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The barriers in the KBS-3 repository in Forsmark

1 The barriers in the KBS-3 repository in Forsmark

This document summarises the function of the three main barriers in a KBS-3 repository for spent nuclear fuel in Forsmark – the canister, the buffer and the rock.

The materials, dimensions and properties of the barriers are presented as well as their intended function in a final repository. Thereafter a summary is made of the most important results in the safety assessment included in SKB's application for a licence to construct a spent fuel repository in Forsmark – the safety assessment SR-Site. Finally, there is a summary of the responses submitted by SKB to the supplements on barrier performance after closure requested by the Swedish Radiation Safety Authority, SSM, in its review of SKB's application under the Nuclear Activities Act.

The purpose of the document is to provide an accessible summary of the material on barriers that serve as a basis for SSM's review. The document is intended to provide an orientation in the technically specialised issues for the review of SKB's application under the Environmental Code.

The material in Sections 1.1 and 1.2 constitutes a summary of parts of the safety assessment SR-Site that is also included in the supporting material for the application under the Environmental Code. The material in Section 1.3 is a summary of the supplements on barrier safety after closure submitted to SSM within the framework of the licensing of SKB's application under the Nuclear Activities Act.

1.1 Barrier function

1.1.1 Safety principles for the design of the 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 not strongly affected by either societal changes or the direct effects of long-term climate change at 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 contain the fuel within a canister.
- Should containment 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 repository shall be designed and constructed so that temperatures that could have detrimental effects on the long-term properties of the barriers are avoided.
- The repository shall be designed and constructed so that radiation induced processes that could have detrimental effects on the long term behaviour of the engineered barriers or of the rock 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.

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 groundwater saturated, granitic rock, see Figure 1-1. The purpose of the KBS-3 repository is to isolate the nuclear waste from man and the environment for very long times. Around 12,000 tonnes of spent nuclear fuel is forecasted to arise from the currently approved Swedish nuclear power programme (where the last of the 10 operating reactors is planned to end operation in 2045), corresponding to roughly 6,000 canisters in a KBS-3 repository.

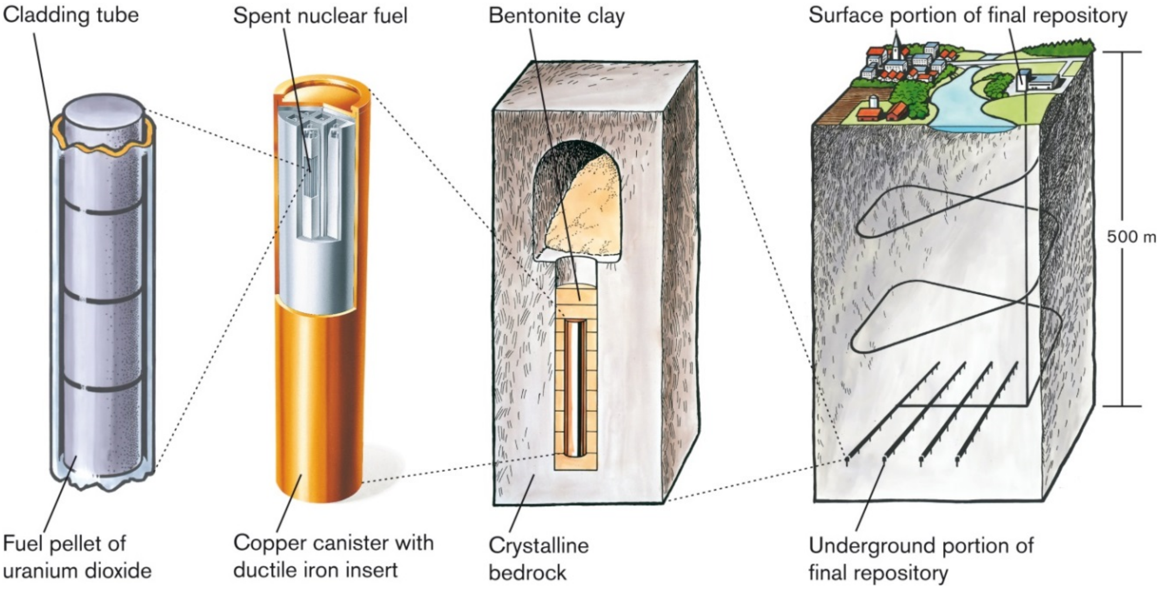

Figure 1-1. *The KBS-3 method for disposal of spent nuclear fuel.*

In practice, safety is achieved through the selection of a site with favourable properties for long-term safety and through the design and construction of a repository that fulfils requirements related to long-term safety. The site conditions today and the design and layout of the KBS-3 repository at Forsmark constitute the initial state of the safety assessment. These are also the aspects that are controlled by the implementer, through the choice of the site and through the design and site adaptation of the repository.

1.1.2 The canister

The canister consists of an insert of nodular cast iron (a form of cast iron with high strength) and a copper shell, see Figure 1-2. The cast iron insert provides mechanical stability and the copper shell protects against corrosion in the repository environment. The copper shell is five centimetres thick and the cylindrical canister is about 4.8 metres long and has a diameter of 1.05 metres. The insert has channels where the fuel assemblies are placed.

The supporting material to SKB's application specifies a number of requirements on the canister material and design. It also demonstrates how the canister components are to be manufactured and put together in such a way that the set requirements are met, as well as how the fuel will be emplaced in the canisters and how the canisters finally will be sealed by welding. The application also shows how the canisters will be deposited in the repository.

