SKB

TECHNICAL REPORT 90-46

SKB ANNUAL REPORT 1990

Including Summaries of Technical Reports Issued during 1990

Stockholm, May 1991

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FOREWORD

The Annual Report on SKB's activities during 1990 covers planning, building and operational activities as well as research, development, demonstration work and information activities.

SKB has an operating and well integrated system for handling of all radioactive residues within Sweden. With the central repository for final disposal of low and medium level waste - SFR - and the central interim storage facility for spent fuel - CLAB - in operation, SKB can take care of all radioactive waste produced inside Sweden for a long time ahead.

For the remaining facility - the final repository for spent nuclear fuel - comprehensive research and planning activities is well under way, aiming at a principal decision on disposal methods and site around the mid 90s.

International co-operation and exchange of information in all fields of the back-end of the nuclear fuel cycle is important and of great value for SKB's work. We hope this Annual Report will be of interest and that it will enhance the international information exchange.

Stockholm in May 1991

SWEDISH NUCLEAR FUEL AND WASTE MANAGEMENT CO - SKB

Sten Bjurström

President

ABSTRACT

This is the annual report on the activities of the Swedish Nuclear Fuel and Waste Management Co, SKB. It contains in part I an overview of SKB activities in different fields. Part II gives a description of the research and development work on nuclear waste disposal performed during 1990.

Lectures and publications during 1990 as well as reports issued in the SKB technical report series are listed in part III.

Part IV contains the summaries of all technical reports issued during 1990.

SKB is the owner of CLAB, the Central Facility for Interim Storage of Spent Nuclear Fuel, located at Oskarshamn. CLAB was taken into operation in July 1985 and to the end of 1990 in total 1310 tonnes of spent fuel (measured as uranium) have been received. Transportation from the nuclear sites to CLAB is made by a special ship, M/S Sigyn.

At Forsmark the the final repository for Radioactive Waste — SFR — was taken in operation in April 1988. The repository is situated in crystalline rock under the Baltic Sea. The first construction phase includes rock caverns for 60 000 m^3 of waste. A second phase for additional 30 000 m^3 is planned to be built and commissioned around the year 2000. At the end of 1990 a total of 6 000 m^3 of waste have been deposited in SFR.

SKB is in charge of a comprehensive research and development programme on geological disposal of nuclear waste. The total cost for R&D during 1990 was 145.6 MSEK of which 19.5 MSEK came from participants outside Sweden.

Some of the main areas for SKB research are:

— Groundwater movements.

— Bedrock stability.

— Groundwater chemistry and nuclide migration.

— Methods and instruments for in situ characterization of crystalline bedrock.

— Characterization and leaching of spent nuclear fuel.

— Properties of bentonite for buffer, backfilling and sealing.

— Natural ageing of recipients in the biosphere.

— Model development and safety assessment.

— Preparations for a new underground research laboratory.

Geological site-investigations are a substantial part of the programme. SKB is also the managing participant of the international Stripa-Project under OECD/NEA.

Cost calculations for the total nuclear waste management system, including decommissioning of all reactors, are updated annually. The total cost is estimated to 53 billion SEK.

SKB also handles matters pertaining to prospecting and enrichment as well as stockpiling of uranium as strategic reserves for the Swedish nuclear power industry.

Consulting services from SKB and associated expert groups are available on a commercial basis. From the start of these services in 1985 and up to the end of 1990 about 60 assignments have been accomplished in a variety of areas.

Information activities are an integrated and important part of the Swedish radioactive waste management system. During 1990 new successful approaches in public information and media relations were made using mobile exhibitions in a tailor-made trailer and on the SKB ship M/S Sigyn.

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SKB ANNUAL REPORT 1990

Part I

Overview of SKB Activities

CONTENTS PART I

1. GENERAL BACKGROUND

1.1 THE SWEDISH NUCLEAR POWER PROGRAMME

The nuclear power programme of Sweden consists of 12 nuclear reactors located at four different sites and with a combined capacity of 9 900 MW net electric power. Main data and location of the 12 units are shown in Figure 1-1. The nuclear power plants generated 46% of the total Swedish electric power produced in 1990.

Swedish reactors

Reactor		Power MWe	Commercial operation	Energy availability in 1990 %
Oskarshamn 1	BWR	440	1972	65
Oskarshamn 2	BWR	605	1974	89
Oskarshamn 3	BWR	1150	1985	86
Barsebäck 1	BWR	600	1975	95
Barsebäck 2	BWR	600	1977	88
Ringhals 1	BWR	750	1976	78
Ringhals 2	PWR	850	1975	72
Ringhals 3	PWR	915	1981	77
Ringhals 4	PWR	915	1983	91
Forsmark 1	BWR	970	1980	88
Forsmark 2	BWR	970	1981	91
Forsmark 3	BWR	1150	1985	92

1.2 LEGAL AND ORGANIZATIONAL FRAMEWORK

The nuclear power plants are owned by the following four companies:

— Statens Vattenfallsverk (Swedish State Power Board; Vattenfall) is the largest electricity producer in Sweden and owns the Ringhals plant.
— Sydsvenska Värmekraft AB (subsidiary of Sydkraft AB) is the owner of the Barsebäck plant.
— OKG AB is the owner of the Oskarshamn plant. Sydkraft is the major shareholder of OKG.
— Forsmark Kraftgrupp AB (FKA) is the owner of the Forsmark plant. Vattenfall has 74.5% of the shares in FKA.

The Swedish Nuclear Fuel and Waste Management Company, SKB (SKB = Svensk Kärnbränslehantering AB) has been formed by these four power utilities. SKB shall develop, plan, construct and operate facilities and systems for the management and disposal of spent nuclear fuel and radioactive wastes from the Swedish nuclear power plants. On the behalf of its owners SKB is responsible for all handling, transport and storage of the nuclear wastes outside of the nuclear power production facilities.

SKB is also in charge of the comprehensive research programme in the waste field which the utilities are responsible for according to the law. Finally SKB handles matters pertaining to enrichment and reprocessing services as well as stockpiling of uranium for the Swedish nuclear power industry and provides assistance at the request of its owners in uranium procurement.

The total central staff of SKB is about 55 persons. The organization is presented in Appendix 1. For the bulk of the work a large number of organizations and individuals outside SKB are contracted. As a whole about 500 persons are involved in SKB waste handling work.

SKB is the organization that has the lead operative role in the Swedish waste management programme both with respect to planning, construction and operation of facilities and systems and with respect to research and development. The role has its roots in the legislation briefly described below. Figure 1-2 gives an overview of the most important laws and the corresponding authorities involved.

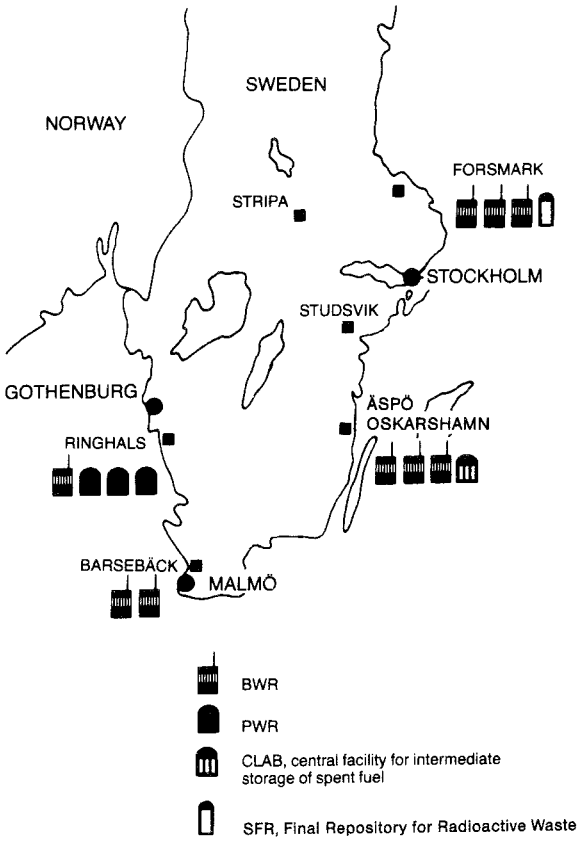


Figure 1-1. The Swedish nuclear power programme.

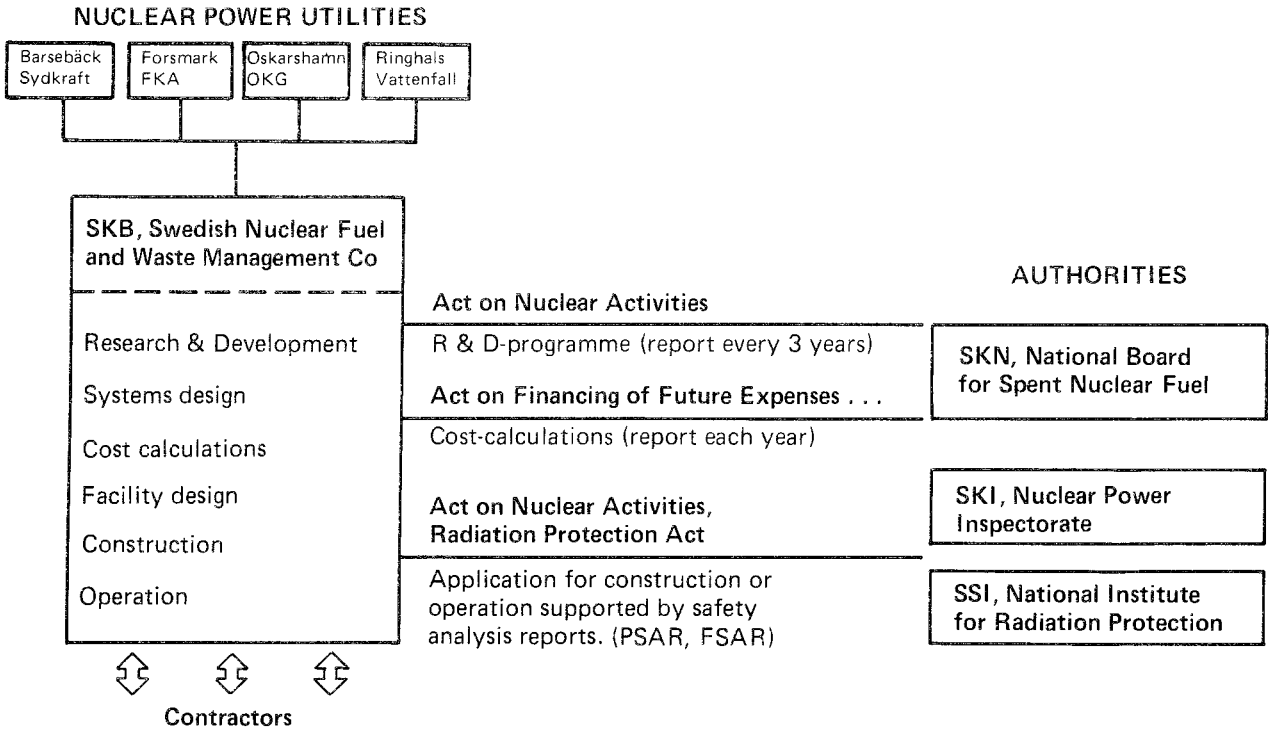


Figure 1-2. *Legal framework for activities of SKB.*

There are three important laws which regulate the nuclear activities.

— The Act on Nuclear Activities.
— The Act on the Financing of Future Expenses for Spent Nuclear Fuel etc.
— The Radiation Protection Act.

The Act on Nuclear Activities /1-1/ puts the primary responsibility for the safety on the owner of a nuclear installation. The owner is thus responsible for safety during design, construction and operation of nuclear facilities, for the handling and final disposal of nuclear wastes and for the dismantling and decommissioning of the facility. The responsibility also includes the necessary research and development in the waste management field. According to the act a research programme must be submitted to the authorities every three years. The first programme was submitted in September 1986 and the second in September 1989.

The authority for supervision of the safety provisions in the Act on Nuclear Activities is the Swedish Nuclear Power Inspectorate (SKI). The National Institute for Radiation Protection (SSI) is supervising provisions of the Radiation Protection Act. The research programme is supervised by the National Board for Spent Nuclear Fuel (SKN).

The latter authority is also supervising the adherence to the Act on Financing of Future Expenses for Spent Fuel. According to this law the waste management activities including future decommissioning of all reactors are financed from funds built up from fees on the nuclear power production.

The fees are revised annually by SKN, which proposes the fees for the next year to the government. The average fee on nuclear electricity since 1984 has been 0.019 SEK per kWh.

The radiation protection act contains basic rules for protection against ionizing radiation for

— those who work at nuclear installations and other facilities with potential radiation hazards,
— the general public who lives or stays outside such installations or facilities.

The competent authority in these matters is the Swedish National Institute for Radiation Protection (SSI).

The three competent authorities have separate funds for the research needed to fulfil their obligations. SKN also support additional waste management research beside the SKB programme.

Table 1–1. Waste categories

WASTE CATEGORY	ORIGIN	WASTE FORM	PROPERTIES	QUANTITY
1 Spent fuel	Operation of nuclear reactors	Fuel rods encapsulated in canisters	High heat flux and radiation at first. Contains long-lived nuclides	5 600 canisters (7 800 tu)
2 Transuranic-bearing waste	Waste from the Studsvik research facility	Solidified in concrete	Low- to medium-level. Contains long-lived nuclides	6 000 m^3
3 Core components and internals	Scrap metal from inside reactor vessels	Untreated or cast in concrete	Low- to medium-level. Contains certain long-lived nuclides	19 700 m^3
4 Reactor waste	Operating waste from nuclear power plants etc.	Solidified in concrete or bitumen. Compacted waste	Low- to medium-level. Shortlived	95 000 m^3
5 Decommissioning waste	From dismantling of nuclear facilities	Untreated for the most part	Low- to medium-level. Shortlived	114 000 m^3

1.3 THE SWEDISH NUCLEAR WASTE MANAGEMENT SYSTEM

A complete system has been planned for the management of all radioactive residues from the 12 nuclear reactors and from research facilities. The system is based on the projected generation of waste up to the year 2010.

Residues generated by the operation of the reactors are spent nuclear fuel and different kinds of low- and medium level wastes. Furthermore, in the future decommissioning waste will be generated when the reactors and other failities are dismantled.

The types and total quantities of various nuclear waste categories currently estimated to be generated are given in Table 1-1. The basic strategy for the management of the waste categories is that short-lived wastes should be deposited as soon as feasible, whereas for spent fuel and other long-lived wastes an interim storage period of 30–40 years is foreseen prior to disposal.

The main features of the planned system for nuclear waste management in Sweden are shown in Figure 1-3.

The first construction stage of the Swedish Final Repository for Radioactive Waste, SFR, was taken in operation in 1988. SFR may later on be extended to accommodate waste also from the decommissioning of the nuclear reactors. For spent fuel a central interim storage facility, CLAB, was taken into operation in July 1985. This facility has with current configuration a capacity of 3 000 tonnes of spent fuel but will by more efficient utilization of the space available in the existing pools be increased to 5 000 tonnes, se chapter 3.

After approx. 40 years of interim storage in CLAB, the fuel will be encapsulated and deposited in the Swedish bedrock. The encapsulation and disposal facility will only start operation around 2020, and the site has thus not yet been chosen. A minor amount of spent fuel has been shipped for reprocessing.

For the transport of spent fuel and other kinds of radioactive wastes a sea transport system is in operation since 1982.

