal expert elicitation can be expected to provide a result that would contribute significantly to improving the quality of the safety case.

As also mentioned in section 2.6, the expert database remains to be fully developed for the SR-Site assessment.

References

Adams J, Wetmiller R J, Drysdale J, Hasegawa H S, 1991. The first surface rupture from an earthquake in eastern North America. Current Research, Geological Survey of Canada 91-1C: 9–15.

Adeloju S B, Duan Y Y, 1994. Influence of carbonate ions on stbility of copper oxides and copper pitting corrosion, Br. Corr. J. 29 (1994) 315.

Agrenius L, 2002. Criticality safety calculations of storage canisters. SKB TR-02-17, Svensk Kärnbränslehantering AB.

Ahokas H, Hellä P, Ahokas T, Hansen J, Koskinen K, Lehtinen A, Koskinen L, Löfman J, Mészáros F, Partamies S, Pitkänen P, Sievanen U, Marcos N, Snellman M, Vieno T, 2006. Control of water inflow and use of cement in ONKALO after penetration of fracture zone R19. POSIVA WR-2006-45, Posiva Oy, Olkiluoto, Finland.

Ahonen L, Vieno T, 1994. Effects of glacial meltwater on corrosion of copper canisters. YJT-94-13, Nuclear Waste Commission of Finnish Power Companies, Finland.

Alekseev A, Alekseeva T, Ostroumov V, Siegert C, Gradusov B, 2003. Mineral transformations in permafrost-affected soils, North Kolyma lowland, Russia. Soil Sci. Soc. Am. J., 67: 596–605.

Alley R B, Dupont T K, Parizek B R, Anandakrishnan S, 2005. Access of surface meltwater to beds of subfreezing glaciers: Preliminary insights. Annals of Glaciology 40(1): 8–14.

Amend J P, Teske A, 2005. Expanding frontiers in deep subsurface microbiology. Palaeogeography, Palaeoclimatology, Palaeoecology Volume 219, Issues 1–2 , 11 April 2005, Pages 131–155.

Andersson J, 1999. Data and data uncertainties. Compilation of data and data uncertainties for radionuclide transport calculations. SKB TR-99-09, Svensk Kärnbränslehantering AB.

Andersson J, Ström A, Svemar C, Almén K-E, Ericsson L O, 2000. What requirements does the KBS-3 repository make on the host rock? Geoscientific suitability indicatiors and criteria for siting and site evaluation. SKB TR-00-12, Svensk Kärnbränslehantering AB.

Andersson J, Munier R, Ström A, Söderbäck B, Almén K-E, Olsson L, 2004. When is there sufficient information from the Site Investigations? SKB R-04-23, Svensk Kärnbränslehantering AB.

Andersson C, Eng A, 2005. Äspö Pillar Stability Experiment. Final experiment design, monitoring results and observations. SKB R-05-02, Svensk Kärnbränslehantering AB.

Andersson C-G, Andersson M, Erixon B, Björkegren L-E, Dillström P, Minnebo P, Nilsson K-F, Nilsson F, 2005. Probabilistic analysis and material characterisation of canister insert for spent nuclear fuel. Summary report. SKB TR-05-17, Svensk Kärnbränslehantering AB.

Andra, 2005. Dossier 2005 Argile, Tome: Evaluation de sûreté du stockage géologique (in French, to appear in English in November 2006). Andra, Châtenay-Malabry, France.

Aquilonius A, 2005. Vegetation in Lake Frisksjön. Oskarshamn site investigation. SKB P-05-173, Svensk Kärnbränslehantering AB.

Archer D, Kheshgi H, Maier-Raimer E, 1997. Multiple timescales for neutralization of fossil fuel CO2: Geophysical Research Letters, 24, 405–408.

Arcos D, Grandia H, Domènech C, 2006. Geochemical evolution of the near field of a KBS-3 repository. SKB TR-06-16, Svensk Kärnbränslehantering AB.

Arvidsson R, 1996. Fennoscandian earthquakes; whole crustal rupturing related to postglacial rebound. Science 274(5288): 744–746.

Auqué L F, Gimeno M J, Gómez J B, Puigdomenech I, Smellie J, Tullborg E-L, Wallin B, 2006. Modelling of groundwater chemistry over a glacial cycle. Background data for SR-Can. SKB TR-06-31, Svensk Kärnbränslehantering AB.

Autio J, Malmlund H, Kemppainen M, Oila E, Siitari-Kauppi M, 2004. Study of rock damage caused by drill and blast excavation at Äspö Hard Rock Laboratory. Posiva Oy, Olkiluoto, Finland. Posiva Working Report 2004-33.

Avila R, 2006. Model of the long-term transfer of radionuclides in forests. SKB TR-06-08, Svensk Kärnbränslehantering AB.

Avila R, Bergström U, 2006. Methodology for calculation of doses to man and implementation in Pandora. SKB-R-06-68, Svensk Kärnbränslehantering AB.

Avila R, Ekström P A, Kautsky U, 2006. Development of landscape dose factors for dose-assessments in SR-Can. SKB TR-06-15, Svensk Kärnbränslehantering AB.

Bamber J L, Layberry R L, Gogenini S P, 2001. A new ice thickness and bed data set for the Greenland ice sheet 1: Measurement, data reduction, and errors. Journal of Geophysical Research 106 (D24): 33773–33780.

Banwart S A, 1999. Reduction of iron(III) minerals by natural organic matter in groundwater. Geochim. Cosmochim. Acta, 63: 2919–2928.

Banwart S A, Gustafsson E, Laaksharju M, 1999. Hydrological and reactive processes during rapid recharge to fracture zones. the Äspö large scale redox experiment. Appl. Geochem., 14: 873–892.

Behrenz P, Hannerz K, 1978. Criticality in a spent fuel repository in wet crystalline rock. KBS TR 108, Svensk Kärnbränsleförsörjning AB.
Berger A, 1978. Long-term variations of daily insolation and Quaternary climatic changes, Journal of the Atmospheric Sciences 35: 2362–2367.
Berger A, Loutre M F, 2002. An exceptionally long interglacial ahead? Science 297:1287–1288.
Bergström U, Nordlinder S, Aggeryd I, 1999. Models for dose assessments. Modules for various biosphere types. SKB TR-99-14, Svensk Kärnbränslehantering AB.
Berner U R, 1987. Modeling porewater chemistry in hydrated Portland cement. In: J.K. Bates, W.B. Seefeldt (Editors), Scientific Basis for Nuclear Waste Management X. Mat. Res. Soc. Symp. Proc. Mater. Res. Soc., Pittsburgh, Penn., Symp. held in Boston, Mass., on Dec. 1986, pp. 319–330.
BIOCLIM, 2003. Continuous climate evolution scenarios over western Europe (1000 km scale), Deliverable D7. Work package 2: Simulation of the future evolution of the biosphere system using the hierarchical strategy. 88 p.
Birgersson M, Johannesson L-E, 2006. PM gällande förväntade slutdensiteter vid deponering enligt konceptet KBS-3V.
Blomqvist P, Nilsson E, Brunberg A-K, 2002. Habitat distribution, water chemistry, and biomass and production of pelagic and benthic microbiota in Lake Eckarfjärden, Forsmark. SKB R-02-41, Svensk Kärnbränslehantering AB.
Boresjö Bronge L, Wester K, 2002. Vegetation mapping with satellite data of the Forsmark and Tierp region. SKB R-02-06, Svensk Kärnbränslehantering AB.
Boresjö Bronge L, Wester K, 2003. Vegetation mapping with satellite data of the Forsmark, Tierp and Oskarshamn regions. SKB P-03-83, Svensk Kärnbränslehantering AB.
Bosson E, 2006. Near-surface hydrogeological model of Laxemar. Open repository – Laxemar 1.2. SKB R-06-66, Svensk Kärnbränslehantering AB.
Bosson E, Berglund S, 2006. Near-surface hydrogeological model of Forsmark. Open repository and solute transport applications – Forsmark 1.2. SKB R-06-52, Svensk Kärnbränslehantering AB.
Boulton G S, Kautsky U, Morén L, Wallroth T, 2001. Impact of long-term climate change on a geological repository for spent nuclear waste. SKB TR-99-05, Svensk Kärnbränslehantering AB.
Brantberger M, Zetterqvist A, Arnbjerg-Nielsen T, Olsson T, Outters N, Syrjänen P, 2006. Final repository for spent nuclear fuel. Underground design Forsmark, Layout D1. SKB R-06-34, Svensk Kärnbränslehantering AB.
Brown G H, 2002. Glacier meltwater hydrochemistry. Appl. Geochem., 17: 855–883.
Brunberg A-K, Carlsson T, Blomqvist P, Brydsten L, Strömgren M, 2004. Identification of catchments, lake-related drainage parameters and lake habitats. Forsmark site investigation. SKB P-04-25, Svensk Kärnbränslehantering AB.
Bruno J, Cera E, de Pablo J, Duro L, Jordana S, Savage D, 1997. Determination of radionuclide solubility limits to be used in SR 97. Uncertainties associated to calculated solubilities. SKB TR-97-33, Svensk Kärnbränslehantering AB.
Bruno J, Duro L, de Pablo J, Casas I, Ayora C, Delgado J, Gimeno M J, Peña J, Linklater C, Pérez del Villar L, Gómez P, 1998. Estimation of the concentrations of trace metals in natural systems. The application of codissolution and coprecipitation approaches to El Berrocal (Spain) and Poços de Caldas (Brazil). Chem. Geol., 151: 277–291.
Bruno J, Arcos D, Duro L, 1999. Processes and features affecting the near field hydrochemistry. Groundwater-bentonite interaction. SKB TR-99-29, Svensk Kärnbränslehantering AB.
Brydsten L, 1999. Change in coastal sedimentation conditions due to positive shore displacement in Öregrundsgrepen. SKB TR-99-37, Svensk Kärnbränslehantering AB.
Brydsten L, 2004. A mathematical model for lake ontogeny in terms of filling with sediments and macrophyte vegetation. SKB TR-04-09, Svensk Kärnbränslehantering AB.
Brydsten L, Strömgren M, 2004. Digital elevation models for site investigation programme in Forsmark. Site description version 1.2. SKB R-04-70, Svensk Kärnbränslehantering AB.
Brydsten L, 2006a. Modelling groundwater discharge areas using only digital elevation models as input data. SKB TR-06-39 Svensk Kärnbränslehantering AB.
Brydsten L, 2006b. A model for landscape development in terms of shoreline displacement, sediment dynamics, lake formation, and lake choke-up processes. SKB TR-06-40, Svensk Kärnbränslehantering AB.
BSC, 2002. Total System Performance Assessment – License Application Methods and Approach, TDR-WIS-PA-000006 REV 00. Las Vegas, Nevada: Bechtel SAIC Company.
Bucher F, Müller-VonMoos M, 1989. Bentonite as a containment barrier for the disposal of highly radioactive wastes. Applied Clay Science, 4 (1989) 157–177.
Buffer and backfill process report, 2006. Buffer and backfill process report for the safety assessment SR-Can. SKB TR-06-18, Svensk Kärnbränslehantering AB.
Bullen K E, Bolt B A, 1985. An introduction to the theory of seismology, Fourth edition. Cambridge University Press. ISBN 1986-022166.

Bäckblom G, Stanfors R, 1989. Interdisciplinary study of post-glacial faulting in the Lansjärv area Northern Sweden 1986–1988. SKB TR 89-31, Svensk Kärnbränslehantering AB.
Bäckblom G, Munier M, 2002. Effects of earthquakes on the deep repository for spent fuel in Sweden based on case studies and preliminary model results. SKB TR-02-24, Svensk Kärnbränslehantering AB.
Bäckblom G, Almén K-E, 2004. Monitoring during the stepwise implementation of the Swedish deep repository for spent fuel. SKB R-04-13, Svensk Kärnbränslehantering AB.
Bäckblom G, Christiansson R, Lagerstedt L, 2004. Choise of rock excavation methods for one Swedish deep repository for spent nuclear fule. SKB R-04-62, Svensk Kärnbränslehantering AB.
Bödvarsson R, 2002. Swedish National Seismic Network (SNSN). SKB P-02-04, Svensk Kärnbränslehantering AB.
Bödvarsson R, 2005. Swedish National Seismic Network (SNSN). A short report on recorded earthquakes during the third quarter of the year 2005. SKB P-05-243, Svensk Kärnbränslehantering AB.
Bödvarsson R, Lund B, Roberts R, Slunga R, 2006. Earthquake activity in Sweden. Study in connection with a proposed nuclear waste repository in Forsmark or Oskarshamn. SKB R-06-67, Svensk Kärnbränslehantering AB.
Bøggild C E, Mayer C, Podlech S, Taurisano A, Nielsen S, 2004. Towards an assessment of the balance state of the Greeland Ice Sheet. Geological Survey of Denmark and Greenland Bulletin 4, 81–84.
Börgesson L, 1992. Interaction between rock, bentonite buffer and canister. FEM calculations of some mechanical effects on the canister in different disposal concepts. SKB TR 92-30, Svensk Kärnbränslehantering AB.
Börgesson L, Johannesson L-E, Sandén T, Hernelind J, 1995. Modelling of the physical behaviour of water saturated clay barriers. Laboratory tests, material models and finite element application. SKB TR-95-20, Svensk Kärnbränslehantering AB.
Börgesson, L, Hernelind, J, 1999. Coupled thermo-hydro-mechanical calculations of the water saturation phase of a KBS-3 deposition hole. Influence of hydraulic rock properties on the water saturation phase. SKB TR-99-41, Svensk Kärnbränslehantering AB.
Börgesson L, Johannesson L-E, Hernelind J, 2004. Earthquake induced rock shear through deposition hole. Effect on the canister and the buffer. SKB TR-04-02, Svensk Kärnbränslehantering AB.
Börgesson, L, Hernelind, J, 2006. Consequeces of loss or missing bentonite in a deposition hole. A theoretical study. SKB TR-06-13, Svensk Kärnbränslehantering AB.
Börgesson L, Johannesson L-E, 2006. Consequences of upwards swelling from a wet deposition hole into a dry tunnel with backfill made of blocks. A preliminary study. SKB TR-06-12, Svensk Kärnbränslehantering AB.
Börgesson L, Sandén T, 2006. Piping and erosion in buffer and backfill materials. Current knowledge. SKB R-06-80, Svensk Kärnbränslehantering AB.
Börgesson L, Fälth B, Hernelind J, 2006. Water saturation phase of the buffer and backfill in the KBS-3V concept. Special emphasis given to the influence of the backfill on the wetting of the buffer. SKB TR-06-14, Svensk Kärnbränslehantering AB.
Carlsson A, Olsson T, 1982. Characterization of deep-seated rock masses by means of borehole investigations. In situ rock stress measurements, hydraulic testing and core-logging. Vattenfall Forskning och Utveckling, Rapport 5:1, 1–155. Stockholm.
Carlsson T, Brunberg A-K, Brydsten L, Strömgren M, 2005. Oskarshamn site investigation. Characterisation of running waters, including vegetation, substrate and technical encroachments. SKB P-05-40, Svensk Kärnbränslehantering AB.
Carlsten S, Stråhle A, 2000. Borehole radar and BIPS investigations in boreholes at the Boda area. SKB TR-01-02, Svensk Kärnbränslehantering AB.
Carslaw H S, Jaeger J C, 1959. Conduction of Heat in Solids, Oxford University Press, New York.
Chan T, Christiansson R, Boulton G S, Ericsson L O, Hartikainen J, Jensen M R, Mas Ivars D, Stanchell F W, Vidstrand P, Wallroth T, 2005. DECOVALEX III BMT 3 / BENCHPAR WP4: The thermo-hydro-mechanical responses to a glacial cycle and their potential implications for deep geological disposal of nuclear fuel waste in a fractured crystalline rock mass. Int J Rock Mech.Min Sci, 42, 805–827.
Cho N, Martin C D, Christiansson R, 2002. Suppressing fracture growth around underground openings. In Proc. 5th North American Rock Mechanics Symposium and 17th Tunnelling Association of Canada Conference NARMS/TAC 2002, Toronto (Ed. R. Hammah, W. Baden, J. Curran, M Telesnicki), vol. 2, pp. 1151–1158, University of Toronto Press.
Claesson J, Probert T, 1996. Thermoelastic stress due to a rectangular heat source in a semi-infinite medium. SKB TR-96-13, Svensk Kärnbränslehantering AB.
Cliffe K A, Kelly M, 2006. COMP23 version 1.2.2 user's manual. SKB R-04-64, Svensk Kärnbränslehantering AB.
Climate report, 2006. Climate and climate related issues for the safety assessment SR-Can. SKB TR-06-23, Svensk Kärnbränslehantering AB.
Coope G R, Lemdahl G, Lowe J J, Walkling A, 1998. Temperature gradients in northern Europe during the last glacial-Holocene transition (14-9 14C kyr BP) interpreted from coleopteran assemblages. Journal of Quaternary Science 13: 419–433.

Cooper R J, Wadham J L, Tranter M, Hodgkins R, Peters N E, 2002. Groundwater hydrochemistry in the active layer of the proglacial zone, Finsterwalderbreen, Svalbard. J. Hydrol., 269: 208–223.
Cosgrove J, Stanfors R, Röshoff K, 2006. Geological characteristics of deformation zones and a strategy for their detection in a repository. SKB R-06-39, Svensk Kärnbränslehantering AB.
Couture R A, 1985. Steam rapidly reduces the swelling capacity of bentonite. Nature, 318, 50–52.
Cox P M, Hungingford C, Jones C D, 2006. Conditions for sink-to-sourcetransitions and runaway feedbacks from the land carbon cycle, In: Schellnhuber, H J, Cramer, W, Nakicenovic, N, Wigley, T and Yohe, G (Eds), Avoiding DangerousClimate Change, Cambridge University Press, pp.155–161.
Cuadros J, Linares J, 1996. Experimental kinetic study of the smectite-to-illite transformation. Gehochemica et Cosmochimica Acta. 60, 439–453.
Cubash U, Meehl G A, 2001. Projections of future climate change. In Climate Change 2001: The Scientific Basis. Houghton et al, (eds.) Cambridge University Press. New York.
Dansgaard W, Johnsen S J, Clausen H B, Dahl-Jensen D, Gundestrup N S, Hammer C U, Hvidberg C S, Steffensen J P, Sveinbjörnsdottir A E, Jouzel J, Bond G, 1993. Evidence for general instability of past climate from a 250-kyr ice-core record. Nature 364: 218–220.
Data report, 2006. Data report for the safety assessment SR-Can. SKB TR-06-25, Svensk Kärnbränslehantering AB.
Degueldre C, Grauer R, Laube A, Oess A, Silby H, 1996. Colloid properties in granitic groundwater systems. II: Stability and transport study. Appl. Geochem., 11: 697–710.
Dehls J F, Olesen O, Olsen L, Blikra L H, 2000. Neotectonic faulting in northern Norway; the Stuoragurra and Nordmannvikdalen postglacial faults Geological Survey of Norway, Trondheim, Norway In: Quaternary Science Reviews 19 (2000) pp. 1447–1460.
Dershowitz W, Wallman O, Kindred S, 1991. Discrete Fracture Modelling for the Stripa Site Characterization and Validation Drift Inflow Predictions. Stripa Project Technical Report 91-16, Svensk Kärnbränslehantering AB.
DHI Software, 2004a. MIKE SHE User's Guide.
DHI Software, 2004b. MOUSE User's Guide.
Dillström P, 2005. Probabilistic analysis of canister inserts for spent nuclear fuel. SKB TR-05-19, Svensk Kärnbränslehantering AB.
Domènech C, Arcos D, Duro L, Grandia F, 2006. Effect of the mineral precipitation-dissolution at tunnel walls during the operational and post-operational phases. SKB R-06-108, Svensk Kärnbränslehantering AB.
Drew M C, 1983. Plant injury and adaptation to oxygen deficiency in the root environment: A review. Plant and Soil, 75: 179–199.
Duro L, Grivé M, Cera E, Gaona X, Domènech C, Bruno J, 2006. Determination and assessment of the concentration limits to be used in SR-Can. SKB TR-06-32, Svensk Kärnbränslehantering AB.
Dziewonski A M, Anderson D L, 1981. Preliminary reference earth model (PREM). Physics of the Earth and Planetary Interiors 25, 297–356.
Ekman M, 1996. A consistent map of the postglacial uplift of Fennoscandia. Terra-Nova 8(2): 158–165.
Elert M, Gylling B, Lindgren M, 2004. Assessment model validity document FARF31. SKB R-04-51, Svensk Kärnbränslehantering AB.
Elhammer A, Sandkvist Å, 2005. Detailed marine geological survey of the sea bottom outside Forsmark. Forsmark site investigation. SKB P-03-101, Svensk Kärnbränslehantering AB.
Emsley S, Olsson O, Stenberg L, Alheid H-J, Falls S, 1997. ZEDEX – A study of damage and disturbance from tunnel excavation by blasting and tunnel boring. SKB TR-97-30, Svensk Kärnbränslehantering AB.
Eng T, Norberg E, Torbacke J, Jensen M, 1996. Information, conservation and retrieval. SKB TR-96-18, Svensk Kärnbränslehantering AB.
Engkvist I, Albinsson Y, Johansson Engkvist W, 1996. The long-term stability of cement. Leaching tests. SKB TR-96-09, Svensk Kärnbränslehantering AB.
Engqvist A, Andrejev O, 2000. Sensitivity analysis with regard to variations of physical forcing including two possible future hydrographic regimes for the Öregrundsgrepen. A follow-up baroclinic 3D-model study. SKB TR-00-01, Svensk Kärnbränslehantering AB.
Eriksson S, Sellei C, Wallström K, 1977. The structure of the plankton community of the Öresundsgrepen (southwest Bothnian Sea). Helgoländer wiss. Meeresunters. Vol. 30: p. 582–597.
Erixon B, Kylberg G, 2006. Kollapslast för modifierade kapslar inklusive inverkan av fel. SKB R-04-07, Svensk Kärnbränslehantering AB (in Swedish).
EU, 2002. SPIN Project, EUR 19965 EN, 2002 Testing of Safety and Performance Indicators (SPIN).
FASSET, 2004. FASSET Framework for Assessment of Environmental Impact. A project within the EC 5th Framework Programme FINAL REPORT Contract No FIGE-CT-2000-00102.
Fastook J L, Chapman J E, 1989. A map plane finite-element model: Three modelling experiments. Journal of glaciology 35(119): 48–52.
Fastook J L, 1994. Modelling the Ice Age: The Finite-Element Method in Glaciology. Computational Science and Engineering 1(1): 55–67.
Fastook J L, Holmlund P, 1994. A glaciological model of the Younger Dryas event in Scandinavia. Journal of Glaciology 40(134), 125–131.

Fenton C, Adams J, Halchuk S, 2006. Seismic hazards assessment for radioactive waste disposal sites in regions of low seismic activity. Geotechnical and Geological Engineering 24: 579–592.

FEP report, 2006. FEP report for the safety assessment SR-Can. SKB TR-06-20, Svensk Kärnbränslehantering AB.

FHA report, 2006. Handling of future human actions in the safety assessment SR-Can. SKB TR-06-24, Svensk Kärnbränslehantering AB.

Follin S, Svensson U, 2003. On the role of mesh discretisation and salinity for the occurrence of local flow cells. Results from a regional-scale groundwater flow model of Östra Götaland. SKB R-03-23, Svensk Kärnbränslehantering AB.

Follin S, Stigsson M, Svensson U, 2005. Regional hydrogeological simulations for Forsmark – numerical modelling using DarcyTools. Preliminary site description Forsmark area – version 1.2. SKB R-05-60, Svensk Kärnbränslehantering AB.

Fredriksson R, Tobiasson S, 2003. Simpevarp site investigation. Inventory of macrophyte communities at Simpevarp nuclear power plant. Area of distribution and biomass determination. SKB P-03-69, Svensk Kärnbränslehantering AB.

Fredriksson R, 2005. Inventory of the marine fauna attached to hard substrates in the Simpevarp area. Oskarshamn site investigation. SKB P-05-45, Svensk Kärnbränslehantering AB.

French H M, 1996. The periglacial environment. Second edition. Addison Wesley Longman Limited.

Fuel and canister process report, 2006. Fuel and canister process report for the safety assessment SR-Can. SKB TR-06-22, Svensk Kärnbränslehantering AB.

Fälth B, Hökmark H, 2006. Seismically induced shear displacement on repository host rock fractures. Results of new dynamic discrete fracture modelling. SKB R-06-48, Svensk Kärnbränslehantering AB.

Gascoyne M, 1999. Long-term maintenance of reducing conditions in a spent nuclear fuel repository. SKB R-99-41, Svensk Kärnbränslehantering AB.

Gaucher E, Blanc P, Matray J-M, Michau N, 2004. Modeling diffusion of an alkaline plume in a clay barrier. Appl. geochem. 2004, vol. 19, n°10, pp. 1505–1515.

Gentschein, B, Levén J, Follin S, 2006. A comparison between well yield data from the site investigation in Forsmark and domestic wells in northern Uppland. SKB P-06-53, Svensk Kärnbränslehantering AB.

Geosphere process report, 2006. Geosphere process report for the safety assessment SR-Can. SKB TR-06-19, Svensk Kärnbränslehantering AB.

Gierszewski P, Avis J, Calder N, D'Andrea A, Garisto F, Kitson C, Melnyk T, Wei K, Wojciechowski L, 2004. Third case study – postclosure safety assessment. Ontario Power Generation, Toronto, Canada.

Gómez P, Garralón A, Buil B, Turrero M J, Sánchez L, de la Cruz B, 2006. Modeling of geochemical processes related to uranium mobilization in the groundwater of a uranium mine. Sci. Total Env., 366: 295–309.

Grandia F, Domènech C, Arcos D, Duro L, 2006. Assessment of the oxygen consumption in the backfill. SKB R-06-106, Svensk Kärnbränslehantering AB.

Gregory J M, Huybrechts P, Raper S C B, 2004. Threatened loss of the Greenland ice sheet. Nature 428: p. 616.

Guimerà J, Duro L, Jordana S, Bruno J, 1999. Effects of ice melting and redox front migration in fractured rocks of low permeability. SKB TR-99-19, Svensk Kärnbränslehantering AB.

Guimerà J, Duro L, Delos A, 2006. Changes in groundwater composition as a consequence of deglaciation: implications for performance assessment. SKB R-06-105, Svensk Kärnbränslehantering AB.

Gustafsson B, 2004a. Millennial changes of the Baltic Sea salinity. Studies of the sensitivity of the salinity to climate change. SKB TR-04-12, Svensk Kärnbränslehantering AB.

Gustafsson B, 2004b. Sensitivity of the Baltic Sea salinity to large perturbations in climate. Climate research 27: 237–251.

Hakami E, Min K-B, 2006. Modelling of the state of stress, Preliminary site description, Laxemar subarea – version 1.2. SKB R-06-17, Svensk Kärnbränslehantering AB.

Hallbeck L, Grivé M, Gaona X, Duro L, Bruno J, 2006. Main organic materials in a repository for high level radioactive waste. SKB R-06-104, Svensk Kärnbränslehantering AB.

Harrington J F, Horseman S T, 2003. Gas migration in KBS-3 buffer bentonite. Sensitivity of test parameters to experimental boundary conditions. SKB TR-03-02, Svensk Kärnbränslehantering AB.

Harrington J F, Birchall D J, 2006. Sensitivity of total stress to changes in externally applied water pressure in KBS-3 buffer bentonite. SKB TR-06-38, Svensk Kärnbränslehantering AB.

Hartikainen J, 2004. Permafrost modeling in DECOVALEX III for BMT3. In Eloranta E ed., DECOVALEX III, 1999–2003. An international project for the modelling of coupled Thermo-Hydro-Mechanical processes for spent fuel disposal. Finnish national contributions. STUK-YTO-TR 209. Helsinki.

Hartley L, Cox I, Hunter F, Jackson P, Joyce S, Swift B, Gylling B, Marsic N, 2005a. Regional hydrogeological simulations for Forsmark – numerical modelling using CONNECTFLOW. Preliminary site description Forsmark area – version 1.2. SKB R-05-32, Svensk Kärnbränslehantering AB.

Hartley L, Hoch A, Hunter F, Jackson P, Marsic N, 2005b. Regional hydrogeological simulations – Numerical modelling using ConnectFlow. Preliminary site description Simpevarp subarea – version 1.2. SKB R-05-12, Svensk Kärnbränslehantering AB.

Hartley L, Hoch A, Jackson P, Joyce S, McCarthy R, Rodwell W, Swift B, Marsic N, 2006a. Groundwater flow and transport modelling during the temperate period for the SR-Can assessment. Forsmark area – version 1.2. SKB R-06-98, Svensk Kärnbränslehantering AB.

Hartley L, Hoch A, Jackson P, Joyce S, McCarthy R, Swift B, Gylling B, Marsic N, 2006b. Groundwater flow and transport modelling during the temperate period for the SR-Can assessment. Laxemar subarea – version 1.2. SKB R-06-99, Svensk Kärnbränslehantering AB.

Hartley L, Hunter F, Jackson P, McCarthy R, Gylling B, Marsic N, 2006c. Regional hydrogeological simulations using CONNECTFLOW. Preliminary site description Laxemar subarea – version 1.2. SKB R-06-23, Svensk Kärnbränslehantering AB.

Hedenström A, 2001. Early Holocene shore displacement in eastern Svealand, Sweden, based on diatom stratigraphy, radiocarbon chronology and geochemical parameters. Quarternaria Ser A: Thesis and Research Papers No.10.

Hedenström A, Risberg J, 2003. Shore line displacement in northern Uppland during the last 6500 calendar years. SKB TR-03-17, Svensk Kärnbränslehantering AB.

Hedin A, 1997. Spent nuclear fuel – how dangerous is it? A report from the project "Description of risk. SKB TR-97-13, Svensk Kärnbränslehantering AB.

Hedin A, 2002a. Safety Assessment of a Spent Nuclear Fuel Repository: Sensitivity Analyses for Prioritisation of Research. Proceedings of the 6th International Conference on Probabilistic Safety Assessment and Management, PSAM6. Elsevier Science Ltd. (2002).

Hedin A, 2002b. Integrated Analytic Radionuclide Transport Model for a Spent Nuclear Fuel Repository in Saturated Fractured Rock. Nuclear Technology 138 2 179 (2002).

Hedin A, 2003. Probabilistic dose calculations and sensitivity analyses using analytic models. Reliability Engineering and System Safety 79 (2003) 195–204.

Hedin A, 2004a. Methodology for Risk Assessment of an SNF Repository in Sweden. Proceedings of the 7th International Conference on Probabilistic Safety Assessment and Management, PSAM7. Springer-Verlag London Ltd. (2004).

Hedin A, 2004b. Integrated near-field evolution model for a KBS-3 repository. SKB R-04-36, Svensk Kärnbränslehantering AB.

Hedin A, 2005. An analytic method for estimating the probability of canister/fracture intersections in a KBS-3 repository. SKB R-05-29, Svensk Kärnbränslehantering AB.

Hernelind J, 2006. Earthquake induced rock shear through a deposition hole when creep is considered − first model. Effect on the canister and the buffer. SKB R-06-87, Svensk Kärnbränslehantering AB.

Hoehn E, Eikenberg J, Fierz T, Drost W, Reichlmayr E, 1998. The Grimsel Migration Experiment: field injection-withdrawal experiments in fractured rock with sorbing tracers. J. Contaminant Hydrol., 34: 85–106.

Hohl V, 2005. Northern European long term climate archives. SKB TR-05-01, Svensk Kärnbränslehantering AB.

Hora S, 2002. Expert Opinion in SR 97 and the SKI/SSI Joint Review of SR 97, SSI report 2002:20, Swedish Radiation Protection Authority.

Hora S, Jensen M, 2002. Expert Judgement Elicitation, SSI report 2002:19, Swedish Radiation Protection Authority.

Hora S, Jensen M, 2005. Expert panel elicitation of seismicity following glaciation in Sweden. SSI Rapport 2005:20, Statens strålskyddsinstitut.

Huang W-L, Longo J M, Pevear D R, 1993. An experimentally derived kinetic model for smectite-to-illite conversion and its use as a geothermometer. Clays and Clay Minerals 41, 162–177.

Humlum O, Houmark-Nielsen M, 1994. Deglaciation rates in Denmark during the late Weichselian – implications for the palaeoenvironment. Geografisk Tidsskrift 94:26–37.

Hummel W, Berner U, Curti E, Pearson F J, Thoenen T, 2002. NAGRA/PSI Chemical Thermodynamic Data Base 01/01, Nagra.