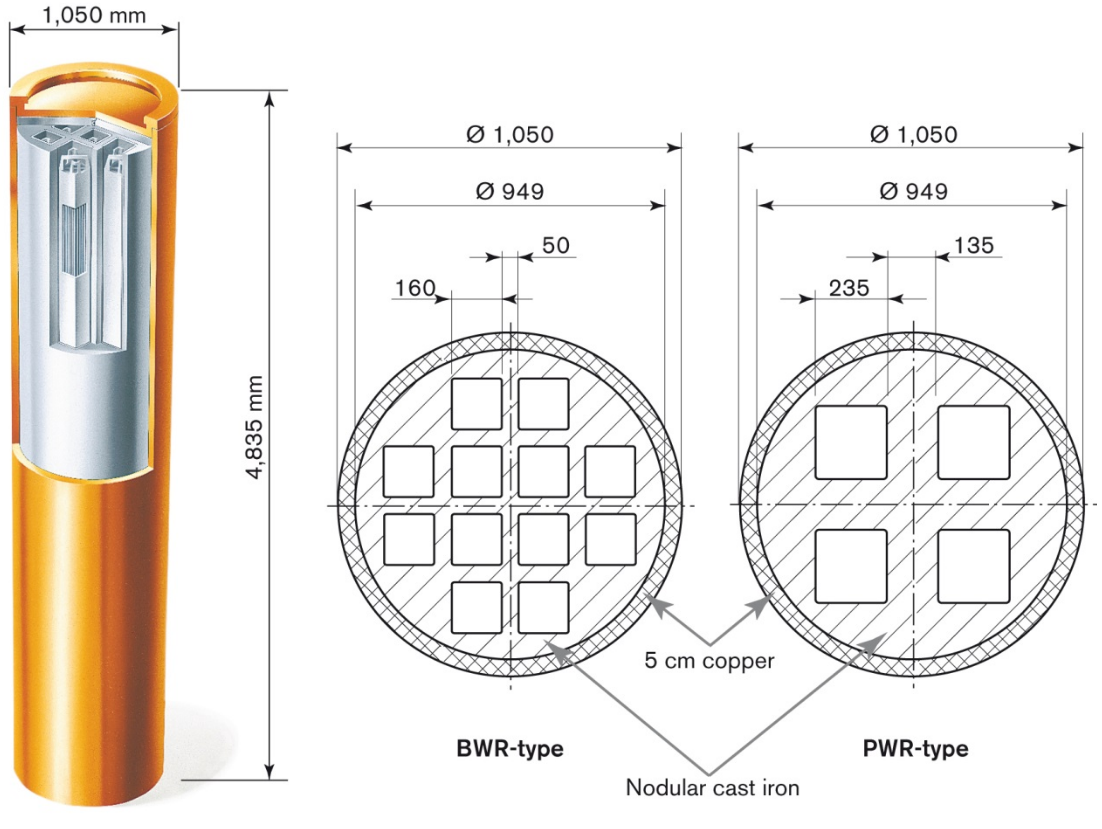

Figure 1-2. *Left: Reference design of the canister with a corrosion-resistant outer copper shell and a load-bearing insert of nodular cast iron. Right: Cross-section of inserts for fuel from the two types of nuclear power plants found in Sweden; boiling water reactors (BWRs) and pressurized water reactors (PWRs).*

1.1.3 The buffer

The main function of the clay buffer is to restrict water flow around the canister. This is achieved by choosing a buffer material of clay that has low water permeability after the material has been saturated with water. The material is also chosen with respect to its self-sealing properties. These are achieved by the clay material swelling and thereby filling in any cavities and irregularities when it is saturated with water. The clay material’s montmorillonite content is a key property for the safety functions of the buffer.

The supporting material to SKB’s application specifies a number of requirements on the buffer material and design. It also demonstrates how the buffer is to be manufactured and emplaced in a quality-assured manner, so that it can maintain its intended functions in the final repository.

In SR-Site, two examples of clay materials that conform to the stipulated requirements are evaluated. The examples, MX-80 and Ibeco RWC, are both from large deposits and are mined by large bentonite suppliers. They are of different origin and should be seen as potential examples of possible alternatives to use in the repository.

1.1.4 The rock

The selected repository site in Forsmark is located in northern Uppland in the municipality of Östhammar, about 120 km north of Stockholm. The Forsmark area consists of crystalline bedrock that belongs to the Fennoscandian Shield and was formed 1.85 to 1.89 billion years ago. Geologically, the area is characterized by the occurrence of a number of so-called tectonic lenses, in which the bedrock is less affected by early geological events, in contrast to surrounding structures that were subject to deformation in early times. The candidate area for the repository is located in the north-westernmost part of one of these tectonic lenses. This lens extends from the north-west of the Forsmark nuclear power plant south-eastwards to the area south of Öregrund, see Figure 1-3.