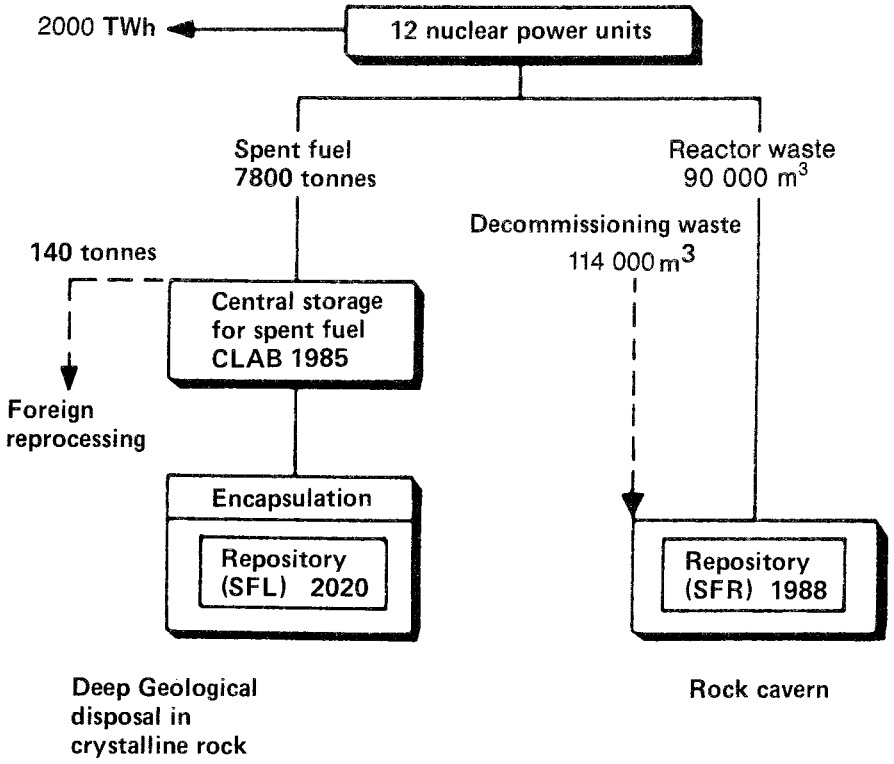


Figure 1-3. Main system for management of radioactive waste in Sweden.

2. NUCLEAR FUEL SUPPLY

In the front end of the nuclear cycle SKB handles matters pertaining to prospecting and enrichment as well as stockpiling of uranium as strategic reserves for the Swedish nuclear power industry. SKB also provides assistance at the request of its owner utilities in uranium procurement.

2.1 NATURAL URANIUM

The Swedish nuclear power programme has an annual demand of about 1 500 metric tonnes. This demand could be higher or lower depending on a number of factors, which means that the planning of supply must be flexible.

The demand for the period 1990 up to 1999 is 14 900 tonnes. At the end of 1990, the Swedish utilities had contracts for supply of 11 000 tonnes during the same period. Most of the supply is based on long-term contracts. As the prices on the spot market were low in 1990, some spot quantities were purchased.

Natural uranium is delivered to Sweden mainly from Canada and Australia, but also from Niger and USA. Canada and Australia will deliver around 40% each of future supplies under present contracts.

Exploration

Uranium occurs in relatively high concentrations in certain parts of the Swedish precambrian rock. SKB has therefore earlier been conducting exploration at a number of places in northern Sweden. Mineralizations containing at least 6 000 metric tonnes of uranium have been found with concentrations higher than 1 000 g uranium per ton ore. These ores constitute important reserves for the future.

As uranium supply is abundant and the market price is low, SKB stopped exploration at the end of 1985.

Ranstad

Sweden has considerable uranium resources. Most of the proven reserves consist of relatively low-grade shale deposits near Ranstad with about 300 g uranium per ton of shale. These deposits are not exploitable at the present low price of imported uranium.

Market-prices

Figure 2-1 shows the price situation for uranium during the last years. Spot prices were low in 1990.

The average price for long term deliveries in 1984-1989 to the European Community was considerably higher than the spot prices for the same delivery years.

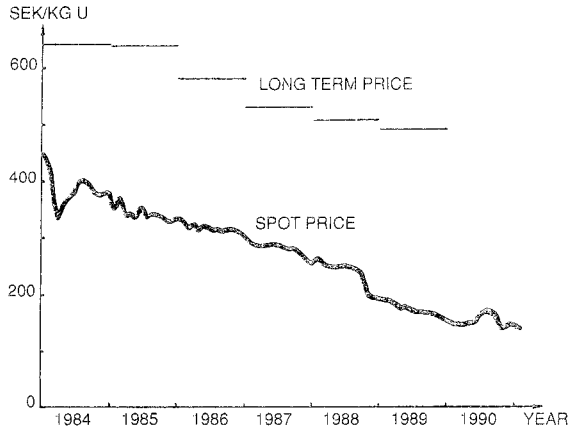


Figure 2-1. Long term and spot prices for uranium.

Long term price = Average price for long term deliveries to the European Community.

Spot price = Average spot price each month published by the German company NUKEM for non US origin uranium.

2.2 CONVERSION

Conversion is a chemical process for production of uranium hexafluoride from uranium concentrates.

The world conversion capacity is around 55 000 tonnes of uranium per year while the demand is about 42 000 tonnes per year.

The Swedish utilities utilize conversion services from Canada, USA, United Kingdom and France.

2.3 ENRICHMENT

Up to 1983, enrichment deliveries to the Swedish utilities were dominated by DOE in the USA and Techsnabexport in the USSR.

The European enrichment industry became price competitive in the beginning of the 1980-ies. During the period 1983-1985 Swedish utilities signed contracts for deliveries from Western Europe, which started already 1984.

For the period 1990-1999, most of the deliveries to Sweden will come from EURODIF with an enrichment plant in France, from URENCO with enrichment plants in the Netherlands, the United Kingdom and in Germany and from the USSR with an enrichment plant near Sverdlovsk. Deliveries from the US(DOE) will continue on a reduced scale.

This situation gives a reliable supply with deliveries from four different suppliers of enrichment.

The USSR has delivered enriched uranium which means that the corresponding quantity of natural uranium is of Soviet origin.

2.4 FABRICATION OF FUEL ASSEMBLIES

The Swedish utilities are purchasing fuel fabrication services with the objective of lowest fuel cycle cost. This procedure has led to many orders for ABB Atom, but also orders to US, German and French companies.

Fabrication of fuel assemblies both for BWRs and for PWRs as well as BWR channels, BWR control rods and other components are made in Sweden at the ABB Atom plant in Västerås.

Fuel fabrication at ABB Atom was around 300 tonnes of UO_2 for nuclear fuel for BWR and PWR during 1990. Of this volume about 100 tonnes were exported to Finland, Federal Republic of Germany, Switzerland, Belgium and USA.

The fuel assembly design, SVEA, where the fuel rods are devided in four minibundles with 4 × 4 or 5 × 5 rods separated by a water cross, is now the dominating BWR fuel in Sweden. All of the ABB Atom BWR deliveries in 1990 were of this design.

The SVEA fuel utilizes the energy from the inner fuel rods in a better way, which means that 8-10 % more energy can be produced from a given amount of enriched uranium compared with the earlier type of fuel.

2.5 NUCLEAR FUEL STOCKPILE

The Swedish Nuclear Fuel and Waste Management Co is on behalf of the utilities responsible for stockpiling enriched uranium and zircaloy corresponding to an electricity production of 35 TWh. This amount has been decided by the Swedish parliament.

Uranium in the above mentioned stockpile, in fuel under fabrication and at the nuclear power stations is sufficient for about two years of operation of all 12 units.

2.6 COSTS

The costs for the front end supply and services of the nuclear fuel cycle in 1990 in Sweden were as shown in Table 2-1 (the production of nuclear electricity was 65.3 TWh in 1990):

Table 2-1. Costs for the front end of the nuclear fuel cycle

	SEK/kWh	Million SEK in 1990
Natural uranium	0.007	460
Conversion	0.001	70
Isotope enrichment	0.009	590
Fuel fabrication	0.009	590
Strategic stockpile	0.001	70
Total front end	**0.027**	**1 780**

The costs for nuclear fuel have decreased during the recent years which is shown in Table 2-2.

Table 2-2. Costs for nuclear fuel 1983-1990.

Year	SEK/kWh
1983	0.038
1984	0.038
1985	0.035
1986	0.031
1987	0.028
1988	0.028
1989	0.028
1990	0.027

3. INTERIM STORAGE OF SPENT FUEL, CLAB

3.1 GENERAL

The Swedish interim spent fuel storage facility CLAB located on the Simpevarp peninsula adjacent to the Oskarshamn nuclear power station, was taken into active operation on July 11th 1985.

The facility has five underground storage pools with a capacity of 3 000 tonnes of uranium. The receiving building and the buildings for auxiliary systems and offices are located on ground level. The facility is designed to receive at least 300 tonnes uranium per year which corresponds to the handling of about 100 transport casks and some 10-20 casks containing reactor core components. For the operation SKB has contracted OKG AB, operating three reactors at the site and one of the SKB shareholders.

3.2 OPERATING EXPERIENCES

After a successful active test period during the second part of 1985 the Swedish Nuclear Power Inspectorate and the National Institute of Radiation Protection granted SKB a permanent operating license valid as from 1985-12-20.

During the years 1986 to 1990 spent fuel and core components have been received in CLAB on a routine basis from the four nuclear power stations in Sweden. Between July 1985 and the end of 1990 1350 tonnes of uranium have been received.

In 1990 89 casks containing spent nuclear fuel have been received, 79 of which contained fuel from Swedish BWR and PWR reactors, see Figure 3-1, and 6 casks PHWR fuel from the old dismantled Ågesta reactor. The Ågesta fuel has been stored at the Studsvik nuclear research centre for some 15 years. 4 casks containing residuals from post irradiation examination of fuel at Studsvik have been received. The total fuel quantity shipped to CLAB during the year amounted to about 240 tU.

In addition 2 casks with core components have been transferred to CLAB.

The performance of the plant has been excellent and the received amount of fuel has been according to the plans. The total occupational dose in 1990 (105 mmanSv) was about 40% of what was expected according to the final safety report.

The release of radioactivity to air and water during the five first years of operation has been negligible, amounting to around 0,01% of the permissible release from CLAB and the three adjacent reactors together.

The operating costs have been considerably reduced year by year and amounted in 1990 to about 75% of those of 1986 in real terms.

3.3 INCREASED STORAGE CAPACITY

The storage capacity of the existing pools, 3000 tU, will be fully utilized by year 1996. During the construction of CLAB preparations were made for a future expansion with new storage caverns parallel to the first one. A study performed in 1988 showed however that there are great advantages if the building of a new cavern could be postponed. This can be achieved by more efficient utilization of the space available in the existing pools by use of new compact storage canisters with a closer packing of the fuel assemblies.

By using borated steel as neutron absorbing material the number of assemblies can be increased from 16 to 25 and from 5 to 9 in one canister for BWR respectively PWR fuel. In regard of the proportion between BWR and PWR-fuel emanating from the reactors in Sweden this corresponds approximately to a gross increase in storage capacity of 60%, see Figure 3-2. Based on this SKB applied to the Swedish government for an increase of the maximum permissible amount of spent fuel in CLAB from 3000 to

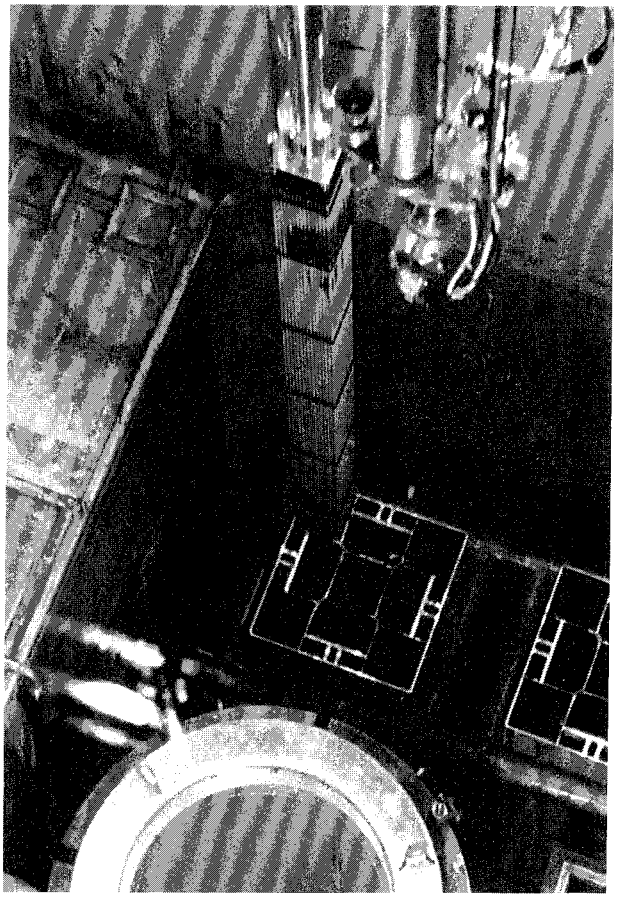
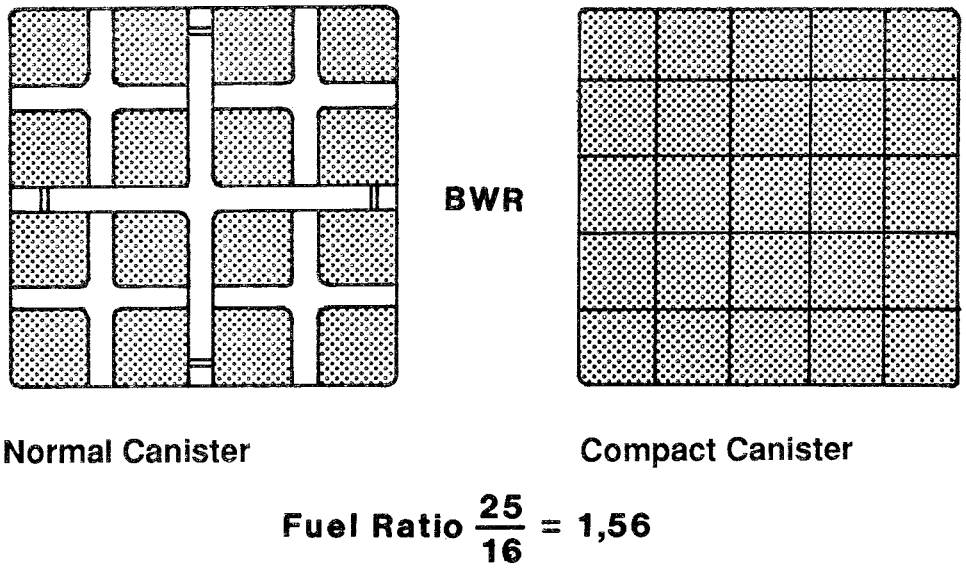


Figure 3-1. *A PWR fuel assembly being loaded into a canister in one of the receiving pools.*

5000 tU. The government gave its permission in December 1989.

3 suppliers were invited to offer the new canisters in 1990. The selected supplier built a prototype of the new compact BWR canister which was subjected to extensive tests in CLAB in december 1990 with satisfactory result. The new compact canister design has entailed modifications of the existing handling equipment. The first serial canister is expected to be delivered by the end of 1991.