Huybrechts P, 1990. A 3-D model for the Antarctic ice sheet: a sensitivity study on the glacial-interglacial contrast. Climate Dynamics 5(2):79–92.

Huybrechts P, Letreguilly A, Reeh N, 1991. The Greenland ice sheet and greenhouse warming. Palaeogeography, Palaeoclimatology, Palaeoecology 89(4): 399–412.

Huybrechts P, de Wolde J, 1999. The dynamic response of the Greenland and Antarctic ice sheets to multiple-century climate warming. Journal of Climatology 12:2169–2188.

Huybrechts P, 2002. Sea-level changes at the LGM fromice-dynam ic reconstructions of the Greenland and Antarctic ice sheets during the glacial cycles. Quaternary Science Reviews 21:203–231.

Håkansson R, 2000. Beräkning av nuklidinnehåll, resteffekt, aktivitet samt doshastighet för utbränt kärnbränsle. SKB R-99-74, Svensk Kärnbränslehantering AB.

Hökmark H, Fälth B, 2003. Thermal dimensioning of the deep repository. Influence of canister spacing, canister power, rock thermal properties and near-field design on the maximum canister surface temperature. SKB TR-03-09, Svensk Kärnbränslehantering AB.

Hökmark H, Fälth B, Wallroth T, 2006. T-H-M couplings in rock. Overview of results of importance to the SR-Can safety assessment. SKB R-06-88, Svensk Kärnbränslehantering AB.

IAEA, 1994. Safety Indicators in Different Time Frames for the Safety Assessment of Underground Radioactive Waste Repositories, First report of the INWAC Subgroup on Principles and Criteria for Radioactive Waste Disposal, IAEA-TECDOC-767, IAEA, Vienna.
IAEA, 2005. Derivation of activity concentration values for the purposes of exclusion, exemption and clearance. Safety Report Series 44, Vienna.
ICRP, 1998. ICRP Publication 81, Radiation Protection Recommendations as Applied to the Disposal of Long-lived Solid Radioactive Waste.
Ide S, Takeo M, 1997. Determination of constitutive relations of fault slip based on seismic wave analysis. Journal of Geophysical Research, B, Solid Earth and Planets 102(12): 27379–27391.
Ikonen K, 2005. Mechanical Analysis of Cylindrical Part of Canisters for Spent Nuclear Fuel. Posiva 2005-12, Posiva Oy.
Imbrie J, Hays J D, Martinson D G, McIntyre A, Mix A C, Morley J J, Pisias N G, Prell W L, Shackleton N J, 1984. The orbital theory of Pleistocene climate: Support from a revised chronology of the marine $^{TM}{}_{18}$O record. Berger A L et al. Eds., Milankovitch and Climate, Part 1, 269–305. Reidel Publishing Company.
Initial state report, 2006. Initial state report for the safety assessment SR-Can. SKB TR-06-21, Svensk Kärnbränslehantering AB.
IPCC, 2001a. Climate Change 2001: Synthesis Report A. Contribution of Working Groups I, II, and III to the Third Assessment Report of the Intrergovermental Panel on Climate Change, R.T. Watson, the Core Writing Team (Editors). Cambridge University Press, Cambridge UK, 398 pp.
IPCC, 2001b. Climate Change 2001: The Scientific Basis. Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change. Eds: Houghton, J.T.,Y. Ding, D.J. Griggs, M. Noguer, P.J. van der Linden, X. Dai, K. Maskell, and C.A. Johnson. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 881pp.
Janson T, Magnusson J, Bergvall M, Olsson R, Cuisiat F, Skurtveit E, Grimstad E, 2006. Final repository for spent nuclear fuel. Underground design Laxemar, Layout D1. SKB R-06-36, Svensk Kärnbränslehantering AB.
Jansson P, 1997. Longitudinal coupling effects in ice flow across a subglacial ridge. Annals of Glaciology 24: 169–174.
Jansson P, Näslund J O, Rodhe L, 2006. Glacial hydrology and eskers. A review of ice sheet hydrology. SKB TR-06-34, Svensk Kärnbränslehantering AB.
Jaquet O, Siegel P, 2006. Regional groundwater flow model for a glaciation scenario. Simpevarp subarea – version 1.2. SKB R-06-100, Svensk Kärnbränslehantering AB.
JNC, 2000. H12 – Project to Establish the Scientific and Technical Basis for HLW Disposal in Japan main report and four supplementary reports. JNC TN1410 2000-001, JNC TN1410 2000-002–005, Japan Nuclear Fuel Cycle Development Institute, Japan.
Jockwer N, Wieczorek K, 2003. Gas generation measurements in the FEBEX project, Clays in Natural and Engineered Barriers for Radioactive Waste Confinement. Experiments in Underground Laboratories. Sci. & Technol. Ser. ANDRA: Agence nationale pour la gestion des déchets radioactifs, Châtenay-Malabry, France, pp. 108–117, ISBN: 2-9510108-5-0. Proc. from the Int. Meeting held in Reims (France) 9–12 Dec. 2002.
Johannesson L-E, Birgersson M, 2006. Prototype Repository – Statistical evaluation of buffer density. ÄHRL IPR-06-15, Svensk Kärnbränslehantering AB.
Johannesson L-E, Nilsson U, 2006. Deep repository – engineered barrier systems. Geotechnical properties of candidate backfill materials. SKB R-06-73, Svensk Kärnbränslehantering AB.
Johansson P-O, Werner K, Bosson E, Berglund S, Juston J, 2005. Description of climate, surface hydrology, and near-surface hydrogeology. Forsmark 1.2. SKB R-05-06. Svensk Kärnbränslehantering AB.
Johnson J, 1994. A basal water model for ice sheets. PhD thesis, University of Minnesota. 187 pp.
Karnland O, Sandén T, Johannesson L-E, Eriksen T, Jansson M, Wold S, Pedersen K, Motamedi M, Rosborg B, 2000. Long term test of buffer material. Final report on the pilot parcels. SKB TR-00-22, Svensk Kärnbränslehantering AB.
Karnland O, Birgersson M, 2006. Montmorillonite stability with special respect to KBS-3 conditions. SKB TR-06-11, Svensk Kärnbränslehantering AB.
Karnland O, Olsson S, Nilsson U, Sellin P, 2006. Mineralogy and sealing properties of various bentonites and smectite-rich clay materials. SKB TR-06-30, Svensk Kärnbränslehantering AB.
Kautsky H, Plantman P, Borgiel M, 1999. Quantitative distribution of aquatic plant and animal communities in the Forsmark-area. SKB R-99-69, Svensk Kärnbränslehantering AB.
Kautsky U (ed), 2001. The biosphere today and tomorrow in the SFR area. SKB R-01-27, Svensk Kärnbränslehantering AB.
Kelly M, Cliffe K A, 2006. Validity document for COMP23. SKB R-06-76, Svensk Kärnbränslehantering AB.
Kijko A, Skordas E, Wahlstroem R, Mantyniemi P, 1993. Maximum likelihood estimation of seismic hazard for Sweden. Natural Hazards 7(1): 41–57.
King F, Ahonen L, Taxén C, Vuorinen U, Werme L, 2001. Copper corrosion under expected conditions in a deep geologic repository. SKB TR-01-23, Svensk Kärnbränslehantering AB (also available as Posiva Report 2002-01 (2002)).

King-Clayton L, Chapman N, Ericsson L O, Kautsky F, 1997. Glaciation and Hydrogeology. Workshop on the Impact of Climate Change & Glaciations on Rock Stresses, Groundwater Flow and Hydrochemistry – Past, Present and Future. Workshop Proceedings. SKI R-97:13, Swedish Nuclear Power Inspectorate.

Korhonen K, Kuivamäki A, Ruotoistenmäki T, Paananen M, 2005. Interpretation of lineaments from air-borne geophysical and topographic data. An alternative model within version Laxemar 1.2 of the Oskarshamn modelling project. SKB P-05-247, Svensk Kärnbränslehantering AB.

Krabill W, Abdalati W, Frederick E, Manizade S, Martin C, Sonntag J, Swift R, Thomas R, Wright W, Yungel J, 2000. Greenland ice sheet; high elevation balance and peripheral thinning. Science 289 (5478): 428–430.

Kuivamäki A, Vuorela P, Paananen M, 1998. Indications of postglacial and recent bedrock movements in Finland and Russian Karelia. Report YST-99, Geological Survey of Finland Nuclear Waste Disposal Research Espoo Finland.

Kujansuu R, 1964. Nuorista siirroksista Lapissa. (Recent Faulting in Lapland). Geologi Vsk 16: 30–36.

Laaksoharju M, Smellie J, Nilsson A-C, Skårman C, 1995. Groundwater sampling and chemical characterisation of the Laxemar deep borehole KLX02. SKB TR-95-05, Svensk Kärnbränslehantering AB.

Laaksoharju M, Gurban I, Skårman C, 1998. Summary of hydrochemical conditions at Aberg, Beberg and Ceberg. SKB TR-98-03, Svensk Kärnbränslehantering AB.

Lagerbäck R, 1979. Neotectonic structures in northern Sweden. Sveriges geologiska undersökning, Uppsala, Sweden, In: Geologiska Föreningens i Stockholm Förhandlingar Vol. 100 (1978) Pt. 3 pp. 263–269.

Lagerbäck R, 1988. Postglacial faulting and paleoseismicity in the Landsjärv area, northern Sweden. SKB TR 88-25, Svensk Kärnbränslehantering AB.

Lagerbäck R, 1992. Dating of Late Quaternary faulting in northern Sweden. Journal of the Geological Society of London 149: 285–291.

Lagerbäck R, Sundh M, Johansson H, 2004. Searching for evidence of late- or post-glacial faulting in the Forsmark region. Forsmark site investigation. SKB P-04-123, Svensk Kärnbränslehantering AB.

Lagerbäck R, Sundh M, Svantesson S-I, Svedlund J-O, 2005. Searching for evidence of late- or postglacial faulting in the Oskarshamn region. Results from 2004. Oskarshamn site investigation. SKB P-05-232, Svensk Kärnbränslehantering AB.

Lang C, Leuenberger M, Schwander J, Johnsen S, 1999. 16°C rapid temperature variation in Central Greenland 70,000 years ago. Science 286(5441):934–937.

Lantenois S, Lanson B, Muller F, Bauer A, Jullien M, Plançon A, 2005. Experimantal study of smectite interaction with metal Fe at low temperature 1. smectite destabilization Clays and Clay Minerals; December 2005; v. 53; no. 6; p. 597–612.

La Pointe P R, Wallmann P, Thomas A, Follin S, 1997. A methodology to estimate earthquake effects on fractures intersecting canister holes. SKB-97-07, Svensk Kärnbränslehantering AB.

La Pointe P R, Cladouhos T, Follin S, 1999. Calculation of displacements on fractures intersecting canisters induced by earthquakes: Aberg, Beberg and Ceberg examples. SKB TR-99-03, Svensk Kärnbränslehantering AB.

La Pointe P R, Cladouhos T, Follin S, 2002. Development, application, and evaluation of a methodology to estimate distributed slip on fractures due to future earthquakes for nuclear waste repository performance assessment. Bulletin of the Seismological Society of America 92(3): 923–944.

Larsson K, 2004. Mining induced seismicity in Sweden. Department of Civil and Envirenmental Engineering. Luleå, Luleå University of Technology. Fil. Lic.: 155.

Larsson-McCann S, Karlsson A, Nord M, Sjögren J, Johansson L, Ivarsson M, Kindell S, 2002. Meteorological, hydrological and oceanographical information and data for the site investigation program in the community of Oskarshamn. SKB TR-02-03, Svensk Kärnbränslehantering AB.

Lay T, Wallace T C, 1995. Modern Global Seismology, Academic Press. ISBN 1995-059917.

Lee W H. K, Kanamori H, Jennings P C, Kisslinger C, 2002. International Handbook of Earthquake & Engineering Seismology: part A and part B. Editors. Academic Press,

Lemdahl G, 1988. Palaeoclimatic and Palaeoecological studies based on subfossil insects from Late Weichselian sediments in southern Sweden. Doctoral Dissertation, Lund University, Lund, 11 pp.

Lidman F, 2006. Radionuclide transport in peat lands. A complete profile from Klarebäcksmossen (PSM006562). Analyzed by Gamma Spectrometry and ICP-AES. SKB TR-06-37, Svensk Kärnbränslehantering AB.

Lidmar-Bergström K, Näslund J O, 2002. Landforms and uplift in Scandinavia. In: Doré, A.G., Cartwright, J.A., Stoker, M.S., Turner, J.P. & White, N.J. (eds.): Exhumation of the North Atlantic Margin: Timings, Mechanisms, and Implications for Petroleum Exploration. Geological Society, London, Special Publication 196:103–116.

Lindborg T, 2005a. Description of surface systems. Preliminary site description Simpevarp subarea – version 1.2. SKB R-05-01, Svensk Kärnbränslehantering AB.

Lindborg T (ed), 2005b. Description of surface systems. Preliminary site description Forsmark area – version 1.2. SKB R-05-03, Svensk Kärnbränslehantering AB.

Lindborg T (ed), 2006. Description of surface systems, Preliminary site description Laxemar subarea – version 1.2. SKB R-06-11, Svensk Kärnbränslehantering AB.

Lindroos H, 2004. The potential for ore, industrial minerals and commercial stones in the Simpevarp area. SKB R-04-72, Svensk Kärnbränslehantering AB.
Lindroos H, Isaksson H, Thunehed H, 2004. The potential for ore and industrial minerals in the Forsmark area. SKB R-04-18, Svensk Kärnbränslehantering AB.
Liu H-H, Rutqvist J, Zhou Q, Bodvarsson G S, 2003. Upscaling of normal stress-permeability relationships for fracture networks obeying fractional levy motion. In GeoProc 2003 International Conference on Coupled T-H-M-C processes in Geo-systems: Fundamentals, Modelling, Experiments & Applications. Royal Institute of Technology. Dept. of Water Resources Engineering, Stockholm.
Liu J, 2006. Coupled Transport/Reaction Modelling of Copper Canister Corrosion Aided by Microbial Processes, SKI Report 2006:07, ISSN 1104–1374.
Liu J, Neretnieks I, 2006. Physical and chemical stability of the bentonite buffer. SKB R-06-103, Svensk Kärnbränslehantering AB.
Lokrantz H, Sohlenius G, 2006. Ice marginal fluctuations during the Weichselian glaciation in Fennoscandia, a literature review. SKB TR-06-36, Svensk Kärnbränslehantering AB.
Ludvigson J-E, 2002. Brunnsinventering i Forsmark. SKB R-02-17, Svensk Kärnbränslehantering AB.
Luna M, Arcos D, Duro L, 2006. Effects of grouting, shotcreeting and concrete leachates on backfill geochemistry. SKB R-06-107, Svensk Kärnbränslehantering AB.
Lunardini V J, 1978. Theory of n-factors and correlation of data. In Proceedings of the 3rd International Conference on Permafrost,10–13 July 1978, Edmonton, Alta. National Research Council of Canada, Ottawa, Ont., Vol. 1, pp. 40–46.
Lund B, 2005. Effects of deglaciation on the crustal stress field and implications for endglacial faulting. A parametric study of simple earth and ice models. SKB TR-05-04, Svensk Kärnbränslehantering AB.
Lund B, 2006. Stress variations during a glacial cycle at 500 m depth in Forsmark and Oskarshamn. Earth model effects. SKB R-06-95, Svensk Kärnbränslehantering AB.
Lundin L, Lode E, Stendahl J, Björkvald L, Hansson J, 2005. Soils and site types in the Oskarshamn area. Oskarshamn site investigation. SKB R-05-15, Svensk Kärnbränslehantering AB.
Lundquist J, Lagerbäck R, 1976. The Pärve Fault: A late-glacial fault in the Precambrian of Swedish Lapland. Geological Survey of Sweden, Stockholm, Sweden, In: Geologiska Föreningens i Stockholm Förhandlingar Vol. 98(1976) pp. 45–51.
Lundqvist J, Wohlfarth B, 2001. Timing and east-west correlation of south Swedish ice marginal lines during the Late Weichselian. Quaternary Science Reviews 20, 1127–48.
Lythe M, Vaughan D G and the BEDMAP Consortium, 2001. A new ice thickness and subglacial topographic model of Antarctica. Journal of Geophysical Research, 106(B6), 11335–11351.
Löfman J, 2005. Simulation of hydraulic disturbances caused by the decay heat of the repository in Olkiluoto, Posiva 2005-07.
Ma K-F, Brodsky E E, Mori J, Ji C, Song T-A R, Kanamori H, 2003. Evidence for fault lubrication during the 1999 Chi-chi, Taiwan, earthquake (M (sub w) 7.6). Geophysical Research Letters 30(5): 4.
Madaragia R, Olssen K, 2002. Earthquake dynamics in International handbook on Earthquakes and engineering seismology. W. Lee, H. Kanamori, P. Jennings and C. Kisslinger, Editors. Academic Press, San Diego, California. ISBN 0124406521.
Martin C D, Christiansson R, Söderhäll J, 2001. Rock stability considerations for siting and constructing a KBS-3 repository. Based on experiences from Äspö HRL, AECL's URL, tunneling and mining. SKB TR-01-38, Svensk Kärnbränslehantering AB.
Martin D, 2005. Preliminary assessment of potential underground stability (wedge and spalling) at Forsmark, Simpevarp and Laxemar sites. SKB R-05-71, Svensk Kärnbränslehantering AB.
Martinerie P, Raynaud D, Etheridge D M, Barnola J-M, Mazaudier D, 1992. Physical and climatic parameters which influence the air content in polar ice. Earth Planet. Sci. Lett., 112: 1–13.
Masurat P A, 2006. Potential for corrosion in disposal systems for high level radioactive waste by Meiothermus and Desulfovibrio, Department of Cell and Molecular Biology, Microbiology, Göteborg University, ISBN 91-628-6773-3.
Miliander S, Punakivi M, Kyläkorpi L, Rydgren B, 2004. Site description. Human population and human activities. SKB R-04-10, Svensk Kärnbränslehantering AB.
Miller B, Lind A, Savage D, Maul P, Robinson P, 2002. Natural Elemental Concentrations and Fluxes: Their Use as Indicators of Repository Safety. SKI Report 02:3, Swedish Nuclear Power Inspectorate; SSI report 2002:02, Swedish Radiation Protection Authority.
Milne G A, 1998. Refining models of the glacial isostatic adjustment process. Ph. D. Thesis, University of Toronto, Toronto.
Milne G A, Mitrovica J X, 1998. Postglacial sea-level change on a rotating Earth. Geophysical Journal International 133, 1–10.
Milodowski A E, Styles M T, Werme L, Oversby V M, 2003. The corrosion of more than 176 million year, old native copper plates from a deposit in mudstone in south devon; United Kingdom, NACE Corrosion 2003, Paper No. 03681.

Mitrovica J X, Milne G A, 2003. On post-glacial sea level: I. General theory. Geophysical Journal International 154, 253–267.
Mo K, Smith S, 1988. Mjukbottenfaunan I Öregrundsgrepen 1978–1986. Naturvårdsverket Rapport 3467. 43 p. (in Swedish).
Moberg A, Sonechkin D M, Holmgren K, Datsenko N M, Karlén W, 2005. Highly variable Northern Hemisphere temperatures reconstructed from low- and high-resolution proxy data. Nature 433: 613–617.
Moberg A, Gouirand I, Wohlfarth B, Schoning K, Kjellström E, Rummukainen M, de Jong R, Linderholm H, Zorita E, 2006. Climate in Sweden during the past millennium. Evidence from proxy data, instrumental data and model simulations. SKB TR-06-35, Svensk Kärnbränslehantering AB.
Model summary report, 2006. Model summary report for the safety assessment SR-Can, SKB TR-06-26, Svensk Kärnbränslehantering AB.
Molinero-Huguet J, Samper-Calvete F J, Zhang G, Yang C, 2004. Biogeochemical reactive transport model of the Redox Zone experiment of the Äspö Hard Rock Laboratory in Sweden. Nucl. Technol., 148: 151–165.
Morén L, Ritchey T, Stenström M, 1998. Scenarios based on human actions. Three Workshops on Issues Related to Method and Safety Assessment. Scenarier baserade på mänskliga handlingar. Tre arbetsmöten om metod- och säkerhetsanalysfrågor. SKB R-98-54. Svensk Kärnbränslehantering AB.
Muir Wood R, 1993. A review of the seismotectonics of Sweden. SKB TR 93-13, Svensk Kärnbränslehantering AB.
Muir Wood R, 1995. Reconstructing the tectonic history of Fennoscandia from its margins: The past 100 million years. SKB TR-95-36, Svensk Kärnbränslehantering AB.
Munier R, Hökmark H, 2004. Respect distances. Rationale and means of computation. SKB R-04-17, Svensk Kärnbränslehantering AB.
Munier R, 2006a. Using observations in deposition tunnels to avoid intersections with critical fractures in deposition holes. SKB R-06-54, Svensk Kärnbränslehantering AB.
Munier R, 2006b. Demonstrating the efficiency of the EFPC criterion by means of sensitivity analyses. SKB R-06-115, Svensk Kärnbränslehantering AB.
Mäder U, Frieg B, Puigdomenech I, Decombarieu M, Yui M, 2004. Hyperalkaline cement leachate-rock interaction and radionuclide transport in a fractured host rock (HPF Project). In: V.M. Oversby, L.O. Werme (Editors), Scientific Basis for Nuclear Waste Management XXVII. Mat. Res. Soc. Symp. Proc. Mater. Res. Soc., Pittsburgh, Penn., pp. 861–866.
Mörner N-A, 1989. Postglacial faults and fractures on Äspö. SKB HRL Progress report 25-89-24, Svensk Kärnbränslehantering AB.
Mörner N-A, 2003. Paleoseismicity of Sweden – a novel paradigm. ISBN 91-631-4072-1.
Nagra, 2002. Project Opalinus Clay: Safety Report. Demonstration of disposal feasibility of spent fuel, vitrified high-level waste and long-lived intermediate-level waste (Entsorgungsnachweis). Nagra Technical Report NTB 02-05. Nagra, Wettingen, Switzerland.
NEA, 1991. Review of safety assessment methods. Nuclear Energy Agency, Organisation for Economic Co-operation and Development, Paris, France.
NEA, 1997a. Lessons learnt from ten performance assessment studies. Nuclear Energy Agency, Organisation for Economic Co-operation and Development, Paris, France.
NEA, 1997b. Disposal of Radioactive Waste. The Probabilistic System Assessment Group: History and Achievements 1985–1994. Nuclear Energy Agency, Organisation for Economic Co-operation and Development, Paris, France.
NEA, 1999. Confidence in the Long-term Safety of Deep Geological Repositories – Its Development and Communication, Nuclear Energy Agency, Organisation for Economic Co-operation and Development, Paris, France.
NEA, 2001. Scenario Development Methods and Practices, An Evaluation Based on the NEA Workshop on Scenario Development, Madrid, Spain, May 1999, Nuclear Energy Agency, Organisation for Economic Co-operation and Development, Paris, France.
NEA, 2004a. The Handling of Timescales in Assessing Post-closure Safety – Lessons Learnt from the April 2002 Workshop in Paris, France, Nuclear Energy Agency, Organisation for Economic Co-operation and Development, Paris, France.
NEA, 2004b. Post-closure Safety Case for Geological Repositories – Nature and Purpose, Nuclear Energy Agency, Organisation for Economic Co-operation and Development, Paris, France.
NEA, 2005. Management of Uncertainty in Safety Cases and the Role Of Risk. Workshop proceedings. Nuclear Energy Agency, Organisation for Economic Co-operation and Development, Paris, France.
Nebot J, Bruno J, 1991. The implications of soil acidification on a future HLW repository. Part I: The effects of increased weathering, erosion and deforestation. SKB TR 91-45, Svensk Kärnbränslehantering AB.
Neretnieks I, 1979. Transport mechanisms and rates of transport of radionuclides in the geosphere as related to the Swedish KBS concept. Proceedings, International Atomic Energy Agency IAEA - SM - 243/108, p. 315–339, July 2–6, 1979.

Neretnieks I, 1986. Some uses for natural analogues in assessing the function of a HLW repository. Chem. Geol., 55: 175–188.
Neretnieks I, 2006a. Flow and transport through a damaged buffer exploration of the impact of a cemented and eroded buffer. SKB TR-06-33, Svensk Kärnbränslehantering AB.
Neretnieks I, 2006b. Flow and solute transport in a damaged zone due to spalling. SKB R-06-91, Svensk Kärnbränslehantering AB.
Neretnieks I, 2006c. Flow and solute transport in backfilled tunnel and collapsed backfill – possible extension of Comp32. SKB R-06-92, Svensk Kärnbränslehantering AB.
Neuman E, 1982. Species composition and seasonal migrations of the coastal fish fauna in the southern Bothnian Sea, in Coastal research in the Gulf of Bothnia, Müller, K., Editor. 1982, Dr. W Junk Publishers.
Nicholls R J, Lowe J A, 2006. Climate stabilisation and impacts of sea-level rise. In Schellnhuber, H. J., Cramer, W., Nakicenovic, N., Wigley, T. M. L. & Yohe, G. (Eds.) Avoiding Dangerous Climate Change. Cambridge: Cambridge University Press.
Nilsson A-C, Karlsson S, Borgiel M, 2003. Forsmark site investigations. Sampling and analyses of surface waters. Results from sampling in the Forsmark area, March 2002 to March 2003. SKB P-03-27, Svensk Kärnbränslehantering AB.
Nilsson A-C, Borgiel M, 2004. Sampling av analyses of surface waters. Results from sampling in the Forsmark area, March 2003 to March 2004. SKB P-04-46, Svensk Kärnbränslehantering AB.
Nilsson K-F, Lofaj F, Burström M, Andersson C-G, 2005. Pressure tests of two KBS-3 canister mock-ups. SKB TR-05-18, Svensk Kärnbränslehantering AB.
Nordstrom D K, Ball J W, Donahoe R J, Whittemore D, 1989. Groundwater chemistry and water-rock interactions at Stripa. Geochim. Cosmochim. Acta, 53: 1727–1740.
Norman S, Kjellbert N, 1990. FARF31 – A far field radionuclide migration code for use with the PROPER package. SKB TR 90-01, Svensk Kärnbränslehantering AB.
Näslund J O, Fastook J L, Holmlund P, 2000. Numerical modelling of the ice sheet in western Dronning Maud Land, East Antarctica: impact of present, past, and future climates. Journal of Glaciology 46(152):54–66.
Näslund J O, Jansson P, Fastook J L, Johnson J, Andersson L, 2005. Detailed spatially distributed geothermal heat flow data for modelling of basal temperatures and melt water production beneath the Fennoscandian ice sheet. Annals of Glaciology 40: 95–101.
Odum E P, 1983. Basic Ecology, Holt-Saunders International Editions. New York.
OECD/NEA, 1995. Future human actions at disposal sites. A report from the NEA Working Group on Assessment of Future Human Actions at Radioactive Waste Disposal Sites. OECD/NEA, France.
Olesen O, Lile O B, Henkel H, Ronning J S, Dalsegg E, 1989. Geophysical investigations of the postglacial Stuoragurra Fault, Finnmark, northern Norway. 17th meeting of the Nordic Association for Applied Geophysics. Anonymous. Amsterdam, Netherlands, Elsevier. 26: 62–63.
Olesen O, Henkel H, Lile O B, Mauring E, Ronning J S, 1992. Geophysical investigations of the Stuoragurra postglacial fault, Finnmark, northern Norway. Journal of Applied Geophysics 29(2): 95–118.
Olsson R, 1998. Mechanical and Hydromechanical Behaviour of Hard Rock Joints. A laboratory study. PhD thesis, Chalmers University of Technology, Dept of Geotechnical Engineering, Göteborg.
Olsson M, Niklasson B, Wilson L, Andersson C, Christiansson R, 2004. Äspö HRL. Experiences of blasting of the TASQ tunnel. SKB R-04-73, Svensk Kärnbränslehantering AB.
ONDRAF/NIRAS, 2001. SAFIR 2: Safety Assessment and Feasibility Interim Report 2, NIROND 2001-06 E, ONDRAF/NIRAS.
Ortlepp W D, 1992a. Assessment of rockburst risk in the Underground Research Laboratory, Pinawa, Manitoba, Canada. Tech. Rep. 195524, Overview Report for Atomic Energy of Canada Limited.
Ortlepp W D, 1992b. The design of support for the containment of rockburst damage in tunnels; an engineering approach, A. A. Balkema, Rotterdam, Netherlands (NLD). ISBN 9054100443.
Ortlepp W D, 1997. Rock fracture and rockbursts. Monograph Series M9, South African Inst of Min & Metall, Johannesburg.
Oversby V M, 1996. Criticality in a high level waste repository. A review of some important factors and an assessment of the lessons that can be learned from the Oklo reactors. SKB TR-96-07, Svensk Kärnbränslehantering AB.
Paananen M, 1987. Geophysical studies of the Venejärvi, Ruostejärvi, Suasselkä and Pasmajärvi postglacial faults in northern Finland. YST-59, Geological Survey of Finland Nuclear Waste Disposal Research Espoo.
Painter S, Cvetkovic V, Pensado O, 2006. Time-domain random walk methods for simulating radionuclide transport in fractured porous rock. Proceedings of the 11th International High-level Radioactive Waste Management Conference, April 30–May 4, 2006, Las Vegas, Nevada.
Parkhurst D L, Appelo C A J, 1999. User's guide to PHREEQC (Version 2) – A computer program for speciation, batch-reaction, one-dimensional transport, and inverse geochemical calculations. USGS/WRI-99-4259, U.S. Geol. Survey, Denver, Colorado, 312 p.
Parkhurst D L, Kipp K L, Engesgaard P, Charlton S R, 2004. PHAST – A program for simulating groundwater flow, solute transport, and multicomponent geochemical reactions. USGS Techniques and Methods 6-A8, U.S. Geol. Survey, Denver, Colorado, 154 p.