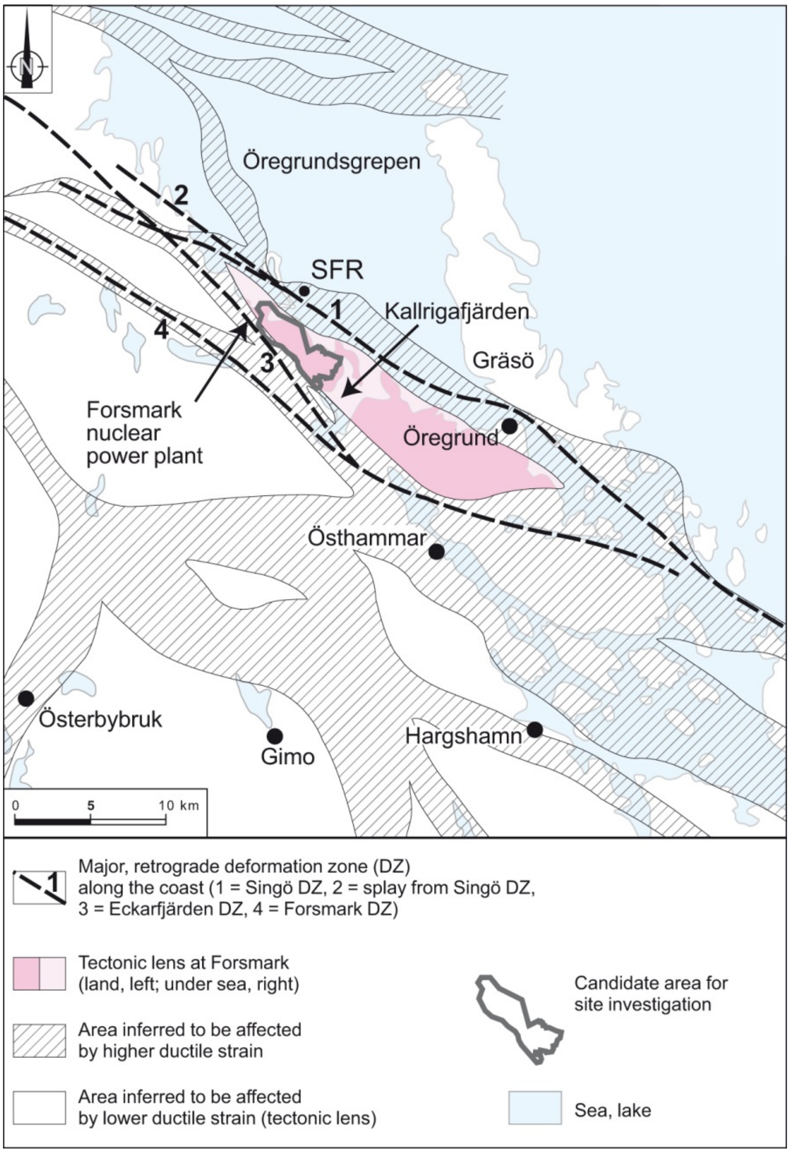

Figure 1-3. *Bedrock in the Forsmark environs with the tectonic lens investigated. The investigated area is located in the north-western part of the lens.*

In summary, the main safety related features of the Forsmark site are:

- A low frequency of water conducting fractures at repository depth.
- Favourable chemical conditions, in particular reducing conditions at repository depth, (which is generally found at depth in granitic rocks in Sweden) and salinity that would ensure stability of the bentonite clay buffer.
- The absence of potential for metallic and industrial mineral deposits within the candidate area at Forsmark.

In addition, the relatively high thermal conductivity at the site facilitates an efficient use of the rock volume and the rock mechanics and other properties of importance for a safe and efficient construction of the repository are also favourable.

1.1.5 Safety functions of barriers

The primary safety function of a KBS-3 repository is to completely contain the spent fuel in the canisters. If a canister for any reason should be damaged, the secondary safety function of the barriers is to delay a potential release of radioactive substances from the repository.

Safety functions of the canister

The canister is the primary *containment* component in the repository. As long as the canister's containment capability remains, no releases of radioactive substances occur. The canister's containment capability could be lost if it is affected chemically or mechanically.

The chemical impact occurs via corrosion, i.e. by substances detrimental to copper reacting with the metallic copper material so that the thickness of the copper decreases at the points where the canister surface is attacked. The detrimental substances may be present initially in the buffer or supplied by the groundwater.

The mechanical impact is of two types: First, the canister may be exposed to high pressure in the repository, so-called isostatic loads from the swelling of the buffer and from the groundwater, and second, the canister may be affected by movements in fractures intersecting the deposition hole, so-called shear movements.

The canister must withstand the chemical load and the two types of mechanical load to maintain its main function, to contain the spent nuclear fuel. Therefore, the canister is assigned three safety functions:

- The canister shall provide a corrosion barrier. The canister maintains this function as long as there is any copper coverage left everywhere on the surface, i.e. as long as the shell is tight.

- The canister shall withstand isostatic (uniform) pressures. If the pressure is too high the canister collapses. This so-called collapse pressure can be determined roughly by calculations and manufactured canisters can also be pressure-tested to determine their strength during this type of load. The canister maintains this function as long as the pressure it is exposed to in the repository does not exceed the collapse pressure.

- The canister shall withstand shear movements in the rock. By extensive calculations and experimental tests of how the buffer and canister reacts to a movement in a fracture intersecting the deposition hole, it has been decided that the canister can withstand movements up to 5 centimetres, and in many cases more.

The safety functions of the buffer

The buffer has a number of important functions in the repository which concern both the containment and retarding capacity of the repository.

- The buffer should impede detrimental substances from reaching the canister, as well as prevent radionuclides from reaching the surrounding rock if the canister is damaged. Primarily it is important that water can not flow through the buffer. The buffer should therefore significantly limit potential water flow through the deposition hole and thereby make transport of solutes with flowing water, so-called advective transport, a negligible phenomenon in the buffer. This function requires that the buffer has a very low water conductivity, so-called hydraulic conductivity. It should not exceed 10^{-12} m/s.

  This function also requires that the buffer swells on contact with water so that any inhomogeneities are smoothed. Swelling capacity is measured by the pressure exerted by the water-saturated buffer against the surroundings. This so-called swelling pressure should be at least 1 megapascal (MPa). One MPa corresponds to the pressure on a water depth of approximately 100 metres.

- The buffer should not be transformed chemically, which requires among other things that its temperature does not exceed 100°C.

- The buffer should not freeze, since it would then expose the canister and the surrounding rock to large pressure. This requires that the temperature in the buffer does not fall below its freezing temperature, which is about -4°C.

- The buffer should filter colloids (small particles that can contribute to the transport of radionuclides), which requires that its density be at least 1,650 kg/m^3.

- The buffer must reduce microbial activity. In initial phases when circumstances can be beneficial for microbial activity, a buffer density of 1,800 kg/m^3 or higher provides a reduction of microbial activity to negligible levels. In later stages, the requirements on the buffer are lower.

- The buffer should mitigate the effects on the canister of shear movements in the rock, which requires that its density be below 2,050 kg/m^3.

- The buffer should prevent the canister from sinking in the deposition hole, which requires a swelling pressure of at least 0.2 MPa.

In order for the buffer to maintain these functions, a number of requirements are set on its design and composition at deposition. These requirements are formulated so that among other things the quantity of buffer material installed will result in a buffer density, after the buffer has been water saturated, in the range of 1,950–2,050 kg/m^3.