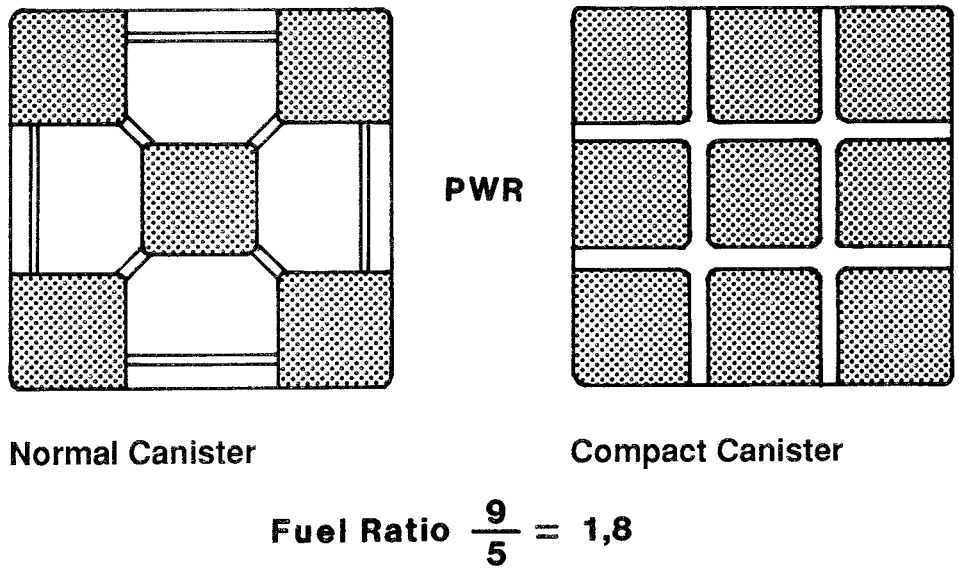


Figure 3-2. Comparison of normal and compact canisters for BWR and PWR fuel in CLAB.

4. TRANSPORTATION SYSTEM

4.1 GENERAL

The sea transportation system consists of the specially designed ship M/S Sigyn, 10 transport casks for spent fuel, 2 transport casks for core components, 27 IP-2 containers (ATB) for transport of low- and intermediate level waste and 5 terminal vehicles. One of the vehicles is specially designed for operation in the SFR repository.

4.2 OPERATING EXPERIENCES

In 1990 the ship, M/S Sigyn, sailed around 34 000 n.m. during 120 days. The transports with spent fuel and reactor waste from the Swedish reactors to the CLAB facility and the repository SFR have been performed without disturbances and in accordance with the annual planning. In total 89 transport casks with spent fuel, 2 transport casks with core components and 93 IP-2 containers (ATB) with reactor waste have been transported with the transportation system during the year, see figure 4-1. Like earlier years, no measurable dose rates have been registered to the ship's crew.

During the summer period, when no scheduled transports are done, M/S Sigyn was used as a floating exhibition of the Swedish nuclear waste handling system, making a voyage along the Swedish coast and visiting 16 cities including the capital, Stockholm.

Figur 4.1. *Loading of ATB-container on board M/S Sigyn.*

5. FINAL REPOSITORY FOR RADIOACTIVE WASTE, SFR

5.1 GENERAL

The Swedish Final repository for Radioactive Waste, SFR, was put into active operation in April, 1988. It is a repository built in the bedrock under the Baltic Sea close to Forsmark nuclear power plant. 60 metres of rock covers the repository caverns under the sea bed, see Figure 5-1. The first stage of SFR, which is in operation includes buildings on ground level, tunnels, operating buildings and disposal caverns for 60 000 m^3 of waste. A second stage for approximately 30 000 m^3 is planned to be built and commissioned around the year 2000.

The waste intended for disposal in SFR originates from the operation of Sweden's 12 nuclear power reactors and CLAB. This waste contains short-lived radionuclides and is classified as low- and intermediate level waste. A small amount of similar waste from research and medical activities will also be disposed of in SFR. The total amount of waste from the Swedish program up to year 2010 has been calculated to about 90 000 m^3.

All waste materials are conditioned at the power plants and CLAB or at the nuclear research centre, Studsvik. Ion exchange resins are incorporated in either cement or bitumen. Scrap from maintenance work can also be treated in the same way, if required. These categories are classified as intermediate level waste (ILW) and need shielding during handling and transport. Low level waste (LLW) is treated in different ways and finally enclosed in standard freight containers.

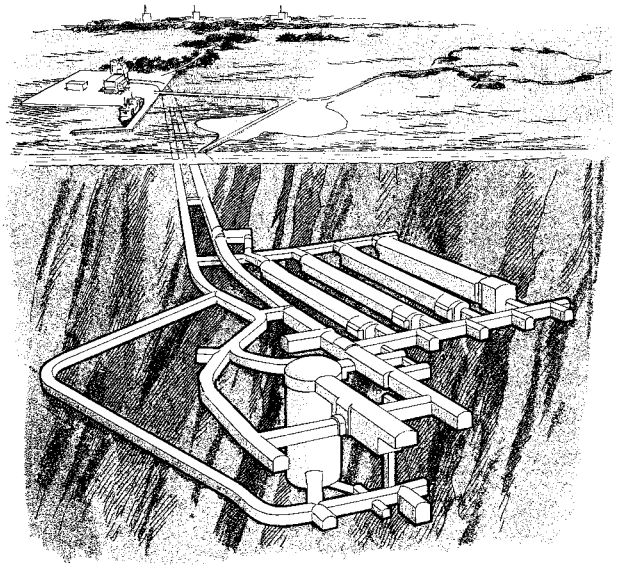


Figure 5-1. *Overview of tunnels and storage chambers in the first construction stage of SFR.*

At the end of 1990 a total of 6000 m^3 of waste have been deposited in SFR. All waste producers have delivered waste. The experiences from the operation have been good and the doses to the personnel have been very low.

5.2 DESIGN AND CONSTRUCTION

The SFR has been sited under the sea in order to minimize the groundwater flow in the repository area. The hydraulic gradients at the site are very small since the sea acts like an equalizer on the hydraulic conditions in the rock below. The host rock is a crystalline rock, which has proven to be very competent for the excavation of tunnels and various caverns. Engineered barriers are used in order to further reduce the groundwater flow inside the caverns and through the waste.

There are different caverns for ILW and LLW in SFR. The ILW-packages containing most of the activity will be disposed of in a silo structure, see Figure 5-2. The cavern is 70 m high and 30 m in diameter. Inside is a 50 m high concrete silo, with a diameter of 28 m, surrounded with a buffer material. Bentonite is used to give a low permeability. A compacted mixture of sand and bentonite (90/10) is used at bottom and granulated pure bentonite is used for the filling around the silo. To seal off the silo a layer of mixed sand/bentonite will be placed on top. The space between the waste packages and the concrete construction in the silo will subsequently be filled with concrete.

Waste containing a minor part of the activity content will be disposed of in 160 m long caverns with various cross sections. Three types of caverns are used. The cavern with the largest cross section is equipped with machines for remotely controlled handling, similar to those used in the silo. The waste is deposited in a concrete structure, and finally a concrete lid is put over the waste.

LLW is handled with an ordinary forklift truck in one of the caverns. The waste is deposited in standard freight containers, which also are used for transport to SFR. This cavern will be sealed without any backfill inside. The third type of cavern is mainly intended for special concrete tanks with dewatered ion exchange resins. Backfilling with concrete and sand will be carried out.

5.3 OPERATION PERMIT

The operational permits for SFR were received at the end of March 1988 from the two safety authorities, SKI and SSI. The permits contain certain conditions of which the most important are:

- Radioactive waste may not be transported to SFR before the waste category has been approved by SKI and SSI for emplacement in SFR.
- Before large quantities of waste can be emplaced in the silo repository, SKB must provide additional information. No grouting is allowed before this information has been approved.
- Waste to be emplaced in SFR must be registered in a computerized waste record.
- The sealing of different repository parts must be accepted by the authorities. A separate permit for the sealing of the entire repository must be granted by the Government.
- A control and supervision program for the repository shall be performed during operation.
- Recurrent safety and environmental assessments shall be performed.

5.4 WASTE ACCEPTANCE

As stipulated in the operational permits all waste that is deposited in SFR should belong to a waste type that has received an approval by the safety authorities. A procedure for the description and approval of waste types has been developed.

As a basis for the approval a special document is prepared, called Waste Type Description (WTD). In the WTD the functional requirements on the waste package during the sequence from production until disposal are identified and translated into requirements on the waste characteristics. These could be different for different waste types, depending on the handling sequence foreseen.

In the WTD also the QA/QC system for the waste type is described. Control actions are mainly performed by the waste producers. All relevant information about each waste package is documented and collected in a computerized waste register. Before the waste is transported to SFR, the contents of the waste register is transferred to a SFR-data base.

The procedure for waste acceptance has been very time consuming. During 1990 eleven waste types (of a total of about 40) were accepted for disposal. Further, about ten additional waste types have had special disposal or storage permits from the authorities during 1990. In 1990 disposal has been carried out in the rock chambers. Some waste was deposited in the silo in 1989. Before full scope disposal and grouting will be permitted, however, some further information is requested by the authorities, mainly on the effect of complexing agents from degradation of cellulose, and on the effect of gas production. This information is being compiled and will be reported in 1991.

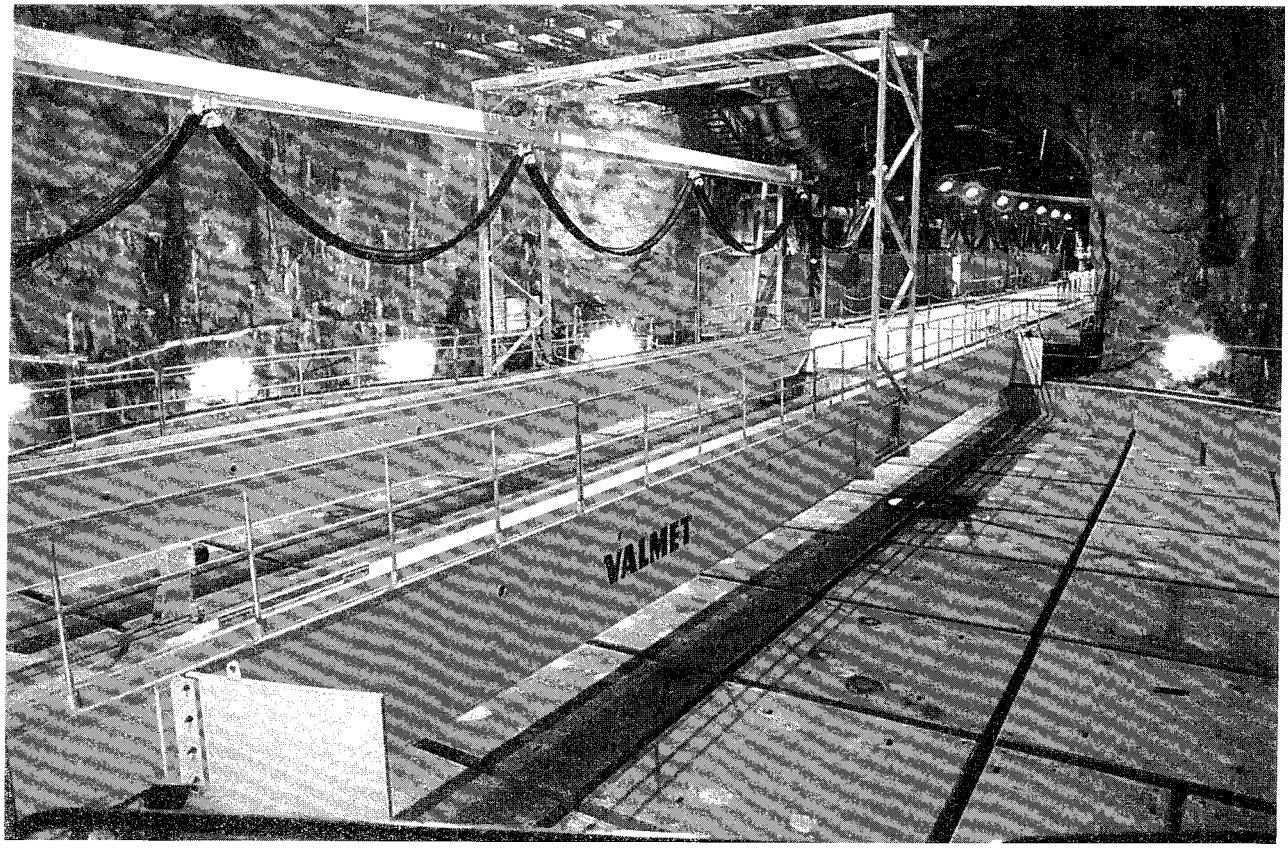


Figure 5-2. View from the top of the silo in SFR showing the shaft lids and the polar crane.

5.5 OPERATION

The operation of SFR has been subcontracted to the Swedish State Power Board, the operator of the nuclear reactors at Forsmark, and is closely integrated in the local organization. The staff for operation and maintenance of SFR consists of about 20 people.

In full operation the facility has an annual disposal capacity of about 6000 m^3. During the first years of operation SFR has successively been put into active operation area by area, starting with the rock chambers. Up till the end of 1990 a total of 6000 m^3 of waste has been deposited.

All activities down in SFR are directed and supervised from the operations centre that is located in a building underground centrally in the repository area. The operations centre contains equipment for remote control of all handling machines, overhead cranes with waste and of the auxiliary systems, etc.

The operating experience is good both with regard to handling and availability. Some problems remain with high moisture content in the repository air during the summer period and with the operation of the transport vehicle. This has not affected the disposal programme. The doses to the personnel have been very low. The total dose was approximately 0.1 mmanSv in 1990.

6. RESEARCH AND DEVELOPMENT 1990

6.1 GENERAL

According to the Act on Nuclear Activities (SFS 1984:3) the owners of Swedish nuclear power plants must together establish a comprehensive programme fo the research and development and other measures that are needed in order to take care of all radioactive wastes from nuclear plants in a safe way.

The Swedish nuclear utilities have commissioned the Swedish Nuclear Fuel and Waste Management Co, SKB, to establish the programme required by the law. The programme must be submitted to the National Board of Spent Nuclear Fuel every three years starting 1986. The second programme was submitted by SKB to the National Board for Spent Nuclear Fuel, SKN, in September 1989/6-1/.

The work done during 1990 has in general followed the 1989 programme. This chapter gives only a few highlights of the results obtained in 1990. For a more comprehensive account the reader is referred to Chapters 10–22.

The programme is executed under the leadership of SKBs division for research and development. The staff of the division was 23 persons in 1990. Some 250 scientists, engineers, specialists and technicians were engaged under contracts with universities, technical institutes, research laboratories, engineering firms and industry. The results were reported in 45 technical reports in the SKB-TR-serie, in numerous progress reports and working reports and in communications to several international meetings and to scientific magazines. A list of the more important publications is given in Appendix 2.

The expenditures on research and development within the SKB budget for 1990 were 126.1 MSEK as compared to 117.7 MSEK in 1989. The increase was due to the start of construction of the Äspö Hard Rock Laboratory.

SKB is also the managing participant in the international Stripa Project and Poços de Caldas Project. The expenditures for these projects were 30.2 MSEK of which 10.7 MSEK were SKB contributions and 19.5 MSEK came from participants outside Sweden. The total turnover of the R&D-division was thus 145.6 MSEK.

6.2 R&D-PROGRAMME 89

The second R&D-programme according to the requirements in the Act of Nuclear Activities was submitted to SKN on September 27, 1989. SKN then sent the programme for an extensive review to some 50 organizations in Sweden. These organizations included universities and other academic institutions, several central and local authorities, major governmental research organizations as well as leading environmental interest groups. SKN received comments from some 30 bodies.

Based on these comments and SKNs internal review the board worked out an evaluation report, which was submitted to the government by the end of March 1990.

SKNs comments on the timeschedule for the work to be done during the 1990s included some new proposals which deviated from the programme presented by SKB. Several of the authorities and some other reviewers and SKB were therefore allowed to comment upon these new proposals before the government announced its decision in December 1991.

A summary of SKNs comments and a translation of the government decision is given in chapter 10.

6.3 REPOSITORY DESIGN STUDIES

The reference design for spent fuel disposal for SKBs various R&D activities and other studies is the KBS-3 method published in 1983. The method was extensively evaluated and found acceptable with respect to safety and radiation protection. It formed basis for the government's approval of starting the reactors number 11 and 12 of the Swedish nuclear power programme.

Beside the KBS-3 method several different methods of disposing spent fuel deep in the bedrock have been or are being studied by SKB. The WP-Cave was evaluated between 1986 and 1988. During 1987 to 1989 a method of disposal in Very Deep Holes, at between 2 and 4 km depth, was developed. These studies have been reported in previous Annual Reports.