Patterson W S B, 1994. The physics of glaciers. 3rd Ed. Elsevier Science Ltd, Oxford. 480 p.
Pattyn F, DeSmedt B, Souchez R, 2004. Influence of subglacial lake Vostok on the regional dynamics of the Antarctic ice sheet: a model study. Journal of Glaciology 50 (171): 583–589.
Payne A J, Huybrechts Ph, Abe-Ouchi A, Calov R, Fastook J L, Greve R, Marshall S J, Marsiat I, Ritz C, Tarasov L, Thomassen M P A, 2000. Results from the EISMINT model intercomparison: the effects of thermomechanical coupling. Journal of Glaciology, 46(153): 227–238.
Pedersen K, Kennedy C, Nederfeldt K-G, Bergelin A, 2004. Äspö Hard Rock Laboratory. Prototype repository. Chemical measurements in buffer and backfill; sampling and analyses of gases. SKB IPR-04-26, Svensk Kärnbränslehantering AB.
Pedersen K, 2006. Microbiology of transitional groundwater of the porous overburden and underlying fractured bedrock aquifers in Olkiluoto, Finland. POSIVA WR-2006-09, Posiva Oy, Olkiluoto, Finland.
Pers K, Skagius K, Södergren S, Wiborgh M, Hedin A, Morén L, Sellin P, Ström A, Pusch R, Bruno J, 1999. SR 97 – Identification and structuring of process. SKB TR-99-20, Svensk Kärnbränslehantering AB.
Pitkänen P, 1999. Geochemical modelling of groundwater evolution and residence time at the Olkiluoto site. POSIVA 98-10, Posiva Oy, Helsinki, Finland.
Pitkänen P, Partamies S, Luukkonen A, 2004. Hydrogeochemical interpretation of baseline groundwater conditions at the Olkiluoto site. POSIVA 2003-07, Posiva Oy, Helsinki, Finland.
Puigdomenech I, Ambrosi J-P, Eisenlohr L, Lartigue J-E, Banwart S A, Bateman K, Milodowski A E, West J M, Griffault L, Gustafsson E, Hama K, Yoshida H, Kotelnikova S, Pedersen K, Michaud V, Trotignon L, Rivas Perez J, Tullborg E-L, 2001a. O_2 depletion in granitic media. The REX project. SKB TR-01-05, Svensk Kärnbränslehantering AB.
Puigdomenech I, Gurban I, Laaksoharju M, Luukkonen A, Löfman J, Pitkänen P, Rhén I, Routsalainen P, Smellie J, Snellman M, Svensson U, Tullborg E-L, Wallin B, Vuorinen U, Wikberg P, 2001b. Hydrochemical stability of groundwaters surrounding a spent nuclear fuel repository in a 100,000 year perspective. SKB TR-01-28, Svensk Kärnbränslehantering AB.
Pusch R, 1990. Radionuclide transport paths in the nearfield – a KBS-3 concept study. SKB TR 90-32, Svensk Kärnbränslehantering AB.
Pusch R, Stanfors R, 1992. The zone of disturbance around blasted tunnels at depth. Int. J. Rock Mech. Min. Sci & Geomech. Abstr. Vol 29, No.5 pp. 447–456.
Pusch R, Karnland O, Lajudie A, Lechelle J, Bouchet A, 1993. Hydrothermal field test with French candidate clay embedding steel heater in the Stripa mine. SKB TR 93-02, Svensk Kärnbränslehantering AB.
Pusch R, 2000. On the effect of hot water vapor on MX-80 clay. SKB TR-00-16, Svensk Kärnbränslehantering AB.
Pusch R, Andersson C, 2004. Äspö HRL. Prototype Repository. Preparation of deposition holes prior to emplacement of buffer and canisters in Section II. IPR-04-21, Svensk Kärnbränslehantering AB.
Pusch R, Kasbohm, J, Pacovsky, Cechova S, 2005. Are all smectite clays suitable as "buffers"? Presentation at Clays in Natural & Engineered Barriers for Radioactive Waste Confinement Conference in Tours 2005, to be published in Applied Clay Science.
Påsse T, 1997. A mathematical model of past, present and future shore level displacement in Fennoscandia. SKB TR-97-28, Svensk Kärnbränslehantering AB.
Påsse T, 2001. An empirical model of glacio-isostatic movements and shore-level displacement in Fennoscandia. SKB R-01-41, Svensk Kärnbränslehantering AB.
Rahmstorf S, Ganopolski A, 1999. Long-term global warming scenarios computed with an efficient coupled climate model. Climatic Change, 43: p. 353–367.
RETROCK, 2005. Treatment of radionuclide transport in geosphere within safety assessments (Retrock), European Commission, Nuclear science and technology, EUR 21230 EN.
Riis F, 1996. Quantification of Cenozoic vertical movements of Scandinavia by correlation of morphological surfaces with offshore data. Global and Planetary Change 12, 331–357.
Risberg J, 2005. Bio- and lithostratigraphy in offshore sediment core PFM004396. Salinity variations in the Bothnian Sea offshore Forsmark. Forsmark site investigation. SKB P-05-139, Svensk Kärnbränslehantering AB.
Ritchey T, 1997. Scenario Development and Risk Management using Morphological Field Analysis. Proceedings of the 5th European Conference on Information Systems. Cork.
Roberts M J, Russell A J, Tweed F S, Knudsen O, 2000. Ice fracturing during jökulhlaups: implications for englacial floodwater routing and outlet development. Earth Surface Processes and Landforms 25(13): 1429–1446.
Roberts M J, 2005. Jökulhlaups: a reassessment of floodwater flow through glaciers. Reviews of Geophysics 43:1–21.
Romero L, Neretnieks I, Moreno L, 1992. Movement of the redox front at the Osamu Utsumi uranium mine, Poços de Caldas, Brazil. J. Geochem. Explor., 45: 471–502.
Romero A L, 1995. The near-field transport in a repository for high-level nuclear waste. PhD. Thesis, Department of Chemical Engineering and Technology, Royal Institute of Technology, Stockholm, Sweden.

Romero L, Thompson A, Moreno L, Neretnieks I, Widén H, Boghammar A, 1999. Comp23/Nuctran user´s guide – Proper version 1.1.6. SKB R-99-64, Svensk Kärnbränslehantering AB.
Rondinella V V, Cobos J, Wiss T, 2004. Leaching behaviour of low-activity alpha-doped UO_2, Mat. Res. Soc. Symp. Proc. Vol. 824, p.167.
Rummukainen M, 2003. The Swedish regional climate modeling program, SWECLIM, 1996–2003. Final report. Reports Meteorology and Climatology 104, Swedish Meteorological and Hydrological Institute, Norrköping, Sweden, 47 pp.
Ruskeeniemi T, Ahonen L, Paananen M, Frape S, Stotler R, Hobbs M, Kaija J, Degnan P, Blomqvist R, Jensen M, Lehto K, Moren L, Puigdomenech I, Snellman M, 2004. Permafrost at Lupin. Report of phase II. Permafrost project GTK-SKB-POSIVA-NIREX-OPG. Report YST-119, Geological Survey of Finland, Helsinki, Finland.
Rühling Å, 1997. Floran i Oskarshamns kommun. Svensk Botanisk Förening, Lund.
Sandström B, Savolainen M, Tullborg E-L, 2004. Fracture mineralogy. Results from fracture minerals and wall rock alteration in boreholes KFM01A, KFM02A, KFM03A and KFM03B. Forsmark site investigation. SKB P-04-149, Svensk Kärnbränslehantering AB.
Schlesinger M E, Yin J, Yohe G W, Andronova N G, Malyshev S, Li B, 2006. Assessing the risk of a collapse of the Atlantic thermohaline circulation in Avoiding Dangerous Climate Change, Cambridge University Press, Cambridge, Chapter 5.
Scholz C H, 1990. The mechanics of earthquakes and faulting, Cambridge University Press USA.
Sidborn M, Neretnieks I, 2003. Modelling of biochemical processes in rocks: Oxygen depletion by pyrite oxidation – Model development and exploratory simulations. In: R.J. Finch, D.B. Bullen (Editors), Scientific Basis for Nuclear Waste Management XXVI. Mat. Res. Soc. Symp. Proc. Mater. Res. Soc., Pittsburgh, Penn., pp. 553–558.
Sidborn M, Neretnieks I, 2004. Modelling biochemical processes in rocks: Analysis and exploratory simulations of competition of different processes important for ferrous mineral oxidation and oxygen depletion. In: V.M. Oversby, L.O. Werme (Editors), Scientific Basis for Nuclear Waste Management XXVII. Mat. Res. Soc. Symp. Proc. Mater. Res. Soc., Pittsburgh, Penn., pp. 829–834.
Sidborn M, Neretnieks I, 2006. Long term redox evolution in granitic rocks: Modelling the redox front propagation in the rock matrix. Appl. Geochem., (submitted).
Sigurdsson T, 1987. Bottenundersökning av ett område ovanför SFR, Forsmark. SFR 87-07, Svensk Kärnbränslehantering AB.
Silver W L, Lugo A E, Keller M, 1999. Soil oxygen availability and biogeochemistry along rainfall and topographic gradients in upland wet tropical forest soils. Biogeochem., 44: 301–328.
Skagius K, Ström A, Wiborgh M, 1995. The use of interaction matrices for identification, structuring and ranking of FEPs in a repository system. Application on the far-field of a deep geological repository for spent fuel. SKB TR-95-22, Svensk Kärnbränslehantering AB.
SKB, 1996. SR 95 – Template for safety reports with descriptive exemple. SKB TR-96-05, Svensk Kärnbränslehantering AB.
SKB, 1999a. SR 97 – Deep repository for spent nuclear fuel. SR 97 – Post-closure safety. Main report – Vol. I, Vol. II and Summary, SKB TR-99-06, Svensk Kärnbränslehantering AB.
SKB, 1999b. SR 97 – Processes in the repository evolution. Background report to SR 97. SKB TR-99-07, Svensk Kärnbränslehantering AB.
SKB, 2001. RD&D programme 2001. Programme for research, development and demonstration of methods for the management and disposal of nuclear waste. SKB TR-01-30, Svensk Kärnbränslehantering AB.
SKB, 2003. Plan 2003. Costs for management of the radioactive waste products from nuclear power production. SKB TR-03-11, Svensk Kärnbränslehantering AB.
SKB, 2004a. Interim main report of the safety assessment SR-Can. SKB TR-04-11, Svensk Kärnbränslehantering AB.
SKB, 2004b. Deep repository. Underground design premises. Edition D1/1. SKB R-04-60, Svensk Kärnbränslehantering AB.
SKB, 2004c. Interim data report for the safety assessment SR-Can. SKB R-04-34, Svensk Kärnbränslehantering AB.
SKB, 2005a. Preliminary safety evaluation for the Simpevarp subarea. Based on data and site descriptions after the initial site investigation stage. SKB TR-05-12, Svensk Kärnbränslehantering AB.
SKB, 2005b. Preliminary safety evaluation for the Forsmark area. Based on data and site descriptions after the initial site investigation stage. SKB TR-05-16, Svensk Kärnbränslehantering AB.
SKB, 2005c. Preliminary site description Forsmark area – version 1.2. SKB R-05-18, Svensk Kärnbränslehantering AB.
SKB, 2005d. Programme for further investigations of geosphere and biosphere. Forsmark site investigation. SKB R-05-14, Svensk Kärnbränslehantering AB.
SKB, 2005e. Hydrogeochemical evaluation. Preliminary site description Forsmark area – version 1.2. SKB R-05-17, Svensk Kärnbränslehantering AB.

SKB, 2006a. Preliminary safety evaluation for the Laxemar subarea. Based on data and site descriptions after the initial site investigation stage. SKB TR-06-06, Svensk Kärnbränslehantering AB.
SKB, 2006b. Preliminary site description. Laxemar subarea – version 1.2 SKB R-06-10, Svensk Kärnbränslehantering AB.
SKB, 2006c. Kapsel för använt kärnbränsle. Svetsning vid tillverkning och förslutning. SKB R-06-04, Svensk Kärnbränslehantering AB (in Swedish).
SKB, 2006d. Kapsel för använt kärnbränsle. Oförstörande provning av kapselkomponenter. SKB R-06-05, Svensk Kärnbränslehantering AB (in Swedish).
SKB, 2006e. Site descriptive modelling Forsmark stage 2.1. Feedback for completion of the site investigation including input from safety assessment and repository engineering. SKB R-06-38, Svensk Kärnbränslehantering AB.
SKB, 2006f. Programme for further investigations of bedrock, soil, water and environment in Laxemar subarea. Oskarshamn site investigation. SKB R-06-29, Svensk Kärnbränslehantering AB.
SKB, 2006g. Hydrogeochemical evaluation. Preliminary site description Laxemar subarea – version 1.2. SKB R-06-12, Svensk Kärnbränslehantering AB.
SKB, 2006h. The biosphere at Forsmark. Data, assumptions and models used in the SR-Can assessment. SKB R-06-82, Svensk Kärnbränslehantering AB.
SKB, 2006i. The biosphere at Laxemar. Data, assumptions and models used in the SR-Can assessment. SKB R-06-83, Svensk Kärnbränslehantering AB.
SKB, 2006j. Plan 2006 Kostnader för kärnkraftens radioaktiva restprodukter. Svensk Kärnbränslehantering AB.
SKBF/KBS, 1983. Kärnbränslecykelns slutsteg. Använt kärnbränsle – KBS-3. Del I–IV. Svensk Kärnbränsleförsörjning AB.
SKI/SSI, 2001. SKI's and SSI's Joint Review of SKB's Safety Assessment Report, SR 97, Summary, SKI Report 01:3, Swedish Nuclear Power Inspectorate; SSI Report 2001:02, Swedish Radiation Protection Authority.
SKI/SSI, 2005a. Sagar, B., Bailey, L., Bennett, D.G., Egan, M. and Röhlig, K., International Peer Review of Swedish Nuclear Fuel and Waste Management Company's SR-Can interim report, SKI Report 05:02, SSI report 2005:02, Swedish Nuclear Power Inspectorate, Swedish Radiation Protection Authority, Stockholm, December 2004.
SKI/SSI, 2005b. Review of SKB's interim report of SR-Can: SKI's and SSI's evaluation of SKB's up-dated methodology for safety assessment, SKI Report 05:40, SSI report 2005:13, Swedish Nuclear Power Inspectorate, Swedish Radiation Protection Authority, Stockholm, July 2005.
Slunga R S, 1991. The Baltic Shield earthquakes. Tectonophysics 189(1-4): 323–331.
Smellie J, 2001. Wyoming Bentonites. Evidence from the geological record to evaluate the suitability of bentonite as a buffer material during the long-term underground containment of radioactive wastes. SKB TR-01-26, Svensk Kärnbränslehantering AB.
Snoeijs P, 1985. Microphytobenthic biomass and environmental data in and around the Forsmark Biotest Basin, 1983–1985. 1985:2, Växtbiologiska Intutionen, Uppsala.
Snoeijs P, 1986 Primary production of microphytobenthos on rocky substrates in the Forsmark biotest basin, 1984 National Swedish environmental protection board report Vol. 3216 p. 1–24.
Snoeijs P, Mo K, 1987. Macrofauna on rocky substrates in the Forsmark biotest basin (March 1984 – March 1985). 3397, National Swedish Environmental Protection Board.
SNV, 1984. Våtmarksinventering inom fastlandsdelen av Kalmar Län: Del 1 Allmän beskrivning och katalog över särskilt värdefulla objekt. Statens Naturvårdsverk, Solna, Rapport PM 1787.
Sohlenius G, Hedenström A, Rudmark L, 2004. Mapping of unconsolidated Quaternary deposits 2002–2003. Forsmark site investigation. Map description. SKB R-04-39, Svensk Kärnbränslehantering AB.
Sposito G, Park S-H, Sutton R, 1999. Molecular simulations of clay mineral surface geochemistry. Science Highlights in 1998 Annual Report, National Energy Research Computing Center (NERSC), Lawrence Berkeley National Laboratory, p. 61.
SSI, 1998. The Swedish Radiation Protection Institute's Regulations on the Protection of Human Health and the Environment in connection with the Final Management of Spent Nuclear Fuel and Nuclear Waste, SSI FS 1998:1, Statens strålskyddsinstitut.
SSI, 2005. The Swedish Radiation Protection Authority's guidelines on the application of the regulations (SSI FS 1998:1) concerning protection of human health and the environment in connection with the final management of spent nuclear fuel and nuclear waste. SSI FS 2005:1, Statens strålskyddsinstitut.
Strömgren M, Brunberg A-K, 2006. Elemental composition of a deep sediment core from Lake Stocksjön in the Forsmark area. SKB R-06-96, Svensk Kärnbränslehantering AB.
Stucki J W, Golden D C, Roth C B, 1984. The effect of reduction and reoxidation on the surface charge and dissolution of dioctahedral smectites: Clays and Clay Minerals 32, 191–197.
STUK, 2001. Long-term safety of disposal of spent nuclear fuel. Guide YVL 8.4. Helsinki.
Stumm W, Morgan J J, 1996. Aquatic Chemistry. Chemical Equilibria and Rates in Natural Waters. John Wiley & Sons, New York, 1022 pp.

Sudicky E A, Frind E O, 1982. Contaminant Transport in Fractured Porous Media: Analytical Solutions for a System of Parallel Fractures, Water Resources Research, 18, 6, 1634.
Sundberg I, Ericsson U, Engdahl A and Svensson J-E, 2004. Phytoplankton and zooplankton. Results from sampling in the Simpevarp area 2003–2004. Oskarshamn site investigation, SKB P-04-253, Svensk Kärnbränslehantering AB.
Sundberg J, Back P-E, Bengtsson A, Ländell M, 2005. Thermal modelling. Preliminary site description Forsmark area – version 1.2. SKB R-05-31, Svensk Kärnbränslehantering AB.
Svendsen J I, Astakhov V I, Bolshiyanov D Y, Demidov I, Dowdeswell J A, Gataullin V, Hjort C, Hubberten H W, Larsen E, Mangerud J, Melles M, Möller P, Saarnisto M, Siegert M J, 1999. Maximum extent of the Eurasian ice sheets in the Barents and Kara Sea region during the Weichselian. Boreas 28, 234–242.
Svensson U, Kuylenstierna H-O, Ferry M, 2004. DarcyTools, Version 2.1 Concepts, methods, equations and demo simulations. SKB R-04-19, Svensk Kärnbränslehantering AB.
Svensson U, 2005. The Forsmark repository. Modelling changes in the flow, pressure and salinity fields, due to a repository for spent nuclear fuel. SKB R-05-57, Svensk Kärnbränslehantering AB.
Svensson U, 2006a. The Laxemar repository. Modelling changes in the flow, pressure and salinity fields, due to a repository for spent nuclear fuel. SKB R-06-57, Svensk Kärnbränslehantering AB.
Svensson U, 2006b. The Laxemar and Forsmark repositories. An analysis of the water inflow distribution. SKB R-06-102, Svensk Kärnbränslehantering AB.
Tanner V, 1930. Studier över kvartärsystemet i Fennoskandias nordliga delar IV. Bulletin de la Commission Géologique de Finlande 88: 594 pp.
Tarasov L, Peltier W R, 2004. A geophysically constrained large ensemble analysis of the deglacial history of the North American ice-sheet complex. Quaternary Science Reviews 23(3-4):359–388.
Thorne M C, Kane P, 2006. Climate and Landscape Change within Tools for Optioneering of Remediation and Decommissioning Solutions. Report to Nexia Solutions Ltd. MTA/P0013/2006-1: Issue 2. Mike Thorne and Associates Limited.
Tjernström M, Rummukainen M, Bergström S, Rodhe J, Persson G, 2003. Klimatmodellering och klimatscenarier ur SWECLIMs perpektiv. Reports Meteorology and Climatology 102, Swedish Meteorological and Hydrological Institute, Norrköping, Sweden, 101 pp.
Tobiasson S, 2003. Tolkning av undervattensfilm från Forsmark och Simpevarp. SKB P-03-68, Svensk Kärnbränslehantering AB.
Tröjbom M, Söderbäck B, 2006. Chemical characteristics of surface systems in the Simpevarp area. Visualisation and statistical evaluation of data from surface water, precipitation, shallow groundwater, and regolith. SKB R-06-18, Svensk Kärnbränslehantering AB.
Tsang C-F, Benier F, Davies C, 2005. Geohydromechanical Processes in the Excavation Damage Zone in Crystalline Rock, Rock Salt and Indurated and Plastic Clays – in the Context of Radioactive Waste Disposal. Int. J. Rock Mech. Min. Sci., Vol. 42, no 1, 109–125.
Tushingham A M, Peltier W R, 1991. ICE-3G; a new global model of late Pleistocene deglaciation based upon geophysical predictions of post-glacial relative sea level change. Journal of Geophysical Research, B, Solid Earth and Planets, 96(3):4497–4523.
Upphed L, 1995. Biological effects of radiation. Strålningens biologiska verkningar. SSI utbildning. Kursmaterial Joniserande strålning grundkurs. SSI 1995, Statens strålskyddsinstitut.
Vahlund F, Hermansson H, 2006. A direct numerical approach to solving the transport equations for radio-nuclide transport in fractured rock. SKB R-04-50, Svensk Kärnbränslehantering AB.
Vidstrand P, Svensson U, Follin S, 2006. Simulation of hydrodynamic effects of salt rejection due to permafrost. Hydrogeological numerical model of density-driven mixing, at a regional scale, due to a high salinity pulse. SKB R-06-101, Svensk Kärnbränslehantering AB.
Vieno T, Nordman H, 1999. Safety assessment of spent fuel disposal in Hästholmen, Kivetty, Olkiluoto and Romuvaara TILA-99. Posiva 99-07, Possiva OY.
Vikström M, Gustafsson L-G, 2006. Modelling transport of water and solutes in future wetlands in Forsmark. SKB R-06-46, Svensk Kärnbränslehantering AB.
Vuorela P, Kuivamäki A, Paananen M, 1987. Neotectonic bedrock movements. A preliminary survey of the Pasmajärvi fault. YST-57, Geological Survey of Finland Nuclear Waste Disposal Research Espoo.
Waddington E D, 1987. Geothermal heat flux beneath ice sheets. In: E.D. Waddington, & J.S. Walder (Eds.): The physical basis of ice sheet modelling. International Association of Hydrological Research (IAHS) publication 170:217–226.
Wald D J, Heaton T H, 1994. Spatial and temporal distribution of slip for the 1992 Landers, California, earthquake. Bulletin of the Seismological Society of America 84(3): 668–691.
Walker D, Rhén I, Gurban I, 1997. Summary of hydrogeologic conditions at Aberg, Beberg and Ceberg. SKB TR-97-23, Svensk Kärnbränslehantering AB.
Washburn A L, 1979. Geocryology. Arnold, E. London.

Wells D L, Coppersmith K J, 1994. New empirical relationships among magnitude, rupture length, rupture width, rupture area, and surface displacement. Bulletin of the Seismological Society of America. Vol. 84(4): p. 974–1002.
Werme L O, 1998. Design premises for canister for spent nuclear fuel. SKB TR-98-08, Svensk Kärnbränslehantering AB.
Werner K, Bosson E, Berglund S, 2005. Description of climate, surface hydrology, and near-surface hydrogeology. Preliminary site description Laxemar subarea – version 1.2. SKB R-05-61, Svensk Kärnbränslehantering AB.
Wersin P, Bruno J, Laaksoharju M, 1994. The implications of soil acidification on a future HLW repository. Part II: Influence on deep granitic groundwater. The Klipperås study site as test case. SKB TR-94-31, Svensk Kärnbränslehantering AB.
Wikberg P, Laaksoharju M, Bruno J, Sandino A, 1988. Site characterization and validation – Hydrochemichal investigations in stage I. Stripa Project Internal Report 88-09, Svensk Kärnbränslehantering AB.
Wikramaratna R S, Goodfield M, Rodwell, W R, Nash P J, Agg P J, 1993. A preliminary assessment of gas migration from the Copper/Steel Canister. SKB TR-93-31, Svensk Kärnbränslehantering AB.
Williams P J, Smith M W, 1989. The Frozen Earth. Cambridge University Press.
Wilmot R D, Wickham S M, Galson D A, 1999. Elements of a Regulatory Strategy for the Consideration of Future Human Actions in Safety Assessments. SKI Report 99:46, Statens kärnkraftinspektion.
Wilmot R D, Galson D A, 2000. Expert Judgement in Performance Assessment SKI report 2000:04, Swedish Nuclear Power Inspectorate.
Wilmot R D, Galson D A, Hora S C, 2000. Expert Judgements in Performance Assessments. Report of an SKI/SSI Seminar, SKI report 2000:35, Swedish Nuclear Power Inspectorate.
Wilson J, Cressey G, Cressey B, Cuadros J, Vala Ragnarsdottir K, Savage D, Shibata M, 2005. The effect of iron on montmorillonite stability: (II) Experimental investigation. Geochimica et Cosmochimica Acta, 2005 (in press).
Winberg A, 1991. The role of the disturbed rock zone in radioactive waste repository safety and performance assessment. A topical discussion and international review. SKB TR 91-25, Svensk Kärnbränslehantering AB.
Witt A, Schumann AY, 2005. Holocene climate variability on millennial scales recorded in Greenland ice cores. Nonlinear Processes in Geophysics 12:345–352.
Wu P, Wood R, Stott P, 2004. Does the recent freshening trend in the North Atlantic indicate a weakening thermohaline circulation? Geophysical Research Letters 31, L02301, doi:10.1029/2003GL018584.
Wänstedt S, 2000. Geophysical and geological investigations of the Boda area. SKB R-00-23, Svensk Kärnbränslehantering AB.
Yershov E D, 1998. General Geocryology. Cambridge University Press.
Yin J, Schlesinger M E, Andronova N G, Malyshev S, Li B, 2006. Is a shutdown of the thermohaline circulation irreversible? Journal of Geophysical Research, 111, D12104, doi:10.1029/2005JD006562, 2006.

Appendix A

Applicable regulations and SKB's implementation of these in the safety assessment SR-Can

This Appendix contains regulatory texts issued by SKI and SSI applicable to a safety assessment for a nuclear waste repository. References to SKB's plan for complying with the regulations have been inserted in italics at relevant places in sections A1.1 (SKIFS 2002:1) and A2.1 (SSI FS 1998:1).

A1 SKI's regulations and general recommendations

SKI has issued i) Regulations concerning Safety in connection with the Disposal of Nuclear Material and Nuclear Waste (SKIFS 2002:1) and ii) General Recommendations concerning the application of those Regulations.

Whereas the Regulations have a clear legal status, General Recommendations are described in 1 § Ordinance on Regulatory Codes (1976:725) as: Such general recommendations on the application of regulations that stipulate how someone can or should act in a certain respect.

A1.1 SKIFS 2002:1

The Swedish Nuclear Power Inspectorate's Regulations concerning Safety in connection with the Disposal of Nuclear Material and Nuclear Waste decided on October 24, 2001.

On the basis of 20 a and 21 §§ of the Ordinance (1984:14) on Nuclear Activities, the Swedish Nuclear Power Inspectorate has issued the following regulations and decided on the following general recommendations.

Application

1 § These regulations apply to facilities for the disposal of spent nuclear fuel and waste (repositories). The regulations do not apply to facilities for landfill disposal of low-level nuclear waste in accordance with 19 § of the Ordinance (1984:14) on Nuclear Activities.

The regulations contain supplementary provisions to the Swedish Nuclear Power Inspectorate's regulations (SKIFS 1998:1) concerning Safety in Certain Nuclear Facilities.

Barriers and their functions

2 § Safety after the closure of a repository shall be maintained through a system of passive barriers.

3 § The function of each barrier shall be to, in one or several ways, contribute to the containment, prevention or retardation of dispersion of radioactive substances, either directly, or indirectly by protecting other barriers in the barrier system.

Handling in SR-Can: *The ways in which the barriers contribute to safety is discussed in detail in chapter 7. The calculation cases in section 10.10 address this issue directly. In general, most of the safety assessment is aiming at demonstrating barrier safety.*

4 § A deficiency in any of the repository's barrier functions that is detected during the construction or operational surveillance of the repository and that can lead to a deterioration in safety after closure in addition to that anticipated in the safety report[1], shall be reported to the Swedish Nuclear Power Inspectorate without delay[2]. The same applies if such a deficiency is suspected to occur or if the possibility that such a deficiency can occur in the future is suspected.

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[1] Cf chapter 4. 2 § of the Swedish Nuclear Power Inspectorate's regulations (SKIFS 1998:1) concerning Safety in Certain Nuclear Facilities.

[2] Cf chapter 2. 2 § of the Swedish Nuclear Power Inspectorate's regulations (SKIFS 1998:1) concerning Safety in Certain Nuclear Facilities.

Design and construction

5 § The barrier system shall be able to withstand such features, events and processes that can affect the post-closure performance of the barriers.

Handling in SR-Can: *The overall purpose of the safety assessment can be said to demonstrate this point.*

6 § The barrier system shall be designed and constructed taking into account the best available technique[3].

Handling in SR-Can: *The issue of BAT is addressed in section 13.3.4.*

7 § The barrier system shall comprise several barriers so that, as far as possible, the necessary safety is maintained in spite of a single deficiency in a barrier.

Handling in SR-Can: *This issue is addressed in many of the analyses. In particular, a set of calculation cases to illustrate this issue are presented in section 10.10.*

8 § The impact on safety of such measures that are adopted to facilitate the monitoring or retrieval of disposed nuclear material or nuclear waste from the repository, or to make access to the repository difficult, shall be analysed and reported to the Swedish Nuclear Power Inspectorate.

Safety assessment

9 § In addition to the provisions of chapter 4. 1 § of the Swedish Nuclear Power Inspectorate's Regulations (SKIFS 1998:1) concerning the Safety in Certain Nuclear Facilities, the safety assessments shall also comprise features, events and processes which can lead to the dispersion of radioactive substances after closure, and such analyses shall be made before repository construction, before repository operation and before repository closure.

Handling in SR-Can: *The systematic management in a database of the mentioned features, events and processes in SR-Can is discussed in chapter 3 and in the **FEP report**. The detailed management of many of these factors is discussed throughout the report.*

10 § A safety assessment shall comprise as long time as barrier functions are required, but at least ten thousand years.

Handling in SR-Can: *The timescales of relevance for SR-Can are discussed in section 2.4.*

Safety report

11 § The safety report for a repository shall, in addition what is required in chapter 4 2 § of the Swedish Nuclear Power Inspectorate's Regulations (SKIFS 1998:1) concerning Safety in Certain Nuclear facilities, contain the information required in Appendix 1 of these regulations and which concerns the time after closure.

Prior to repository closure, the final safety assessment must be renewed and subjected to a safety review in accordance with chapter 4. 3 § of the Swedish Nuclear Power Inspectorate's regulations (SKIFS 1998:1) Concerning Safety in Certain Nuclear Facilities and must be reviewed and approved by the Swedish Nuclear Power Inspectorate.

Exceptions

12 § The Swedish Nuclear Power Inspectorate may grant exceptions, if particular grounds exist, from these regulations if this can be achieved without departing from the purpose of the regulations and on condition that safety can be maintained.

Appendix 1

The following shall be reported with regard to analysis methods:

– how one or several methods have been used to describe the passive system of barriers in the repository, its performance and evolution over time; the method or methods shall contribute to providing a clear view of the features, events and processes that can affect the performance of the barriers and the links between these features, events and processes,

[3] Cf chapter 2. 3 § of the Swedish Environmental Code.

Handling in SR-Can: *The format for system description is discussed in chapter 4 (initial state), chapter 5 (external conditions) and chapter 6 (processes). The description of system evolution is related to the entire assessment and is analysed in detail as a reference evolution in chapters 9 and 10. Alterations to this evolution are analysed for a number of scenarios in chapter 12.*

– how one or several methods have been used to identify and describe relevant scenarios for sequences of events and conditions that can affect the future evolution of the repository; the scenarios shall include a main scenario that takes into account the most probable changes in the repository and its environment,

Handling in SR-Can: *The scenario selection for SR-Can is provided in chapter 11.*

– the applicability of models, parameter values and other conditions used for the description and quantification of repository performance as far as reasonably achievable,

Handling in SR-Can: *This is done in the* ***Model summary report****, see e.g. section 6.5 and the* ***Data*** *report, see chapter 8.*

– how uncertainties in the description of the functions, scenarios, calculation models and calculation parameters used in the description as well as variations in barrier properties have been handled in the safety assessment, including the reporting of a sensitivity analysis which shows how the uncertainties affect the description of barrier performance and the analysis of consequences to human health and the environment.

Handling in SR-Can: *The management of uncertainties permeates the safety assessment. A plan for the management of uncertainties is given in section 2.7.3 and is further elaborated in section 11.5. Sensitivity analyses occur in a number of places in the reference evolution and the analyses of different scenarios. A general discussion on the approach to sensitivity analysis is given in section 10.11. Sensitivity of the main risk contributor to various conceptual uncertainties is analysed in section 12.7.*

The following shall be reported with respect to the analysis of post-closure conditions:

– the safety assessment in accordance with 9 § comprising descriptions of the evolution in the biosphere, geosphere and repository for selected scenarios; the environmental impact of the repository for selected scenarios, including the main scenario, with respect to defects in engineered barriers and other identified uncertainties.

Handling in SR-Can: *This is essentially the reporting of the analyses of the reference evolution in chapters 9 and 10 and of the selected scenarios in chapter 12.*

A1.2 Excerpts from SKI's general recommendations concerning SKIFS 2002:1

The Swedish Nuclear Power Inspectorate's General Recommendations concerning the Application of the Regulations concerning Safety in connection with the Disposal of Nuclear Material and Nuclear Waste (SKIFS 2002:1)

The following is the unabbreviated Recommendations relevant to 9 and 10 § and Appendix of SKI FS 2002:1, i.e. those sections that concern the safety assessment.

On 9 § and appendix

The safety of a repository after closure is analysed quantitatively, primarily by estimating the possible dispersion of radioactive substances and how it is distributed in time for a relevant selection of future possible sequences of events (scenarios). The purpose of the safety assessment is to show, inter alia, that the risks from these scenarios are acceptable in relation to the requirements on the protection of human health and the environment issued by the Swedish Radiation Protection Authority (SSIFS 1998:1). The safety assessment should also aim at providing a basic understanding of the repository performance on different time-periods and at identifying requirements regarding the performance and design of different repository components.

A ***scenario*** in the safety assessment comprises a description of how a given combination of external and internal conditions affect repository performance. Two groups of such conditions are:

- external conditions in the form of features, events and processes which occur outside repository barriers; this includes climate changes and their consequential impact on the repository environment, such as permafrost, glaciation, land subsidence and elevation as well as the impact of human activities,
- internal conditions in the form of features, events and processes which occur inside the repository; this includes properties, including defects, of nuclear material, nuclear waste and engineered barriers and related processes as well as properties of the surrounding geological formation and related processes.

Based on an analysis of the probability of occurrence of different types of scenarios in different time-periods, scenarios with a significant impact on repository performance should be divided into different categories:

- main scenario,
- less probable scenarios,
- other scenarios or residual scenarios.