The safety functions of the host rock

The rock shall above all constitute a long-term stable and favourable environment for the repository. Technically this is expressed in four main safety functions. The rock shall provide the repository with chemically favourable conditions, favourable transport and hydrological conditions, stable mechanical conditions and favourable thermal conditions. Each of these principal functions can be broken down into a number of subfunctions.

In order to provide *chemically favourable conditions* the groundwater in the rock should, among other things:

- not contain oxygen, i.e. reducing conditions should prevail.

- not have too high a salinity so as not to damage the buffer; the margin is, however, large between the salinities that may damage the buffer and those encountered at repository depth in Swedish groundwaters.

- have a sufficient content of positive ions, primarily calcium ions, to protect the buffer from dissolving; the limit here is at a concentration of 2 millimoles of Ca^{2+} per litre; if sodium ions are the only positive ions, 4 millimoles of Na^+ is required.

- have low concentrations of substances that could damage the canister and buffer, such as potassium, sulphide and iron.

- have a pH-value below 11 so as not no damage the buffer.

In order to provide *favourable transport and hydrological conditions* should, among other things:

- the ability of rock fractures to lead water be limited

- differences in groundwater pressure between different parts of the repository rock be limited (these differences constitute the driving force for groundwater movement).

- the concentration of colloids in the water be low (colloids are small particles that through uptake of radionuclides can accelerate the transport of radionuclides due to these particles not adhering to the rock surfaces).

In order to provide *stable mechanical conditions* should, among other things:

- movements in fractures intersecting the deposition hole never be larger than 5 cm, and

- the groundwater pressure be limited.

In order to provide *thermally favourable conditions* the temperature in the rock should exceed the freezing point of the buffer, which is -4°C.

1.2 The safety assessment SR-Site

The report on post-closure safety is a cornerstone of SKB's application for a final repository for spent nuclear fuel in Forsmark. The safety assessment underlying the application is called SR-Site and the following summarizes some significant points from SR-Site, with emphasis on the long-term function of the barriers in the repository.

1.2.1 Assessment methodology

According to SSM's regulations, repository safety is evaluated for a time period of a million years after closure. The regulations also impose a number of requirements on the content of a safety assessment and on systematic handling of uncertain factors in the supporting material for the assessment.

SSM has also formulated a risk criterion that states "*... 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*." Slightly simplified, this entails that the individuals thought to be most affected by a possible future release from the repository may be exposed to radiation doses that correspond to approximately one percent of the natural background radiation in Sweden.

A safety assessment is a comprehensive and in many respects complex study of how a repository develops after it has been closed and sealed. The repository system is broadly defined as the deposited spent nuclear fuel, the engineered barriers, the host rock and the biosphere in the proximity of the repository. The future states of the system will depend on

- the initial state of the system, when it is recently constructed,

- a number of thermal, hydraulic, mechanical and chemical processes acting internally in the repository system over time and

- external influences on the system.

Internal processes are for example the decay of radioactive substances in the fuel, which causes heating of the fuel, the engineered barriers and the bedrock. Groundwater movements and chemical processes affecting the engineered barriers and the composition of groundwater are other examples. External influences include future climate and climate-related processes, such as glaciations and land uplift. Also, future human actions may influence the repository.

The initial state, the internal processes and the external influences and the way these factors 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 safety assessment. A central theme in any safety assessment methodology is therefore handling of all relevant types of uncertainties. Often a “worst case” is assumed in the safety assessment, when there is uncertainty about the conditions.

The primary safety function of the KBS-3 system is to completely contain the spent nuclear fuel in copper/iron canisters throughout the assessment period. If a canister is damaged, the secondary safety function is to delay and disperse any releases of radioactive substances from the canister so that these do not cause unacceptable consequences. The two issues of containment and retardation are, therefore, in focus in the assessment.

The methodology for the safety assessment SR-Site has been developed over many years, and is based on the methodology used in SKB’s previous safety assessments. The methodology has been reviewed several times by SSM and the two expert regulatory authorities that previously had the role SSM has today. Feedback from each of these reviews has been used to improve the methodology for the subsequent safety assessment. The methodology has also been developed in international cooperation, above all in OECD’s Nuclear Energy Agency (NEA).

The methodology for the safety assessment SR-Site consists of eleven steps that are described in detail in the main report of the assessment.

1.2.2 Scenarios

Barrier function is evaluated in the assessment in the study of a number of scenarios. These are designed to critically evaluate whether the safety functions of the barriers could be impaired by the conditions they may be exposed to in the repository in the long term.

As an example, one of the canister’s basic safety functions is to withstand isostatic, i.e. evenly distributed, pressure. An isostatic load scenario, therefore, evaluates all the factors that cause isostatic loads on the canister. The focus is on identifying the largest loads that on any reasonable basis could occur in the repository in the perspective of a million years. In the same way, corrosion is evaluated in a corrosion scenario and shear loads, i.e. the type of mechanical strain that can occur during earthquakes, in an earthquake scenario.

In the following, the results of the most important scenario analyses in SR-Site are summarized.

Buffer scenarios

The purpose of the scenarios which analyse the safety functions of the clay buffer can be said to be answering the following three questions:

• Can the buffer freeze?

• Can the buffer clay be transformed into a material with unfavourable characteristics?

• Can the buffer be lost?

These problems are analysed in three buffer scenarios. The conclusions in SR-Site were, in short, the following.

Freezing of the buffer

The buffer would freeze if the temperature at repository depth was less than the freezing temperature of the buffer, which is about -4°C. In the scenario which analyses freezing of the buffer, it was concluded that this will not take place, not even for extreme assumptions concerning future climate.

Transformation of the buffer

The buffer clay can be transformed if the temperature is too high and/or if the chemical conditions are unfavourable; especially a high pH-value can lead to transformation. The analysis of the temperatures and chemical conditions that might occur in the repository in the most unfavourable cases led to the conclusion that transformation to such an extent that the function of the buffer would be adversely affected can be excluded.