During 1990 a Very Long Hole concept was defined. The layout is similar to the Swiss NAGRA's "Project Gewähr" published in 1985 although that concept was developed for vitrified HLW from reprocessing. The proposed design based on present know-how is described in Chapter 11 of this annual report.

The ongoing studies and development work on alternative repository designs have since late 1990 been coordinated in one project called "Project Alternative System Studies", PASS. The main goal for PASS is to be able to evaluate and rank the various alternatives studied in mid-1992. The evaluation considers mainly technological feasibility, long-term and operational safety and differences in cost.

The concepts considered in PASS are KBS-3, Very Long Holes and Very Deep Holes. For each concept some alternative canister designs are evaluated. Of particular

interest beside the KBS-3 type copper canisters are canisters with steel containers for mechanical support and copper as a corrosion protective outer container. Such containers are developed and studied in cooperation with TVO in Finland. Also some other studies within PASS are made in cooperation with TVO.

6.4 SAFETY ANALYSIS

A new comprehensive integrated safety analysis, SKB-91, on the final disposal of spent nuclear fuel is underway since 1989. The main goal for this project is to form part of the background material for the initiation of site selection.

The reference site for the study is Finnsjön, where an extensive geologic database has been collected since the late 1970s. In general the geologic conditions in the Finnsjön area seem to be somewhat less favourable than on the sites evaluated for KBS-3. This has been considered an advantage when evaluating the role of site-dependent data for the safety of the repository. Part of the SKB-91 study will be to make variation analyses in particular on geologic data characterizing a site. For such variations the experiences from the about ten other study sites investigated in Sweden throughout the late 1970s and the 1980s will be utilized.

The reference design for the repository in SKB 91 is the KBS-3 design.

Through 1990 the main parts of the various conceptual and numerical models to be used in SKB-91 have been defined. As compared to the models used for KBS-3 (published 1983) extensive new development work and new data are included for almost all aspects of the analysis. In particular a specific glaciation (iceage) scenario has been developed in 1990 in cooperation with TVO in Finland.

The SKB 91 safety analysis should be completed and reported in 1991. It will, however, serve as a basis fo future safety assessments concerning various alternatives, various sites, priorities for future R&D-work etc. during the 1990s.

In parallel to the SKB 91 several important developments in safety analysis methodology are being made. These are reported in Chapter 12.

6.5 WASTE FORMS

The studies of Waste Forms at SKB are presently concentrated on the properties of spent nuclear fuel in a repository environment. The work on developing an understanding of these properties started in the early 1980s and has now generated an extensive data base. This forms the background for the conceptual and numerical model of spent fuel corrosion that has been developed for use in the SKB 91 study. Highlights of the major developments in 1990 and of the new model are given in Chapter 13.

6.6 ENGINEERED BARRIERS

The work on canisters has been concentrated on designs with copper as the outer corrosion barrier. As mentioned above a new concept, an advanced cold process (ACP) canister is being studied. The concept was originally proposed by TVO in Finland.

To assist SKB in the evaluation of different canister design a reference group for mechanical integrity of canisters has been founded. The group will also give advice on the future canister development programme.

The studies of creep in copper canisters continues. The reasons for observed embrittlement in some experiments are not fully understood, but believed to be a high temperature effect.

The corrosion studies on carbon steel has been concentrated on anaerobic corrosion (producing hydrogen). Results from such studies could be of great importance in the evaluation of some failure modes for the composite canister (steel + copper).

A nearfield performance evaluation of the ACP-canister has been made jointly with TVO. The major conclusions are that internal processes cannot cause canister breach under foreseen conditions and that outer processes that could degrade the canisters are extremely slow. The service life of the canisters would thus be several million years.

The heater test in Stripa with a highly compacted smectite rich French clay was finalized in September 1990. The test has been run for four years with temperatures up to 170° in the clay.

The results are now evaluated in conjunction with the evaluation of effects of gammaradiation on the French clay (and on MX-80 bentonite clay) from experiments at Saclay in France.

6.7 GEOSCIENCE

The geoscience programme at SKB is to a great extent organized in projects as the Stripa Project and the Äspö Hard Rock Laboratory Project. The programme also includes separate development and research tasks as studies of ground water movements, of bedrock stability, of glaciation and ice age scenarios and developments and improvements in instruments and methods to measure important properties and parameters of the bedrock. The work is concentrated on the crystalline rocks that constitute the Scandinavian shield and covers most part of Sweden.

In 1990 the studies of ground water movements have included a broad spectrum of tasks related to numerical modelling of ground water flow. The models under development have been applied to experiments at Stripa, Äspö and Finnsjön. Tracer tests with nonsorbing radioactive tracers performed earlier at Finnsjön have been reported. A first set of tracer experiments using radioactive tracers was also made at Äspö.

In 1986 SKB initiated an interdisciplinary study of the post-glacial faults in the Lansjärv area in northern Sweden. Some results have been reported previously and in the summer of 1990 some supplementary investigations were conducted. The main aim of these works was to make a detailed study of the bedrock along two excavated trenches 50 m apart across a fault scarp. The study included petrology, structural features and fracture infillinngs. Three cored drillholes cutting the fault at different depths supplemented the surface observations. The Lansjärv project will be ended by a scientific excursion in the summer of 1991.

In cooperation between TVO in Finland and SKB scientists from the two countries have worked out a future ice age scenario. The scenario is based on a compilation of the present knowledge of earlier glaciations that have occured in Northern Europe (and elsewhere). From these experiences it is evident that the glaciations are correlated to small periodic variations in the parameters describing the earths orbit around the sun - the Milankovitch orbital parameters. According to the scenario the climate will start to be colder about 5000 years from now and remain colder for a long time, more than 100 000 years, before the next warm period. The climate is expected to vary considerably even troughout the cold period with glaciation peaks at about 20 000, 60 000 and 100 000 years. The scenario will form a basis for one of the scenarios to be analysed in the SKB 91 safety assessment. Details in timing of the scenario are not important for the overall safety analysis.

Efforts have also been made to model the influence of a thick land ice on a hypothetical repository at Finnsjön site.

In preparation for the forthcoming siting process a review of previously collected field data from the study sites investigated since 1977 has started. The aim is to structure and summarize the data in a consistent manner with regard to the experience gained from recent research. The database collected from the study sites is an important background material in the siting process.

6.8 CHEMISTRY

The chemistry programme covers geochemistry, radionuclide chemistry and transport of dissolved species (radioactive and other) in ground water.

The studies of groundwater chemistry at Äspö have continued. The new data confirm the previously observed trend that the salinity increases with depth. The waters found at depth are mixtures of water of different age. The evaluation of the data continues.

Studies of groundwater and minerals from three different fracture zones at Klipperås show that K_d values derived from these field data are two to three orders of magnitude higher than those obtained by laboratory measurements on thorium and rare earth elements. For uranium the K_d values from field and laboratory data agree. The distribution coefficient K_d is a measure of the uptake of radionuclides in the rock from the water. A high K_d implies a considerable retention of radionuclides as compared to the flow of water.

The work to establish a consistent, evaluated and high quality thermodynamic data base for the important radionuclides in the longlived radioactive wastes continues in international cooperation. Experiment with uranium, thorium and technetium have been performed and evaluated. SKB also supports the international effort organized by NEA in order to compile and evaluate data.

The CHEMVAL project is organized by CEC with the aim to validate geochemical computer codes. SKB participates actively in this project.

The studies of organic complexes, colloids and microbes in deep ground waters continue. Experiments on the uptake of promethium on Shewanella bacteria have been reported.

SKB participates in the international INTRAVAL project aiming at validation of models for solute transport in groundwater. In-situ experiments from Stripa and Finnsjön are among those included in the project. A phase two of the project has recently been decided.

6.9 STRIPA PROJECT

The International Stripa Project is being performed under the sponsorship of the OECD Nuclear Energy Agency (NEA). The management is entrusted to the Research and Development Division of the Swedish Nuclear Fuel and Waste Management Company (SKB). The project is now at the end of its third phase (Phase 3) where seven countries - Canada, Finland, Japan, Sweden, Switzerland and the United States - are participating. The research activities in Phase 3 are carried out under two headings:

— Fracture Flow and Nuclide Transport with Site Characterization and Validation (SCV) as the major subproject. The SCV-study is focussed on validating the diagnosticity of techniques and approaches, developed for and used, in site characterization. In close relation to the SCV-study are the developments of high resolution and directional radar antennas, improved techniques for high resolution borehole seismic measurements and, fracture network modelling.

— Groundwater Flow Path Sealing where the principal objective is to identify suitable grouts and grouting techniques for the long-term sealing of groundwater flow paths in the Stripa granite.

The basic experiment of the SCV Project is to predict the distribution of water flow into a potential drift (tunnel), excavate the drift, measure the inflows and compare measurements with the prediction. In support of the basic experiment there are a number of subsidiary experiments such as an assessment of channeling, the small scale hydrogeological effects of drift excavation, and tracer tests associated with fracture zones.

The five year program (1986-1991) of the SCV Project contains two cycles of data gathering, prediction, and validation as follows:

Stage	Title of stage	Period	Type of work	Cycle
I	Preliminary site characterization	86-88	data gathering	first
II	Preliminary prediction	87-88	prediction	first
III	Detailed characterization & preliminary validation	88-89	validation/ data gathering	second
IV	Detailed predictions	89-90	prediction	second
V	Detailed evaluation	90-92	validation	second

Stage IV was completed during 1990 and Stage V is currently in progress. The last stage includes a tracer test that was started in the second half of 1990.

The predictions are made in parallell by four modelling groups using a spectrum of computer programmes based on the most recent developments in fracture flow modelling. Particular emphasis is placed on statistical discrete fracture models.

The general objective of the Rock Sealing Test is to identify suitable grouts and grouting techniques for sealing fine rock fractures in repositories. The grouts have to be sufficiently erosion-resistant and chemically stable to make them serve for long periods of time and part of the project is therefore focussed on the testing of candidate materials not only with respect to their initial sealing ability but also to their potential to survive in repository environment.

The Stripa Project will be finished with the completion of phase 3. All experiments in the mine will be ended by June 30, 1991 and after that the mine will be closed. Reporting of results will continue through 1991 and in mid-1992 two comprehensive overview reports of the whole Stripa Project will be issued. A final Stripa symposium is planned for the fall of 1992.

A comprehensive summary of the Stripa phase 3 work is given in Chapter 18.

6.10 ÄSPÖ HARD ROCK LABORATORY PROJECT

The work on planning the Äspö Hard Rock Laboratory started in 1986. The area around the Oskarshamn nuclear power plant was from the beginning selected as an interesting area. In 1988 the southern part of the island Äspö, 2 km north of the power plant, was chosen as the candidate site for the laboratory. The site was confirmed by additional borehole and surface investigations, which also gave data for designing the access tunnel. Applications to build the laboratory were submitted in 1989.

The Swedish government granted a permit according to the Act on Conservation of Natural Resources in April 1990. Additional permits required were then obtained from the local community council in Oskarshamn according to the Building and Planning Act and from the Water Rights Court according to the Act on Water Rights.

With these permits at hand it was possible to start the excavation of the access tunnel on October 1, only two months later than planned in the original time schedule 1987.

The main contractor for the construction work was selected after evaluation of six competitive bids to be Siab, Swedens third largest construction company. They established themselves on site after the summer vacation in August. In parallell SKB also established a site office at Äspö with overall responsibility for the day to day work on site. The office includes a specialist group responsible for the scientific documentation of the tunnel, for performing special investigations and for monitoring of the logging equipment in boreholes etc.

An extensive effort has been made to plan in detail the integration of data collection at the front of the access tunnel and the continued excavation of the same tunnel. The first 800 m of the tunnel is considered to be a test stretch to be used to smoothline the procedures in this and other respects.

Before start of construction several supplementary field investigations were made in 1990. Among the more interesting was the drilling of an inclined cored borehole along part of the planned route of the access ramp from Simpevarp to Äspö. The borehole is 700 m long and provides important information on the rock conditions along the planned ramp. Another large experiment was a second long-term pump test (LPT2). Included in this was a tracer test using radioactive tracers.

Considerable efforts were devoted to the evaluation of the results from the preinvestigation phase and to predictions of what will be seen and what will happen during the laboratory construction. The predictions, which will be published in mid-1991, include descriptions, models or forecasts of geological, geohydrological and geochemical conditions, data, parameters and/or changes in different scales. These range from the full site scale via 50 m scale down to typical 5 m scale. The emphasis has been to predict in a quantitative or qualitative manner such data or parameters that can be measured or observed throughout the construction.

By the end of the year the tunnel had been excavated to a length of 260 meters.

6.11 NATURAL ANALOGUE STUDIES

The studies of natural analogues is an important tool to validate our models with regard to long-term processes to some extent. SKB has during 1990 been engaged in three such studies i e the Poços de Caldas project, the Cigar Lake project and the newly initiated studies at Oklo.

The Poços de Caldas project started in 1986 and was completed in 1990. It was a cooperative effort by SKB in Sweden, NAGRA in Switzerland, DOE in UK, DOE in USA and the Brazilian host organizations CNEN, URANIO do BRAZIL and universities in Rio de Janeiro and Saõ Paolo. SKB was responsible for project management.

The project was officially ended by a seminar in conjunction with a meeting of the CEC natural analogue working group in Pitlochry, Scotland in June 1990. Results were obtained concerning geochemical models, colloids, redox front modelling and hydrothermally induced transport. Highlights of the results are given in chapter 20.

The Cigar Lake project is a joint effort by AECL in Canada and SKB to investigate some properties of a high grade uranium ore body found at Cigar Lake in northern Saskatchewan. The first phase started in 1989 and was reported in April 1990. Based on the results from this phase it was agreed to continue with a second phase for two years. The main objective is to describe and model the water-mineral interactions in the deposit and the trace element migration around it. The ground water at Cigar Lake is similar to the waters found at the SKB study sites. The year 1990 has been mainly devoted at field measurements, sampling, laboratory analyses and hydrogeologic modelling.

The new studies at Oklo are managed by CEA in France and sponsored by CEC in their new four-year research programme. Through our bilateral agreement with CEC (and with CEA) it has been possible for SKB to join as an external participant. Oklo is a uranium mine in Gabon in Africa where several so called natural reactor zones have been identified. Natural criticality was maintained for more than 100 000 years some 2 billion years ago. Despite the very long time period, the reactor zones are very well preserved and not much of the material involved in the reactions has escaped.

6.12 BIOSPHERE STUDIES

Although the aim of the disposal of radioactive waste is to isolate the radioactive substances form the biosphere, as long as they could be considered as dangerous, the studies of some properties of the biosphere are essential for performing a safety analysis of the long-term behaviour of a repository. The studies are directed towards modelling of radionuclide transport.

In 1990 the (first) BIOMOVS project was finished and reported. The project has been administered by SSI (the Swedish National Institute of Radiation Protection) and had a very broad international representation. The BIOPATH model used by SKB was one of the codes participating in the intercomparison of models. The general conclusion from the project is that there are a very large discrepancies between results from various modellers even when they use the same conceptual model. Thus there is much room for improvements in models. Sometimes they probably are overly conservative due to e g lack of experimental data.

The studies of the migration of radioactive fallout nuclides from Chernobyl at the study sites Finnsjön and Gideå have continued. Some of the results are discussed in Chapter 21.

7. SYSTEM PLANNING AND COST CALCULATIONS

7.1 SYSTEM PLANNING ACTIVITIES

The Swedish waste management system is described in Chapter 1. Activities performed by SKB concern implementation, operation and improvement of the different part of this system. Technological developments are likely to be made during the long time period of the back-end operations, and changes in the system are therefore expected in the long run.

The next major project in the operating parts of the system is the expansion of the storage capacity in the CLAB facility. In a first step the capacity is increased from 3000 to 5000 tonnes by closer packing of the fuel elements, see Chapter 3. Around 2005 a further expansion is planned by constructing a new storage rock chamber.