The main scenario should be based on the probable evolution of external conditions and realistic, or where justified, pessimistic assumptions with respect to the internal conditions. It should comprise future external events which have a significant probability of occurrence or which cannot be shown to have a low probability of occurrence during the time covered in the safety assessment. Furthermore, it should be based, as far as possible, on credible assumptions with respect to internal conditions, including substantiated assumptions concerning the occurrence of manufacturing defects and other imperfections, and which allow for an analysis of the repository barrier functions (it is, for example, not sufficient to always base the analysis on leaktight waste containers, even if this can be shown to be the most probable case). The main scenario should be used as the starting point for an analysis of the impact of uncertainties (see below), which means that the analysis of the main scenario also includes a number of calculation cases.

Less probable scenarios should be prepared for the evaluation of scenario uncertainty (see also below). This includes variations on the main scenario with alternative sequences of events as well as scenarios that take into account the impact of future human activities such as damage inflicted on barriers. (Damage to humans intruding into the repository is illustrated by residual scenarios, see below). The analysis of less probable scenarios should include analyses of such uncertainties that are not evaluated within the framework of the main scenario.

Residual scenarios should include sequences of events and conditions that are selected and studied independently of probabilities in order to, *inter alia*, illustrate the significance of individual barriers and barrier functions. The residual scenarios should also include cases to illustrate damage to humans intruding into the repository as well as cases to illustrate the consequences of an unclosed repository that is not monitored.

Handling in SR-Can: *The methodology for selection of scenarios and its implementation is provided in chapter 11.*

The lack of knowledge and other uncertainties in the calculation conditions (assumptions, models, data) is denoted in this context as uncertainties[4]. These uncertainties can be classified as follows:

- scenario uncertainty: uncertainty with respect to external and internal conditions in terms of type, degree and time sequence,
- system uncertainty: uncertainty as to the comprehensiveness of the description of the system of features, events and processes used in the analysis of both individual barrier performance and the performance of repository as a whole,
- model uncertainty: uncertainty in the calculation models used in the analysis,
- parameter uncertainty: uncertainty in the parameter values (input data) used in the calculations,
- spatial variation in the parameters used to describe the barrier performance of the rock (primarily with respect to hydraulic, mechanical and chemical conditions).

[4] This explanation of the term uncertainty only makes sense in Swedish where the same word (säkerhet) is used to denote both certainty and safety.

There are often no clear boundaries between the different types of uncertainties. The most important requirement is that the uncertainties should be described and handled in a consistent and structured manner.

The evaluation of uncertainties is an important part of the safety assessment. This means that uncertainties should be discussed and examined in depth when selecting calculation cases, calculation models and parameters values as well as when evaluating calculation results.

Handling in SR-Can: *The management of uncertainties permeates the safety assessment. A plan for the management of uncertainties is given in section 2.7.3 and is further elaborated in section 11.5.*

The assumptions and calculation models used should be carefully selected with respect to the principle that the application and the selection should be justified through a discussion of alternatives and with reference to scientific data. In cases where there is doubt as to a suitable model, several models should be used to illustrate the impact of the uncertainty involved in the choice of model.

Handling in SR-Can: *This matter is mainly addressed in the* ***Process reports*** *and, for external influences, in the* ***Climate report****, see further chapters 6 and 5, respectively. A structured account of important selected models is given in the* ***Model summary report****. Alternative models are used to illustrate e.g. uncertainties in the hydrogeological interpretation of the Forsmark site (section 9.3.6), of the extent of buffer colloid release/erosion (e.g. section 12.3), the effect of co-precipitation of radium (section 10.5.7, covering also several other conceptual uncertainties that are addressed through the selection of alternative input data) and of near-field releases when advective conditions prevail in a deposition hole (10.6.3).*

Both deterministic and probabilistic methods should be used so that they complement each other and, consequently, provide as comprehensive a picture of the risks as possible.

Handling in SR-Can: *Most of the calculations in SR-Can are deterministic. Probabilistic calculations are used essentially as a means of handling data uncertainty and spatial variability in modelling radionuclide transport and dose, in particular in chapter 10.*

The probabilities that the scenarios and calculation cases will actually occur should be estimated as far as possible in order to calculate risk. Such estimates cannot be exact. Consequently, the estimates should be substantiated through the use of several methods, for example, assessments by several independent experts. This can be done, for example, through estimates of when different events can be expected to have occurred.

Handling in SR-Can: *Probabilities of scenarios that are not excluded from the risk summation as being "residual" are derived pessimistically. This is a component of the general approach to risk estimates, see section 2.9.2. Of relevance is also the method for scenario selection described in sections 11.3 and 11.4 and its implementation in chapter 12.*

Based on scenarios that can be shown to be especially important from the standpoint of risk, a number of ***design basis cases*** should be identified. Together with other information, such as on manufacturing method and controllability, these cases should be used to substantiate the design basis such as requirements on barrier properties.

Handling in SR-Can: *See section 13.4.*

Particularly in the case of disposal of nuclear material, for example spent nuclear fuel, it should be shown that criticality cannot occur in the initial configuration of the nuclear material. With respect to the redistribution of the nuclear material through physical and chemical processes, which can lead to criticality, it should be shown that such a redistribution is very improbable.

Handling in SR-Can: *See section 10.3 and further the* ***Fuel and canister process report****, section* 2.1.3.

The result of calculations in the safety assessment should contain such information and should be presented in such a way that an overall judgement of safety compliance with the requirements can be made.

Handling in SR-Can: *This is an overall requirement on the quality of the safety reporting, which has governed the compilation of the SR-Can report. Compliance is discussed in section 13.3.*

The validity of assumptions used, such as models and parameter values, should be supported, for example through the citing of references to scientific literature, special investigations and research results, laboratory experiments on different scales, field experiments and studies of natural phenomena (natural analogues).

Handling in SR-Can: *Justification of models, on the bases mentioned, is done in the* ***Process reports****, and for external influences, in the* ***Climate report****. A structured account of all important models is given in the* ***Model summary report****. Parameter values are justified in the* ***Data report****.*

Scientific background material and expert assessments should be documented in a traceable manner by thoroughly referring to scientific literature and other material.

Handling in SR-Can: *This is addressed in much of the documentation of SR-Can, in particular the* ***Process report****, the* ***Climate report*** *and the* ***Data report****.*

On 10 §

The time-period for which safety has to be maintained and demonstrated should be a starting point for the safety assessment. One way of discussing and justifying the establishment of such a time period is to start from a comparison of the hazard of the radioactive inventory of the repository with the hazard of radioactive substances occurring in nature. However, it should also be possible to take into consideration the difficulties of conducting meaningful analyses for extremely long time-periods, beyond one million years, in any other way than through showing how the hazard of the radioactive substances in the repository declines with time.

In the case of a repository for long-lived waste, the safety assessment may have to include scenarios which take into account greater expected climate changes, primarily in the form of future glaciations. For example, the next complete glacial cycle which is currently estimated to be on the order of 100,000 years, should be particularly taken into account.

Handling in SR-Can: *The timescale for SR-Can is discussed in section 2.4.*

In the case of periods up to 1,000 years after closure, in accordance with the regulations of SSIFS 1998:1, the dose and risk calculated for current conditions in the biosphere constitute the basis for the assessment of repository safety and its protective capabilities.

Furthermore, in the case of longer periods, the assessment can be made using dose as one of several safety indicators. This should be taken into account in connection with the calculations as well as the presentation of analysis results. Examples of such supplementary safety indicators are the concentrations of radioactive substances from the repository which can build up in soils and near-surface groundwater or the calculated flow of radioactive substances to the biosphere.

(Compare SSIFS 1998:1 and SSI's comments on those regulations).

Handling in SR-Can: *Alternative safety indicators are selected in section 2.9.3 and applied in sections 10.5.6 and 10.6.7.*

A2 SSI's Regulations and general guidance

SSI has issued Regulations concerning the Protection of Human Health and the Environment in connection with the Final Management of Spent Nuclear Fuel or Nuclear Waste (SSI FS 1998:1), see section A2.1.

SSI has also issued General Guidance concerning the application of SSI FS 1998:1, see section A2.2.

Whereas the Regulations have a clear legal status, General Recommendations are described in 1 § Ordinance on Regulatory Codes (1976:725) as: Such general recommendations on the application of regulations that stipulate how someone can or should act in a certain respect.

A2.1 SSI FS 1998:1

The Swedish Radiation Protection Institute's Regulations concerning the Protection of Human Health and the Environment in connection with the Final Management of Spent Nuclear Fuel or Nuclear Waste; decided on September 28, 1998.

On the basis of 7 and 8 §§ of the Radiation Protection Ordinance (1988:293), the Swedish Radiation Protection Institute stipulates the following.

1 § These regulations are to be applied to the final management of spent nuclear fuel or nuclear waste. The regulations do not apply to landfills for low-level nuclear waste in accordance with 19 § of the Ordinance (1984:14) on Nuclear Activities.

Definitions

2 § In these regulations, concepts are defined as follows:

- *best available technique:* the most effective measure available to limit the release of radioactive substances and the harmful effects of the releases on human health and the environment which does not entail unreasonable costs,
- *intrusion:* human intrusion into a repository which can affect its protective capability,
- *optimisation:* keeping the radiation doses to mankind as low as reasonably achievable, economic and social factors taken into account,
- *harmful effects:* cancer (fatal and non-fatal) as well as hereditary defects in humans caused by ionising radiation in accordance with paragraphs 47–51 of the International Radiation Protection Commission's Publication 60, 1990,
- *protective capability:* the capability to protect human health and the environment from the harmful effects of ionising radiation,
- *final management:* handling, treatment, transportation, interim storage prior to, and in connection with final disposal as well as the final disposal,
- *risk:* the product of the probability of receiving a radiation dose and the harmful effects of the radiation dose.

Terms and concepts used in the Radiation Protection Act (1988:220) and the Act (1984:3) on Nuclear Activities have the same meanings in these regulations.

Holistic approach etc

3 § Human health and the environment shall be protected from the harmful effects of ionising radiation, during the time when the various stages of the final management of spent nuclear fuel or nuclear waste are being implemented as well as in the future. The final management may not cause impacts on human health and the environment outside Sweden's borders that are more severe those accepted inside Sweden.

4 § Optimisation must be achieved and the best available technique shall be taken into consideration in the final management of spent nuclear fuel or nuclear waste.

The collective dose, as a result of the expected outflow of radioactive substances during a period of 1,000 years after closure of a repository for spent nuclear fuel or nuclear waste shall be estimated as the sum, over 10,000 years, of the annual collective dose. The estimate shall be reported in accordance with 10–12 §§.

Handling in SR-Can: *From SKI's and SSI's joint review of SR 97 it is noted that optimisation and best available technique are not primarily seen as issues for a safety assessment by the authorities (section 3.3.6 of /SKI/SSI 2001/). SKB broadly shares this view and the issues in 4 § are therefore only partially addressed in SR-Can. See section 13.3.4.*

Protection of human health

5 § A repository for spent nuclear fuel or nuclear waste shall be designed so that the annual risk of harmful effects after closure does not exceed 10^{-6} for a representative individual in the group exposed to the greatest risk[5].

The probability of harmful effects as a result of a radiation dose shall be calculated using the probability coefficients provided in the International Radiation Protection Commission's Publication 60, 1990.

Handling in SR-Can: *Estimation of risk and assessing compliance with the above criterion is one of the main purposes of SR-Can. Much of the methodology outlined in chapter 2 is aimed at achieving this end-point. Issues directly related to the calculation of risk are discussed in section 2.9. A discussion of compliance is given in section 13.2.1.*

[5] With respect to facilities in operation, the limitations and instructions that apply are provided in the Swedish Radiation Protection Institute's regulations (SSI FS 1991:5, amended 1997:2) concerning the limitation of releases of radioactive substances from nuclear power plants and the Swedish Radiation Protection Institute's regulations (SSI FS 1994:2, amended 1997:3) concerning health physics for activities involving ionising radiation at nuclear facilities.

Environmental protection

6 § The final management of spent nuclear fuel or nuclear waste shall be implemented so that biodiversity and the sustainable use of biological resources are protected against the harmful effects of ionising radiation.

7 § Biological effects of ionising radiation in living environments and ecosystems concerned shall be described. The report shall be based on available knowledge concerning the ecosystems concerned and shall take particular account of the existence of genetically distinctive populations such as isolated populations, endemic species and species threatened with extinction) and in general any organisms worth protecting.

Handling in SR-Can: *This issue is addressed in chapter 10, sections 10.2.5, 10.5.5 and 10.6.6. Conclusions are provided in section 13.3.3. The method for addressing this issue is under development.*

Intrusion and access

8 § A repository shall be primarily designed with respect to its protective capability. If measures are adopted to make access easier or to make intrusion difficult, the effects on the protective capability of the repository shall be reported.

9 § The consequences of intrusion into a repository shall be reported for the different time periods specified in 11–12 §§.

The protective capability of the repository after intrusion shall be described.

Handling in SR-Can: *Intrusion issues are discussed in section 5.3 and analysed in section 12.10 as further documented in the* ***FHA report****.*

Time periods

10 § An assessment of a repository's protective capability shall be reported for two time periods of orders of magnitude specified in 11–12 §§. The description shall include a case, which is based on the assumption that the biospheric conditions which exist at the time that an application for a licence to operate the repository is submitted will not change. Uncertainties in the assumptions made shall be described and taken into account in the assessment of the protective capability.

The first thousand years following repository closure

11 § For the first thousand years following repository closure, the assessment of the repository's protective capability shall be based on quantitative analyses of the impact on human health and the environment.

Period after the first thousand years following repository closure

12 § For the period after the first thousand years following repository closure, the assessment of the repository's protective capability shall be based on various possible sequences for the development of the repository's properties, its environment and the biosphere.

Handling in SR-Can (11 § and 12 §): *This is mainly addressed in the reference evolution, chapter 9, which is divided into several time frames. The first 1,000 years are treated as part of the initial temperate period. During this period, no canister failures are expected, based on the result of the analysis of the reference evolution and of additional scenarios (chapter 12). For the period after the first 1,000 years, a number of scenarios are analysed (chapters 9, 10 and 12), covering various possibilities for the repository evolution.*

Exceptions

13 § If special grounds exist, the Swedish Radiation Protection Institute may announce exceptions from these regulations.

A2.1 General guidance on SSI FS 1998:1

The Swedish Radiation Protection Authority's guidelines on the application of the regulations (SSI FS 1998:1) concerning protection of human health and the environment in connection with the final management of spent nuclear fuel and nuclear waste; decided upon on 5 September 2005.

Unofficial translation

Guidelines concerning geological disposal of spent nuclear fuel and nuclear waste

On section 1: Area of application

These guidelines are applicable to final geological disposal of spent nuclear fuel and nuclear waste. The guidelines cover measures undertaken with a view to develop, site, construct, operate and close a repository, which can affect the protective capability of the repository and environmental consequences after closure.

The guidelines are also applicable to measures that are to be undertaken with spent nuclear fuel and nuclear waste before final disposal and which can affect the protective capability of the repository and environmental consequences after closure. This includes activities at other installations such as the conditioning of waste that takes place by casting waste in concrete and by encapsulation of spent nuclear fuel, as well as transportation between installations and steering of waste to different repositories, including shallow land burials for low-level nuclear waste that are licenced in accordance with section 19 of the Ordinance (1984:14) on Nuclear Activities. However, the guidelines, like the regulations, are not applicable to the landburial itself.

On section 2: Definitions

Terms used in the Radiation Protection Act (1988:220), the Act (1984:3) on Nuclear Activities and SSI's regulations on protection of human health and the environment in connection with final management of spent nuclear fuel and nuclear waste have the same meaning in these guidelines. In addition, the following definitions are used:

Scenario:	A description of the development of the repository given an initial state and specified conditions in the environment and their development.
Exposure pathway:	The migration of the radioactive substances from a repository to a place where human beings or an organism covered by the environmental protection regulations are present. This includes dispersion in the geological barrier, transport with water and air flows, migration in ecosystems and uptake in human beings or organisms in the environment.
Risk analysis:	An analysis with the aim to clarify the protective capability of a repository and its consequences with regard to the environmental impact and the risk for human beings.

On sections 4, 8 and 9: Holistic approach etc, intrusion and access

Optimisation and best available technique

The regulations require that optimisation must be performed and that best available technique should be taken into account. Optimisation and best available technique should be applied in parallel with a view to improving the protective capability of the repository.

Measures for optimisation of a repository should be evaluated on the basis of calculated risks.

Application of best available technique in connection with final disposal means that the siting, design, construction, operation and closure of the repository and appurtenant system components should be carried out so as to prevent, limit and delay releases from both engineered and geological barriers as far as is reasonably possible. When striking balances between different measures, an overall assessment should be made of their impact on the protective capability of the repository.

In cases where considerable uncertainty is attached to the calculated risks, for instance, in analyses of the repository a long time after closure, or analyses made at an early stage of the development work with the repository system, greater weight should be placed on best available technique.

In the event of any conflicts between application of optimisation and best available technique, priority should be given to best available technique.

Experiences from recurrent risk analyses and the successive development work with the repository should be used in the application of optimisation and best available technique.

Handling in SR-Can: *From SKI's and SSI's joint review of SR 97 it is noted that optimisation and best available technique are not primarily seen as issues for a safety assessment by the authorities (section 3.3.6 of /SKI/SSI 2001/). SKB broadly shares this view and the issues of optimisation and BAT are therefore only partially addressed in SR-Can. See section 13.3.4.*

Collective dose

The regulations require an account of the collective dose from releases that take place during the first thousand years after closure. For final disposal the collective dose should also be used in comparisons between alternative repository concepts and sites. The collective dose need not be reported if the repository concept entails a complete isolation of the spent nuclear fuel or the nuclear waste in engineered barriers during the first thousand years after closure.

Handling in SR-Can: *Collective dose is not accounted for since the concept under consideration entails a complete isolation during the first thousand years after closure.*

Occupational radiation protection

An account should be given of measures undertaken for radiation protection of workers that may have a negative impact on the protective capability of the repository or make it more difficult to assess.

Handling in SR-Can: *No such measures have been identified in SR-Can.*

Future human action and the preservation of information

When applying best available technique, consideration should also be given to the possibility to reduce the probability and consequences of inadvertent future human impact on the repository, for instance, inadvertent intrusion. Increased repository depth and avoidance of sites with extractable mineral assets may, for instance, be considered to decrease the probability of unintentional human intrusion.

Handling in SR-Can: *Ore potential is evaluated for the analysed sites, see section 4.3. This information is propagated to the analyses of FHA-scenarios in section 12.10. Inadvertent intrusion is discussed as one of many factors when feedback is given to the selection of repository depth in section 13.6.8.*

Preservation of knowledge about the repository could reduce the risk of future human impact. A strategy for preservation of information should be produced so that measures can be undertaken before closure of the repository. Examples of information that should be taken into consideration are information about the location of the repository, its content of radioactive substances and design.

Handling in SR-Can: *The production of such a strategy is not an issue for the safety assessment. Work is in progress elsewhere within SKB and the results will be presented prior to the submission of an application for a final repository.*

On sections 5–7: Protection of human health and the environment

Risk for the individual from the general public

The relationship between dose and risk

According to the regulations, the recommendations of the International Commission on Radiological Protection (ICRP) are to be used for calculation of the harmful effects of ionizing radiation. According to ICRP Publication No. 60, 1990, the factor for conversion of effective dose to risk is 7.3% per sievert.

The regulation's criterion for individual risk

According to the regulations, the risk for harmful effects for a representative individual in the group exposed to the greatest risk (the most exposed group) shall not exceed 10^{-6} per year. Since the most exposed group cannot be described in an unambiguous way, the group should be regarded as a way of quantifying the protective capability of the repository.

One way of defining the most exposed group is to include the individuals that receive a risk in the interval from the highest risk down to a tenth of this risk. If a larger number of individuals can be considered to be included in such a group, the arithmetic average of individual risks in the group can be used for demonstrating compliance with the criterion for individual risk in the regulations. One example of such exposure situation is a release of radioactive substances into a large lake that can be used as a source of drinking water and for fishing.

If the exposed group only consists of a few individuals, the criterion of the regulations for individual risk can be considered as being complied with if the highest calculated individual risk does not exceed 10^{-5} per year. An example of a situation of this kind might be if consumption of drinking water from a drilled well is the dominant exposure path. In such a calculation example, the choice of individuals with the highest risk load should be justified by information about the spread in calculated individual risks with respect to assumed living habits and places of stay.

Handling in SR-Can: *The suggested definition where the group includes the individuals that receive a risk in the interval from the highest risk down to a tenth of this risk is adopted in SR-Can, see section 10.2.3.*

Averaging risk over a lifetime

The individual risk should be calculated as an annual average on the basis of an estimate of the lifetime risk for all relevant exposure pathways for every individual. The lifetime risk can be calculated as the accumulated lifetime dose multiplied by the conversion factor of 7.3% per sievert.

Handling in SR-Can: *This approach is used in SR-Can, see section 10.2.3. However, as mentioned in section 10.2.3, to avoid speculations about the age of the most exposed individual the maximum dose conversion factor for all age groups are used /Avila and Bergström 2006/, which thus overestimates the risk.*

Averaging risk between generations

Deterministic and probabilistic calculations can both be used to illustrate how risk from the repository develops over time. A probabilistic analysis can, however, in certain cases give an insufficient picture of how an individual detrimental event, for instance, a major earthquake, would affect the risk for a particular generation. The probabilistic calculations should in this case be supplemented as specified in Appendix 1.

Handling in SR-Can: *This so called risk dilution phenomenon is addressed in general terms in section 2.9.2, subheading "*Risk dilution*" and analysed in sections 10.5.10, 10.6.10 and 10.7.1 under the same subheading, for three failure modes of the canister.*

Selection of scenarios

The assessment of the protective capability of the repository and the environmental consequences should be based on a set of scenarios that together illustrate the most important courses of development of the repository, its surroundings and the biosphere.

Handling of climate evolution

Taking into consideration the great uncertainties associated with the assumptions on climate evolution in a remote future and to facilitate the interpretation of the risk to be calculated, the risk analysis should be simplified to include a few possible climate evolutions.

A realistic set of biosphere conditions should be associated with each climate evolution. The different climate evolutions should be selected so that they together illustrate the most important and reasonably foreseeable sequences of future climate states and their impact on the protective capability of the repository and the environmental consequences. The choice of the climate evolutions that serve as the basis for the analysis should be based on a combination of sensitivity analyses and expert judgements. Additional guidance is provided in the section with guidelines on sections 10–12.

The risk from the repository should be calculated for each assumed climate evolution by summing the risk contributions from a number of scenarios that together illustrate how the more or less probable courses of development in the repository and the surrounding rock affects the repository's protective capability and environmental consequences. The calculated risk should be reported and evaluated in relation to the criterion of the regulations for individual risk, separately for each climate evolution. The repository should thus be able to be shown to comply with the risk criterion for the alternative climate evolutions. If a lower probability than one (1) is stated for a particular climate evolution, this should be justified, for instance, by expert judgements.

Handling in SR-Can: *The method for selection of scenarios is described in section 11.3. A reference climate evolution is used in the definition of a base variant of the main scenario. In a greenhouse variant of the main scenario, a climate perturbed by the effects of anthropogenic greenhouse gas emissions is assumed. In the analyses of each of the additional scenarios in chapter 12, both these variants are considered. In addition, for each scenario, the impact of uncertainties regarding the climate related factors of concern in that particular scenario, are analysed. The results of all these scenarios are considered in the risk summation.*

Future human action

A number of scenarios for inadvertent human impact on the repository should be presented. The scenarios should include a case of direct intrusion in connection with drilling in the repository and some examples of other activities that indirectly lead to a deterioration in the protective capability of the repository, for example by changing groundwater chemistry or the hydrological conditions in the repository or its surroundings. The selection of intrusion scenarios should be based on present living habits and technical prerequisites and take into consideration the repository's properties.

The consequences of the disturbance of the repository's protective capability should be illustrated by calculations of the doses for individuals in the most exposed group, and reported separately apart from the risk analysis for the undisturbed repository. The results should be used to illustrate conceivable countermeasures and to provide a basis for the application of best available technique (see guidelines on optimisation and best available technique).

An account need not be given of the direct consequences for the individuals intruding into the repository.

Handling in SR-Can: *The above approach is used in SR-Can, see section 12.10. The results have, however, not been used to illustrate conceivable countermeasures or to provide a basis for the application of BAT within SR-Can.*

Special scenarios

For repositories primarily based on isolation of the spent nuclear fuel or nuclear waste, an analysis of a conceivable loss, during the first thousand years after closure, of one or more barrier functions of key importance for the protective capability should be made separately from the risk analysis. The intention of this analysis should be to clarify how the different barriers contribute to the protective capability of the repository.

Handling in SR-Can: *Such an analysis is provided in section 10.10.*

Biosphere conditions and exposure pathways

The future biosphere conditions for calculations of consequences on human beings and the environment should be selected in agreement with the assumed climate state. Unless it is clearly unreasonable, however, today's biosphere conditions at the repository and its surroundings should be evaluated, i.e. agricultural land, forest, wetland (mire), lake, sea or other relevant ecosystems. Furthermore, consideration should be taken to land uplift (or subsidence) and other predictable changes.

The risk analysis can include a limited selection of exposure paths, although the selection of these should be based on an analysis of the diversity of human use of environmental and natural resources which can occur in Sweden today. Consideration should also be taken to the possibility of individuals being exposed to combinations of exposure pathways within and between different ecosystems.

Handling in SR-Can: *The above approach is used in SR-Can, see section 10.2. Concentrations are determined and compared to screening limits. For the few cases where these limits are exceeded, the further handing remains to be developed. This will be done within the internationally ongoing work in this field, in which SKB takes part.*

Environmental protection

The description of exposure pathways should also include exposure pathways to certain organisms in the ecosystems that should be included in the risk analysis. The concentration of radioactive substances in soil, sediment and water should be accounted for where this is relevant for the respective ecosystem.

When a biological effect for the identified organisms can be presumed, a valuation should be made of the consequence this may have for the affected ecosystems, with the view to facilitating an assessment of impact on biological diversity and a sustainable use of the environment.

The analysis of consequences for organisms in "today's biosphere", carried out as above, should be used for the assessment of environmental consequences in a long-term perspective. For assumed climates, where the present biosphere conditions are evidently unreasonable, for instance, a colder climate with permafrost, it is sufficient to make a survey based on knowledge currently available about applicable ecosystems. Additional guidelines are contained in Appendix 2.

Handling in SR-Can: *The approach used in SR-Can is explained in section 10.2.5.*

Reporting of uncertainties

Identification and assessment of uncertainties in for instance, site-specific and generic data and models should take place in accordance with the instructions given in general recommendations from the Swedish Nuclear Power Inspectorate. The different categories of uncertainties, which are specified there, should be evaluated and reported on in a systematic way and evaluated on the basis of their importance for the result of the risk analysis. The report should also include a motivation of the methods selected for handling different types of uncertainties, for instance, in connection with the selection of scenarios, models and data. All calculation steps with appurtenant uncertainties should be reported on.

Peer review and expert panel elicitation can, in the cases where the basic data is insufficient, be used to strengthen the credibility of assessments of uncertainties in matters of great importance for the assessment of the protective capability of the repository.

Handling in SR-Can: *The approach to handling of uncertainties is described in section 2.7 and further developed in section 11.5.*

On sections 10–12: Time periods

Two time periods are defined in the regulations: the period up to a thousand years after closure and the subsequent period.

For longer time periods, the result of the risk analysis should be successively regarded more as an illustration of the protective capability of the repository given certain assumptions.

Limitation of the risk analysis in time

The following principles should provide guidance for the limitation of the risk analysis in time:

1. For a repository for spent nuclear fuel, or other long-lived nuclear waste, the risk analysis should at least include approximately one hundred thousand years or the period for a glaciation cycle to illustrate reasonably predictable external strains on the repository. The risk analysis should thereafter be extended in time as long as it provides important information about the possibility of improving the protective capability of the repository, although at the longest for a time period of up to one million years.
2. For other repositories for nuclear waste, than those referred to in point 1, the risk analysis should at least cover the time until the expected maximum consequences in terms of risk and environmental impact have taken place, although at the longest for a period of time up to one hundred thousand years.

The arguments for the selected limitations of the risk analysis should be presented.

Handling in SR-Can: *The assessment period in SR-Can is one million years, see section 2.4.*

Reporting on the first thousand years after closure

The period of time of a thousand years should be regarded as the approximate time period for which a risk analysis can be carried out with high credibility with regard to factors such as climate and biosphere conditions. For this time period, available measurement data and other knowledge about the initial conditions should be used for a detailed analysis and reporting on the development of the protective capability of the repository and its surroundings.

The conditions and processes during the early development of the repository, which can affect its long-term protective capability, should be described in as much detail as possible. Examples of such conditions and processes are the resaturation of the repository, stabilisation of hydrogeological and geochemical conditions, thermal evolution and other transient events.

Biosphere conditions and known trends in the surroundings of the repository should also be described in detail, partly to be able to characterise "today's biosphere" (see guidelines to section 5), and partly to be able to characterise the conditions applicable to a conceivable early release from the repository. Known trends here refer, for instance, to land uplift (or subsidence), any trends in climate evolution and appurtenant changes in use of land and water.

Handling in SR-Can: *The above approaches are used in SR-Can, in particular in the analysis of the reference evolution, where the first thousand years after closure are included in the detailed evaluation of the excavation/operation phase, section 9.2, and of the initial temperate period, section 9.3. The landscape development is considered in the biosphere modelling, see further section 10.2. See also the discussion of compliance for this time period in section 13.3.2.*

Reporting on very long time periods

Up to one hundred thousand years

Reporting should be based on a quantitative risk analysis in accordance with the guidelines to sections 5-7. Supplementary indicators of the repository's protective capability, such as barrier functions, radionuclide fluxes and concentrations in the environment, should be used to strengthen the confidence in the calculated risks.

The given period of time of one hundred thousand years is approximate and should be selected in such a way that the effect of expected large climate changes, for instance, a glaciation cycle, on the protective capability of the repository and consequences to the surroundings can be illustrated.

Handling in SR-Can: *The above approach is used in SR-Can, in particular in the analysis of the first glacial cycle after closure, as part of the reference evolution, see section 9.4. See also the discussion of compliance for this time period in section 13.3.2.*

Beyond one hundred thousand years

The risk analysis should illustrate the long-term development of the repository's barrier functions and the importance of major external disturbances on the repository such as earthquakes and glaciations. Taking into consideration the increasing uncertainties over time, the calculation of doses to people and the environment should be made in a simplified way with respect to climate development, biosphere conditions and exposure pathways. Climate development can simplified be described as a repetition of identical glaciation cycles.

A strict quantitative comparison of calculated risk in relation to the criterion for individual risk in the regulations is not meaningful. The assessment of the protective capability of the repository should instead be based on reasoning on the calculated risk together with several supplementary indicators of the protective capability of the repository such as barrier functions, radionuclide fluxes and concentrations in the environment. If the calculated risk exceeds the criterion of the regulations for individual risk or if there are other indications of substantial disruptions of the protective capability of the repository, the underlying causes of this should be reported on as well as possible measures to improve the protective capability of the repository.

Handling in SR-Can: *The above approach is used in SR-Can, in particular in the analysis of the period after the first glacial cycle up to one million years, as part of the reference evolution, see section 9.5. See also the discussion of compliance for this time period in section 13.3.2.*

Summary of arguments for demonstrating compliance with the requirements of the regulations

The reporting should include an account of how the principles for optimisation and the best possible technique have been applied in the siting and design of the repository and appurtenant system components and how quality assurance has been used in the work with the repository and appurtenant risk analyses.

Handling in SR-Can: *Regarding the account of optimisation and BAT in the safety assessment, see above and section 13.3.4. Quality assurance for the safety assessment is accounted for in section 2.8.*

The arguments for the protective capability of a repository should be evaluated and reported on in a systematic way. The reporting should include a logically structured argument for the protective capability of the repository with information on calculated risks, uncertainties in the calculations made and the credibility of the assumptions made. To provide a good understanding of the results of the risk analysis, it should be evident how individual scenarios contribute to the risk from the repository.

Handling in SR-Can: *The arguments for the protective capability of the repository are provided in the discussion of compliance in section 13.3, and in the various parts of the analysis that support the conclusions in that section.*

SWEDISH RADIATION PROTECTION AUTHORITY

LARS-ERIK HOLM

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Appendix 1. Guidelines on the averaging of risk between generations

For certain exposure situations an annual risk, calculated as an average of all conceivable outcomes of a probabilistic risk assessment, provides an insufficient picture of how risk is allocated between future generations. This applies in particular to events which:

- can be assessed as leading to doses during a limited period of time in relation to the time period covered by the risk analysis,
- if they arise, can be assessed as giving rise to a conditional individual risk exceeding the criterion in the regulations for individual risk,
- can be assessed as having such a high probability of occurring during the time period covered by the risk analysis that the product of this probability and the calculated conditional risk is of the same order of magnitude as, or larger than, the criterion for individual risk in the regulations.