Loss of the buffer

Many of the safety functions of the buffer are based on the presence of sufficient buffer, which can also be expressed as the buffer must have a sufficiently high density. The buffer could be lost from the deposition hole if it is exposed to groundwater with too low salinity. This can lead to the clay "dissolving" and being carried away with the groundwater; this phenomenon is a form of erosion. The groundwater in Forsmark today has sufficiently high salinity to prevent erosion. Groundwater with low salinity may, however, possibly occur during glacial periods and after long periods of temperate climate similar to the present. The analyses in this scenario led to the conclusion that it cannot be excluded that the buffer may be lost in about one percent of the deposition holes in the long term, to such an extent that the buffer's protective function is impaired. It is a question of time periods of tens of thousands to hundreds of thousands of years and concerns the deposition holes where groundwater flow rates are the highest.

Since it could not be ruled out that the scenario with loss of the buffer will occur, this result was propagated to the analysis of canister scenarios.

Canister scenarios

The purpose of the scenarios where the canister's safety functions are analysed can be said to be answering the following three questions:

- Can the canister be damaged by the pressure from the swelling bentonite clay and the groundwater pressure at repository depth?
- Can the canister be damaged by earthquakes?
- Can the canister be damaged by corrosion?

These problems are analysed in the three canister scenarios. The conclusions in SR-Site were, in short, the following.

The isostatic load scenario

The analysis of the isostatic load scenario studies which isostatic, i.e. evenly distributed, pressures the canister may be subjected to as a maximum. This includes pressure from the groundwater, from the surrounding clay buffer and from the overlying ice sheets during the periods of glacial conditions expected in very long time perspectives. The conclusion in the scenario analysis was that the canister will withstand the pressures it may be exposed to in the final repository, also with pessimistic assumptions regarding how large these pressures maximally can be.

The earthquake scenario

The analysis of the earthquake scenario studies what mechanical loads the canister may be subjected to in conjunction with a major earthquake in the proximity of the repository. Large earthquakes are very unusual in Sweden today, but could conceivably occur in conjunction with future glaciations that cause increased mechanical load on the bedrock, especially when an ice sheet retreats. In this context, it is also worth noting that an earthquake that has large consequences on the earth surface is associated with considerably less dramatic effects down in the bedrock.

Large earthquakes can only occur in large fracture zones, and therefore no canisters are placed closer than 100 metres to such zones. An earthquake can also generate movements in minor rock fractures at some distance from the major zone where the earthquake was triggered. It cannot be excluded that such secondary movements in minor fractures transecting a deposition hole may damage a canister. Therefore, deposition positions intersected by fractures that are judged to be sufficiently large for the movements in them to damage a canister are avoided. Such an assessment is, however, associated with uncertainties, and it can thus not be fully ruled out that a canister could be damaged due to an earthquake. Even with pessimistic assumptions of several of the input factors, the conclusion was that the probability is low that any of the 6,000 canisters would be damaged even in a perspective of a million years. The limited extent of canister damage due to earthquakes calculated in the earthquake scenario was used as input to the calculations of dose consequences in a later step of the assessment.

The corrosion scenario

A number of corrosion phenomena were analysed in the corrosion scenario. The results showed that all canisters hold for the combined effect of all these phenomena provided that the clay buffer is intact. If the clay buffer is degraded by erosion to the extent that is described in the buffer scenarios, it cannot be excluded that one of the most exposed canisters is damaged in a perspective of a million years. The corrosion here is caused by sulphide in the groundwater. The extent of canister damage calculated in the corrosion scenario was used as input to the calculations of dose consequences in a later step of the assessment.

A research team had, some time before the SR-Site assessment was completed, interpreted their experimental results to mean that pure water would corrode copper to a much greater extent than predicted by established science. Therefore, a hypothetical case with this interpretation as a basis was also analysed. The results of the analysis gave a negligible effect in comparison with the limited corrosion caused by sulphide always occurring in the bedrock in Forsmark.

Combinations of scenarios

In addition to the combinations of detrimental phenomena for the repository's barriers that are covered by the scenarios above, for example the combined effect of clay erosion and subsequent corrosion, a systematic review of possible combinations of all the scenarios and phenomena analysed in SR-Site was made, in order to clarify whether any combination would have larger effects than the individual scenarios/phenomena. It was found that the combination of an earthquake later followed by buffer erosion could be a more severe scenario than the individual scenarios. Therefore, such a scenario was included in the calculations of dose consequences for the earthquake scenario.

Dose consequences

For the scenarios where canister damage cannot be ruled out, calculations are made of the doses to individuals that may live in the proximity of the repository in the future. For such calculations, besides information on the barriers in each scenario, data on the spent fuel and the biosphere above the repository are also needed. The spent fuel is in itself a very resistant material in the environment offered by a final repository, and this contributes to limiting the release of the radionuclides embedded in the fuel if a canister should be damaged. For the biosphere, among other things a scenario is analysed where the groundwater contaminated by releases of radionuclides from the repository reaches a hypothetical self-supporting farm in the proximity of the repository. The release from the repository is assumed to accumulate in the ground used for cultivation and water from a well contaminated by the release is assumed to be used both for irrigation of crops and as drinking water.

Figure 1-4 shows the result of the calculation of dose consequences for the scenarios in which canister damage could not be ruled out. The result is expressed in the form of an annual risk for individuals in the proximity of the repository of suffering from cancer due to the exposure. The risk limit stipulated by SSM is also shown in the figure, as well as the risk that corresponds to the natural background radiation in Sweden. The latter is about 100 times higher than the regulatory risk limit. The figure shows that the calculated maximum sum of risks from the corrosion and earthquake scenarios for a KBS-3 repository in Forsmark is below the regulatory risk limit throughout the period analysed.