7.2 REPROCESSING

The Swedish policy for the management of spent fuel is the once-through strategy without reprocessing of the spent fuel. SKB has therefore transferred the rights to use its contracts with COGEMA to other customers.

A small portion of the Swedish spent nuclear fuel (about 140 tonnes) is planned to be reprocessed at BNFL's facility of Sellafield.

7.3 COST CALCULATIONS AND BACK-END FEE

According to Swedish law all back-end activities including the decommissioning of the nuclear power plants are the responsibility of the nuclear power plant owners. The costs are covered by a fee on nuclear electricity paid to the State and collected in funds, one for each nuclear power plant. The fee is set annually by the government.

Each year SKB calculates the future electicity production and the future costs for the back-end operations related to this electricity production. The results of the 1990 calculations were presented in PLAN 90 /7-1/. The total future electricity production (from 1990) was estimated to be about 1400 TWh, if all twelve reactors are operated to year 2010. Up to the end of 1990 about 600 TWh have been produced making a total of about 2000 TWh in the Swedish programme. For this production a fuel volume of about 7 800 tonnes of U is required.

The total future back-end costs were estimated to be about GSEK 45.5 (price level of January 1990). Up to and including 1990 already SEK 7.8 billion have been spent. The total cost for the back-end of the nuclear fuel cycle is thus about SEK 53 billion. The breakdown of the costs are roughly:

Transportation of waste	8%
Interim storage of spent fuel	21%
Encapsulation and final disposal of spent fuel and long-lived waste	39%
Final disposal of operational and nuclear power plant decommissioning waste	4%
Decommissioning and dismantling of nuclear power plants and	19%
Miscellaneous including R&D, pilot facilities	9%

Based on SKB's cost calculations and a discussion about the time of operation of the reactors and the estimated real interest rate, the government has decided that the fee for 1991 shall be SEK 0.019 per kWh on an average. This is the same fee as for the last seven years.

The fee is periodically paid into funds at the Bank of Sweden. These funds are administrated by the state authority, the National Board for Spent Nuclear Fuel, SKN. The total sum in the four funds was at the end of 1990 about GSEK 7.8.

7.4 DECOMMISSIONING OF NUCLEAR POWER PLANTS

During 1989 SKB's engagement continued in the international cooperate programme, which is sponsored by OECD/NEA. SKB is responsible for the programme coordinator function. This programme comprises 19 decommissioning projects in ten countries. The majority of the projects are small first generation power demonstration reactors.

The projects include all stages of decommissioning from preparation for a long-term rest and surveillance period of the plant to a total dismantling. Examples of the latter are the Shippingport reactor where dismantling was completed in 1988, the Japanese JPDR reactor dismantling is in progress and the reactor pressure vessel was removed in 1990 and the Niederaichbach reactor where dismantling has just started.

Earlier studies of the dismantling of the Swedish reactors have shown that there is no immediate need for substantial decommissioning R&D in Sweden. A study of the possibilities to remove the reactor pressure vessel in one piece and transport it intact for disposal is, however, in progress. The results of the first phase of this study showed a good potential for simplification reducing exposure and cost. More details will be given in the now ongoing second phase.

8. CONSULTING SERVICES

The achievements in the Swedish Nuclear Waste Management program have been recognized internationally and several foreign organizations have shown interest in utilizing SKB's specialized know-how and experience in their programmes. In 1984, therefore a small group within SKB was set up for marketing and management of consulting services conducted in cooperation with groups and individuals associated to the Swedish programme, see Figure 8-1.

From the start in 1985 and up to the end of 1990 about 60 assignments have been accomplished in a variety of areas such as field measurements in boreholes (hydrological, geophysical, rock stresses), canister and buffer material studies, feasibility studies and reviews of investigation programme and facilities. The consulting services performed during 1990 are summarized below.

Taiwan

In August 1989 SKB was contracted by Taiwan Power Co, TPC, to assist in the Phase II of TPC's Spent Fuel Disposal Program. The concern of the Phase II is to prepare a comprehensive plan for TPC's Spent Fuel Disposal Program with an emphasis on near-term activities. As main contractor for the Phase II TPC has appointed the Institute for Nuclear Energy Research, INER.

According to TPC's instructions the main objective for SKB's advisory function was to transfer to TPC/INER the know-how and experience gained in the Swedish spent fuel disposal programme. Instruments for this transfer have been informal communication reports, delivery of documents of interest, discussions at two meetings in Taiwan combined with visits to various institutions and a field trip to the Penghu Islands and one meeting held in Sweden. Beside the activities under the contract a representative of Taipower visited Sweden during a couple of weeks in order to get familiarized with the Swedish programme and SKB's way of working.

In the final report, SKB's views and comments on different parts of a plan for a spent fuel disposal programme are summarized and some recommendations given. The recommendations are based mainly on the Swedish experience and may not always be fully relevant for conditions in Taiwan. This may be the case particularly for items more or less linked to local organizational and administrative conditions where SKB's insight is limited or lacking. The work of the Phase II programme was finalized in December 1990.

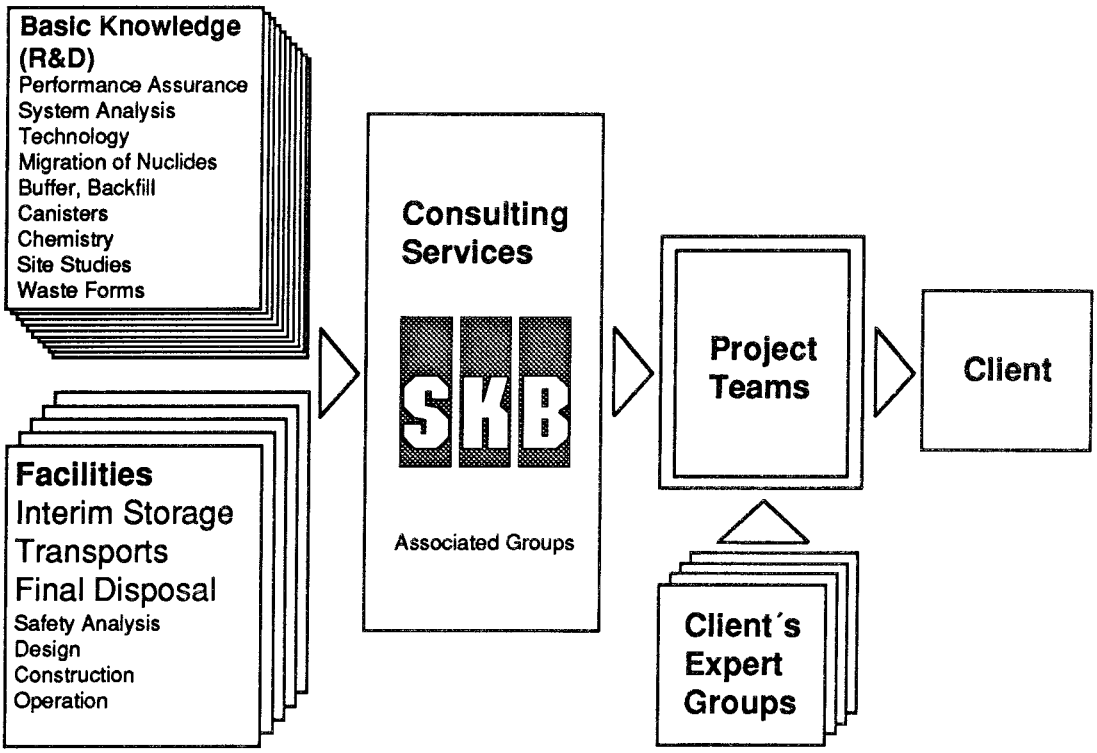


Figure 8-1. The SKB Consulting Services.

Japan

In July 1989 SKB was entrusted by Japan Nuclear Fuel Industries (JNFI) for consulting services concerning gas generation, gas transport and properties of bentonite with respect to the ROKKASHO low level waste repository planned to be constructed during the first part of the 1990th. The study has been carried out in several stages with meeting in Japan and visit to the repository site area. The final report was presented to JNFI in March 1990.

The Nuclear Fuel Transport Co., Ltd (NFT) in Japan responsible for all domestic sea transports entrusted SKB to transfer their experiences and know-how on low- and intermediate waste. During a period a group of NFT engineers were dispatch to Sweden in order to gain such know-how. Demonstration of the Swedish sea transportation system with respect to organization, soft and hardware, loading operation at a nuclear plant transport to the final repository for low- and medium level waste, unloading the ship at the repository site (SFR) and attending the disposal operation at the SFR-facility were examples on know-how transfer to NFT.

During the second part of 1990 the Power Reactor and Nuclear Fuel Development Corporation, PNC, in Japan entrusted SKB to carry out hydraulic borehole testing and water sampling in a crystalline environment in a 1000 meters deep borehole in Japan. The measurement programme will start in early 1991.

Republic of Korea

Korea Advanced Energy Research Institute, KAERI, is planning for an underground repository for low- and medium level waste from the nuclear power reactors in Korea. In October 1989 SKB was contracted by KAERI in order to, on a joint study base, provide the basis for the planning of such a repository. The duration of the study was nine months and was conducted on a prefeasibility level. The study carried out jointly covered the following areas:

— Waste Inventory and Categorization

— Preliminary Conceptual Design of the Repository and Guidelines for Subsequent Steps

— Guidelines for Performance Assessment and Safety Analysis

— Preliminary Master Time Schedule for the Project

— QA Program for Radioactive Waste

During a part of the joint study some 3-4 Korean engineers were dispatch to Sweden to work in the project group. The final report was presented to KAERI in September 1990.

Finland

As a part of the Finnish site investigation programme for high level radioactive waste disposal in deep crystalline rock formations, SKB has been contracted by TVO for carrying out a number of borehole investigations. Within the very extensive site characterization programme of TVO, mainly carried out during 1988-1989, SKB with subcontractors ABEM, SGAB and Renco AB have performed geophysical loggings, borehole radar investigations and rock stress measurements with the hydrofracturing method. In total some 25 boreholes down to depth of 1000 m have been measured at the five investigation sites in Kuhmo, Hyrynsalmi, Konginkangas, Sievi and Eurajoki. While most of the geophysical logging were conducted in 1988 the main part of radar and rock stress measurements have been performed during 1989 and 1990. In addition some radar investigations have been carried out, single hole as well as cross hole measurements, for the characterization of the rock at Olkiluoto, during the construction of the low- and medium level radioactive waste repository.

Australia

The SYNROC STUDY GROUP is conducting a pre-feasibility study of the management of spent nuclear fuel. Within this study SKB has been entrusted the subtask to study different alternatives for a regional spent fuel management system and to estimate the capital and operating costs for some of alternatives.

Spain

On behalf of EMPRESA NACIONAL DE RESIDUOS RADIACTIVOS, SA (ENRESA) SKB is conducting a study with respect to a Spanish HLW underground final repository in granite. Several different repository concepts are studied. At a later stage in the study a conceptual design of a reference concept and a back-up concept will be developed.

9. PUBLIC AFFAIRS AND MEDIA RELATIONS

9.1 GENERAL

Public information is an integrated and important part of the Swedish radioactive waste management system. The need for support by the general public calls for extensive activities by SKB both locally and on the national level.

The aim, based on the awareness that the Swedish public is entitled to open and comprehensible information on all aspects of the handling and disposal of radioactive waste, is to give a clear and unbiased description of the main issues today and the principal plans for tomorrow.

The energy debate in Sweden has during the last year changed towards increasing acceptance of nuclear power following earlier government decisions for early shut-down of two reactors and the parliament decision to abolish nuclear energy in 2010.

9.2 SKB INFORMATION ACTIVITIES

Two mobile SKB exhibitions toured Sweden during part of 1990 - one on wheels between April and October and one aboard the SKB transport ship M/S Sigyn during the summer, see Figure 9-1, 3, 4. Altogether 96,000 visitors were received at 73 different places around Sweden. Local politicians, associations, schools, and local media were invited individually to special receptions.

This very important activity within the field of public information and media relations was supplemented by a series of three advertisements in selected newspapers and magazines. The themes of these ads were some fairly unknown facts about waste management, such as the existence of natural analogues and the total volume of Swedish radioactive waste.

The overall success of these varied approaches was mirrored in increased confidence in radioactive waste management shown by the Swedish people in the recurring opinion polls commissioned by SKB, but made by the independent research institute SIFO.

Early Winter 1990 saw 53 per cent accepting final storage of spent nuclear fuel in their own neighbourhood. They said "Yes, I accept" to the question "Do you accept a final spent fuel repository in your own local district?". (In April, 1991, this figure was raised to 56 per cent when the question was repeated in a similar poll.) Those

Figure 9-1. *The spacious cargo hold of m/s Sigyn permits display of real transport containers like this one used for low level waste between the nuclear power plants and the SFR facility. The sign says "Reactor Waste". (Photo by Bengt O. Nordin.)*

opposed numbered 37 per cent and the don't knows 10 per cent, see Figure 9-2.

An overwhelming majority of 86 % is for storage of Swedish waste in Sweden. A majority of 53 per cent says that nuclear waste is taken care of in Sweden in a more safe way than in other countries.

On a number of occasions during the year SKB representatives have appeared on radio and TV programmes, in Sweden and internationally. Swedish politicians, other opinion leaders, foreign specialists and politicians, as well as members of the general public, have been frequent visitors to all the different facilities owned by SKB.

The permanent exhibitions on the SKB facilities were updated during the year. Preparations have started for adding a new one to the Äspö Laboratory that is currently being built close to the CLAB facility.

The in-house magazine SKB-nytt (SKB News) appeared seven times during 1990. The distribution includes a wide selection of scientists, researchers and consultants working for SKB.

9.3 PRINTED MATERIAL

Much of the SKB printed material was updated during 1990. The most basic presentation of the SKB activities, in the form of a pocket-size folder, was thoroughly remade. A new brochure in the form of an annual report was published in Swedish and it will be printed in English in its 1991 version.

Currently available printed material in the English language:

— Nuclear Waste Management in Sweden (co-produced with OECD/NEA, order no. X99 E 842 020, also available in French as order no. F99 842 010 and in German as order no. D99 939 010)

— Radioactive Waste (annually updated pocket-size folder, order no. C12 E 022 010)

— SFR, Swedish Final Repository for Radioactive Waste (order no. C003 E 818 025)

— CLAB, Central Interim Storage Facility for Spent Nuclear Fuel

— Stripa, A Deep Underground Facility

These titles can be ordered without cost from SKB, Public Affairs & Media Relations.

9.4 VIDEO CASSETTES AND FILMS

Currently available video cassettes and films in the English language:

— CLAB in Action (order no. C 1002 602), also in French

— SFR. A Final Repository for Radioactive Waste (order no. C 1001 835), also in German.