For exposure situations of this kind, a probabilistic calculation of risk should be supplemented by calculating the risk for the individuals who are assumed to live after the event has taken place and who are affected by its calculated maximum consequence. The calculation can be made for instance by illustrating the importance of an event occurring at different times (T_1, T_2, …, T_n), taking into consideration the probability of the event occurring during the respective time interval (T_0 to T_1, T_0 to T_2, …, T_0 to T_n, where T_0 corresponds to the time of closure of the repository). The results from these, or similar calculations, can in this way be expected to provide an illustration of the effects of the spreading of risk between future generations and should, together with other risk calculations, be reported on and evaluated in relation to the regulation's criterion for individual risk.

Annex 2. Guidelines on the evaluation of environmental protection

The organisms included in the analysis of the environmental impact should be selected on the basis of their importance in the ecosystems, but also according to their protection value according to other biological, economic or conservation criteria. Other biological criteria refers, among other things, to genetic distinctiveness and isolation (for example, presently known endemic species), economic criteria refers to the importance of the organisms for different kinds of obtaining a livelihood (for instance, hunting and fishing), and conservation criteria if they are protected by current legislation and local regulations. Other aspects, for instance, cultural history, should also be taken into consideration account in the identification of such organisms.

The assessment of effects of ionising radiation in selected organisms, deriving from radioactive substances from a repository, can be made on the basis of the general guidance provided in the International Committee for Radiation Protection's (ICRP) Publication 91[6]. The applicability of the knowledge and databases used for the analyses of dispersion and transfer of radioactive substances in ecosystems and for analysing the effects of radiation on different organisms should be assessed and reported on.

[6] A Framework for Assessing the Impact of Ionising Radiation on Non-human Species, ICRP Publication 91, Annals of the ICRP 33:3, 2003.

Appendix B

Miscellaneous calculation models

Canister corrosion for an intact buffer

The concept of equivalent flow rate, Q_{eq}, /Neretnieks 1979/ is used to quantify exchange of solutes between the flowing groundwater in the rock and the deposition hole. The expression used to calculate the canister corrosion rate, R, for the case of an intact buffer is

$$R = \left[HS^{-}\right] \cdot Q_{eq} \cdot \frac{BufferConcentrationFactor}{2\pi r_{Can} h_{Can}} \frac{fM_{Cu}}{\rho_{Cu}}$$

where R [m/yr] is the corrosion rate,

Q_{eq} [m^3/yr] is the equivalent flow rate as obtained from hydrogeological calculations, including effects of spalling, as further explained in the **Data report**, section 6.6.

BufferConcentrationFactor = 7 [–] accounts for the fact that the corrosion attack is concentrated to the section of the canister side closest to the fracture /Liu 2006, text below Figure 3, p. 19/,

r_{Can} = 0.525 m and h_{Can} = 5 m are the radius and the height of the canister, respectively,

$[HS^{-}]$ [kmoles/m^3] is the sulphide concentration in the groundwater,

ρ_{Cu} = 8,920 kg/m^3 is the density of copper,

M_{Cu} = 63.55 kg/kmoles is the molar mass of copper and

f is a stoichiometric factor equal to 2 in the case of sulphide corrosion, see section 9.3.12, subheading "Corrosion during the initial 1,000 years".

It is noted that the transport resistance offered by the buffer is not included in the above expression since it adds little to the resistance offered by the slow rate of groundwater flow.

Buffer erosion/colloid release

The calculations of buffer erosion/colloid release rate R_{Buffer}, in section 9.4.8, subheading "Colloid release from buffer and backfill" is done using the expression

$R_{Buffer} = C_{Max} \cdot Q_q$

where C_{Max} = 50 kg/m^3 is the maximum observed concentration of bentonite in a water suspension and Q_{eq} is the equivalent flow rate as above.

As noted in section 9.4.8, there are considerable conceptual uncertainties regarding this process and thus how it should be quantified.

Canister corrosion for an eroded buffer

This subsection describes how the canister corrosion rate for a partially eroded buffer is calculated in SR-Can.

When corrosion commences, the height of the eroded zone of the buffer, h_{Zone}, is assumed to be equal to the thickness of the buffer, i.e. 0.35 m. This assumption is a rough estimate based on the results of the swelling calculations reported in section 9.3.9 and is also obtained if one crudely assumes that the buffer lost through the fracture originates from a region that is equally high along the deposition hole wall as deep in the axial direction from the mouth of the fracture. Furthermore, a half-cylindrical volume of the buffer is assumed to be eroded away and half the circumference of the canister side on the upstream side of the flow is assumed to be exposed and evenly corroded. This accounts for the unequal erosion on the up- and downstream sides and also for the fact that the upstream side of the canister wall will be more exposed to corroding agents entering the deposition hole. Thus the corroded area, A, of the canister is

$A = h_{Zone} \cdot \pi \cdot r_{Can}$

and the eroded volume, V_{Zone}, is taken to be

$V_{Zone} = h_{Zone} \cdot \pi \cdot (r^2_{DepHole} - r^2_{Can})/2$

It is noted that the estimate of the geometry of the eroded zone is crude. It is possible to envisage temporarily smaller values of A thus concentrating the corrosion attack further, but, as erosion continues, A and V_{zone} are likely to grow beyond the estimates given here and this results in lower corrosion rates as a larger part of the canister surface is exposed.

When advective conditions prevail in the part of the deposition hole where the buffer is lost, the corrosion rate will be proportional to the equivalent flow rate for the deposition hole, Q_{eq}, times the concentration of corroding agents in the groundwater /Neretnieks 2006a/. For low and moderate flow rates, q, all corroding agents carried by the flowing water will attack the canister, hence $Q_{eq} = q$.

If the flow rate is sufficiently high, the residence time of the corroding agents in the deposition hole is too short to allow all corroding agents to contact the canister. In that case, Q_{eq} is given by /Neretnieks 2006a, Equation (8)/.

Furthermore, the flow rate, q, for a deposition hole with intact buffer needs to be multiplied by a *FlowFactor*, approximately equal to 2 /Neretnieks 2006a/, to account for the lost flow resistance in the eroded buffer.

The corrosion rate, R, is then given by

$$R = \frac{CQ_{eq} f M_{Cu}}{A \rho_{Cu}}$$

where C [kmoles/m^3] is the concentration of corroding agents in the groundwater, A [m^2] is the exposed canister surface area defined above, ρ_{Cu} = 8,920 kg/m^3 is the density of copper, M_{Cu} = 63.55 kg/kmoles is the molar mass of copper and f is a stoichiometric factor equal to 2 in the case of sulphide corrosion, see section 9.3.12, subheading "Corrosion during the initial 1,000 years".

In the calculations of copper corrosion, q is obtained from the calculation results of the hydrogeological model. Deposition holes are excluded if they are *i)* intersected by fractures longer than 1,000 m, or if *ii)* they fulfil the FPC criterion, or if *iii)* the particle released to the Q1 fracture does not exit the geosphere (see note in Table 10-10).

Geosphere transmission

Geosphere transmission is calculated in sections 10.5.9 and 10.6.9 using Equation (64) in /Hedin 2002b/, with the substitutions given in Table V in /Hedin 2002b/. Furthermore, the fracture half-width, b, in /Hedin 2002b/ is obtained as $b = t_w/F$, where t_w and F are the advective travel time and the geosphere transport resistance as obtained from the hydrogeological calculations. F is divided by 10 to account for channelling.

Peak pulse height

The expression for calculation of the peak amplitude of the release curve for a pulse release inlet to the geosphere in section 10.6.3 is derived from Equation (65) in /Hedin 2002b/ setting $\lambda = 0$.

The time of occurrence of the peak, τ_{geo}, is given by Equation (66) in /Hedin 2002b/, which, in the limit of $\lambda \rightarrow 0$, becomes

$$\tau_{geo} = \frac{R_f z}{v} - \frac{1}{6}\left(\frac{R_f z}{A_R v}\right)^2.$$

This expression is inserted in Equation (65), yielding, with the transformations given in Table V in /Hedin 2002b/ the expression used in section 10.6.3. (The fracture half-width, b, in /Hedin 2002b/ is obtained as in the subsection "Geosphere transmission" above.)

Release model for a deposition hole with advective conditions

This subsection describes the model used for calculations of radionuclide near-field releases for advective conditions in the deposition hole, sections 10.6.3 and 10.6.5. Benchmarking of the analytic models for both near-field and geosphere releases are also presented.

For a species with a time-dependent inventory of activity $A(t)$ embedded in the fuel matrix, the release rate R from the fuel, assumed to have a dissolution rate D_F is

$$R = A(t)D_F$$

valid until the fuel matrix is completely dissolved, after which time the release rate is zero.

For an in-growing species, $A(t)$ is given by the solutions to the Bateman equations, see e.g. /Hedin 2002b, Equation (40) (expressed in mass rather than activity)/.

In general, all nuclides released from the fuel matrix are assumed to be released to the geosphere so that the release rate from the near field is given by R.

For the two model alternatives discussed in sections 10.6.3 and 10.6.5, uranium in the first model and uranium and thorium in the second model is assumed to be confined to the near field due to precipitation, sorption and crystallisation processes. This means that the fraction of these elements released from the fuel matrix is subsequently confined and generates daughter nuclides that are accessible for release at the same rate as they are generated. Here, the total activity precipitated as a function of time is simply

$$A^{preciptated}(t) = A(t)D_F\, t$$

until the entire fuel matrix is dissolved at time $1/D_F$ after the onset of fuel dissolution. For example, a precipitated parent nuclide of U-234 in the first model alternative will generate releases of Th-230 according to

$$R_{Th-234} = A_{U-234}^{precipitated}(t)\frac{\lambda_{Th-230}}{\lambda_{U-234}}$$

Similarly, the release rate of Ra-226 in the second model is

$$R_{Ra-226} = A_{Th-230}^{precipitated}(t)\frac{\lambda_{Ra-226}}{\lambda_{Th-230}}$$

In addition to these releases, Th-230 in the first model and Ra-226 in the second are released according to their release rates directly from the fuel matrix, as for all other species, as explained above.

Thus all elements except U in the first model and U and Th in the second are assumed to not precipitate.

Benchmarking

The first model, assuming precipitation of uranium only, has been benchmarked against a numerical calculation with the COMP23 model using Compulink assuming the same concentration limits in the 1 m^3 canister void as for the pinhole failure case, a flow rate out of the canister of 0.3 m^3/yr and otherwise data as for the deterministically calculated case in Figure 10-40 in section 10.6.5. The assumed flow rate essentially means that nuclides are released at the same rate as they enter the canister void. The agreement is very good for both the directly released species and the thorium isotopes, which have a considerable contribution from precipitated uranium isotopes.

Figure B-1 shows a similar benchmark case for the second model. Again, the agreement is very good for all significant radionuclides. This agreement is expected as the modelled situation is simple and straight-forward to express analytically.

Geosphere transport is expressed as a simple transmission expression, the same as described above in this Appendix and used to evaluate geosphere retention properties in sections 10.5.9 and 10.6.9.

Figure B-2 shows a benchmark case of probabilistically calculated geosphere releases for the second model, using the numerical models COMP23 and FARF31. The corresponding calculation with the model described above is shown in Figure 10-42, section 10.6.5 and the two are in very good agreement.

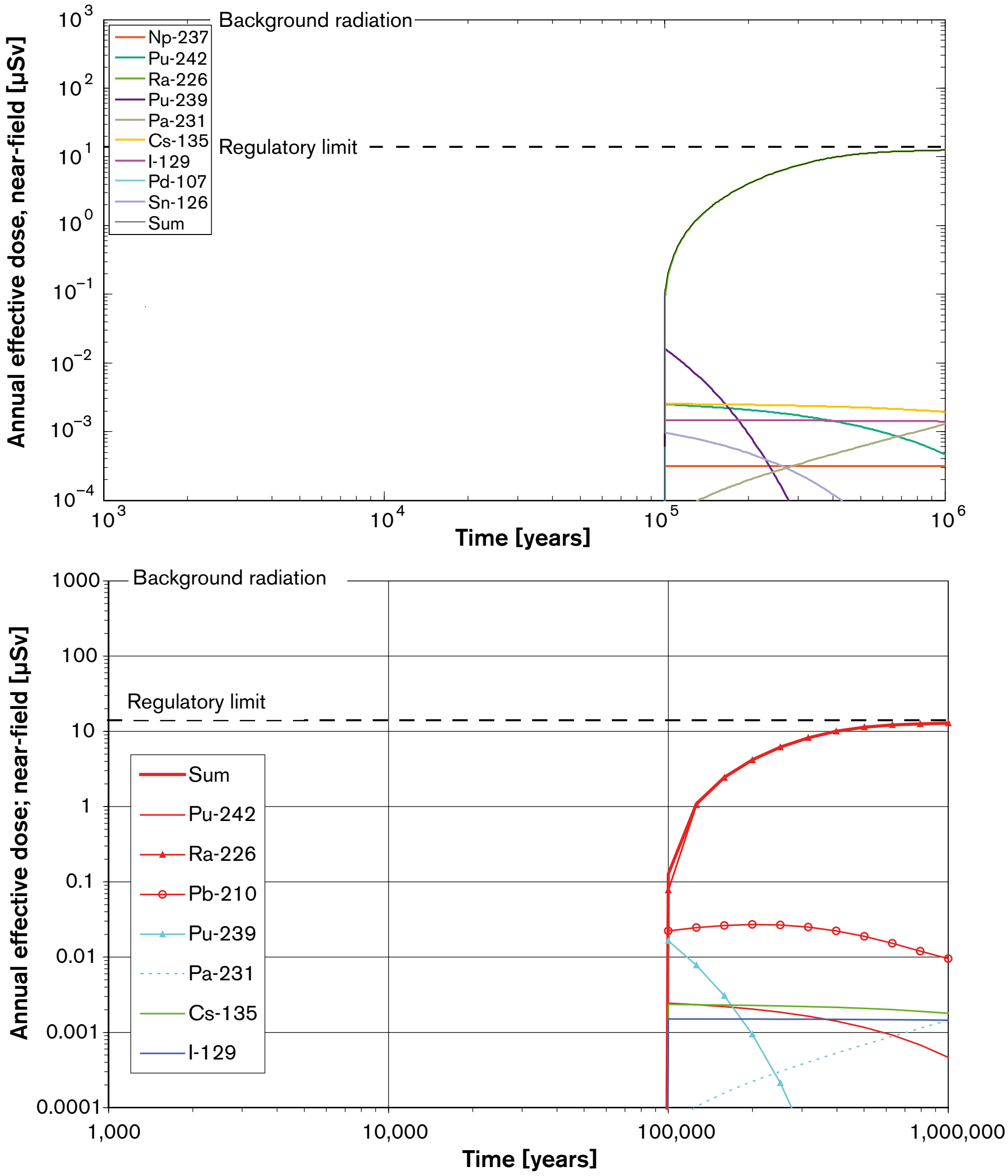


Figure B-1. *Near-field releases converted to dose for the model where Th-230 is confined in the canister and its daughter nuclide, Ra-226, is released. Upper: numerical calculation using COMP23. Lower: Analytical calculation using the model described above.*

Permafrost depth

The analytical permafrost calculation mentioned in section 9.4.1, subheading "Reference evolution at Forsmark and Laxemar", is briefly described below and a benchmark calculation is provided.

Consider a semi-infinite sold, extending in the positive z direction, of thermal conductivity λ, heat capacity K, density ρ and thus thermal diffusivity

$$\kappa = \frac{\lambda}{K\rho}$$

Assume further that the surface temperature varies as $\phi(t)$, the initial temperature is $f(z)$ and that radiogenic heat production occurs at a rate decreasing with depth according to

$A_0 \exp(-\alpha z)$.

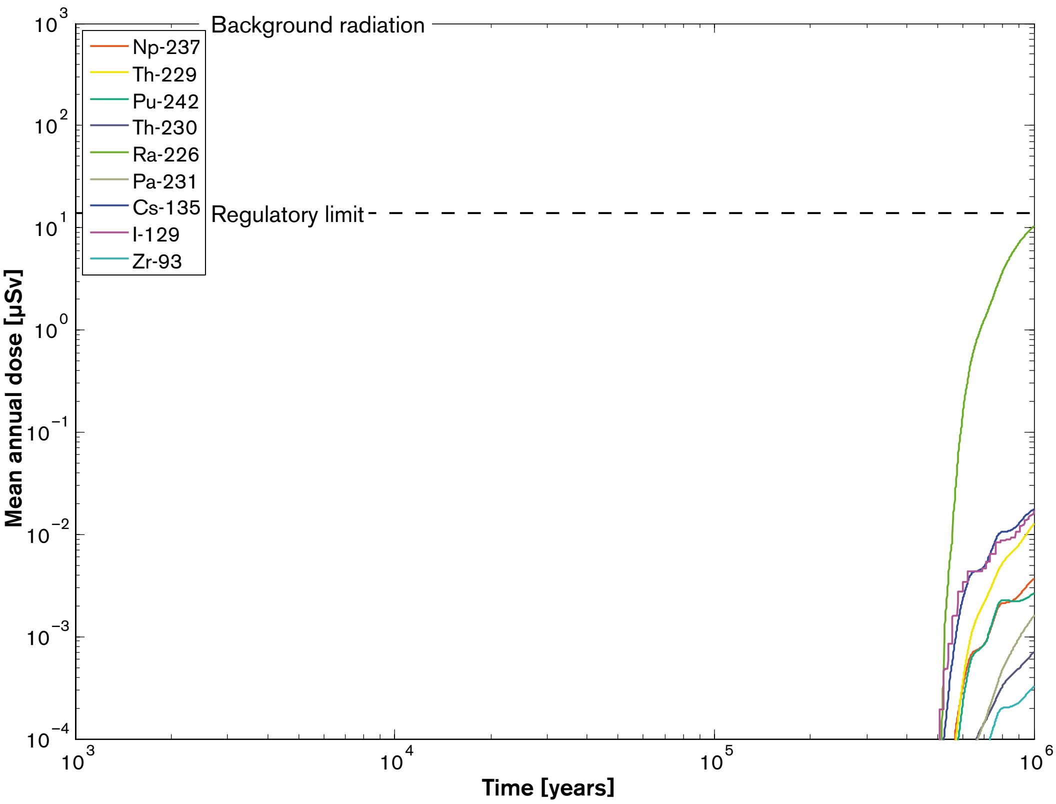


Figure B-2. *Probabilistically calculated geosphere release for the model where Th-230 is confined to the canister and its daughter nuclide, Ra-226 is released. Numerical calculation using COMP23 and FARF31.*

Consider first the case of zero surface temperature, no radiogenic heat production and initial temperature $f(z)$. This problem has the general solution /Carslaw and Jaeger 1959, section 2.4, Equation (1)/

$$T(z,t) = \frac{1}{2\sqrt{\pi\kappa t}} \int_0^\infty f(z')\left[\exp\left(-(z-z')^2/4\kappa t\right) - \exp\left(-(z+z')^2/4\kappa t\right)\right] dz'$$

For the case of linearly increasing initial temperature $f(z) = a + bz$, the solution is /Carslaw and Jaeger 1959, section 2.4, Equation (13)/

$$T(z,t) = a \cdot erf\left(\frac{z}{2\sqrt{\kappa t}}\right) + b \cdot z \qquad (1)$$

Consider now the case of zero initial temperature, no radiogenic heat production and surface temperature $\phi(t)$. This case has the solution /Carslaw and Jaeger 1959, section 2.5, Equation (1)/

$$T(z,t) = \frac{z}{2\sqrt{\pi\kappa}} \int_0^t \phi(\tau) \frac{\exp\left(-z^2/4\kappa(t-\tau)\right)}{(t-\tau)^{\frac{3}{2}}} d\tau$$

From this general case, it follows that the solution for the case $\phi(t) = T_1$ for $t_1 < t < t_2$ and zero otherwise is

$$T(z,t) = \left[H(t-t_1)\, erfc\left(\frac{z}{2\sqrt{\kappa(t-t_1)}}\right) - H(t-t_2)\, erfc\left(\frac{z}{2\sqrt{\kappa(t-t_2)}}\right)\right]$$

where $H(\cdot)$ is the unit step function.

If the surface temperature is given at a number of points in time as (T_i, t_i), the above form can be used to express the temperature at time t_k as

$$T(z,t_k) = \sum_{i=0}^{k-1} (T_{i+1} - T_i)\, erfc\left(\frac{z}{2\sqrt{\kappa(t-t_i)}}\right) H(t-t_i) \qquad (2)$$

Consider now the case of zero initial temperature, zero surface temperature and radiogenic heat production according to $A_0 \exp(-\alpha z)$. This case has the solution /Carslaw and Jaeger 1959, section 2.11, Equation (3)/

$$T(z,t) = \frac{A_0}{K\alpha^2}\left[erfc\left(\frac{z}{2\sqrt{\kappa t}}\right) - \exp(-\alpha z) + \frac{1}{2}\exp(\kappa\alpha^2 t - \alpha z)\, erfc\left(\alpha\sqrt{\kappa t} - \frac{z}{2\sqrt{\kappa t}}\right) \right.$$
$$\left. - \frac{1}{2}\exp(\kappa\alpha^2 t + \alpha z)\, erfc\left(\alpha\sqrt{\kappa t} + \frac{z}{2\sqrt{\kappa t}}\right)\right] \qquad (3)$$

The combined case of interest for permafrost depth calculations includes radiogenic heat production according to the above, varying surface temperature and initial temperature increasing with depth. Since heat conduction is linear, the solution can be composed of solutions to the simpler problems, i.e. $T(z,t)$ is given by the sum of Equations (1), (2) and (3). A benchmark calculation, comparing results obtained with the above model with results from the same numerical model as used in section 9.4.1 is shown in Figure B-3 below. The comparison is made for a case with unrealistically low surface temperature.

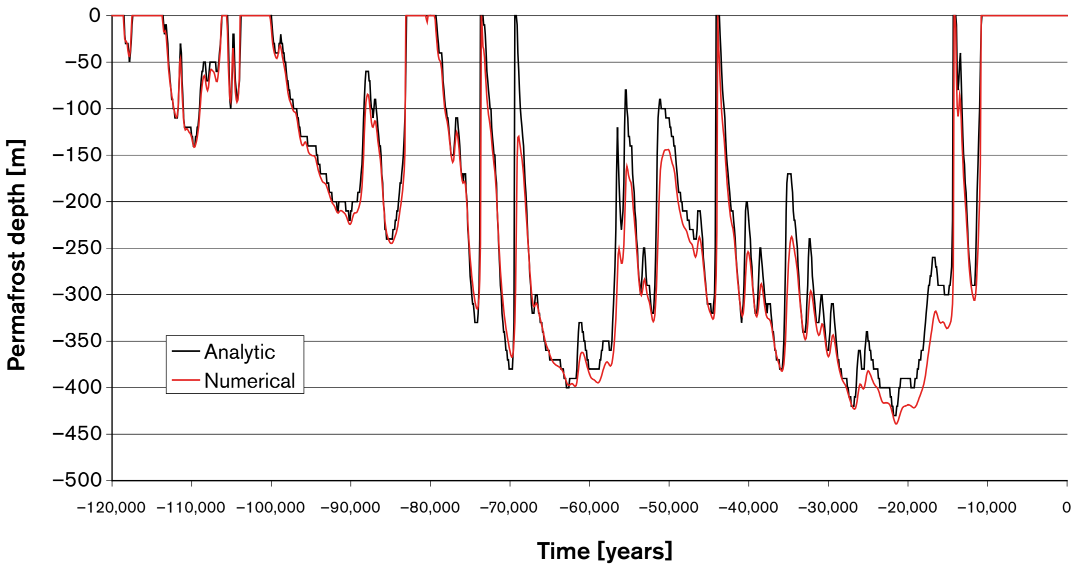
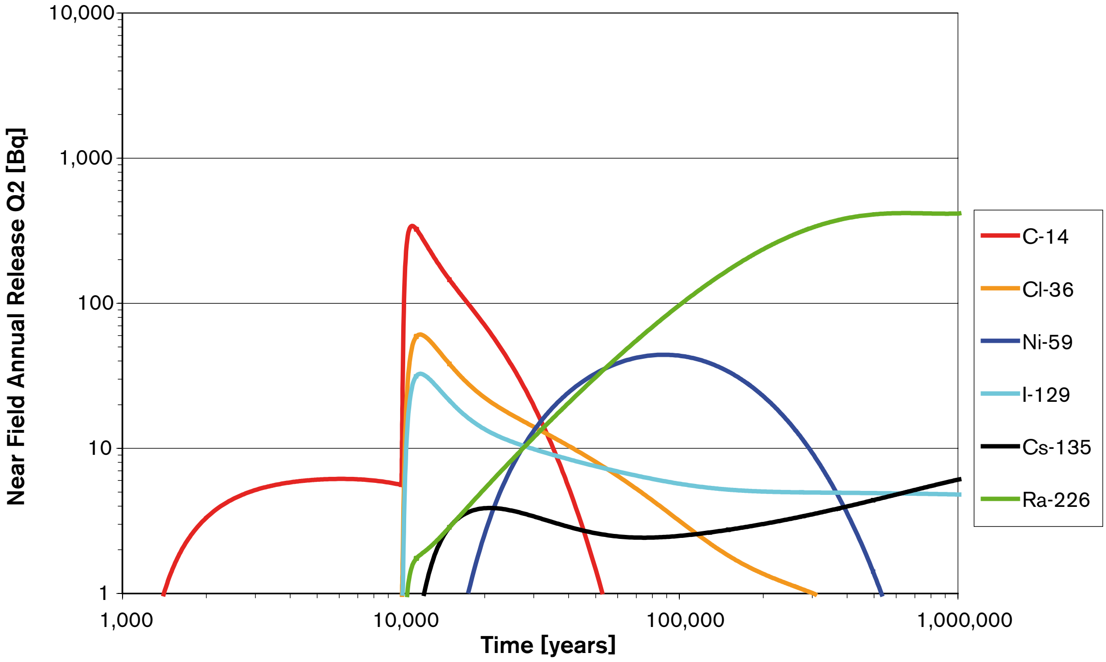


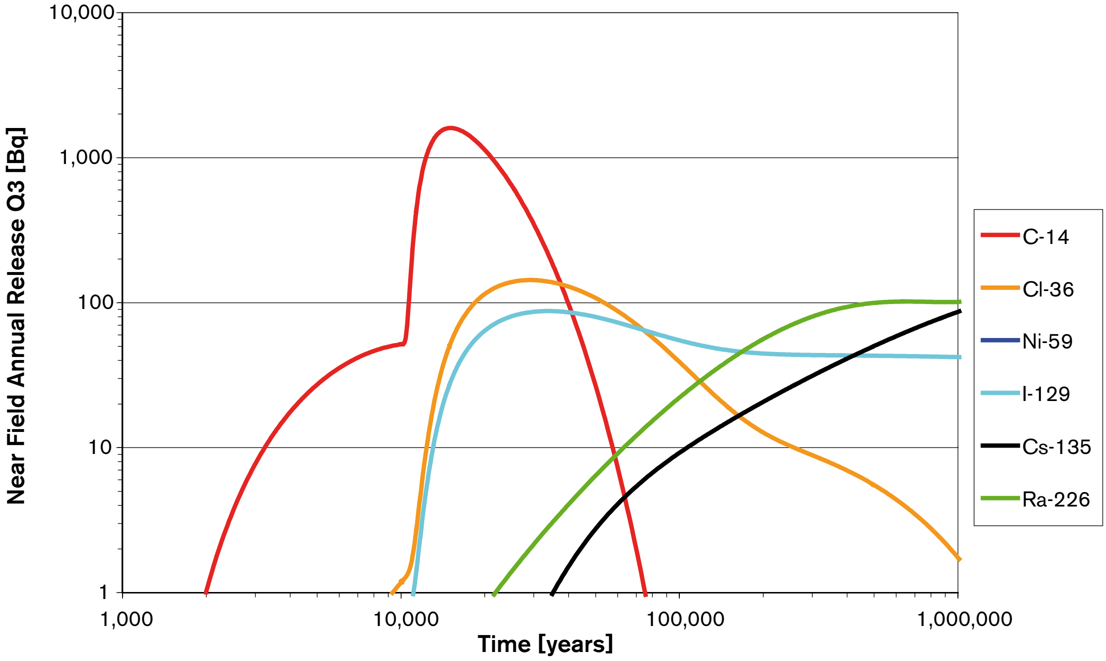
***Figure B-3.** Permafrost depth as a function of time for an unrealistically low time-dependent surface temperature. Benchmark calculation.*

Additional numerical calculation results

Figure B-4 shows near-field releases to the EDZ (Q2), and the diffusive and advective components to the releases to a fracture intersecting the deposition tunnel (Q3 and QA) for the deterministic base case calculation in section 10.5.4. QA is the advective transport rate over the entire tunnel cross-section at the point where the fracture Q3 intersects.

Figure B-5 shows the results for Forsmark for the analytical calculation reported in Figure 10-51, repeated with the numerical model COMP23. (No geosphere retention is assumed in this case, meaning that near-field and far-field releases are equal.)





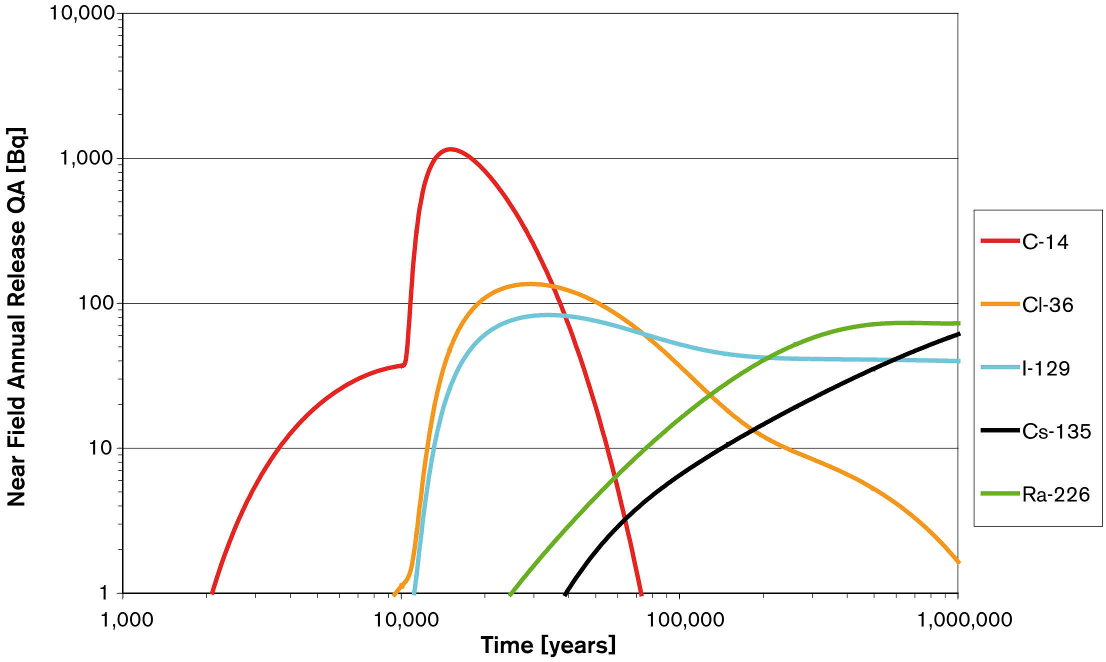


Figure B-4. *Numerically calculated releases through Q2, Q3 and QA.*

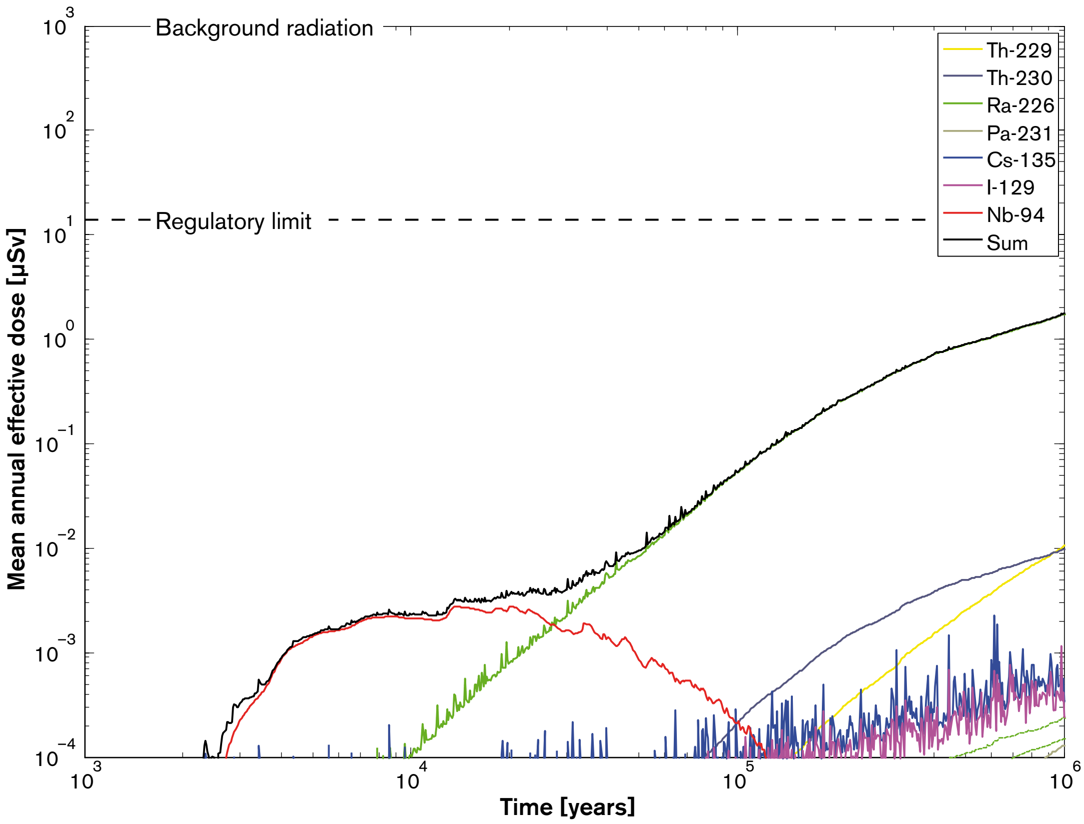


Figure B-5. *Probabilistically calculated consequences of shear failure at Forsmark. Rapid fluctuations in the curves are due to IRF pulses. Numerical model COMP23.*

Appendix C

Handling of findings in the review of the SR-Can Interim report

This Appendix contains excerpts from the Swedish regulators' report /SKI/SSI 2005b/ of the review of the interim version of the SR-Can report /SKB 2004a/. The regulators' report builds on findings /SKI/SSI 2005a/ by their international review team.