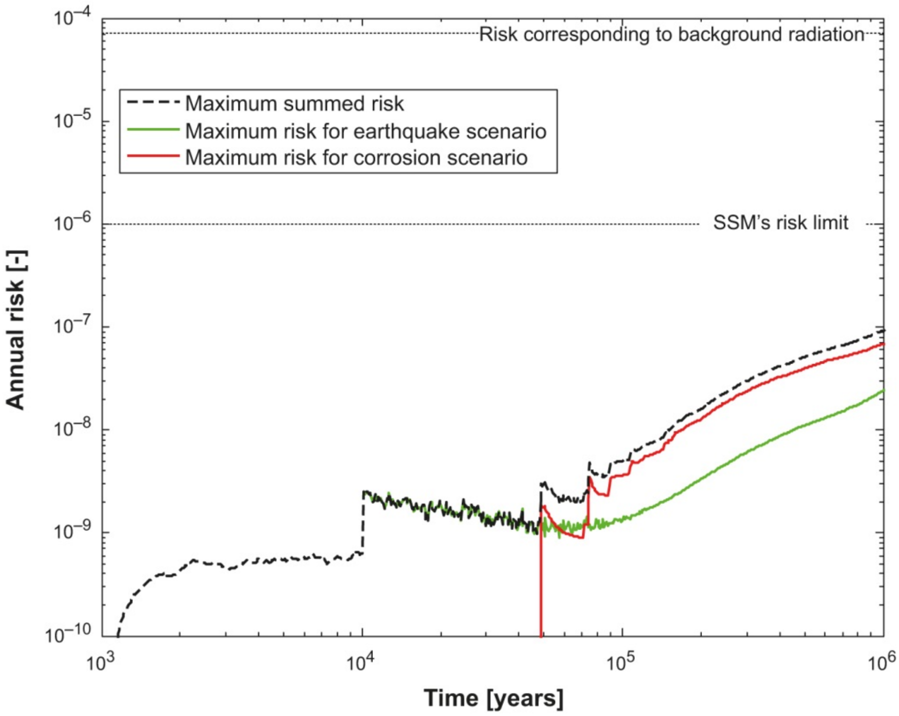

Figure 1-4. *Calculated risks for the earthquake and corrosion scenarios for a spent fuel repository in Forsmark.*

Hypothetical barrier losses

To further illustrate the function of the barriers in a final repository, the safety assessment can make hypothetical assumptions on barrier losses. Such scenarios were also analysed in the safety assessment SR-Site.

What happens if the buffer in all deposition holes has lost its function initially?

The calculated dose in a hypothetical case where the buffer in all 6,000 deposition holes lacks its function to protect the canister against corrosion already at deposition is shown in Figure 1-5, the green line. The buffer then neither hinders the outward transport of radionuclides from the canisters that are caused penetrating breaches in the copper shell. The doses are moderate, which is due to the fact that the canisters' copper shells themselves constitute a strong corrosion barrier.

What happens if all canisters are damaged initially?

The calculated dose in a hypothetical scenario where all canisters are damaged initially, but where the buffer is in place and functions as intended is illustrated by the blue and the orange lines in Figure 1-5. The blue line shows a scenario where all canisters have an initial, penetrating defect in the form of a small cylindrical hole with a diameter of 1 millimetre. The analysis of the case shows that it should take around 1,000 years before radionuclides emerge from the canister. After an additional 10,000 years, the small hole has widened and the releases of radionuclides increase. At this time the peak doses are calculated to be about 30 times higher than the doses that correspond to SSM's risk criterion, but they are still below the dose from the natural background radiation. With time the doses decrease to in the long term become about three times higher than those corresponding to SSM's risk criterion.

The orange line shows the calculated dose for a scenario where all canisters initially have a large penetrating hole. Naturally, the dose corresponding to SSM's risk criterion is also exceeded here, but it is nevertheless calculated to be below the dose from the natural background radiation.

What happens if both the buffer and the canister are initially damaged in all deposition holes?

The calculated dose in an even more hypothetical case where both the buffer and the canister have lost their functions initially in all deposition holes is illustrated by the red line in Figure 1-5. The canisters are assumed to have a large penetrating defect already at deposition. Here the dose from the natural background radiation is exceeded by a factor of about three after some hundred years. With time the dose decreases in the long term to become about three times larger than that corresponding to SSM's risk criterion.