— The Stripa Project (order no. C 1005 950)

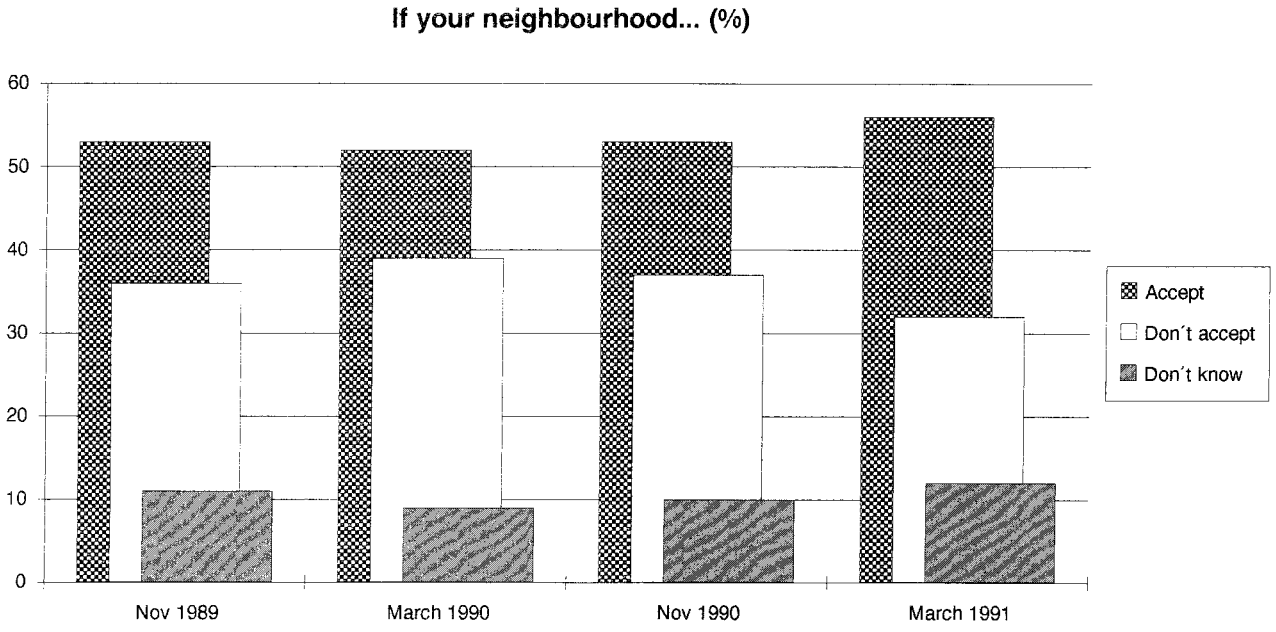


Figure 9-2. Opinion polls made for SKB by the independent research institute SIFO include the question "Do you accept a final repository for spent nuclear fuel in your neighbourhood or do you not?". Acceptance have been stated by 53 %, 52 %, 53 % and 56 % between 1989 and 1991. Corresponding negative answers are 36 %, 39 %, 37 % and 32 %, while the Don't knows are registered as 11 %, 9 %, 10 % and 12 %.

— Spent Nuclear Fuel on the Way (order no. C 1003 615)

— Nuclear Fuel and Waste (order no. C 1004 704)

These titles can be rented from SKB, Public Affairs & Media Relations.

Figure 9-3. *The long haul trailer used by SKB for the exhibition tours is specially built to expand sideways making the interior capable of accomodating more than 20 visitors at the same time. The red signs on the rear walls say "Handle with care". (Photo by Bengt O. Nordin.)*

Figure 9-4. *Featured in the middle of the trailer is a fuel assembly and a mock up of the copper canister (weight 2.5 metric tonnes) proposed to be used by SKB in isolating the spent fuel in a future repository. Also seen here a model of a transport container used on Sigyn for spent nuclear fuel. (Photo by Bengt O. Nordin.)*

REFERENCES PART I

CHAPTER 1

1-1 NEW SWEDISH NUCLEAR LEGISLATION
Swedish ministry of industry, DSI 1984:18

CHAPTER 6

6-1 Handling and Final Disposal of Nuclear Waste
SKB R&D-Programme 89
Stockholm, September 1989

CHAPTER 7

7-1 Plan 90
Kostnader för kärnkraftens radioaktiva restprodukter
(In Swedish)
June 1990

SKB ANNUAL REPORT 1990

Part II

Research and Development during 1990

CONTENTS PART II

10. REVIEW OF R&D-PROGRAMME 89

The second R&D-programme according to the requirements in the Act of Nuclear Activities was submitted to the National Board for Spent Nuclear Fuel, SKN, on September 27, 1989 /10-1/. SKN then sent the programme for review to some 50 organizations in Sweden. These organizations included universities and other academic institutions, several central and local authorities, major governmental research organizations as well as leading environmental interest groups. SKN received comments from some 30 bodies.

Based on these comments and SKNs internal review the board worked out an evaluation report, which was submitted to the government by the end of March 1990.

SKNs comments on the timeschedule for the work to be done during the 1990s included some new proposals which deviated from the programme presented by SKB. Several of the authorities and some other reviewers and SKB were therefore allowed to comment upon these new proposals before the government announced its decision in December 1991.

10.1 SHORT SUMMARY OF SKNs EVALUATION OF R&D-PROGRAMME 89

The following short summary is a direct translation from the SKN cover letter to its report to the government in March 1991 /10-2/.

"The Board has structured its comments on SKBs R&D-programme 89 around three main sections.

Under the headline Strategic Questions (...) the Board discusses primarily such main questions as goals and guidelines for the waste management, the requirement on comprehensiveness in studies of alternatives, the overall time schedule and analyses of costs.

The two remaining sections, Research Programme 1990-1995 (...) and Dismantling of nuclear power plants, etc (...), contain detailed reviews of what SKB has written in R&D-programme 89 on various issues.

The National Board of Spent Nuclear Fuel proposes that the government requests that the reactor owners during the present programme period:

— investigate whether the disposal of the waste can be achieved in stages, with the possibility of reevaluating the situation at the end of each stage, and to within the framework of this investigation, plan for the construction of a demonstration plant (...),

— review its siting strategy with the aim of giving the public a good insight into the selection process (...),

— review its timetable so that selection of the disposal system is scheduled before the site selection and so as to take advantage of experience from the Hard Rock Laboratory to a greater extent (...) as well as to

— adopt the Board's recommendations regarding
  - resources for the SKB 91 safety assessment
  - design studies of canisters
  - Hard Rock Laboratory
  - the geologic data for the siting of a final repository

Furthermore, the Board proposes that the government requests the reactor owners to

— report any deviations from the Boards recommendations and the reasons for these deviations no later than in R&D-programme 92.

The comments about the emphasis of the research programme made (by the Board) in remaining parts of the sections 3 and 4 should in the boards opinion be guiding for the research work.

The Board intends to request in accordance with 11§ of the act on financing on future expences for spent nuclear fuel etc (1981:669) the reactor owners to

— present cost-estimates and explain the factors behind the prioritisation of the areas covered in the research programme as well as to submit, on a yearly basis and starting no later than November 30, 1990, to the Board, an overall report on the estimated costs for the research work over the next three years (...).

The Board also considers that the reactor owners should continue their planned studies of the alternatives "deep borehole" and "long disposal tunnels under the Baltic seabed". The Board intends to return later to the "WP-Cave" alternative, after further investigation (...).

On the condition that the measures that the Board recommends are adopted the Board considers that R&D-programme 89 fulfills the requirements which can reasonably be made on the basis of the stipulations of the Act on Nuclear Activities. (...)"

The four recommendations from the board which SKB should "adopt" are more fully expressed in the evaluation report as

1. SKN "recommends that SKB thoroughly evaluate whether the company's resources, including any planned increase in resources not mentioned in the

programme report, are sufficient for the implementation of the integrated safety assessment, SKB 91, as planned."

2. SKN "would like to emphasize the importance of SKB initiating design studies of canisters made of combinations of materials, as soon as possible. With such a focus, it will be possible to identify different issues at an early stage, such as those relating to manufacturing and testing, which need further investigation in order to bring the level of knowledge of such canisters to the same level as that of copper canisters. (...) To summarise, the Board supports, for the period from 1990 to 1995, SKB's proposal to concentrate, in general, on canisters made of copper and combinations of copper and other materials. The Board particularly recommends that SKB initiate studies on the design and manufacturing of such canisters, as soon as possible."

3. " To summarise the Board recommends SKB to

   - revise and supplement previously presented models of the region and the site,

   - compile the experience gained concerning investigation methods used, interpretations of investigation results and comparisons with the successively produced prediction models, before the start of construction."

4. " To summarise the Board recommends SKB to

   - continue the study of rock types in Sweden and persue a more detailed classification,

   - further investigate basic plutonic rock types."

10.2 SKBs COMMENTS TO SKNs PROPOSALS IN THEIR EVALUATION REPORT

The government gave SKB and a number of other organizations which had reviewed the R&D-programme 89 the possibility to comment on the proposals put forward in SKNs evaluation report. SKBs comments were submitted to the government on September 13, 1990. In summary the following comments were made:

"In general the review gives a support to the technical content of the R&D-programme 89 presented by SKB. Extensive comments and proposal of changes are however given to some guidelines and to the time shedule in R&D-programme 89.

SKB agrees with that the siting process for the repository for spent nuclear fuel must be carried out with extensive insight och with good opportunities for authorities and the general public to thouroughly evaluate different steps in the process.

SKB finds it very important to test all possibilities to reach a concensus agreement with the local interests on the candidate sites, in particular with regard to the fact that the work on the site finally selected for the repository will continue for 50-60 years.

As the waste already exists and must be taken care of within Sweden SKB means that there are realistic possibilities and also sufficient time to reach concensus both with communities and local interests in such a way that the siting will not be blocked by a "local veto".

In such a case will, as is evident from the preparatory work for the recent revision of the "vetoparagraph" in the Act on the Conservation of Natural Resources, the demands on studies of alternative siting be less.

SKB proposes that no decision should be taken today to postpone the presentation of candidate sites to 1995. According to SKBs view there is not sufficient background for such a decision. The necessary background required for a presentation should be available in the autumn 1992. SKB will therefore in connection with R&D-programme 92 come back with a further detailing of the time schedule for siting the repository.

SKNs proposal to construct the repository in steps and let the first step serve as a demonstration plant is interesting but does not affect the research programme during the present six year period. SKB intends to come back to the demand for demonstration plants in future R&D-programmes.

In SKNs evaluation report a number of valuable detailed comments are given on the technical content of the research programme; the comments will be considered by SKB in its work."

10.3 THE GOVERNMENT DECISION ON THE R&D-PROGRAMME

The government decision concerning the R&D-programme 89 was dated December 20 and contains the following statement (in SKBs translation):

"The government finds that the recommendations from the National Board of Spent Nuclear Fuel concerning the safety analysis SKB 91, design studies of canisters, underground research laboratory and the geologic basis for site selection of a repository should be payed regard to. In addition the statements the board makes in sections 3 and 4 of its evaluation report should be guiding for the continued research and development work.

The government reminds on that the research work should include an account of and an evaluation of alternative management and disposal metods being developed during the continued research in the waste management area through the domestic research as well as the research in other countries.

The government emphasizes that any tie to a specific management or disposal method should not be made until

those safety and radiation problems that may occur can be surveyed.

The government wants as its meaning to express that one of the guidelines for the continued research and development work should be that a final repository for nuclear waste and spent nuclear fuel shall be possible to take in operation in steps with evaluation points and possibilities for correcting measures.

SKB should in its next R&D-programme according to the Act on Nuclear Activities investigate the possibilities to let a repository of demonstration scale be a step in the work to develop a repository.

The government further wants to express that the alternatives with deep boreholes and long disposal drifts under the bottom of the Baltic sea, which are studied by SKB, seem to be less suitable as repositories according to the governments judgement.

The government notes that SKBs selection of sites suitable for a repository will be reviewed by different authorities in connection with SKBs application for permits to make detailed investigation of two such sites according to the act on conservation of natural resources etc (1987:12), the environmental protection act (1969:387) and the planning and building act (1987:383).

The government reminds on that it in its proposal (to the Swedish parliament) 1989/90:126 about changes of the act on conservation of natural resources etc (NRL) is prescribed how so called exempt cases should be treated according to NRL.

The government shares the view of the National Board of Spent Nuclear Fuel that a good public insight is desireable into the selection process that leads to choice of sites suitable for a repository. SKB should therefore in the next R&D-programme to be submitted according to the act on nuclear activities give information on the background material that SKB has acquired for the selection of sites suitable for a repository. SKB should also throughout the ongoing work give information to the National Board of Spent Nuclear Fuel, the planning and building administration, the affected county boards and communities on the work with selection of sites suitable for a repository.

In its next R&D-programme according to the act on nuclear activities SKB should in particular report on any measures taken which deviate from what the government has expressed in this decision.

The government desides that R&D-programme 89 should be put aside."

11. REPOSITORY DESIGN STUDIES

11.1 BACKGROUND

Since 1984, following the Swedish government's approval, the KBS-3 method has been the Swedish reference concept for final waste disposal. In parallel to the continuing development of this concept other alternatives have as well been analyzed.

Between 1986 and 1988 the WP-Cave concept was studied by SKB and eventually compared with the reference concept. The work was presented in SKB's Annual Reports for 1986 to 1988. The outcome of the comparison clearly showed that the reference concept has major technical as well as economical advantages.

During 1987 to 1989 the concept of disposal in Very Deep Holes (VDH), at between 2 and 4 km depth, was developed. A conceptual design of drilling and deployment of canisters with spent fuel has been presented, see Annual Report 1989.

During 1990 a Very Long Hole (VLH) concept was defined. The layout is similar to the Swiss NAGRA's Projekt Gewähr /11-1/ although the dimensions chosen are different. The proposed design based on the present know-how is described below.

The two alternative repository concepts, VDH and VLH, are based on different canister dimensions, and methods of excavation and backfilling, see Figure 11-1. The R&D work has been concentrated on some designs and some materials. This work continues, but will in the future be coordinated in a project called "Projekt Alternativstudier" abbreviated PASS (in English the project title is "Project Alternative System Studies").

11.2 CONCEPTUAL DESIGN OF VLH CONCEPT

11.2.1 General

The technical feasibility of a VLH repository has been studied primarily with the concentration on layout variables and presently available techniques for underground

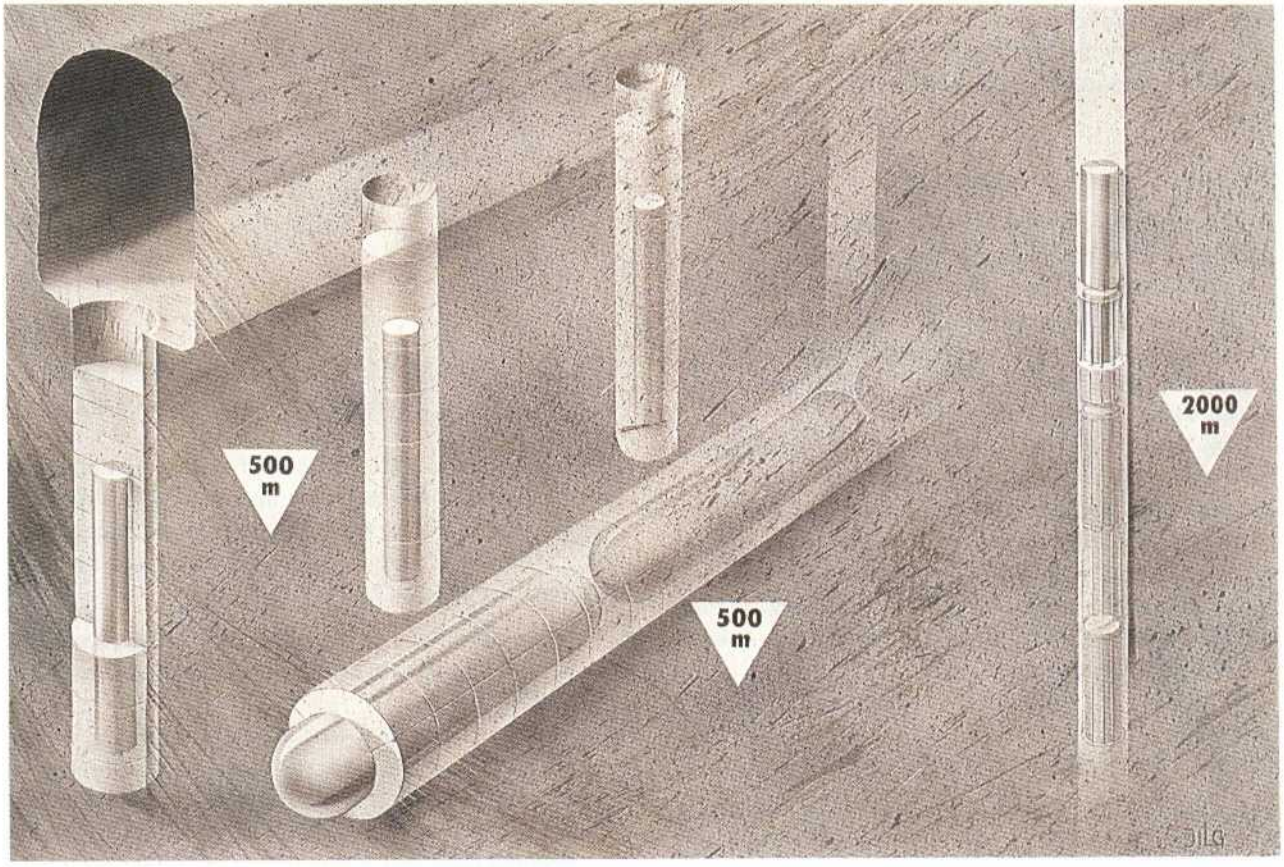


Figure 11-1. *Left; KBS-3 - The Swedish reference concept for final spent fuel disposal with deposition holes containing one canister each. Middle; VLH - An alternative concept with bigger canisters in a long deposition drift made by full face boring machine (TBM). Right; VDH - An alternative concept with smaller canisters deployed in vertical deep boreholes. In all concepts the canisters are surrounded by a buffer of bentonite clay.*

construction and canister deployment. The basis for the layout studies has been a dispersed repository with such a distance between the disposal drifts that no temperature interference between the drifts is obtained. The temperature limit in the bentonite buffer provides the major guiding parameter in the engineering of the near field.