It is important to note that the review of the SR-Can Interim report was carried out in a context where the final SR-Can report was intended to support an application for an Encapsulation plant. The role of SR-Can has changed (see section 1.1.1) and this has influenced the way in which SKB has responded to the review comments in this fnial SR-Can report.

The following is a reproduction of section 2.2 of /SKI/SSI 2005b/, where the authorities present their overall views on SKB's methodology for safety assessment. SKB's comments to the issues raised are inserted as *italicised text*.

The authorities' overall views on SKB's methodology

SKB outlines in chapter 2 of the interim report a method in eleven steps for carrying out the safety assessment SR-Can. Among the new points mentioned in comparison with previous safety analyses the following may be listed:

- the use of function indicators to describe the repository's safety functions,
- preliminary assessment of the function indicators with the help of analytical models,
- a clearer connection between SKI's and SSI's regulations and the choice of scenarios,
- a more thoroughly conceived strategy for handling expert assessments in the safety assessment,
- a clearer focus on the safety function of containment in relation to retardation in the rock.

The authorities agree with the international panel of experts that SKB's overall method description is logically formulated and has the conditions to provide a good starting point for future safety analyses. However, SKB's reporting of the different steps of analysis in the interim report is uneven: some points are described in fairly great detail and illustrated with calculations while others are described in very general terms or not at all. As far as the authorities understand, this is due to the fact that certain components in SKB's methodology are not yet fully developed.

Safety principles

Generally SKB has placed greater emphasis on the safety function of containment in relation to retardation in the rock, which in the authorities' view may be reasonable provided that the regulatory requirements on several barrier functions and the use of the best available technology are met. SKB places special emphasis on the copper canister's isolating capacity. This also means that the requirements for reporting factors of importance for containment increase, compared with a case where greater emphasis is placed on the potential of the repository system and the surroundings to delay the release of radionuclides. The authorities feel that there are certain weaknesses in SKB's handling of basic questions relating to the copper canister's isolating capacity. For example, SKB has not provided sufficiently detailed information on how different types of initial defects in the copper canister should be dealt with. The international panel of experts reached the same conclusion and believe that SKB has not yet provided support to show that the assumptions concerning the canister's initial state, on which the analysis is based, might actually be reached.

Comment by SKB: *This information was not fully available when the interim report was written. The current report is based on a considerably more thorough analysis of e.g. initial defects. See section 4.2.3, the* ***Data report****, section 4.2 and references therein.*

SKB states a number of additional safety principles for the KBS-3 system. Among other things, the repository should be sited at a location without workable mineral assets and the system's manufactured barriers should be made from natural materials of long-term stability. SKB explicitly states that dilution should not be considered a safety principle for the repository, nor should it be given any importance in terms of the design and siting of the repository. SKB intends to base the assessment of compliance with SSI's criterion for individual risk on the time periods when release of radioactive substances takes place in a terrestrial environment, when the greatest consequences are expected to occur. The authorities have no objection to these principles.

Comment by SKB*: Also this final report is based on these principles.*

Time period for the safety assessment

SKB presents a reasoning on the amount of time that the safety assessment needs to cover. SKB states that a limitation based on the maximum individual dose occurring within a million years does not seem applicable bearing in mind the system's expected high containment capacity and the continuous ingrowth of radium-226. SKB also presents an analysis of the fuel's radiotoxicity as a function of the time and compares this with the radiotoxicity of the uranium originally mined in order to produce the fuel. SKB concludes that these toxicities are comparable after a hundred thousand years. Based on both these arguments SKB states that the safety assessment needs to cover one million years.

The authorities conclude that the time limitation specified by SKB is in accordance with the guidelines presented by the authorities, especially SKI's general advice, which SKB uses for support, as well as SSI's recently submitted proposal for general advice (SSI dnr 2004/3790- 26).

***Comment by SKB:** The same time period is used in this final report, now also with reference to SSI's recently submitted general advice, see section 2.4.*

System description and data

The authorities consider that the interim report and its accompanying supporting reports give a good picture of how SKB intends to handle the system description, the initial state of the repository and its surroundings, and also the data and general principles for evaluation of different types of uncertainty. The authorities' detailed opinions on these points are presented in chapter 3 and section 6.2.

***Comment by SKB:** Similar approaches are used in this final report.*

Function indicators

The use of function indicators and preliminary assessments as a basis for more complete scenario analyses is a new element in SKB's method and the authorities have therefore given fairly detailed comments in chapter 4.

Like the international panel of experts, the authorities have responded positively to this new feature of SKB's programme and believe that it should provide a valuable contribution to the understanding of the final disposal system's function, especially for long time periods when the uncertainties associated with the risk analysis increases. The role that the function indicators will finally have in the safety assessment needs, however, to be further clarified. This particularly applies to how the function indicators and the preliminary assessment of them will be used, together with other considerations, in order to guide the selection of scenarios for the more in-depth analyses. The systematics for how the function indicators are chosen and analysed should be seen as critical in determining which role they are to have in future analyses.

***Comment by SKB:** The role of the function indicators has been clarified. Their most important roles are i) to provide a structure for the evaluation of safety in the reference evolution, chapter 9 and ii) to provide a structure for the selection of scenarios in chapter 11. The preliminary assessment of the indicators is no longer an element in SKB's methodology. The derivation of function indicators is briefly discussed in section 7.2, subheading "Derivation of safety functions, indicators and criteria".*

Choice of scenarios

The choice of scenarios for the analyses of the repository's long-term safety is a central part of each safety assessment. In the interim report SKB presents an updated method for the choice of scenarios and also provides preliminary examples of scenarios and their evaluation in the example calculations.

The authorities believe that the generally accepted starting points for the choice of scenarios as set out in section 8.1 of the interim report are good. The authorities' overall assessment, however, is that SKB's method as described in the interim report is insufficiently developed for use in the safety assessment SR-Can.

Like the international panel of experts, the authorities believe that it is difficult to see a clear and systematic method for the identification and choice of scenarios. The descriptive examples of how (in particular) variants and calculation cases should be identified and integrated in the risk analysis give a confusing impression. The authorities are also not convinced that SKB's preliminary choice of scenarios will cover a broad enough spectrum of uncertainties and adverse FEP. The authorities feel that SKB needs to have a broader approach in the preliminary choice of scenarios, even though not all scenarios need to be evaluated in the full risk analysis.

In conclusion, the authorities feel that SKB needs to produce a better conceived method for the selection of scenarios, variants and calculation cases and show how the method fulfils the various requirements that might be placed upon the choice of a scenario, e.g.:

- to provide a good basis for the overall risk analysis
- to cover adverse FEP not dealt with in the main scenario's base variant
- to give feedback for site investigations and ongoing research and technological development.

The authorities' detailed views on SKB's scenario selection are given in chapter 5.

Comment by SKB: *The method for selection of scenarios has been revised. The new approach is described in chapter 11. It is demonstrated how the scenarios*

- *provide a basis for the overall risk analysis, by considering conceivable losses of each of the identified safety functions (chapters 11 and 12)*
- *cover adverse FEPs, through a systematic search of all factors that could lead to the loss of a particular safety function (chapters 11 and 12)*
- *provide feedback for site investigations and site modelling, section 13.7, ongoing research, section 13.8, and technological development, sections 13.5 and 13.6, based on the findings in the scenario analyses, including the main scenario which builds on the analysis of the reference evolution.*

Scenario analysis

The method of analysis of the chosen scenarios is illustrated in different parts of the interim report with the aid of simplified calculation examples. The method description shows that the repository's isolating capacity is analysed in a first stage. A calculation is then made of dose consequences in the event that the canister's isolating function should cease. There is, however, no overall description of how different types of more or less detailed models for the repository's short-term (resaturation phase) and long-term development should be applied and combined. The authorities feel there is a need for a schematic description (e.g. a flow chart) illustrating how different models are intended to be used, including information and data flows. The authorities do, however, approve of the fact that SKB is planning to document how different models deal with the processes identified in the process report (SKB R-04-33).

Comment by SKB: *Two such flow charts are now provided in section 6.5. The handling of processes are summarised in* Table 6-2 *through* Table 6-6*. Justification for the selection of models is provided in the* ***Model summary report****.*

SKB states that there is still a great deal of development work to be done to produce all the models needed for the scenario analyses, e.g. in biosphere modelling, the description of the repository's resaturation processes and the effect of glaciation on the repository. The authorities appreciate that it is not possible for all models to be ready at this stage but they stress that adequate time must be given to assess and verify the models and calculation tools that are to be used as the basis for an application.

Comment by SKB: *This work has progressed considerably since the publication of the interim report as evidenced in various sections of this report. Some work remains before the final set of tools are available for an application.*

The authorities also believe that SKB should clarify how the iterative element of the safety assessment will work, i.e. how the preliminary choice of scenarios should be evaluated and the grounds on which supplementary scenarios and analyses should be formulated. This also applies to the way in which the scenario analyses will be used to generate variants and new calculation cases. The authorities are of the opinion that these iterations will be of great importance in ensuring the completeness of the safety assessment.

Comment by SKB: *The iterative aspect of the assessment consists, in the revised methodology, of first analysing and evaluating safety for a reference evolution and then considering again the potential loss of each of the safety functions through a scrutiny of uncertainties not addressed in the reference evolution. This is explained in chapter 11, in particular in section 11.4.2.*

The authorities' detailed views on SKB's method of analysis of scenarios are presented in chapter 6.

Handling of uncertainties

SKB outlines in chapter 2 of the interim report its method of handling uncertainties in the different parts of the safety assessment. The authorities support SKB's argument that the handling of uncertainties should be an integral part of all aspects of the safety assessment. The authorities comment here only on a few overall issues, while SKB's different methods for handling uncertainty in the individual steps of the safety assessment are commented on in other sections of this review report.

In the opinion of the authorities, SKB has identified in the interim report the most important types of uncertainties that need in some way to be addressed in the safety assessment. The authorities also feel that SKB has methods suitable for the assessment of these uncertainties in several important areas, for example the system description with FEP databases, process descriptions and descriptions of initial state and data handling.

Comment by SKB: *The same approaches are used in this final report.*

As can be seen from this review, the authorities point out that SKB's method of safety assessment, and thereby the stated handling of uncertainties, needs to be developed and better described in other areas. This applies, for example, to choice of scenarios, the role of the function indicators, the iterative method for scenario analysis and the reporting of how assumptions about the canister's properties are linked to experiences from manufacturing and testing. The authorities question therefore whether the method described by SKB in section 2.22.3 (page 64) of the interim report is sufficiently well developed to show that all important FEP and uncertainties have been taken into account in the scenario analysis.

Comment by SKB: *All aspects in this above paragraph have been responded to in the above sections.*

The authorities take a positive view of SKB's plans to discuss conceptual uncertainties and alternative models in the process report. The authorities feel, however, that SKB should produce a more detailed description of how different types of alternative conceptual models will be handled in the overall risk analysis.

Comment by SKB: *The detailed description is provided through the analyses and model selections made. Alternative conceptual models are used to illustrate e.g. uncertainties in the hydrogeological interpretation of the Forsmark site (section 9.3.6), of the extent of buffer colloid release/erosion (e.g. section 12.3), the effect of co-precipitation of radium (section 10.5.7, covering also several other conceptual uncertainties that are addressed through the selection of alternative input data) and of near-field releases when advective conditions prevail in a deposition hole (10.6.3). In several other cases pessimistic models are used.*

The authorities believe that SKB has chosen a good set of methods for sensitivity analysis of consequence calculations. The authorities feel, however, that SKB should justify the methods chosen through a discussion of the advantages and disadvantages with the different methods that are available. The authorities also believe that SKB should clarify how sensitivity and uncertainty analyses are intended to be used in other parts of the safety assessment, for example in the calculations designed to illustrate the repository's capacity for containing radionuclides.

Comment by SKB: *Sensitivity analyses occur in a number of places in the reference evolution and the analyses of different scenarios. The different nature of the issues related to isolation (containment) makes if difficult to select a single method for sensitivity analyses. A general discussion on the approach to sensitivity analysis is given in section 10.11, see also section 10.5.10, subheading "Sensitivity analyses". Sensitivity of the main risk contributor to various conceptual uncertainties is analysed in section 12.7.*

Quality assurance

Now that SKB is approaching the stage of license applications for new installations, the importance of quality assurance and traceable documentation increases. Future safety reports need to be traceable and transparent, and it should be possible to reproduce analyses that are important for long-term safety and radiation protection. SKB should, to a greater extent than has hitherto been the case, evaluate the quality and availability of all relevant supporting material connected with its work. The international panel of experts has made it clear that one of their most important conclusions is that SKB must be clearer and in particular must take into account traceability with regard to such things as the handling of uncertainties and scenarios. The group also calls for sufficiently rigorous procedures for project work and quality assurance. The authorities feel that it would be valuable if the quality programme which SKB announces for SR-Can could be evaluated before the safety assessment has been completed. The review of the safety assessment could then be focused more on the compliance with the quality programme than on the quality programme as such. The programme should be drawn up and put into effect as early as possible so that documentation and quality controls are implemented in direct connection to the work.

Comment by SKB: *A preliminary QA-plan was presented to the authorities for scrutiny after the review of the interim report. However, since SR-Can has no longer the role of supporting an application, it is rather the updated plan presented in this report and the final plan for the SR-Site assessment that are of interest. As noted in section 2.8, due to time constraints, the QA plan has not been fully implemented in SR-Can.*

The authorities feel that there are deficiencies in the quality assurance of the interim report which in some respects have obstructed the assessment of SKB's methods of safety assessment. The following are examples of quality issues that SKB needs to work on prior to the completion of SR-Can:

- uniform terminology,
- uniform use of symbols and designations,
- correct and sufficient cross references between different sections of the safety assessment including its main references,
- uniform use of sufficiently specific references to technical reports and scientific publications,
- source references for data,
- subject index (e.g. as outlined in SKB's planned system report),
- decisions on the handling of FEP should be linked to clear arguments,
- explanations also for FEP, parameters etc that are considered irrelevant or possibly neglected,
- checks to ensure that cited technical reports provide adequate support for the conclusions utilised in the safety assessment,
- checks to ensure that important statements in the safety assessment are expressed in an appropriate way with regard to the quality of the data on which they are based.

Comment by SKB: *Several of these aspects have been improved in this final report. Evaluation of the need for further measures will be done as the QA-plan for SR-Site is established.*

There are also a number of quality assurance requirements that can be linked to the extensive modelling that forms a major part of the safety assessment, e.g.:

- that codes used directly or indirectly in the safety assessment are tested and documented, and are accessible for review and verification,
- that changes and further development of models lead to the production of updated documentation,
- that the use of old references which clearly do not fulfil current quality assurance requirements is avoided,
- that consistent routines should be established for program runs with storage of incoming and outgoing data files and sorting of information so that it is easily accessible for review.

Comment by SKB: *These issues are addressed in the* ***Model summary report****.*

Taking into account the extensive amount of data and information that will support future safety assessment, SKB should ensure at the earliest opportunity that the hierarchy of documents supporting the safety assessment is adapted to its purpose and consistently applied. All information required for detailed reviews should be accessible. The safety reporting should, however, be structured so as to provide a good overview and to facilitate the review.

Comment by SKB: *It has been the intention to structure the material supporting the SR-Can assessment according to these principles. An overview of the report hierarchy is given in section 2.2.1. The structure of the main report has been revised, reflecting the revised methodology but also for improved clarity.*

Expert judgements

SKB describes a model for how experts will be identified and documented with regard to such things as training, experience and their role in SR-Can. The authorities approve of the fact that SKB intends to utilise a broader base of experts than in the past and believes that this is necessary since previous safety analyses were in some sections produced by a very limited number of individuals. It still remains, however, for SKB to give examples of how the method of choosing experts will operate in practice. It is also not clear from the report how SKB intends to achieve the breadth of views needed for a comprehensive examination of critical issues concerning the repository's function. The authorities believe that it is necessary to ensure that any spread of scientific opinions of central importance is evaluated in the safety assessment.

Comment by SKB: *As mentioned in section 2.6.1, the documentation of experts providing input to the safety assessment is not complete in SR-Can. Furthermore, the results of the SR-Can project are suitable for identifying critical issues concerning the repository's function. The method for achieving a sufficient breadth of views for these issues in SR-Site remains to be determined. See also section 13.9.3.*

The authorities agree that a small group with a good overview of the safety assessment should take the decisions as to how the basic data should be used in the analysis. To ensure traceability a system for documenting review comments needs to be devised, a point also highlighted by the international panel of experts. In addition to this, there should be, in accordance with SKI's regulations, an independent safety review. In this regard it is important to clarify, for example, the role of SKB's SIERG group (reference group for the ongoing site investigations).

Comment by SKB: *Comments from the external reviews of this main report and of all the main references are now documented in the SR-Can project archive as part of the SR-Can QA plan, see section 2.8. Actions taken in response to these comments are also described in these documents. The SIERG group is the external review group used e.g. for this main report (see the preface to this report).*

SKB states that formal expert panel elicitations may be used. This method has been used in other countries mostly in areas where the knowledge situation is such that facts cannot be accessed through direct measurements, e.g. in the USA to assess the likelihood of volcanism. The authorities believe that the method could also be used in SKB's programme.

Comment by SKB: *SKB's view of expert panel elicitations is discussed in section 13.9.3.*

Risk analysis

SKB presents in chapter 2 of the interim report a method of probabilistic risk analysis. The method is also outlined in the calculation examples in chapter 12. The authorities believe that SKB's method largely conforms to the guidelines set out in the authorities' regulations and the instructions given in SSI's proposal for general advice in connection with SSI FS 1998:1 (SSI dnr 2004/3790-26). Certain questions still remain, however, regarding the application of SKB's method since the interim report does not contain a complete risk analysis. One question which the international panel of experts and SKB themselves discuss in the interim report concerns the weighing up of risk contributions from different variants and calculation cases, e.g. mutually exclusive site-descriptive models and other alternative conceptual models. The unclear elements highlighted by the authorities in connection with SKB's method of choosing scenarios also mean that SKB's method of risk analysis cannot be assessed in its entirety.

Comment by SKB: *A complete risk analysis is presented in this report and a comprehensive assessment should now be possible.*

SKB plans to present risk analyses for the time period up to 1 million years after closure. The authorities wish, however, to make clear that the complete risk analysis should include the period of a glaciation cycle (or around 100,000 years after closure). For long periods (hundreds of thousands of years after closure) it is sufficient to present a simplified risk analysis with the aim of illustrating the repository's protective capacity. Bearing in mind the increasing uncertainties with extremely long periods of time, the risk analysis should be based on a stylised description of the development of the climate and the biosphere as suggested in SSI's proposal for general advice (SSI dnr 2004/3790-26). For the period beyond one million years the report can be limited to a schematic description of the repository's conceivable development together with information on how the hazard of radioactive substances diminishes with time.

Comment by SKB: *These approaches are used in SR-Can, see e.g. the compliance discussion in section 13.3.2.*

The authorities approve of the fact that SKB intends to present the risk from the repository as a function of time and that different climatic developments are not included in the same risk calculation. This helps to create a transparent and comprehensible picture of how the risk from the repository can develop over time.

Comment by SKB: *This approach is used also in this final version of SR-Can.*

The authorities consider that SKB's way of choosing the scenarios and variants that give the greatest consequences in each time interval for the risk summary can be fit for the purpose of assessing whether SSI's risk limitation is complied with. The risk calculation can, however, be difficult to interpret if it consists of risk contributions from different (mutually exclusive) scenarios at different times, as discussed in section 2.12.2 of the interim report. To be able to develop an understanding of the importance of different scenarios and to be able to provide feedback to the site investigations and the R&D-programme, the results from the different scenarios should also be presented separately (see also below in the section on presentation of arguments for demonstration of compliance).

Comment by SKB: *This approach is used in SR-Can. Each scenario is analysed separately. Frequently, the feedback to site investigations and the R&D-programme is based on a result from a particular scenario or calculation case.*

As has been mentioned in several places in this review, the authorities question SKB's choice to, a priori, exclude certain less likely but adverse FEP and deviations from the initial state from the risk analysis. Unless it is possible to show that the risk contribution (due to low probability or small consequences) is negligible, they should be included in the risk analysis. This view has also been expressed by the international panel of experts.

Comment by SKB: *All relevant initial state deviations are considered in the analysis of a particular scenario, see chapter 12. Some internal processes are excluded from further handling, based on information in the Process reports. These are documented in the process tables in section 6.4. It is SKB's view that sufficient information for justifying these exclusion is given in the Process reports.*

It is good that SKB has drawn attention to different types of risk dilution. A particular case of risk dilution can occur for individual events with major but relatively short-term consequences, e.g. certain types of serious canister failure. If there is great uncertainty about when over time such an event will occur, the risk of being affected by the consequences will be spread over a large number of generations in a probabilistic calculation. The estimated risk can then, in certain circumstances, be substantially lower compared with a case where it is known when the event occurs. The authorities are aware that this is a result of the fact that SSI's risk criterion is expressed in the form of annual risk in combination with the very long time periods that need to be taken into account in the risk analysis. This does not mean, however, that it is acceptable to disregard such effects in the risk analysis, as stated in SSI's draft general advice (SSI dnr 2004/3790-26) associated with the regulations SSI FS 1998:1. The authorities consider that SKB in its risk analysis should assess this and other forms of risk dilution and take into account the results when evaluating the calculation results. The method that SKB reports in the calculation examples, namely of comparing the probabilistically calculated risk (as a function of time) with a risk based on the maximal doses (independent of time) can be one way of attacking the problem. The authorities intend, however, to continue the dialogue with SKB on these issues as part of the ongoing consultation concerning systems and safety assessment.

Comment by SKB: *Risk dilution is addressed in general terms in section 2.9.2, subheading "Risk dilution" and analysed in sections 10.5.10, 10.6.10 and 10.7.1 under the same subheading, for three failure modes of the canister.*

The arguments put forward by SKB concerning the size of the most exposed group for risk calculations are reasonable. SSI's proposal for general advice (SSI dnr 2004/3790-26) in respect of SSI FS 1998:1 contains more detailed guidance on how the most exposed group can be delimited in terms of the estimated distribution of radiological doses among different individuals. SSI's proposal on general advice also gives guidance on how SSI's risk criterion should be applied, depending on how many individuals are expected to be involved. The main principle is that the risk criterion, an annual risk of 10^{-6}, should be used if more than a small number of individuals may be deemed to be included in the most exposed group. If only a few individuals are deemed to be involved, it is acceptable to compare the estimated risk against the risk level of 10^{-5}.

Comment by SKB: *The approach used in SR-Can conforms with these principles, see further section 10.2.3.*

Presentation of arguments for demonstration of compliance

The last two steps of SKB's method of safety assessment, assessment of chosen scenarios and FEP handling, and analysis of results and conclusions, are very summarily described in the interim report and cannot therefore be assessed by the authorities at this stage. The authorities believe that SKB should produce a structure at an early stage of how the different arguments for safety and radiation protection should be reported, not least to ensure that, for example, the choice of scenarios and the form of the scenario analyses have the necessary conditions to provide the basic data required. SKB presents in the interim report a number of calculation examples but it is unclear how SKB intends to utilise the information and the results that these calculations give.

Comment by SKB: *All steps in SKB's revised methodology have been implemented in this final report.*

The overall report of arguments for compliance with requirements should, in the view of the authorities, include logically formulated argumentation concerning the repository's protective capacity over different time periods with information on estimated risks, uncertainties in calculations made and the reasonableness of assumptions. The authorities also wish to emphasise in this regard that the presentation of the results of the risk analysis does not simply involve a quantitative report of risk figures. To gain a good understanding of what the estimated risks represent, they need to be substantiated by a discussion on how individual scenarios and calculation cases contribute to the total risk. Such a discussion should be based on a special report on doses and risks for critical scenarios and calculation cases.

Comment by SKB: *Scenarios are analysed and presented in a disaggregated fashion in SR-Can. This has facilitated comprehensive feedback to be given from the SR-Can project to projects providing input to SR-Can, and, at a later stage, to SR-Site. See further chapter 13.*

A related issue is how SKB intends to report that the repository meets the radiation protection requirement for an optimised repository and that account has been taken of the principle of best available technology, among other ways through analysis of different design variants. Evaluations and assessments of alternative site locations and design alternatives are made continuously during the development work for the repository. The overall presentation of compliance should show how the principles of optimisation and best available technology have been taken into account in this work. The design alternatives which are still open in the production of the safety report, e.g. the method of backfilling tunnels, should be evaluated on an individual basis against the safety and radiation protection requirements rather than be treated as variables in the risk analysis.

Comment by SKB: *Conclusions regarding optimisation and BAT are given in section 13.3.4. Design options are evaluated based on individual merits. However, a realistic risk calculation may provide less useful information than an evaluation based on safety functions. This is e.g. the case for the alternative methods of backfilling deposition tunnels.*

Appendix D

Glossary of abbreviations and specialised terms used in SR-Can

The glossary is intended to explain all acronyms, SKB-specific terms, and technical terms that occur often in this report. It is not intended to contain all technical terms found in the report. Chemical formulae and units are usually not included in the glossary. For a translation of Latin names found in the main report of the SR-Can project, see /Lindborg 2005ab/. In the glossary, the letters *x*, found in for example ZFMNE*xxxx*, have replaced the numbers/letters in the name of for instance the specific deformation zone ZFMNE00A2.

1-D/1D	One-dimensional.
2-D/2D	Two-dimensional.
3-D/3D	Three-dimensional.
30/70 mixture	Mixture of 30% bentonite and 70% crushed rock used as tunnel backfill.
3DEC	A numerical modelling code for analysis of rock and structural support in three dimensions, used to simulate the response of fractured rock that is subject to either static or dynamic loading.
^{3}H data	Data on groundwater tritium content.
ABAQUS	Finite element computer code used for the calculation of buffer swelling and saturation, as well as stress changes as response to advancing glaciers.
AD	Anno Domini.
Additional scenarios	Scenarios defined in order to cover uncertainties not addressed in the main scenario.
AMF	Assessment Model Flow chart.
Andra	Agence Nationale pour la Gestion des Déchets Radioactifs, France.
APSE	Äspö Pillar Stability Experiment.
ART	Average Retention Time.
ASM000208	A specific, directly exposed, outcrop mapped at Laxemar.
Äspö HRL	Äspö Hard Rock Laboratory.
BAT	Best Available Technique.
BC	Best Choice value.
BC	Before Christ.
Back-fill	The material used as filling in the deposition tunnels.
Barrier safety function	A role through which a repository component (barrier) contributes to safety.
Base variant	A variant of the Main Scenario based on the base variant of the reference climate evolution.
BET	A method for determining the specific surface area, available for sorption, of a solid material by use of gas adsorption.
BIOCLIM	EU research project on modelling sequential biosphere system under climatic change for radioactive waste disposal.
BP	Before Present.
Buffer	One of the barriers in the KBS-3 concept, consisting of bentonite clay that surrounds the canister.
BWR fuel	Boiling Water Reactor fuel.
CCC	Critical Coagulation Concentration.
CCDF	Complementary Cumulative Distribution Function.
CEC	Cation exchange capacity. A measurement of sites available for ion-exchange.
Clab	Central interim storage facility for spent nuclear fuel in Oskarshamn.
Climate domain	A climatically determined environment with a specific set of characteristic processes of importance for repository safety.
COMP23	Near-field model calculating the release rate of radionuclides into the geosphere farfield.
Connectflow	Computer code for simulation of groundwater flow.
CPM	Continuous Porous Medium.
CSH	Calcium silicate hydrates.
CSI programme	Complete Site Investigation programme.
D1	A preliminary repository design and layout produced after the Initial Site Investigations (ISI). This design and layout is assessed by SR-Can.

D2	The repository design and layout to be produced after the completion of the Site Investigations. This layout will be assessed in SR-Site.
D&B	Drilling and Blasting.
DarcyTools	Computer code for simulation of groundwater flow.
Darcy velocity	Specific discharge, or flux, given by product of hydraulic conductivity and hydraulic gradient.
DBT-1	Borehole in Forsmark, drilled in exploration for the cooling water tunnel of the Forsmark nuclear power plant, i.e. before the current site investigation programme.
Deformation zone	An essentially 2-dimensional structure (a sub-planar structure with a small thickness relative to its lateral extent) in which deformation (strain) has been concentrated (or, in the case of active faults, is being concentrated).
Degree-of-utilisation	A measure of how many of the planned canister positions that is suitable for canister emplacement.
$\delta^{18}O$	Oxygen isotope ratio used as proxy data for temperature in atmosphere or ocean.
DECOVALEX III	International co-operative project for the DEvelopment of COupled models and their VALidation against EXperiments in nuclear waste isolation. DECOVALEX III was the third in a series of such projects.
DEM	Digital Elevation Model.
Deponit CA-N	A brand name of a bentonite clay, used as one of the reference materials for the buffer in SR-Can.
DFN	Discrete Fracture Network.
DOC	Dissolved Organic Carbon.
Design basis case	A calculation cases formulated on the basis of a scenario that is shown to be especially important from the standpoint of risk. The result of the calculation of a design basis case is used as input to the formulation of requirements on barriers.
Design criteria	Measurable quantities through which the state of a component or sub-system at a specific occasion can be determined.
Design step D1	A preliminary repository design and layout produced after the Initial Site Investigations (ISI), and linked to the 1.2 versions of the site descriptions. This design and layout is assessed by SR-Can.
DFN	Discrete Fracture Network.
Domain A	A rock domain at Laxemar.
ε	Calculated fraction of canister positions intersected by fractures exceeding a specified size.
EBS	Engineered Barrier System.
EBW	Electron-Beam Welding.
ECPM	Equivalent Continuous Porous Medium.
EDZ	Excavation Damaged Zone.
EFPC	Extended full perimeter criterion.
Eh	Redox potential.
EIA	Environmental Impact Assessment.
EMCL	Environmental Media Concentration Limit.
ERICA project	European Union project in 6^{th} framework on protection of the environment from radiation.
EU	European Union.
EW*xxxx*	Deformation zones at Laxemar with a strike in the East-West direction.
External conditions	Conditions occurring exterior to the final repository that are considered in the safety assessment and may impact the safety functions of the repository.
F1.2	Forsmark site-descriptive model version 1.2.
F_m	Formation factor defined as De/Dw where De and Dw are effective diffusivity and diffusivity of tritiated water in free water. The formation factor quantifies the reduced diffusion rate obtained in the rock material relative to the diffusion rate in pure electrolyte.
FARF31	Far-field model for calculation of radionuclide transport in geosphere.
FEM	Finite Element Model.
FEPs	Features, Events and Processes.
F-factor	Transport resistance along flow path [T/L], expressing the relation between flow wetted surface and groundwater flow. It controls retention of nuclides in geosphere.
FHA	Future Human Actions.
FPC	Full Perimeter Criterion.
FPC criteria	A set of full perimeter intersection criteria denoted FPC and EFPC.
Friedland Clay	A brand name of a bentonite clay, used as one of the reference materials for the backfill in SR-Can.
FSW	Friction-Stir Welding.