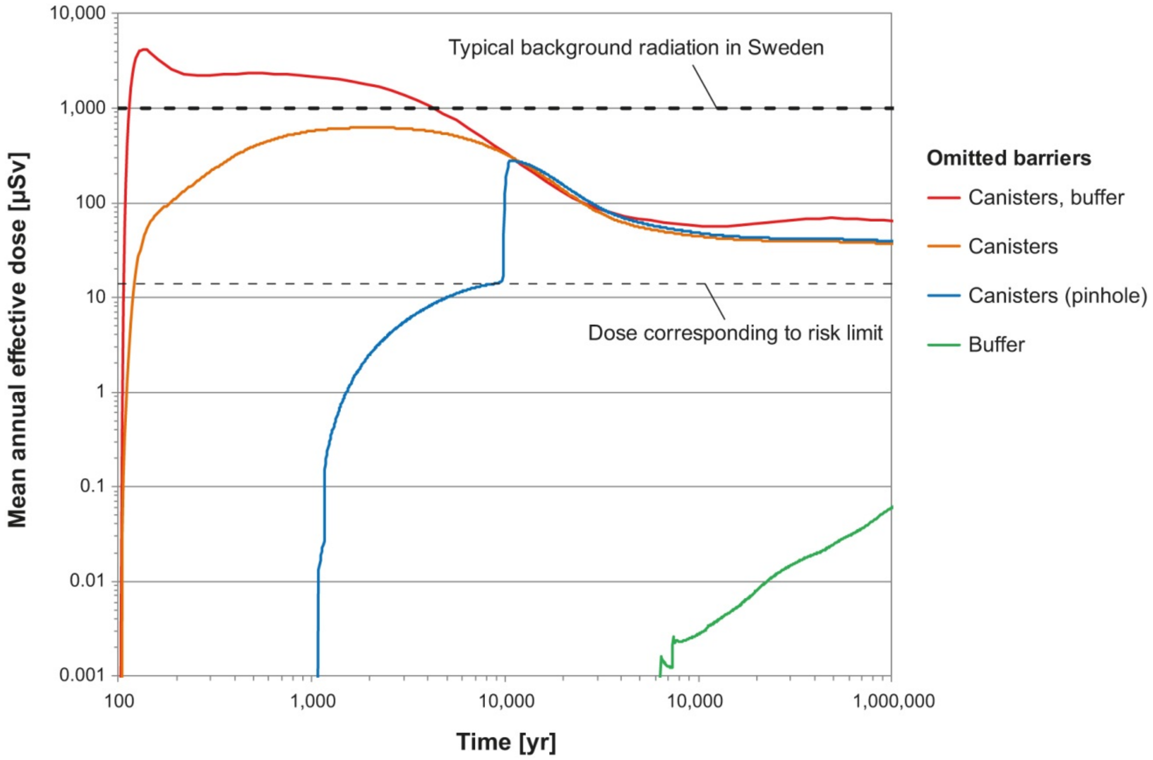

Figure 1-5. *Calculated dose consequences for hypothetical cases of barrier losses in all deposition holes.*

Conclusions from the analyses of hypothetical barrier losses

The results in Figure 1-5 can be summarized in two conclusions: The engineered barriers canister and buffer are necessary in order to achieve a spent fuel repository that fulfils society's requirements on post-closure safety. However, it is also clear that even very far-reaching hypothetical assumptions regarding initially lost functions of these barriers result in doses that only for the worst cases and for a limited time slightly exceed those from natural background radiation.

1.2.3 Conclusion of the safety assessment SR-Site

The main conclusion of the safety assessment SR-Site is that a KBS-3 repository constructed at the Forsmark site meets the requirements on post-closure safety. The results in Figure 1-4 shows that the calculated risk is below SSM's risk criterion for the entire assessment period of one million years. Pessimistic assumptions have been made in the risk calculation for several factors in cases where future conditions are difficult to predict.

This conclusion is reached since the favourable properties of the Forsmark site ensure that the barriers of the KBS-3 repository are durable in the long-term. In particular, the analyses show that the copper canisters with their iron inserts are sufficiently resistant to the mechanical and chemical loads to which they may be subjected in the repository environment.

The conclusion is underpinned by the following considerations.

- The KBS-3 repository's safety philosophy based on i) a geological environment where the properties that are important for safety after closure – i.e. mechanical stability, low flow rates of groundwater at repository depth and the absence of high concentrations of detrimental substances in the groundwater – are stable in a long time perspective and ii) the choice of naturally occurring and, in the repository environment, sufficiently durable materials (copper and bentonite clay) for the engineered barriers, which ensures the life of the barriers that is required to achieve long-term safety.

- The understanding of the phenomena that affect safety after closure. This has been acquired through decades of research at SKB and through international collaboration, which has led to a mature knowledge base for the safety assessment.

- The knowledge of the site properties. This has been reached by several years of surface-based investigations of the conditions at depth and of scientific interpretation of the data emerging from the investigations.

- A quality-assured initial state for the safety assessment, obtained through detailed specifications of the engineered parts of the repository and demonstration of how components can be manufactured and quality assured so that they fulfil the specifications.

1.3 Supplementary information on barriers, requested by SSM within the framework of the review under the Nuclear Activities Act of SKB's application

SSM has, within the framework of the licensing of SKB's application for a final repository for spent nuclear fuel in Forsmark under the Nuclear Activities Act, requested supplements on a number of points. Some of these concern the post-closure safety of the repository's engineered barriers canister and buffer as well as the natural barrier that the bedrock at Forsmark constitutes. The supplement requests are highly specialised in nature. The following gives a summary of the most important supplement requests and SKB's response to these for the canister, the buffer and the rock.

1.3.1 The canister

Regarding the canister, SSM has requested supplementary information on manufacturing aspects, on the mechanical integrity of the canister and on corrosion.

Manufacturing aspects

SSM has requested supplementary information on the manufacturing of the canister. Issues of concern are for example material selection, requirements on purity and risk for defects during manufacturing. SSM also requests more information on the welding method for closure of the canisters such as the chemical influence on the material during welding, the risk for defect formation during welding, etc. SKB gave an extensive report of these issues in the application and has now in response to SSM's requests left an additional account.

SKB has also reported, in response to the request for supplements, as far as is possible today, how quality control and inspection of the canister should be carried out when it is in industrial production. SKB's work with developing these aspects of canister manufacture continues. SKB's conclusion in the application, that it will be possible to fabricate canisters that conform to the stipulated manufacturing requirements, remains unchanged.

Mechanical integrity

SSM has requested supplementary information on the mechanical integrity of the canister. All questions concern aspects of the resilience of the nodular cast iron insert and the copper shell to the loads that may occur in a final repository. It primarily concerns rock movements that can occur during earthquakes and the elevated pressures that may occur when the repository is covered by an ice sheet.

The arguments concerning these issues are based on material properties being measured in sample canisters. These data are used in data calculations of how the canister reacts to the mechanical loads it may be exposed to in the final repository. A similar approach is used for example to ensure that the various components in a nuclear power plant are designed to, with margin, withstand the loads they may be subjected to. Some aspects of the canister's ability to withstand mechanical loads have also been tested directly on sample canisters.

In the safety assessment SR-Site, extensive calculations of the canister's resilience to mechanical loads was carried out based on then existing data from the sample canisters. The additional questions posed by SSM primarily concern details of how these calculations have been carried out. There are also questions regarding the way in which material data has been used in the calculations and regarding the understanding of how copper reacts to mechanical loads in the long term. Based on SSM's questions, SKB has conducted extended calculations, additional analyses of available material data and further studies of how copper reacts to mechanical loads in the long term and reported the results to SSM.

In the safety assessment SR-Site, SKB concluded that the canisters withstand the loads the may be exposed to in the final repository to such an extent that the repository with margin complies with SSM's risk criterion for future individuals in the proximity of the repository. This conclusion remains after the supplementary studies on the mechanical integrity of the canister made because of the additional requests from SSM.