11.2.2 Canister design

The reference canister in the KBS-3 method has an outer diameter of 800 mm and an inner of 600 mm. This inner measure is chosen in order to provide space for three times three BWR assemblies. In the VLH study a larger canister with a higher load is assumed. The temperature analysis clearly indicates that the thermal load would decide the canister size. In the initial study it was assumed that the outer surface of the canister should provide the cooling surface without any introduction of specific cooling devices.

Based on a temperature increase in the bentonite buffer of no more than 85°C during any longer period of time and a maximum weight of the canister in the range of 60 to 70 metric tons, a canister with a diameter of 1.6 m was considered for the reference case. The canister length is 5.9 m including hemi-spherical ends. This canister has a capacity of 24 BWR assemblies with 40 year old reference fuel.

No detailed investigation on the canister material has so far been conducted. The prime preference is a composite canister with a self-supporting steel body covered by a 60 mm thick corrosion protective layer of copper.

11.2.3 Layout of repository

In order to develop as good a heat conductivity as possible the blocks of bentonite buffer are assumed to be compressed with a high water content. Furthermore, the bentonite buffer is designed with a limited thickness of 400 mm. A dry bentonite or thicker bentonite buffer will result in a lower thermal load per canister for the same temperature increase in the buffer.

With the above dimensions the disposal drifts would have a diameter of 2.4 m. Altogether about 13 000 m of disposal drifts would be required for the Swedish program of spent fuel, if 90% of the drifts could be utilized for deposition. This length is considered in the proposed layout with three disposal drifts each about 4 400 m long. The distance between the drifts is set to 100 m in order to avoid thermal interference.

11.2.4 Tunnelling technology

The 2.4 m drift is well suited for full face boring by Tunnel Boring Machines (TBM). The rock surrounding the drift is disturbed to a minimum and the circular drift section is advantageous for the cylindrical canister.

TBM has been used for commercial boring in hard rock for about 10 years. Leading countries are Canada and Norway. Falconbridge Mining Company in Canada has together with others developed a TBM for 2.4 m drifts. The machine has a curve radius of 25 m and is designed for rock with a strength of up to about 300 MPa.

11.2.5 Canister deployment technology

The sequence of deployment of canisters is schematically shown in Figure 11-2. The conceptual method considered comprises three major stages.

1) The bottom part of the bentonite buffer is placed around the periphery of the drift in the form of highly compacted bentonite blocks. An opening is, however, maintained along the center of the floor with ample space for a canister deposition wagon.
2) The canister is transported up to the front and pushed over to the rolls of the deposition wagon. The canister is then lower until it rests on the bentonite. The deposition wagon is withdrawn.
3) Bentonite blocks are pushed into the space of the deposition wagon. The space above the canister is as well filled with bentonite blocks. These blocks could preferably be prepacked in a cassette which is inserted into the space. The cassette is withdrown leaving the bentonite in place. Finally the end blocks are put in place.

11.2.6 Future studies

In the next phase the performance in the near field will be analyzed. The studies are basically made as a comparison with KBS-3 and VDH, but the results shall also be used in the safety characterization of the concept later on.

11.3 PROJECT ALTERNATIVE SYSTEM STUDIES (PASS)

The overall aim for the PASS is defined to be a ranking of the studied alternatives by the middle of year 1992. The ranking shall consider technical questions including economy. Three main headings in the comparison are considered: Technology, Safety and Costs.

— Technology focuses on the feasibility of construction, rock excavation etc. with respect to available methods and equipment;
— Safety concentrates on the long-term safety of the repository. Safety in encapsulation and disposal operations is also considered to an appropriate extent;
— Costs are compared for the "reference" designs on the detailed level that is possible to define for each concept.

The repository concepts and canister designs in the ranking process are:

— KBS-3
— Copper canister filled with cast lead (KBS-3 reference canister)
— Hot Isostatic Pressed copper canister (HIP)
— Composite canister of steel and copper with flat ends
— Steel canister with flat or hemi-spherical ends

— VLH
— Composite canister of steel and copper with hemi-spherical ends
— Copper canister with hemi-spherical ends

— VDH
— Titanium canister with self-supporting shell
— Titanium canister filled with cast lead
— HIP copper canister

The comparison with respect to long term safety is planned to be focused on the difference between the repository concepts in the release of radionuclides to the far field at about 500 m depth below surface.

During 1990 the PASS project was planned and in December the first meeting with the Project Group was held.

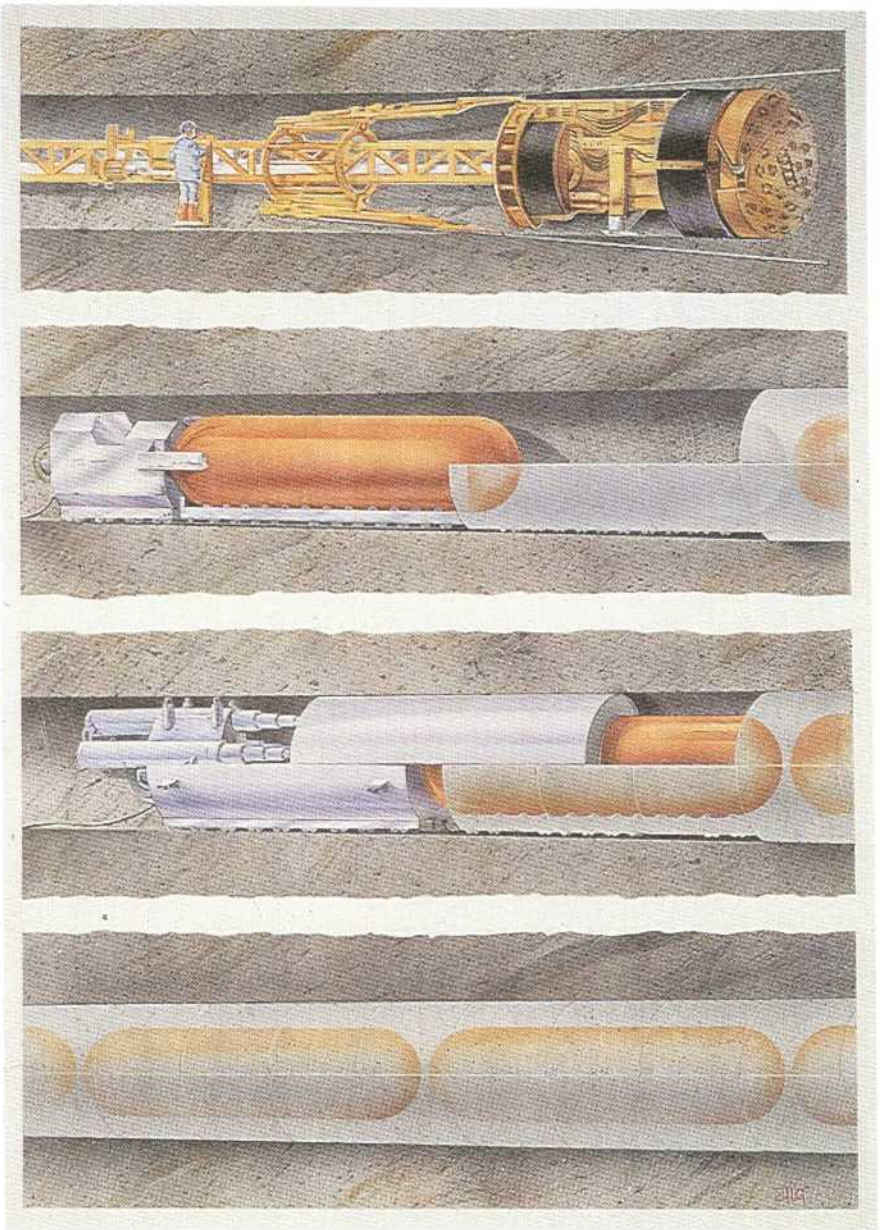


Figure 11-2. *Full face boring of disposal drifts, deposition of canisters and emplacement of bentonite buffer.*

12. SAFETY ANALYSIS

12.1 GENERAL

According to the general planning for SKB, presented in R&D-programme 1989, a new integrated safety evaluation of the final storage of spent nuclear fuel will be finalized during 1991 (SKB 91). The report will be one important part of the background material to the future site selection process in Sweden. The primary objective of the assessment is to clarify the role and importance of site-specific factors for the total safety of the repository /12-1/.

During the 1990-ies both the repository site and the barrier configuration will be selected for the disposal system, and it is the intention to also use the model-structure of SKB 91 in the evaluation and selection of alternatives. Thus, an effort will be made to avoid excessive safety margins and simplifications that might jeopardize the possibility for meaningful variation analyses.

During 1990 the safety assessment work has been focused on SKB 91.

12.2 SKB 91

At large, the work done for SKB during 1990 has involved the definition of:

— a conceptual design for the repository,
— a reference scenario and other scenarios,
— the data and models to be used,
— the modelling strategy and model coupling.

Many of the above selections will be successively revised in their details during 1991. Below the main structure of the SKB 91 assessment will be presented.

The assessment will be finalized during 1991.

12.2.1 Design

The repository layout has been selected according to the KBS-3 design /12-2/, ie the spent fuel is encased in copper containers filled with lead and deposited in separate holes drilled in the floor of a tunnel system excavated in crystalline rock at about 500 m depth. The space between canister and the rock is filled with a bentonite clay.

The reference fuel is a BWR fuel representing an average of what is expected to be in the repository. It has a burnup of 38 GWd/tonne, and the total amount is expected to be 7800 tonnes. The canisters are loaded and distributed in such a way that the temperatures at the canister surface is limited to less than 100°C.

The site selected for the assessment is Finnsjön, where an extensive database has been collected during more than ten years of field studies. The area has in general a higher hydraulic conductivity than the areas evaluated in KBS-3. This has been considered an advantage when trying to clarify the role of the site-dependent data for the safety of the repository.

12.2.2 Scenarios

The reference scenario is a steady state environment based on the present hydraulic and environmental conditions. The canisters are affected by corrosive substances in the near field and the groundwater or have defects due to faults in the production.

A glaciation scenario has been defined in cooperation with TVO in Finland /12-3/, starting with a temperature drop after about 5 000 years to a tundra-like climate in middle Sweden followed by a sequence of glaciations at 25 000, 60 000 and 100 000 years from now.

The safety importance of differences between the possible sites will be evaluated by varying the geologic parameters of the Finnsjön site. The variations will be selected with regard to differences manifested in the about 10 study-site investigations that have been made in Sweden.

12.2.3 The modelling

The general sequence of calculations for SKB 91 is presented in Figure 12-1.

The shaded areas represent input parameters given by the selected reference design and site. Arrows represent information flow in the analysis.

The near-field analysis in SKB 91 is to serve as a source term for the transport in the rock. Therefore, to simplify variation studies in the far-field most parameters in the near-field will in general be kept constant.

Below, some highlights are given of the progress during 1990.

Canister: The reference canister in SKB 91 is a 6 cm thick lead-filled copper canister with 8 BWR elements. In practice there is a number of combinations of BWR and PWR fuel that are equivalent with regard to heat generation. Three different failure modes will be studied:

— initial damage
— mechanical failure due to internal pressure
— failure due to corrosion

A preliminary calculation /12-4/ has been done to evalute the influence of different canister lifetimes on the overall performance of the repository near-field.

In KBS 3 the barrier function of the canister was removed after the canister was penetrated. It is obvious that also a damaged canister will provide a transport

resistance especially in the case of an initial damage, when the hole size will be very limited. A model has been developed for this resistance /12-5/ and it shows that a hole with 1 mm diameter (welding defect) will reduce the release of solubilty controlled radionuclides by several orders of magnitude.

Spent fuel: A new fuel dissolution model will be used in SKB 91. It is based on experimentally measured leaching rates and -dose rates /12-6/. A new set of radionuclide solubilities has been calculated /12-7/.

Near-field migration: The near-field model from the PROPER package has been converted to a stand-alone code and is used as a basis for the new model: "Tullgarn".

The major paths for radionuclide transport from KBS-3 canisters have been defined with a focus on the nearfield rock /12-8/. The primary purpose was to document the hydraulic properties of the "disturbed zones" around blasted tunnels. It is concluded that such zones extend about 1 m from the tunnel periphery and have an averagec hydraulic conductivity of no less than 10^{-8} m/s.

A second purpose was to generalize the structure of granitic rock with respect to water-bearing fractures. The major transport paths of the rock have been identified. A quantification is suggested and the pathways have been combined in a general simplified model. The model is intended for calculation of radionuclide transport through water flow and diffusion through continuous water passages.

Ground-water transport: The geohydrological data from the Finnsjön site were summarized during 1989, and have been used for initial groundwater flow calculations. The modelling was based on a porous media approach using the NAMMU code /12-9/. The modelling gives an overview of the groundwater movements in the Finnsjön area and boundary conditions for forthcoming modelling for SKB 91.

Another concept for modelling the geohydrology will also be used in SKB 91. A package called HYDRASTAR has been developed for stochastic continuum modelling. It will be used for conditional simulation of conductivity fields based on measured drill-hole data and for equation solution in three dimensions. The main reason for using HYDRASTAR is to take account of the spatial variability of the hydraulic properties of fractured rock.

The existence of saline groundwater at depths at the Finnsjön site and its effect on the groundwater movements is studied. Numerical simulations have been performed using the PHOENICS code /12-10/ and the present conditions with saline water below the upper boundary of the gently dipping fracture zone is explained by steady-state two-dimensional calculations.

Far-field migration: For far-field transport calculations a stream-tube approach will be applied /12-20/. Advection, dispersion and one-dimensional matrix diffusion is taken into account as well as chain decay.