Function indicator criteria	Short for Safety function indicator criteria.
GCM	Global Circulation Model or General Circulation Model.
GIA	Glacial Isostatic Adjustment
GIS	Geographical Information System
Glacial	Cold period typically associated with ice sheet growth and decay. An alternative word is glaciation.
Glacial domain	Regions that are covered by ice sheets.
Glacially induced faults	Faults caused by earthquakes occurring after, or in direct association with, the retreat of an ice sheet.
Greenhouse variant	A warm variant of the Main Scenario in which the future climate and hence external conditions are assumed to be substantially influenced by human-induced greenhouse gas emissions, i.e. a situation with an increased greenhouse effect.
GRIP	European Greenland Ice Core Project.
GW	Ground Water.
HCD	Hydraulic Conductor Domain.
High confidence zones	Structures that have been confirmed by many independent methods and which, therefore, have a high probability of representing existing deformation zones.
HLX*xx*	Percussion drilled borehole in Laxemar.
HPF experiment	The Hyperalkaline Plume in Fractured Rock Experiment performed at the Grimsel Test Site in Switzerland.
HRD	Hydraulic Rock Domain.
Hydrogeological DFN	Hydrogeological Discrete Fracture Network.
IAEA	International Atomic Energy Agency.
ICE3G	A global ice sheet reconstruction by W.R. Peltier.
ICP/AES	Inductively Coupled Plasma/Atomic Emission Spectrometry.
ICRP	International Commission on Radiological Protection.
Initial state	The state at the beginning of an analysis, e.g. the time of deposition of the canister and buffer and backfilling and sealing of deposition tunnels.
Internal processes	Processes occurring within the final repository that are considered in the safety assessment and may impact the safety functions of the repository.
IPCC	Intergovernmental Panel on Climate Change.
IRF	Instant Release Fraction.
ISO 10005	Quality management – guidelines for quality plans.
ISO 9001:2000	Quality management system standard.
JNC	Japan Nuclear Cycle Development Institute, Japan.
K	Hydraulic conductivity [L/T].
ka	Kilo-annum or kiloyear, a unit of time.
k_r	The shape parameter of the powerlaw distribution.
KBS-1	KärnBränsleSäkerhet – 1. KBS was a project, and later a department, within SKBF (Svensk kärnbränsle försörjning AB). KBS-1 is an abbreviation included in the first final report of the project giving name to the method of final disposal of high level waste from reprocessing presented and analysed in the report.
KBS-2	KärnBränsleSäkerhet – 2. Abbreviation included in the second final report of the KBS project. This report analysed direct disposal of spent nuclear fuel.
KBS-3	KärnBränsleSäkerhet – 3. Method for final disposal of spent nuclear fuel where: the spent nuclear fuel is enclosed in water-tight and load bearing canisters; the canisters are deposited at 400-700 meters depth in crystalline rock; the canisters are surrounded by a buffer preventing groundwater flow and protecting the canister; the rock cavities required to deposit the canisters are backfilled.
KBS-3H repository	Final repository for spent nuclear fuel based on the KBS-3 method with horizontal deposition holes, each for deposition of several canisters.
KBS-3V repository	Final repository for spent nuclear fuel based on the KBS-3 method with vertical deposition holes each for deposition of one canister.
K	Hydraulic conductivity.
K_d	Distribution coefficient for sorption [L^3/T].
KFM*xxx*	Core drilled borehole in Forsmark.
KLX*xx*	Core drilled borehole in Laxemar.
L1.2	Laxemar site-descriptive model version 1.2.
LDF	Landscape Dose Factor.

Less likely (less probable) scenario	According to the general guidance to SKIFS 2002:1 a scenario that is included to address such uncertainties that are not evaluated within the framework of the main scenario.
LGM	Last Glacial Maximum.
Low confidence zones	Deformation zones in the site descriptive model that cannot univocally be confirmed as deformation zones due to either lack of information or weak deformation zone signatures.
LOT experiment	Long Term Test of Buffer Material experiment conducted at the Äspö Hard Rock Laboratory.
L-S tectonite	A highly deformed rock with very strong linear (L) *and* planar (S) fabrics.
M6	Magnitude 6.
Ma	Million years, a unit of time.
Main scenario	According to SKIFS 2002:1, a scenario that takes into account the most probable changes in the repository and its environment. In SR-Can defined as a reasonable evolution of the repository system, analysed essentially by referring to the reference evolution.
mbsl	Meter below sea level.
MH	Mechanico-Hydro.
MIKE SHE	Computer code for surface hydrogeological modelling.
MIS	Marine Isotope Stage, alternating warm and cool periods in the Earth's palaeoclimate.
Margin for construction	Distance from deformation zones to deposition holes imposed in the repository layouts. The selected margins are judged to be sufficient to handle construction problems related to the zones. Long term safety issues are handled by respect distances, see below.
MOX fuel	Mixed Oxide fuel, blend of plutonium and natural or depleted uranium.
MX-80	A brand name of bentonite clay, used as one of the reference materials for the buffer in SR-Can.
Nagra	Nationale Genossenschaft für die Lagerung Radioactiver Abfälle, Switzerland.
Natural analogues	A natural system studied in order to make it possible to investigate processes that have proceeded for a much longer time than can normally be followed by experiments in the laboratory or in the field.
NDT	Non-Destructive Testing.
NEA	Nuclear Energy Agency.
NGU	Geological Survey of Norway.
NEA/RWM/PAAG	Nuclear Energy Agency/Radioactive Waste Management/Performance Assessment Advisory Group
NEONOR project	A neotectonic study conducted by NGU.
NUCTRAN	Old version of COMP23; see COMP23.
OECD	Organisation for Economic Co-operation and Development.
ONDRAF/NIRAS	The Belgian Agency for Radioactive Waste and Enriched Fissile Materials.
Optimisation	Defined in SSI FS 1998:1 as follows: "keeping the radiation doses to mankind as low as reasonably achievable, economic and social factors taken into account".
P_{10}	Fracture intensity (1D), expressed as intercept per unit length (m^{-1}). Synonymous to fracture frequency.
$P10_c$	Fracture frequency of conductive fractures.
$P10_{PFL}$	Fracture frequency based on PFL data.
P_{21}	Fracture intensity (2D), expressed as trace length per unit area (m/m^2).
P_{32}	Fracture intensity (3D), expressed as fracture area per unit volume (m^2/m^3).
Perfectly correlated DFN models	See DFN models; perfect correlation between fracture size and transmissivity.
Permafrost domain	Regions that contain permafrost. Cold regions without the presence of an ice sheet. The permafrost occurs either as sporadic-, discontinuous-, or continuous permafrost.
PFL	Posiva Flow Log.
PGF	Postglacial Faulting.
pH	Measure of the acidity of a solution in terms of activity of hydrogen ions.
PHREEQC	Computer code for chemical speciation, batch-reaction, one-dimensional transport, and inverse geochemical calculations.
Piping	Formation of hydraulically conductive channels in the buffer clay by erosion.
PORSS	Particles On Random Streamline Segments, a methodology for radionuclide transport simulation.
Posiva	Short for Posiva Oy, the organisation responsible for the final disposal of spent nuclear fuel in Finland.
Preliminary Safety Evaluation	A Preliminary Safety Evaluation (PSE) made after the initial site investigation of each site, aiming at determining whether the feasibility study's judgement of the suitability of the candidate area with respect to long-term safety holds up in the light of the actual site investigation data.

PREM	Preliminary Reference Earth Model.
PSE	Preliminary Safety Evaluation.
PSS	Pipe String System. A type of hydraulic pressure test.
PWR fuel	Pressurised Water Reactor fuel.
Q1	Release position for particle tracking; Q1 refers to path starting at fracture intersection with deposition hole.
Q2	Release position for particle tracking; Q2 refers to EDZ path.
Q3	Release position for particle tracking; Q3 refers to path starting at fracture intersection with deposition tunnel.
QA	Quality Assurance.
QD	Quaternary Deposits.
Q_{eq}	Equivalent flowrate; used in COMP23.
Q_{eqDZ}	Equivalent flowrate in excavation damaged zone, used in COMP23.
R&D	Research and Development.
RD&D	Research, Development and Demonstration.
Reference evolution	A description of a plausible evolution of the repository system, based *inter alia* on a repetition of the last glacial cycle.
Reference repository concept	Includes basic dimensions of the repository facilities as well as reference technical solutions for buffer and backfill.
Regolith	In this report the term is used to designate all deposits on bedrock, including Quaternary deposits, soils, sediments, peat, organic debris, roads, buildings, waste dumps and also the surface of rock outcrops.
Repository layout	The layout in space of the repository components such as deposition tunnels, central area and access.
Residual scenario	In the general guidance to SKIFS 2002:1 defined as a scenario that is selected and studied independently of probability in order to, inter alia, illustrate the significance of individual barriers and barrier functions. A residual scenario is not included in the risk assessment for the repository.
Respect distance	The perpendicular distance from a deformation zone that defines the volume within which deposition of canisters is prohibited, due to anticipated, future seismic effects on canister integrity.
RETROCK	EU project dealing with how retention processes are handled in safety assessment modelling.
RFM*xxx*	Rock domain in Forsmark.
Risk criterion	A regulatory criterion to which a calculated risk is compared.
Risk dilution	The seemingly paradoxical situation where less knowledge about e.g. a detrimental phenomenon leads to lower calculated individual risks.
RN-transport	Radionuclide transport.
S D	Standard Deviation.
SAFE	The renewed safety assessment of the low level waste repository (SFR) at Forsmark.
Safety function	A role through which a repository component contributes to safety.
Safety function indicator	A measurable or calculable property of a repository component that indicates the extent to which a safety function is fulfilled.
Safety function indicator criteria	A quantitative limit such that if the safety function indicator to which it relates fulfils the criterion, the corresponding safety function is achieved.
Scenario	In the general guidance to SKIFS 2002:1 defined as a description of how a given combination of external and internal conditions affect repository performance
SDM	Site Descriptive Model.
Semi-correlated DFN	See DFN; correlation between fracture size and transmissivity follows functional relationship with stochastic component.
SFM*xxxx*	Rock domain at Forsmark.
SFR	Repository in Forsmark for low-and intermediate-level radioactive waste.
Site description	A model of the site providing descriptions of the present geosphere and biosphere conditions. It is the same as Site Descriptive Model (SDM).
SKB	Swedish Nuclear Fuel and Waste Management Company.
SKBF	Svensk kärnbränsle försörjning AB, precursor to SKB.
SKB-TDB	Thermodynamic database.
SKI	Swedish Nuclear Power Inspectorate.
SKIFS	Swedish Nuclear Power Inspectorate's regulations.
SNV	Swedish Environmental Protection Agency.
Sorption	In this report the term is used to designate all processes by which a dissolved species is retained at a solid surface.

Spalling	Rock surface failure in which rock chips are shed from the rock wall.
SPIN Project	EU research project.
SR 97	Safety Report 97. The previous safety assessment to SR-Can.
SRB	Sulphate-reducing bacteria.
SR-Can	Safety Report – Canister.
SR-Site	Safety Report – Site.
SSI	Swedish Radiation Protection Authority.
SSI FS	Swedish Radiation Protection Authority's regulations.
STUK	Finnish Radiation and Nuclear Safety Authority.
SWECLIM	Swedish Regional Climate Modelling programme.
TASQ	Tunnel at the Äspö Hard Rock Laboratory.
TBM	Tunnel Boring Machine.
TDS	Total Dissolved Solids.
Temperate domain	Regions without permafrost or ice sheet conditions. It is dominated by a temperate climate in a broad sense. Within the temperate domain, a site may also at times be submerged by the sea or by an ice dammed lake.
Thermal spalling	Spalling induced by the stresses resulting from the added thermal load from the canister heat.
THM processes	Thermo-Hydro-Mechanical processes.
TIB	Transscandinavian Igneous Belt.
Till	Dominantly unsorted and unstratified material, generally unconsolidated, deposited directly by a glacier or an ice sheet.
T_R	Rock transmission.
t_w	Advective travel time.
Type A–D groundwater	Groundwater types of various salinity defined in the site characterisation models.
UCS	Uniaxial Compressive Strength.
Underground Design Premises	A document presenting the design premises for design of the underground excavations.
Upconing	Raising the saline water interface due to reduction of the groundwater pressure, e.g. due to pumping in a well or in and underground excavation.
URL	Underground Research Laboratory, Canada.
US	United States of America.
Weichselian	Name of the last glacial in north-eastern Europe.
Weichselian glacial cycle	The last glacial cycle, defined as comprising the Weichselian glacial and the Holocene interglacial periods.
WLP	WireLineProbe. Hydraulic tests conducted during drilling.
XRD	X-rar diffraction.
ZEDEX	Experiment conducted at the Äspö HRL designed to compare damage from drill and blast excavation with excavations by a tunnel boring machine.
ZFMNE*xxxx*	Fracture zone in Forsmark.
ZSMEW*xxx*	Deformation zone in Simpevarp.
ZSMNE*xxxx*	Deformation zone in Simpevarp.
ZSMNW*xxxx*	Deformation zone in Simpevarp.

ISSN 1404-0344
CM Digitaltryck AB, Bromma, 2006

Interim storage facility, encapsulation plant and final repository for spent nuclear fuel

Long-term safety for KBS-3 repositories at Forsmark and Laxemar – a first evaluation

Summary of the SR-Can project

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November 2006

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Summary

Introduction

This document is the main report from the safety assessment project SR-Can. The SR-Can project is a preparatory stage for the SR-Site assessment, the report that will be used in support of SKB's application for a final repository. The purposes of the safety assessment SR-Can are the following:

1. To make a first assessment of the safety of potential KBS-3 repositories at Forsmark and Laxemar to dispose of canisters as specified in the application for the encapsulation plant.
2. To provide feedback to design development, to SKB's R&D programme, to further site investigations and to future safety assessment projects.
3. To foster a dialogue with the authorities that oversee SKB's activities, i.e. the Swedish Nuclear Power Inspectorate, SKI, and the Swedish Radiation Protection Authority, SSI, regarding interpretation of applicable regulations, as a preparation for the SR-Site project.

The assessment relates to the KBS-3 disposal concept in which copper canisters with a cast iron insert containing spent nuclear fuel are surrounded by bentonite clay and deposited at approximately 500 m depth in saturated, granitic rock, see Figure 1. Preliminary data from the Forsmark and Laxemar sites, presently being investigated by SKB as candidates for a KBS-3 repository are used in the assessment.

An important aim of this report is to demonstrate the proper handling of requirements placed on the safety assessment in applicable regulations. Therefore, regulations issued by the Swedish Nuclear Power Inspectorate (SKIFS 2002:1) and the Swedish Radiation Protection Institute (SSI FS 1998:1) are reproduced in an Appendix where references are given to sections in the main text where the handling of the different requirements is discussed. The principal acceptance criterion requires that "the annual risk of harmful effects after closure does not exceed 10^{-6} for a representative individual in the group exposed to the greatest risk". "Harmful effects" refer to cancer and hereditary effects. The risk limit corresponds to an effective dose limit of about $1.4 \cdot 10^{-5}$ Sv/yr. This, in turn, corresponds to around one percent of the effective dose due to natural background radiation in Sweden.

The timeframe for the assessment is one million years after repository closure, in accordance with regulatory requirements. The above risk limit is applicable as a quantitative regulatory limit during approximately the first one hundred thousand years, and thereafter as a basis for discussing the protective capability of the repository, according to SSI.

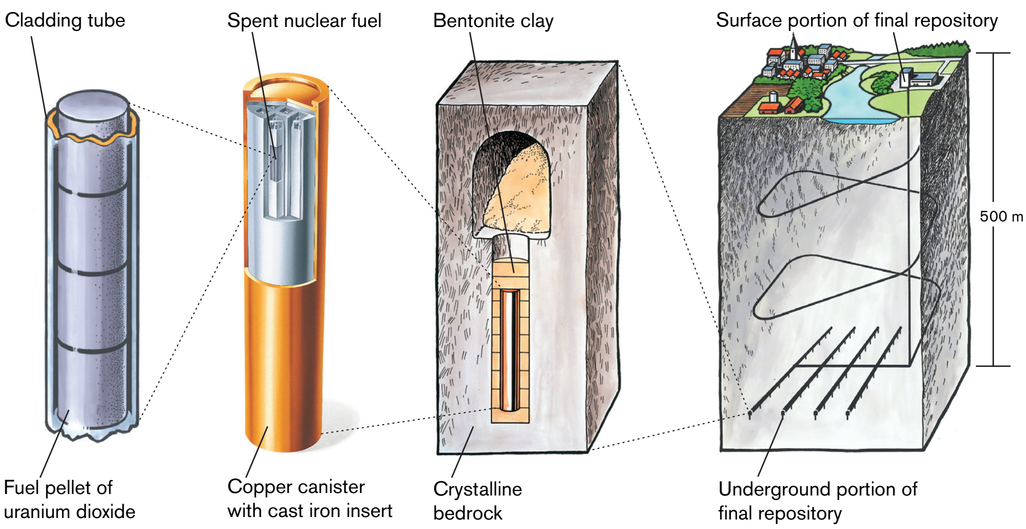

***Figure 1.** The KBS-3 concept for disposal of spent nuclear fuel.*

Methodology

The repository system, broadly defined as the deposited spent nuclear fuel, the engineered barriers surrounding it, the host rock and the biosphere in the proximity of the repository, will evolve over time. Future states of the system will depend on:

- the initial state of the system,
- a number of radiation-related, thermal, hydraulic, mechanical, chemical and biological processes acting internally in the repository system over time and,
- external influences acting on the system.

A methodology in ten steps has been developed for SR-Can, as summarised in Figure 2. The steps are carried out partly concurrently and partly consecutively.

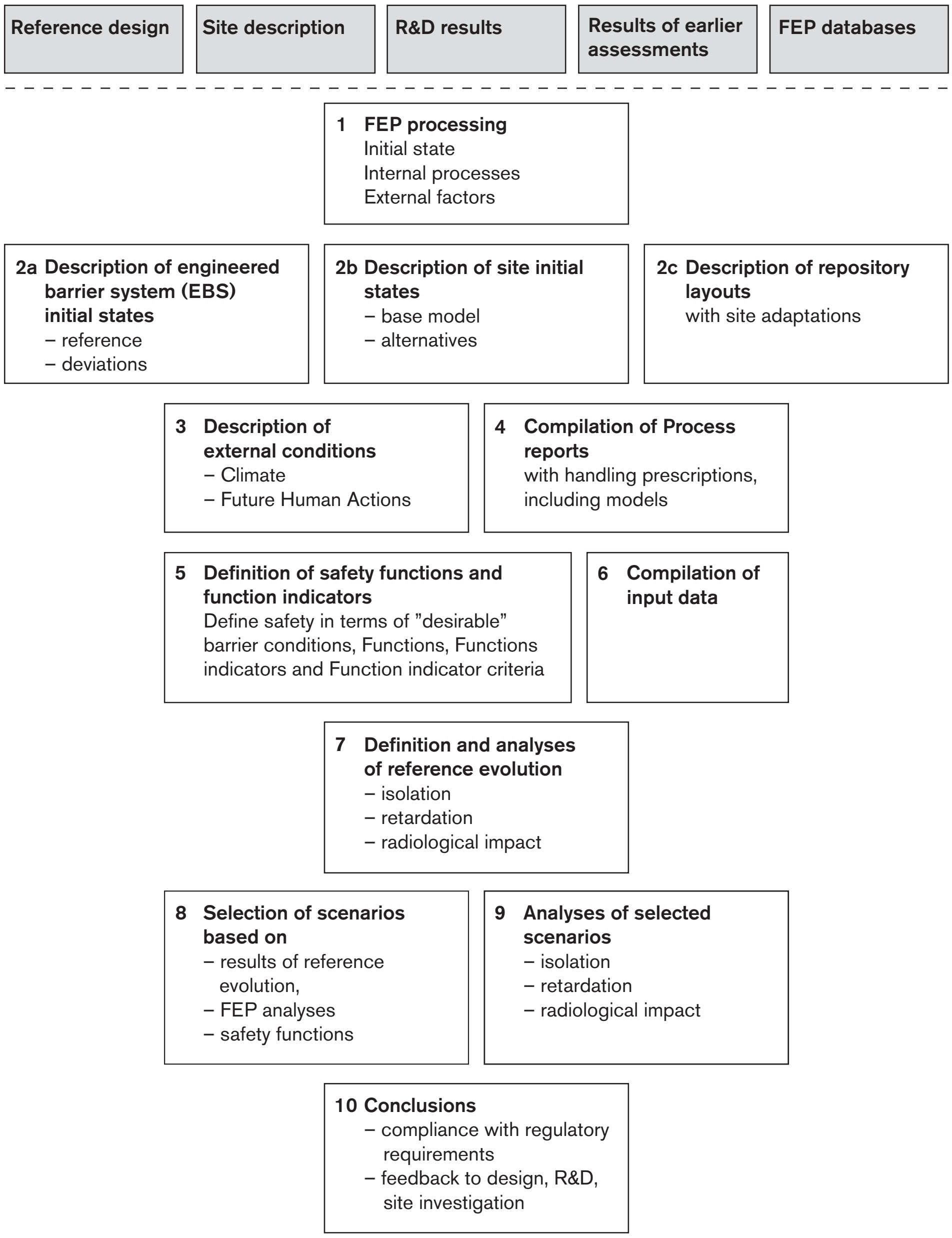

Figure 2. *Outline of the ten main steps of the SR-Can safety assessment. The boxes at the top above the dashed line are inputs to the assessment.*

The ten steps are described in more detail below.

1. Identification of factors to consider (FEP processing)

   This step consists of identifying all the factors that need to be included in the analysis. Experience from earlier safety assessments and KBS-3 specific and international databases of relevant features, events and processes (FEPs) influencing long-term safety are utilised. An SKB FEP database is developed where the great majority of FEPs are classified as being either initial state FEPs, internal processes or external FEPs. Remaining FEPs are either related to assessment methodology in general or determined to be irrelevant for the KBS-3 concept. Based on the results of the FEP processing, an SR-Can FEP catalogue, containing FEPs to be handled in SR-Can, has been established. This step of FEP processing is further described in the SR-Can **FEP report**[1].

2. Description of the initial state

   The initial state of the system is described, based on the design specifications of the KBS-3 repository, a descriptive model of the repository site and a site-specific layout of the repository. The initial state of the fuel and the engineered components is that immediately after deposition as described in the **Initial state report**. The initial state of the geosphere and the biosphere is that of the natural system prior to excavation, as described in the site descriptive models of the Forsmark /SKB 2005c/ and Laxemar /SKB 2006b/ sites. The repository layouts adapted to the sites are provided in underground design reports for each site /Brantberger et al. 2006/ and /Janson et al. 2006/.

3. Description of external conditions

   Factors related to external conditions are handled in the three categories “climate related issues”, “large-scale geological processes and effects” and “future human actions”. The handling of these factors is described in the **Climate report,** the **Geosphere process report**, and the **FHA report**, respectively.

4. Description of processes

   The identification of relevant processes is based on earlier assessments and FEP screening. All identified processes within the system boundary relevant to the long-term evolution of the system are described in dedicated **Process reports**. Short-term geosphere processes/alterations due to repository excavation are also described in these Process reports and are taken into account in the assessment. For each process, its general characteristics, the time frame in which it is important, the other processes to which it is coupled and how the process is handled in the safety assessment are documented.

5. Definition of safety functions, safety function indicators and safety function indicator criteria

   This step consists of an account of the safety functions of the system and of how they can be evaluated by means of a set of safety function indicators that are, in principle, measurable or calculable properties of the system. Criteria for the safety function indicators are provided. The process reports are important references for this step. A FEP chart is developed, showing how FEPs are related to the safety function indicators.

6. Compilation of input data

   Data to be used in the quantification of repository evolution and in dose calculations are selected using a structured procedure. The process of selection and the data values adopted are reported in a dedicated **Data report**. Also, a template for discussion of input data uncertainties has been developed and applied.

7. Definition and analysis of reference evolution

   A reference evolution, providing a description of a plausible evolution of the repository system, is defined and analysed. The isolating potential of the system over time is analysed in a first step, yielding a description of the general system evolution and an evaluation of the safety function indicators. If the evolution indicates breaching of isolation, the retarding potential of the repository and its environs is analysed and dose consequences are calculated for the long-term conditions identified in the first step. Also some canister failure modes not resulting from the reference evolution are analysed in order to further elucidate the retarding properties of the system. Each process is handled in accordance with the plans outlined in the process reports.

[1] The FEP report is one of several principal references in the SR-Can report.

8. Selection of scenarios

   A set of scenarios for the assessment is selected. A comprehensive main scenario is defined in accordance with SKI's regulations SKIFS 2002:1. The main scenario is closely related to the reference evolution analysed in step 7. The selection of additional scenarios is focused on the safety functions of the repository and the safety function indicators defined in step 4 form an important basis for the selection. For each safety function, an assessment is made as to whether any reasonable situation where it is not maintained can be identified. If this is the case, the corresponding scenario is included in the risk evaluation for the repository with the overall risk determined by summation over such scenarios. The set of selected scenarios also includes e.g. scenarios explicitly mentioned in applicable regulations, such as human intrusion scenarios, and scenarios and variants to explore the roles of various components in the repository.

9. Analysis of selected scenarios

   The main scenario is analysed essentially by referring to the reference evolution in step 7. An important result is a calculated risk contribution from the main scenario. The additional scenarios are analysed by focussing on the factors potentially leading to situations in which the safety function in question is not maintained. In most cases, these analyses are carried out by comparison with the evolution for the main scenario, meaning that they only encompass aspects of repository evolution for which the scenario in question differs from the main scenario. For these scenarios, as for the main scenario, a risk contribution is estimated.

10. Conclusions

   This step includes integration of the results from the various scenario analyses, development of conclusions regarding safety in relation to regulatory criteria and feedback concerning design, continued site investigations and SKB's RD&D programme.

The sites and the repository layouts

From site data to SR-Can

The information transfer from field investigation to the safety assessment application involves several steps. *Field data* are obtained from various investigation activities, such as air-borne and surface-based geophysics, borehole drilling and borehole testing. The data are quality controlled and then entered into the SKB site characterisation database, Sicada. The field data are interpreted and evaluated into an overall inter-disciplinary *Site Descriptive Model* (SDM), being a synthesis of geology, rock mechanics, thermal properties, hydrogeology, hydrogeochemistry, bedrock transport properties and surface system properties. The SDM is reported in an SDM report. Site data used in SR-Can are assessed in the **Data report**, using the SDM versions 1.2 as input. The data report also describes how non-site specific information were taken into account, adds judgements, based on how the data will be used in SR-Can, on how to handle the uncertainties identified in the SDM and reports the final selections of model input data.

Forsmark

The Forsmark site is located in northern Uppland within the municipality of Östhammar, about 170 km north of Stockholm. The landscape in Forsmark is a relatively flat bedrock plain that dips gently towards the east. The whole area is located below the highest shoreline that occurred during the last deglaciation. Today's landscape is strongly influenced by the ongoing vertical shore-level uplift of approximately 6 mm per year.

The bedrock in the Forsmark region has been affected by both ductile and brittle deformation. The ductile deformation has resulted in large-scale ductile high-strain zones, but the candidate area is situated within a tectonic lens enclosed between ductile high-strain zones. The bedrock inside the lens is relatively homogeneous, and is dominated by a metagranite with high content of quartz, whereas the lithology and deformation is more complex outside the lens. No potential for metallic and industrial mineral deposits has been recognised within the candidate area. Due to its rather high quartz content, the bedrock is characterised by high thermal conductivity and high mechanical strength compared to typical rock conditions in Sweden.

Three major sets of deformation zones with distinctive orientations have been recognized. In addition to vertical and steeply dipping zones, there are also gently south-east- and south-dipping zones. These gently dipping zones are more frequent in the south-eastern part of the candidate volume and have higher hydraulic transmissivity than vertical and steeply dipping deformation zones at the site. They seem to play an important role in determining the properties of the Forsmark site, such as the distribution of stress, fracturing and the transmissivity distribution of the fractures. The frequency of open and partly open fractures is very low below approximately 300 m depth compared to what is observed in the upper part of the bedrock in the north-western part of the candidate volume, which is the target volume for a potential repository at the site. In addition, the rock stresses are high compared to typical values of the Swedish bedrock, with a potential correlation to the low fracture frequency in this part of the bedrock. The more fractured upper part of the bedrock overlying the target volume is highly transmissive in the horizontal plane and in good hydraulic contact over long distances, whereas at depth the rock appears to have very low permeability with few transmissive fractures. Meteoric water is present in the uppermost approximately 200 m of the bedrock. At depths between 200 and 800 m, the salinity remains fairly constant (5,000–6,000 mg/L) and the water composition indicates remnants of Littorina Sea water. At depths between 800 and 1,000 m, the salinity increases to higher values.

Laxemar

The Laxemar site is part of the Simpevarp candidate area located in the municipality of Oskarshamn, about 300 km south of Stockholm. The topography is relatively flat. The whole area is located below the highest shoreline associated with the last deglaciation. There is still vertical shore-level uplift of approximately 1 mm per year.

The northern and central parts of the area is dominated by Ävrö granite, whereas in the southern part of the area there are rock domains consisting mainly of quartz monzodiorite and diorite to gabbro forming an arc-shaped body dipping to the north with the concave side to the north. No potential for metallic and industrial mineral deposits has been recognised within the area. Many of the rock types of the Laxemar subarea have low and spatially varying quartz contents. This results in relatively low and varying thermal conductivity, compared to typical values of Swedish bedrock. The mean uniaxial compressive strength is comparatively low in most of the rock types and it also shows a quite large spread. However, these results are based on data from a few samples and are possibly biased by their proximity to a larger deformation zone.

The principal orientations of deformation zones are north-south and east-west. It is judged that most of the local major, steeply dipping zones have been identified at the surface and that gently dipping regional zones do not exist within the local model domain. There remain, however, uncertainties as to the details. There is a high variability in the fracturing and the fracture network description is uncertain. Both measurement data and stress modelling results suggest that the Laxemar subarea can be divided into two different stress domains (I and II), where Stress Domain II has lower stress. The limited data available for the Laxemar 1.2 SDM at the time of the data freeze for this report suggested that the rock volume could be divided into hydraulic domains with different and depth-dependent hydraulic properties. New data available after the data freeze, strongly support these previous indications that there is a depth dependence of hydraulic conductivity and that the rock domains in southern Laxemar have lower conductivities than those in northern Laxemar.

The complex groundwater evolution and patterns at the Laxemar subarea are a result both of the past evolution of groundwater flow and modifications of the groundwater composition caused by microbial processes and water/rock interactions. In the Laxemar subarea, fresh (meteoric) water is found down to 800 m depths, whereas the interface is much shallower at the Simpevarp subarea, which is closer to the sea. Brackish water is found at intermediate depths (500–950 m) and deeper (900–1,200 m) the water becomes saline (6,000–20,000 mg/L Cl, 25–30 g/L TDS). Highly saline water (> 20,000 mg/L Cl, max TDS ~ 70 g/L) has only been found in one borehole at depths larger than 1,200 m.

Although the Laxemar 1.2 SDM is based on a significant amount of data, only a few of these are representative of the potential repository volume(s). This is especially evident for the fracture, thermal and hydraulic data. Data acquired after the data freeze as well as data that will be acquired in the future will allow a more elaborate set of analyses as for Forsmark to be performed also for Laxemar. At this time, it has been decided within the SR-Can team to only carry out a limited set of analyses of the Laxemar site.

Repository layouts

Preliminary repository layouts, based on the site descriptions, have been developed for the two sites. The layouts relate to a repository for 6,000 canisters. At Forsmark, the reference layout, assessed in SR-Can, is developed for the –400 m level. At Laxemar, the reference layout is developed for the –500 m level.