Corrosion

Regarding corrosion, SSM has requested supplements on the corrosion of copper in oxygen-free water and other corrosion phenomena. All these aspects of corrosion were treated in the safety assessment SR-Site, and the request by SSM is for more detailed information on technical and scientific questions concerning corrosion phenomena.

The most noticeable question is whether copper can corrode in pure, oxygen-free water. While established science states that this occurs to such a minor extent that it could not be observed with available methods in laboratory experiments, a group of researchers at the Royal Institute of Technology (KTH) in Stockholm have interpreted their experiments to mean that corrosion could occur to a much greater extent than stated by established science. More specifically, the KTH group has observed hydrogen gas in their experiments and interpret this as a sign of corrosion. SSM has requested that SKB complements the application with deepened analyses of the phenomenon.

SKB is conducting several studies to investigate what takes place in a system with copper in pure oxygen-free water. The purpose is to refine the experimental conditions so that reliable conclusions can be drawn regarding what occurs in such a system, and to clarify the cause of the observations made by the KTH group and others.

SKB has submitted several progress reports to SSM on the subject, as supplements within the framework of the review of SKB's application under the Nuclear Activities Act. In the most recent report, submitted in December 2013, SKB makes the combined judgement that the scientific basis for copper corroding in the way claimed by the KTH group has been further weakened. In particular, SKB's standpoint is based on experiments where copper of the purest quality has been used in an experimental environment where far-reaching measures have been taken to eliminate factors that could disturb the measurements. In such experiments no hydrogen gas was detected and SKB therefore draws the conclusion that copper behaves in the way predicted by established science in an environment with pure, oxygen-free water. Further, ongoing studies corroborate this conclusion and will be reported in the summer of 2014.[1]

For other corrosion phenomenon, SSM has requested supplements on ten points. Prominent questions concern corrosion during the early period after closure when the repository has not yet become saturated with water, corrosion caused by stray currents from existing or future ground cables for transfer of electricity in the vicinity of the repository and the so-called stress corrosion. SKB has conducted a number of in-depth studies as a result of SSM's request and reported the results to SSM.

In the safety assessment SR-Site, SKB concluded that the canisters withstand the corrosion they may be exposed to in the final repository to the extent that the repository, with margin, complies with SSM's risk criterion for future individuals in the proximity of the repository. This conclusion remains after the supplementary studies of corrosion of the canister made because of the additional requests from SSM.

1.3.2 The buffer

SSM has requested supplementary information on the clay buffer's properties and function in the final repository. The questions concern, for example, interaction between expected copper corrosion products and bentonite, the extent of buffer erosion and the properties of a buffer exposed to erosion. SKB has clarified in the responses that the interaction between copper corrosion products and bentonite is expected to be negligible and developed arguments that the aspects of buffer erosion addressed by SSM are pessimistically handled in the supporting material for the application.

SSM also poses questions on how the clay buffer and tunnel backfill are expected to be water-saturated in the final repository. SKB has here conducted supplementary analyses that include both model calculations and account of experimental data. SSM has requested an additional account of the time differences for achieving water saturation that are expected in the different parts of a real repository in Forsmark and the safety-related importance of this. SKB has conducted and reported additional calculations that in more detail quantify the relatively large difference in times in Forsmark that was presented in the application. The supplemental response also shows more extensively that a long time for water saturation is not of importance for the post-closure safety. SKB has also chosen not to water saturate the buffer artificially and this is justified in more detail in one of the supplemental responses.

In the safety assessment SR-Site, SKB concluded that the buffer maintains its safety functions in the final repository to the extent that the repository with margin complies with SSM's risk criterion for future individuals in the proximity of the repository. This conclusion remains after the supplementary studies on the buffer made as a result of the additional requests from SSM.

1.4 The rock

SSM has requested supplementary information on calculations of groundwater flow. The questions concern, for example, how calculation models have been calibrated to the hydrological data measured during the site investigations and which equations and assumptions have been used in different detail aspects of the modelling. SKB has presented responses to the posed questions. SSM has also requested a supplementary analysis of how the groundwater flow

[1] The present document was published in Swedish in June 2014. Since then, several additional reports, that further strengthen the conclusion that copper corrodes in pure water in accordance with established scientific knowledge, have been issued by SKB. A comprehensive assessment of the matter was submitted by SKB to SSM in March 2015.

at repository depth is affected by the load from an overlying ice sheet. SKB has shown that this impact is very limited.

SSM has also requested an in-depth analysis of whether the heat from the canisters can affect the repository mechanically in such a way that minor, local rock movements could arise. SKB has in the response further substantiated that this is judged to be a negligible effect.

SSM has requested supplementary information on aspects of the calculation of the long-term evolution of groundwater chemistry at repository depth and requested that the influence of different assumptions and simplifications in the calculations should be studied further. SKB has in its response shown that the variations in results due to these assumptions and simplifications are within the framework of the results presented in the application. SSM has also requested a calculation of the evolution of groundwater chemistry for a scenario with extremely long periods of temperate climate. SKB has presented such a calculation and it shows that the changes are small compared with the longest times of temperate climate presented in the application.

1.5 Conclusions

SKB has, through several decades of research, development and technical demonstration developed the KBS-3 method for final disposal of spent nuclear fuel. The two engineered barriers canister and buffer are, together with the natural barrier that the bedrock constitutes, the central safety-bearing components in a KBS-3 repository.

SKB's application for a final repository for spent nuclear fuel in Forsmark includes an extensive analysis of the safety of the repository after closure. A general conclusion of the assessment is that the barriers of a KBS-3 repository in Forsmark meet all requirements made with respect to safety after closure and thereby a safe KBS-3 repository can be built at the Forsmark site.

Within the review of SKB's application under the Nuclear Activities Act, SSM requested supplements on among other things barrier safety after closure. As a result, SKB has carried out a number of supplementary studies. The conclusion that a safe KBS-3 repository can be built at the Forsmark site remains after these studies.