In order to avoid detrimental impacts from potential future earthquakes, the design applies a respect distance for deformation zones with traces longer than 3 km. For zones with traces shorter than 3 km, a margin for construction, less than 100 m, is applied. A minimum canister separation distance is determined based on the thermal properties. A degree-of-utilisation is estimated by considering mechanical stability, the probability of deposition holes intersecting fractures or deformation zones with radius R > 75 m, and the inflow of water to tunnels and deposition holes using criteria defined in preset design premises. The degree-of-utilisation affects the size of the repository in the layout, i.e. the repository is made large enough to find space for 6,000 accepted canister positions. At Forsmark, the degree-of-utilisation is 89% in the layout and at Laxemar the design is based on a degree-of-utilisation of 80%.

The canister position selection criteria that are applied in the design are preliminary. SR-Can has, therefore, explored the importance of such criteria. The full perimeter intersection criterion (FPC) states that if a fracture is observed over the entire perimeter of the deposition tunnel no deposition hole should be located such that it would be intersected by the assumed extension of that fracture. The evaluation of this criterion has indicated a high efficiency in reducing the number of deposition holes that are intersected by large fractures and at the expense of only a moderate increase in total deposition tunnel length. It is, therefore, assumed in SR-Can that the FPC rule has been implemented in the layouts at the two sites. It is likely that practical criteria concerning flow conditions would relate to results of hydraulic tests, observations of seepage in deposition tunnels or in deposition holes. However, the practicalities or effectiveness of such hydraulic criteria have not yet been assessed by SKB, and SR-Can only makes some initial exploration on the potential importance of flow-related acceptance criteria.

Safety

The development of the KBS-3 repository concept has been guided by a number of *safety principles*. The long-term performance of the repository can be expressed by studying a set of *safety functions* that should preferably be upheld during the one million year time period covered by the assessment. The safety principles and the implementation of safety functions in SR-Can are summarised below.

Safety principles

Since work on the Swedish final repository project commenced at the end of the 1970s, SKB has established a number of principles for the design of a final repository. The principles can be said to constitute the safety philosophy behind the KBS-3 concept. They are summarised below.

- By placing the repository at depth in a long-term stable geological environment, the waste is isolated from the human and near-surface environment. This means that the repository is strongly affected neither by societal changes nor by the direct effects of long-term climate change on the ground surface.
- By locating the repository at a site where the host rock can be assumed to be of no economic interest to future generations, the risk of human intrusion is reduced.
- The spent fuel is surrounded by several engineered and natural safety barriers.
- The primary safety function of the barriers is to isolate the fuel.
- Should isolation be breached, the secondary safety function of the barriers is to retard a potential release from the repository.
- Engineered barriers shall be made of naturally occurring materials that are stable in the long term in the repository environment. The long-term properties of the materials shall be verifiable.
- The repository shall be designed and constructed so that temperatures that could have significant detrimental effects on the long-term properties of the barriers are avoided.

- The barriers should be passive, i.e. they should function without human intervention and without artificial supply of matter or energy.

Together with many other considerations, like the geological setting in Sweden and the requirement that the repository must be feasible to construct from a technical point of view, these principles have led to the development of the KBS-3 system for spent nuclear fuel.

Safety functions

The key safety related features of the KBS-3 disposal system can be summarised in the safety functions isolation and retardation.

A detailed and quantitative understanding and evaluation of repository safety requires a full description of how the main safety functions of isolation and retardation are achieved by the components of the repository. Based on the understanding of the properties of the components and the long-term evolution of the system, a number of subordinate safety functions to isolation and retardation can be identified. The following definitions are used:

- A safety function is a role through which a repository component contributes to safety.
- A safety function indicator is a measurable or calculable property of a repository component that indicates the extent to which a safety function is fulfilled.
- A safety function indicator criterion is a quantitative limit such that if the safety function indicator to which it relates fulfils the criterion, the corresponding safety function is maintained.

An overview of the safety functions, their indicators and the indicator criteria is given in Figure 3.

Safety functions aid in the evaluation of safety, but the fulfilment of all safety function indicator criteria is neither necessary nor sufficient to argue safety. The different safety function indicator criteria are furthermore determined with varying margins to acceptable performance.

Safety functions are related to, but not the same as, design criteria. Whereas the latter relate to the initial state of the repository and primarily to its engineered components, the former should be fulfilled throughout the assessment period and relate, in addition to the engineered components, to the natural system.

Reference evolution of the repository

A reference evolution of KBS-3 repositories at the Forsmark and Laxemar sites over the entire one million year assessment period is studied to gain an understanding of the overall evolution of the system as a basis for scenario selection and scenario analyses. The aim is to describe a reasonable evolution of the repository system over time.

Two variants of the reference evolution are analysed:

- A base variant where the external conditions during the first 120,000 year glacial cycle are assumed to be similar to those experienced during the last cycle, the Weichselian. Thereafter, seven repetitions of that cycle are assumed to cover the entire one million year assessment period.
- A greenhouse variant in which the future climate and, hence, external conditions are assumed to be substantially influenced by antropogenic greenhouse gas emissions.

The analysis is carried out in four time frames and in each frame the safety functions mentioned above are evaluated.

The excavation/operation phase

The analyses for the excavation and operation phases of the repository, expected to last several decades, mainly focus on disturbances of the mechanical, hydrological and chemical conditions induced by the excavation/operational activities. Issues of potential importance to long term safety include:

- The creation of an excavation damaged zone (EDZ) around deposition holes and in particular deposition tunnels, impairing the retention properties of the rock, relating to the safety functions R2a and R2b in Figure 3.

- The potential for the buffer to experience piping, i.e. the formation of hydraulically conductive channels, immediately after deposition, due to the high groundwater pressure gradients in the open repository. This, in turn, may lead to erosion of the deposited buffer, caused by water flowing in the pipes. This relates to the safety function Bu1 in Figure 3.

The initial temperate period

This period is expected to last several thousand years. The host rock and back-filled tunnels are expected to be re-saturated and the subsequent evolution in the geosphere is characterised by a return to the natural, undisturbed situation prior to excavation. The analysis of this period includes comprehensive thermal, hydrogeological, mechanical and chemical modelling.

An important safety relevant issue with long-term consequences is the occurrence of spalling of the rock around the deposition holes, induced by additional stresses from the thermal load of the deposited waste. This relates to the safety functions R2a and R2b in Figure 3.

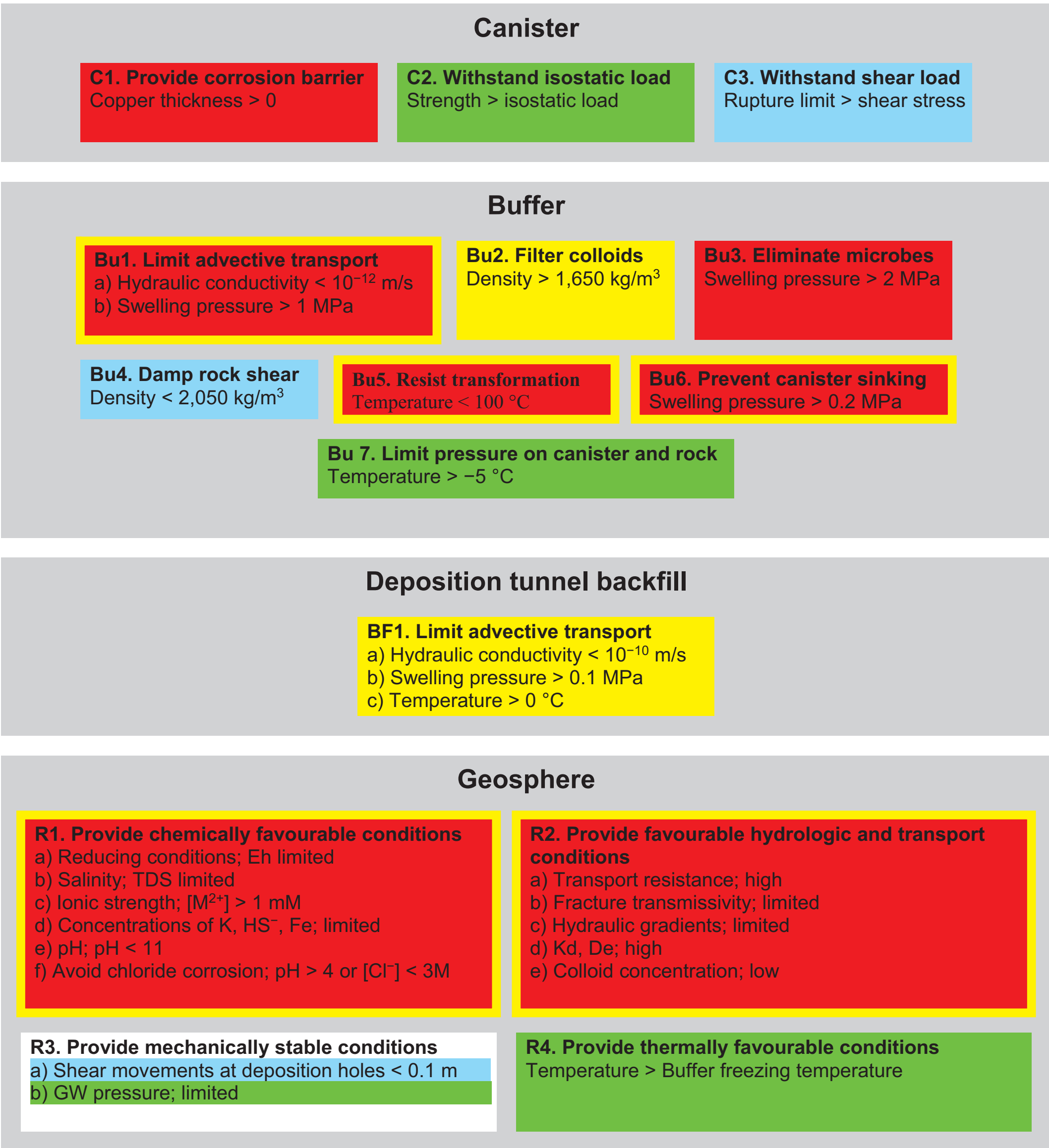

Figure 3. *Safety functions (bold), safety function indicators and safety function indicator criteria. When quantitative criteria cannot be given, terms like "high", "low" and "limited" are used to indicate favourable values of the safety function indicators. The colour coding shows how the functions contribute to the canister safety functions C1 (red), C2 (green), C3 (blue) or to retardation (yellow). Many functions contribute to both C1 and retardation (red box with yellow board).*

The evolution during the initial temperate period does not imply that any other safety functions are jeopardised.

The first glacial cycle

The occurrence of permafrost and glacial conditions, exemplified by a model reconstruction of the last glacial cycle, called the Weichselian and comprising the Weichselian glacial and the Holocene interglacial, implies major alterations on the ground surface and also of some of the bedrock conditions of importance for repository safety. These include:

- The development of permafrost.
- Altered mechanical loads on the bedrock from an overlying ice sheet, leading to altered rock stresses and potentially the occurrence of large earthquakes.
- Increased hydrostatic pressures at repository depth for glacial conditions.
- The occurrence of dilute groundwaters during glacial conditions potentially causing erosion of buffer and backfill through colloid-formation that, in turn, would lead to enhanced canister corrosion.
- The possible penetration of oxygen to repository depth for short periods of increased groundwater flow during glacial conditions.
- Factors affecting retardation in the geosphere, such as temporarily increased groundwater flows.

The results of the analyses imply the following.

- Large earthquakes, of magnitude 6 or larger, in the vicinity of the repository are highly unlikely but cannot be completely ruled out. The results of the probabilistic calculations imply that the mean number of canister failures during the initial glacial cycle due to such events is 0.014 and 0.0077 for the Forsmark and Laxemar sites, respectively. This relates to safety functions C3 and R3a in Figure 3.
- Dilute groundwaters may occur for extended periods of time when glacial conditions prevail. This may lead to loss of buffer mass in some deposition holes, to the extent that advective conditions are created. This leads to enhanced canister corrosion, but no canisters are assessed to fail during the initial glacial cycle. This relates mainly to the safety functions C1, Bu1 and R1c in Figure 3.

Other aspects of the evolution during the first glacial cycle are assessed not to threaten any of the safety functions of the repository.

The time after the first glacial cycle up to one million years

The continued evolution of the repository system is analysed by assuming another seven repetitions of the 120,000 year Weichselian glacial cycle.

The same phenomena as for the initial glacial cycle could impair safety for the repeated glacial cycles:

- The likelihood of large earthquakes is assessed to increase with time. The mean number of canister failures for the entire one million year assessment period is calculated to 0.12 for Forsmark and to 0.065 for Laxemar.
- The extent of loss of buffer mass due to erosion is expected to increase with time. The resulting enhanced canister corrosion may lead to failures of a few canisters during the one million year assessment period. The result is sensitive to a number of factors analysed in the reference evolution.

The results of the analysis do not implicate threats to any additional safety functions.

The greenhouse variant

In the greenhouse variant, it is assumed that a temperate climate prevails for 50,000 years before the relatively mild onset of the base variant of the next glacial cycle, as opposed to a few thousand years of initial temperate conditions without an increased greenhouse effect. Throughout the report it is implicitly understood that the greenhouse variant describes a situation with an increased greenhouse effect.

As seen above, the processes that are potentially the most detrimental to repository safety are related to glacial conditions. Therefore, a prolonged period of temperate climate is essentially beneficial for safety.

Radiological consequences

Radionuclide transport and dose calculations are carried out for four canister failure modes. Two of these, failure due to corrosion and due to shear movements, were identified in the reference evolution. Two additional failure modes are analysed to further illustrate retardation, the secondary safety function of the repository.

A comprehensive set of calculation cases are carried out to analyse retardation and to elucidate the impact of a number of uncertain factors identified in the reference evolution. In the biosphere, radionuclide transport and dose consequences are estimated using a novel approach based on site specific biosphere data and taking the temporal development of the landscape into account.

The results imply that the canister failures potentially resulting from *the reference evolution* yield consequences that are well below the regulatory risk limit.

Scenarios

The further assessment of repository safety is broken down into a number of scenarios. A comprehensive main scenario represents a reasonable evolution of the repository system. The evolution of this scenario is closely linked to the reference evolution. A set of additional scenarios are defined in order to cover uncertainties not addressed in the reference evolution, e.g. more extreme climate conditions than those obtained from the reconstruction of the Weichselian glacial cycle in the reference evolution.

The safety functions are used to obtain a comprehensive set of additional scenarios, focussing on issues of relevance to repository safety. When defining a scenario, a violation of a safety function is *postulated* and all conceivable routes to such a violation are then scrutinised. The aim is to answer the question: Is there any reasonable way in which this scenario could occur? If this is found to be the case, the consequences of the scenario in question are included in a risk summation for the repository. If not, the scenario is considered as “residual”, and consequences may be analysed for illustrative purposes.

A scenario addressing canister failure due to isostatic over-pressure exemplifies the approach. In this scenario, mishaps in the manufacturing of the load bearing canister insert, higher than reference buffer swelling pressures and very large ice sheets yielding high groundwater pressures are considered.

In addition to the so derived scenarios, scenarios required by regulations or otherwise identified as relevant for the assessment are also sought, resulting in a selection of several scenarios related to future human actions. These are residual scenarios, i.e. they are not included in the risk assessment for the repository. Table 1 gives an overview of the selected scenarios.

The selected scenarios are analysed, often as extensions of the analyses of the reference evolution. Two failure modes of the canister were found to contribute to risk:

- Failure due to copper corrosion when advective conditions prevail in the deposition hole as a result of buffer erosion. The buffer erosion is caused by colloid formation due to glacial melt waters of low ionic strength. This failure occurs in the reference evolution and hence in the main scenario. In the canister corrosion scenario, which is analysed to cover uncertainties not addressed in the reference evolution, larger consequences than for the reference evolution are predicted.
- Failure due to rock shear movements caused by large earthquakes. This failure mode has a low probability, but cannot be entirely ruled out.

Table 1. Result of scenario selection. Green cells denote conditions for the base variant of the main scenario, red cells denote deviations from these conditions. EBS stands for engineered barrier system, i.e. the canister, the buffer and the deposition tunnel.

Main scenario				
Name	**Initial state EBS**	**Initial state Site**	**Process handling**	**Handling of external conditions**
Base variant	Reference ± tolerances	Site descriptive model version 1.2 (with variants/ uncertainties)	According to Process Reports	Reference climate (repetitions of Weichselian glacial cycle) No future human actions (FHA)
Greenhouse variant	Reference ± tolerances	Site descriptive model version 1.2 (with variants/ uncertainties)	According to Process Reports	Extended warm period No future human actions (FHA)
Additional scenarios based on potential loss of safety functions (“less probable” or “residual” based on outcome of analysis)				
Name	**Initial state EBS**	**Initial state Site**	**Process handling**	**Handling of external conditions**
Buffer advection	Scrutinise uncertainties of relevant initial state factors, internal processes and external conditions possibly leading to violation of safety function indicator under consideration. Analysis of main scenario used as starting point.			
Buffer freezing	See above			
Buffer transformation	See above			
	Consider each of above three buffer states + intact buffer when analysing below three canister scenarios.			
Canister failure due to isostatic load	Scrutinise uncertainties of relevant initial state factors, internal processes and external conditions possibly leading to violation of safety function indicator under consideration. Analysis of main scenario used as starting point.			
Canister failure due to shear movement	See above			
Canister failure due to corrosion	See above			
Scenarios related to future human actions				
Name	**Initial state EBS**	**Initial state Site**	**Process handling**	**Handling of external conditions**
Boring intrusion	As base variant of main scenario	As base variant of main scenario	As base variant of main scenario, except processes affected by boring	Reference climate + boring
Additional intrusion cases, e.g. nearby rock facility	As base variant of main scenario	As base variant of main scenario	As base variant of main scenario, except processes affected by intrusion	Reference climate + intrusion activity
Unsealed repository (not analysed in SR-Can)	As base variant of main scenario, but insufficient sealing	As base variant of main scenario	As base variant of main scenario, modified according to initial state	Reference climate

Main results and conclusions

The most important findings in the SR-Can project are summarised in subsections A, B and C below. A more detailed discussion on compliance with the regulatory risk limit is given in subsection D and additional results and conclusions are summarised in subsection E.

A. Compliance with the regulatory risk criterion

No canisters are assessed to fail during the initial temperate period, expected to last several thousand years

No canister failures are expected for either of the sites during the initial temperate period after deposition, estimated to last several thousand years. Furthermore, the evaluations of the canister sealing procedure undertaken so far, have led to the conclusion that all canisters will be tight at deposition.

A repository at Forsmark is assessed to comply with the regulatory risk criterion

The preliminary analyses carried out in SR-Can suggest that a KBS-3 repository at Forsmark will comply with the regulatory risk criterion issued by SSI.

Uncertainties in the hydrogeological interpretation and understanding of the Forsmark site are, however, considerable and, when propagated to various parts of the analyses, lead to a wide range of conclusions regarding e.g. buffer colloid release and water flow properties. A reduction of these uncertainties would allow more definite conclusions in future assessments. Even the most pessimistic interpretation of the Forsmark site is, however, assessed to comply with the regulatory risk criterion.

A repository at Laxemar is preliminarily assessed to comply with the regulatory risk criterion – but more representative data is required

The Laxemar site descriptive model version 1.2 is not sufficiently representative of the potential repository volume to allow definite conclusions regarding compliance. In particular, the hydraulic interpretation of the site is based on data partly obtained outside the candidate volume for the repository. Furthermore, recently obtained data indicate more favourable hydraulic properties than those on which the site model used in SR-Can is based.

However, it is noted that with the data used for Laxemar, the site is assessed to comply with the risk criterion and that use of more recent data would likely strengthen this conclusion.

B. Issues related to glacial conditions

In general, the most severe impact on the repository will occur during future glacial conditions. A number of conclusions regarding effects of such conditions can be drawn.

Freezing of an intact buffer is assessed as ruled out – even for very pessimistically chosen climate conditions

Freezing of an intact buffer is assessed as ruled out for both sites, even for the most pessimistic climate conditions considered. For a water-filled cavity in an eroded buffer, freezing is not entirely ruled out for the most pessimistically chosen climate development at Forsmark, but calculations demonstrate that the mechanical pressure on the canister is acceptable in such cases.

Canister failure due to isostatic load is assessed as ruled out – even for very pessimistically chosen climate conditions

Canister failure due to isostatic load is assessed as ruled out for both sites, also for the most severe future glacial conditions considered.

Oxygen penetration is preliminarily assessed as ruled out – even for very pessimistically chosen conditions

Oxygen penetration to repository depth for enhanced groundwater flows under an ice sheet, jeopardising the favourable reducing chemical conditions, is assessed as ruled out, based on the analyses carried out in SR-Can. This result is in agreement with conclusions from several earlier assessments. The modelling example is, however, stylised and simplified, meaning that additional analyses are warranted to increase confidence in the results. Such studies will be undertaken in SR-Site.

The risk contribution from earthquakes is assessed as small

Canister failures due to post-glacial earthquakes cannot be completely ruled out. The risk contribution from this failure mode is, however, small. The probabilistic analyses made imply that, on average, it would take considerably more than one million years for even one such canister failure to occur.

Loss of buffer may occur from exposure to glacial melt waters but the extent is uncertain – further studies are required

Substantial loss of buffer through buffer erosion/colloid release may occur as a result of intrusion of low ionic strength glacial melt waters in a 100,000 year perspective. The knowledge of the processes involved is uncertain and further research is being undertaken as a matter of priority. A status report will be given in SKB's RD&D programme 2007 to be published in 2007.

Substantial loss of buffer may lead to canister failures in very long time perspectives

Loss of buffer mass, to the extent that advective conditions prevail in the buffer, which cannot be ruled out in a 100,000 year perspective, will lead to enhanced canister corrosion rates. In a one million year perspective, this may lead to failures of some tens of canisters for the pessimistic hydraulic interpretation of the Forsmark site, with cautious assumptions regarding sulphide concentrations and cautious assumptions regarding deposition hole acceptance rules.

A prolonged period of warm climate (increased greenhouse effect) before the next glacial period is assessed as primarily beneficial for repository safety

Since the processes that are potentially the most detrimental to repository safety are related to glacial conditions, a prolonged period of temperate climate is deemed as beneficial for safety. This concerns in particular the two main contributions to the calculated risk in SR-Can, namely i) potential buffer erosion with subsequent enhanced canister corrosion as a result of intrusion of glacial melt waters and ii) the occurrence of large earthquakes during deglaciation. Further evaluations of the geochemical evolution for a prolonged warm period are required in order to better substantiate the conclusion that the geochemical conditions would remain beneficial.

C. Other issues related to barrier performance and design

Crucial to avoid deposition positions intersected by large or highly water conductive fractures – further studies are required

The main risk contributors in SR-Can are related to the occurrence of large and/or highly transmissive fractures intersecting deposition holes. This applies to the buffer colloid release process and the impact of major earthquakes in the vicinity of the repository. These two phenomena are related to canister failures due to canister corrosion and to secondary rock shear movements, respectively. As also the retention in a large, highly transmissive fracture is small, such failures are in general associated with high consequences. Such fractures will be avoided when identified. The likelihood of occurrence of such fractures and the probability of unsuitable deposition holes remaining unidentified are, in many respects, uncertain and the results of the analysis are sensitive to these uncertainties. It is important to establish well-founded acceptance criteria for deposition holes as a basis for future assessments. This needs to be studied both by simulation of the effects of applying potential criteria and by exploring the practicability of applying the criteria.

The heat from the canister may fracture the rock in the deposition hole wall, which may enhance the in- and outward transport of dissolved substances – further studies are required

Thermally induced spalling around deposition holes may have a considerable impact on mass exchange between the flowing groundwater and the buffer as long as diffusion is the dominant transport mechanism in the buffer. If advective conditions prevail in the buffer, the effects of spalling are much less pronounced because it adds little to the already increased flow rate. There are uncertainties regarding the extent and the consequences of spalling and further studies are ongoing.

The importance of the backfilled deposition tunnels as a transport path for radionuclides is limited

The importance of the backfilled deposition tunnel as a transport path for radionuclides is limited in comparison with fractures intersecting a deposition hole. Also, deterioration of the deposition tunnel backfill material has limited consequences in terms of radionuclide releases from the near field.

The importance of the excavation damaged zone in the rock around the deposition tunnels as a transport path for radionuclides is limited

The importance of the excavation damaged zone (EDZ) around deposition tunnels is limited in comparison to other transport routes for radionuclides, even for very pessimistic assumptions about the EDZ in relation to the reference excavation method.

Cautious excavation methods are still recommended for the deposition tunnels, because competing transport routes may be assessed as less important with additional data and because the conclusion regarding the EDZ is based on simplified, stylised modelling.

D. Calculated individual risks

The calculated individual risks for repositories at Forsmark and Laxemar are presented in Figure 4. Note that temperate conditions are assumed for the biosphere, whereas it is expected that the sites will be submerged or covered by ice during a considerable part of the one million year assessment time, yielding negligible risks for these periods. Also, several pessimistic assumptions have been made in order to not underestimate the risk.

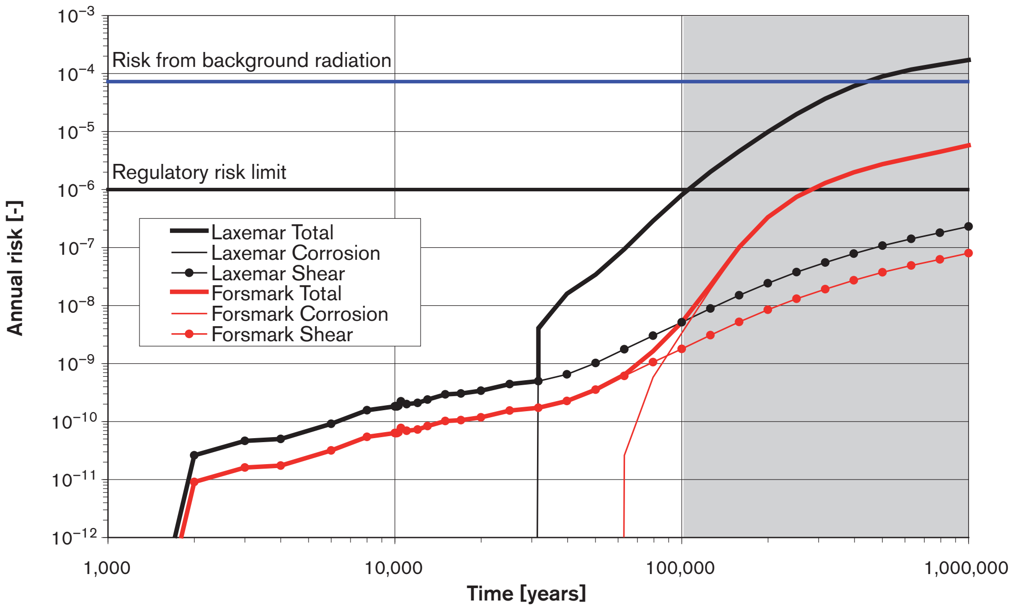

Figure 4. *Risk summation for the two sites. Temperate conditions are assumed for the biosphere, whereas it is expected that the sites will be submerged or covered by ice during a considerable part of the one million year assessment period, yielding negligible doses. Several other uncertainties are handled pessimistically.*

Compliance for the initial glacial cycle

For the initial glacial cycle, two risk contributions are identified: That from earthquakes and that from canister failures due to corrosion if the buffer has been eroded by glacial melt waters.

The probability of canister failures due to earthquakes for this period is very small and this probability is included in the risk estimate.

As concerns failures due to corrosion, a few canisters are calculated to fail during the initial glacial cycle at both sites. The total calculated risk up to 100,000 years is at most, i.e. after 100,000 years, close to the regulatory risk limit at Laxemar and about two orders of magnitude below at Forsmark. The risk is pessimistically based on that calculated for the canister corrosion scenario, where several uncertainties are handled pessimistically, due to insufficient understanding of groundwater flow and composition for glacial conditions and of the response of the buffer to glacial groundwaters. The risk calculated for Forsmark is based on a pessimistic interpretation of the current hydraulic situation. As also pointed out previously, the representativity of the Laxemar hydrogeological model is questionable. More recent site data from the candidate repository area indicate that the hydrogeological conditions are more favourable than those adopted in the model used in SR-Can. This would reduce the risk contribution from canister failures due to corrosion.

It is, thus, concluded that the calculated risks for the two sites comply with the regulatory requirements during the initial glacial cycle after closure.

Repository performance for the time beyond the initial glacial cycle

The same canister failure modes as for the initial glacial cycle contribute to individual risk during the period after the initial glacial cycle up to one million years after closure.

For Forsmark, the calculated risk contribution from earthquakes is more than one order of magnitude below the regulatory limit throughout the assessment period, whereas the contribution from corrosion failures is above the regulatory limit at the end of the one million year period.

For Laxemar, the contribution from earthquakes is similar to that for Forsmark, whereas that from corrosion failures exceeds the risk limit by about two orders of magnitude at the end of the assessment period.

As stated in SSI's general guidance, "*a strict quantitative comparison of calculated risk in relation to the criterion for individual risk in the regulations is not meaningful*" for this time period. Rather, the results are used as a basis for discussing how pessimistically handled uncertainties can be reduced and how the protective capability of the repository can be improved as suggested by the general guidance.

It is important to note that the calculated risks, although exceeding the risk limit applicable for the initial 100,000 years, are considerably less than those due to the background radiation throughout the assessment period for Forsmark. For Laxemar, they are well below the background radiation for several hundred thousand years and become comparable to the background radiation only at the end of the one million year assessment period. Furthermore, as for the initial glacial cycle, a number of issues have been treated pessimistically and further knowledge may lead to a substantial reduction of these risk estimates in future assessments.

It is, thus, concluded that calculated risks for the time beyond the initial glacial cycle fulfil the regulatory requirements for this time period.

E. Additional results and conclusions

A number of additional results have been obtained on which conclusions are drawn from the SR-Can assessment:

- A first evaluation of effects on the environment from release of radionuclides has been made. Most radionuclides fall below screening limits, meaning that no additional analyses are required. A few nuclides in the most pessimistic calculation cases exceed the screening limits at the end of the assessment period, requiring more detailed assessments.
- Two alternative safety indicators have been used as a complement to the risk indicator; release constraints issued by the Finnish regulator STUK and contents of naturally occurring radionuclides in the environment at the repository sites.

- A first account is made of the aspects of Best Available Technique, BAT, that can be addressed based on the results of the safety assessment.
- A number of bounding cases, assuming fictitious complete loss of one or several barrier functions have been analysed. The results indicate that the calculated doses are below the natural background radiation also for very severe losses of safety functions. For example, an initial total loss of the canister and buffer in all deposition holes yields, for a repository at the Forsmark site, doses that are comparable to those caused by the background radiation. The bounding analyses demonstrate the multi-barrier character of the KBS-3 system.
- A set of design basis cases have been derived. These are to be used as one of several inputs to substantiate the design basis for the repository which includes the establishment of requirements on barrier properties.
- Detailed feedback is provided to canister design and fabrication, to repository design, to further site investigations and site modelling, to SKB's RD&D programme and to the next safety assessment, SR-Site.

References

Brantberger M, Zetterqvist A, Arnbjerg-Nielsen T, Olsson T, Outters N, Syrjänen P, 2006. Final repository for spent nuclear fuel. Underground design Forsmark, Layout D1. SKB R-06-34, Svensk Kärnbränslehantering AB.

Climate report, 2006. Climate and climate related issues for the safety assessment SR-Can. SKB TR-06-23, Svensk Kärnbränslehantering AB.

Data report, 2006. Data report for the safety assessment SR-Can. SKB TR-06-25, Svensk Kärnbränslehantering AB.

FEP report, 2006. FEP report for the safety assessment SR-Can. SKB TR-06-20, Svensk Kärnbränslehantering AB.

FHA report, 2006. Handling of future human actions in the safety assessment SR-Can. SKB TR-06-24, Svensk Kärnbränslehantering AB.

Geosphere process report, 2006. Geosphere process report for the safety assessment SR-Can. SKB TR-06-19, Svensk Kärnbränslehantering AB.

Initial state report, 2006. Initial state report for the safety assessment SR-Can. SKB TR-06-21, Svensk Kärnbränslehantering AB.

Jansson P, Näslund J O, Rodhe L, 2006. Glacial hydrology and eskers. A review of ice sheet hydrology. SKB TR-06-34, Svensk Kärnbränslehantering AB.

SKB, 2005. Preliminary site description Forsmark area – version 1.2. SKB R-05-18, Svensk Kärnbränslehantering AB.

SKB, 2006a. Long-term safety for KBS-3 repositories at Forsmark and Laxemar – a first evaluation. Main report of the SR-Can project. SKB TR-06-09, Svensk Kärnbränslehantering AB.

SKB, 2006b. Preliminary site description. Laxemar subarea – version 1.2. SKB R-06-10, Svensk Kärnbränslehantering AB.