The Biosphere: The magnitude of the doses caused by a release of radionuclides are strongly affected by how the nuclides reach the biosphere. In all release scenarios, however, the duration of the radionuclide release from a canister lasts for many hundred thousands of years. Compared to that, the primary biosphere recipients of the ground-water like wells, streams, bogs, lakes, agricultural

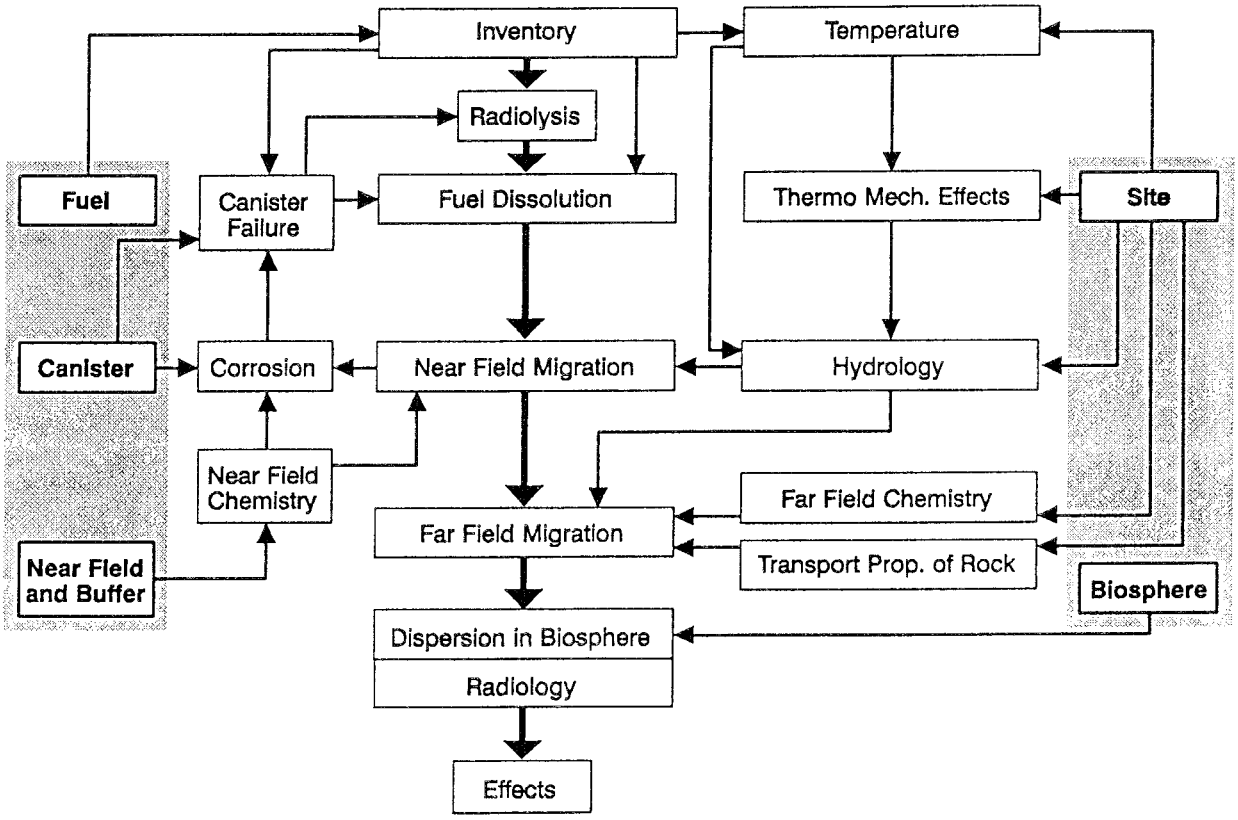


Figure 12-1. General sequence of calculation for SKB 91.

areas etc, change quickly because of sea-level changes, eutrophication, lake drainage and changes in land use. Major climatic changes will come and go over the release period.

Since such changes in the biosphere can change the release-dose relationship for a given release with many orders of magnitudes, and since the possibilities for such changes exist in all areas that have been investigated as potential sites for a repository, a large uncertainty that is only very little affected by the sites is brought into the assessments.

In order to avoid that biosphere dependent uncertainty in SKB 91, the recipient area has been simplified into a standardized agricultural biosphere with reasonably pessimistic pathways to man.

For this a set of dose conversion factors will be used, relating release rate from the far field, directly to dose to individuals in a critical group. These dosefactors shall apply to a relatively conservative situation that gives high doses but still has a reasonable probability of occurring within the studied timescale.

The standard biosphere consists of a well and lake with adjacent farmland /12-11, 12/. A fraction of 1 % of the activity reaches a well directly while the remaining part is dispersed in a lake before reaching man. Ten exposure pathways originating from activity in well and lake water are considered. The ecosystem diet and living habits are selected similar to present conditions in Sweden. No delay or reduction of activity by accumulation in the interphase geosphere and biosphere have been taken into account. A seven compartment model of the studied biosphere was designed, see Figure 12-2. Flows of activity are described by arrows. The BIOPATH code has been used for solving the differential equations and calculating the doses to adults and five year old children.

The uncertainty in the results due to the uncertainty in input parameter values have been examined with the PRISM-system. The major contribution to the uncertainty in the results was caused by the dilution volume for the nuclides in the groundwater. This dilution has been studied by varying reservoir volumes as well as varying the fraction of activity reaching the water in the well.

The pathways for ingestion of nuclides are via different types of food and drinking water. The intake of soil is also included. This latter pathway is valid via e.g. consuming unwashed vegetables. This intake is adopted to 10 g/y mainly from the garden plot.

Earlier calculations of the doses from these long-lived nuclides showed that the internal exposure dominates the exposure for the nuclides considered. The only external exposure considered is from ground.

Results, as arithmetic mean values of the total dose are presented in Table 12-1. All these results do not consider any contributions from daughter nuclides. These contributions were only notable for Zr-93 and Th-229. Including them the conversion factors would increase with 7 and 36 percent, respectively.

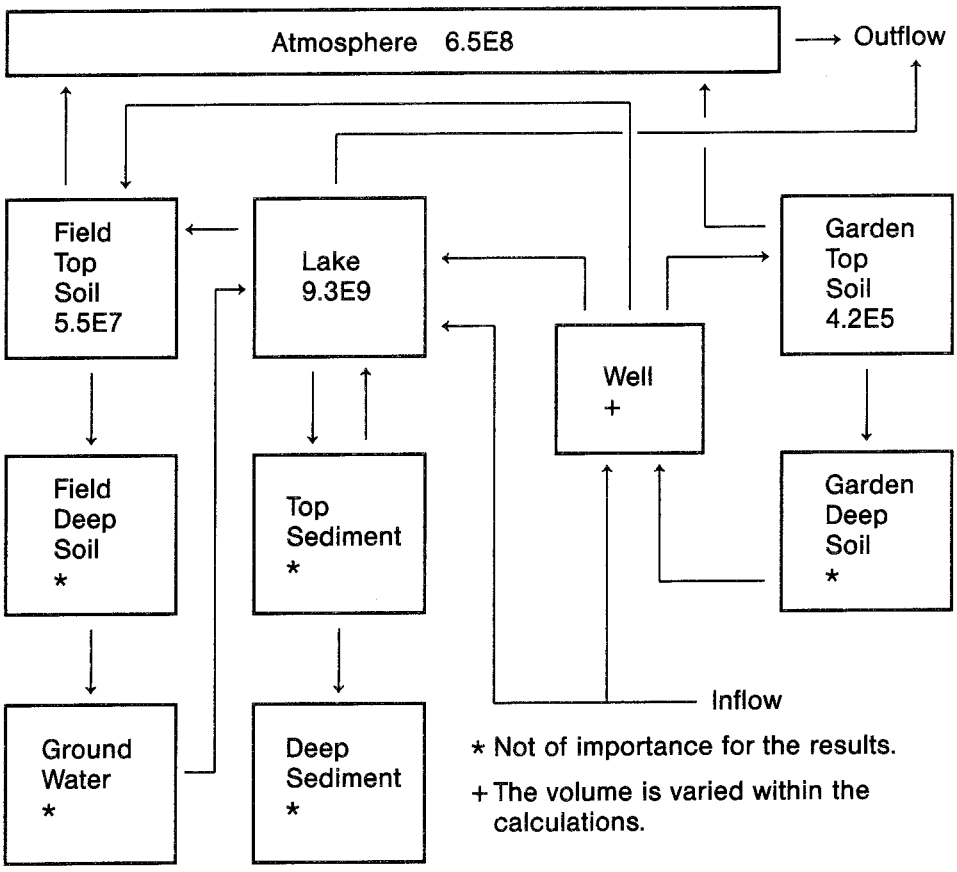


Figure 12-2. The structure of the seven compartment model with masses (kg).

The drinking water from the well is the dominant pathway for most nuclides.

Table 12-1. *Individual doses from a release of 1 % of the activity directly to a well while the remaining fraction will be diluted into a lake. Calculated doses to adults living close to the lake and taking there drinking water from the well. Arithmetic mean and ranges corresponding to 2.5 and 97.5 percentiles (Sv/Bq).*

Nuclide	Arithm mean	Ranges
C-14	1.3E-14	(0.6 - 2.3)E-14
Se-79	6.3E-14	(1.6 - 37)E-14
Sr-90	2.2E-13	(1.4 - 4.1)E-13
Zr-93	2.5E-15	(1.6 - 4.3)E-15
Tc-99	1.7E-15	(1.2 - 2.5)E-15
Sn-126	3.7E-14	(2.2 - 7.6)1E-14
I-129	5.4E-13	(3.1 - 13)1E-13
Cs-135	3.9E-14	(1.2 - 17)1E-14
Cs-137	2.4E-13	(0.7 - 9.9)1E-13
Pb-210	6.7E-12	(4.6 - 9.9)1E-12
Po-210	8.1E-13	(6.1 - 11)1E-13
Ra-223	3.5E-14	(2.3 - 6.6)1E-14
Ra-225	9.2E-14	(6.1 - 17)1E-14
Ra-226	1.8E-12	(1.1 - 3.4)1E-12
Ac-227	1.7E-11	(1.1 - 2.4)1E-11
Th-229	4.4E-12	(3.1 - 6.6)1E-12
Th-230	7.5E-13	(4.9 - 12)1E-13
Pa-231	1.0E-10	(0.6 - 1.5)1E-lO
U-233	1.6E-12	(1.1 - 2.5)1E-12
U-234	1.6E-12	(1.0 - 2.4)1E-12
U-235	1.5E-12	(1.0 - 2.3)1E-12
U-236	1.5E-12	(1.1 - 2.3)1E-12
U-238	1.4E-12	(1.0 - 2.2)1E-12
Np-237	2.2E-12	(1.4 - 3.3)1E-12
Pu-239	4.3E-12	(3.1 - 6.1)1E-12
Pu-240	4.3E-12	(2.9 - 6.2)1E-12
Pu-241	7.9E-14	(5.7 - 11)1E-14
Pu-242	3.9E-12	(2.6 - 5.6)1E-12
Am-241	4.2E-12	(2.8 - 6.8)1E-12

12.3 METHODOLOGY DEVELOPMENT

12.3.1 Near-field

In the SKB work it has been found that there is a need to describe the evolution of the chemical changes in the rock as the water flows through it. A development of a computer program to deal with mass-transport and geochemical reactions and their reaction fronts has been going on for a year /12-13/. The model can be applied to concrete and bed-rock in the repository environment. It is based on the quasi-stationary state equation.

When calculating the radiolysis in KBS-3 it was assumed that the fuel pellets were covered by a water film which thickness was assumed to be maintained forever. That situation gave a high fuel oxidation rate. A study /12-14/ has been carried out on two mechanisms which may decrease the radiolysis rate. The first is the capillary forces in the pores of the bentonite which do not permit the release of water if there is a gas overpressure inside the canister. The second is the accumulation of fuel corrosion products in the gap between the fuel and the cladding which will reduce the water available for radiolysis. Both effects seem to, independently, have a potential of reducing the rate radiolysis by a few orders of magnitude.

An international workshop on near-field performance assessment organized by SKB in cooperation with ENRESA and PNL was held in Madrid 15-17th October 1990 with 45 participants from 11 countries. The Workshop was convened to review and compare approaches of near-field performance assessment for high-level waste disposal. The objective was to establish a technical consensus of the credibility of current models and to guide needs for further research.

The comparison of the Pu-thermodynamic database with experimental measurements is completed and will be published.

12.3.2 Far-field

A computer code package for simulating radionuclide transport in streamtubes has been evaluated and tested /12-15/. The package consists of the computer programs NAMMU, HYPAC, PRETRU and TRUCHN. Given the geometry of the disposal site, site hydrologic characteristics and geochemical data, the code package calculates the flow field and the concentrations along the specified streamtubes.

A computer program for sensitivity analysis of groundwater flow, GWHRT-S, has earlier been developed. The model serves as a complement to flow models and can be used to study how different input data parameters and boundary conditions affect the output data. The method is thoroughly described in /12-16/. An application of the method for the Finnsjön site is presented in /12-17/.

Two stochastic continuum approaches, the parametric and the non-parametric, have been described in /12-18/. An application has been performed on hydraulic conductivity data from the Finnsjön site. This included statistical analysis and generation of realizations of hydraulic conductivity that are consistent with available single-hole injection test data. Flow and mass transport were evaluated for each two-dimensional realization /12-19/.

12.3.3 The PROPER Code Package

A new, faster and more flexible Monitor/Executive has been develloped for the PROPER package. A first version of a new postprocessing code (APROPOST = A PROper POSTprocessor) has also been introduced, but the final testing and verification is not yet finalized.

The further development of PROPER submodels from the present stage has mainly been done within SKB 91,

using the previous generation /12-20, 21, 22/ as a basis. No distinction is presently made between models to be used in the deterministic parts of the SKB 91 assessment and the models of potential use in uncertainty analysis.

12.3.4 Quality Assurance in Safety Assessments

In 1990 SKB established a Quality Assurance Policy for the company as a whole. Accordingly, a set of Quality Assurance Guidelines were developed for the application in major safety assessments. These Guidelines require that a QA Plan is to be produced identifying the persons responsible for the QA of the project and for each part of the assessment, the computer codes and versions used and the set of parameters and data approved for the assessment. A "SKB 91 QA-Plan" has been established. It will be used to find a practical and resource-effective level for future assessments connected with siting and licensing.

12.3.5 Long term availability of information

An important issue when discussing human intrusion scenarios for spent fuel repositories is whether the intrusion is intentional or unintentional. The availability of information on the site, the layout and the manmade barriers of a repository can also be connected with issues like retrievability, reparability, protection against sabotage, non proliferation etc.

To evaluate the need for information over long time, and the possibilities and problems with long term preservation of information, a joint Nordic 5-year study has been initiated. The study comprises an inventory of available information on waste facilities both on the industry and the authority side. National archive rules and regulations in the Nordic countries regarding archive media and archive designs are looked upon. The study also involves views on survival of old archives through times of different political situations. The result of the study will be a recommendation on how to handle and preserve information on waste facilities in the Nordic countries.

13. WASTE FORMS

13.1 SPENT FUEL

During 1989, the work on waste form studies has been concentrated entirely on spent fuel. The close contacts with other groups in the world performing similar studies have been continued. The 1990 meeting of the tenth spent fuel workshop was held in Canada and arranged by Atomic Energy of Canada Limited.

No activities other than literature studies have been devoted to vitrified high level waste. The final summary report of the results obtained within the JSS project, which was formally terminated in 1989, has been printed in Journal of Materials Research /13-1/.

13.1.1 Fuel Characterization Studies

The fuel characterization studies has during 1990 been concentrated on post-corrosion examinations. There is very little published information on the identification of corrosion sites in spent fuel exposed to water. At Studsvik, results are now becoming available from an on-going programme, where selected fragments of the reference BWR fuel, exposed to DIW and modified groundwater (varied bicarbonate concentration) for four years or more, are subjected to systematic examination for comparison with the original material.

It is reasonable to assume that corrosion is most probable in fuel zones with extended networks of inter-linked porosity, such as at the fuel pellet rim. At the outer rim of the fuel, there is also a steep increase in both fission rate and actinide build-up, due to neutron spectrum effects. The porosity and the alpha rim effect have been quantified for the reference BWR fuel used in the experiments /13-2/ and is shown in Figure 13-1.

Comparison of Figure 13-2a (reference material) and Figures 13-2b (240 ppm groundwater) and 13-2c (distilled water) clearly shows that there has been pore enlargement and interlinkage, and loss of material in the outermost 20 m or so of the fuel rim /13-3/. Further in, grain boundary

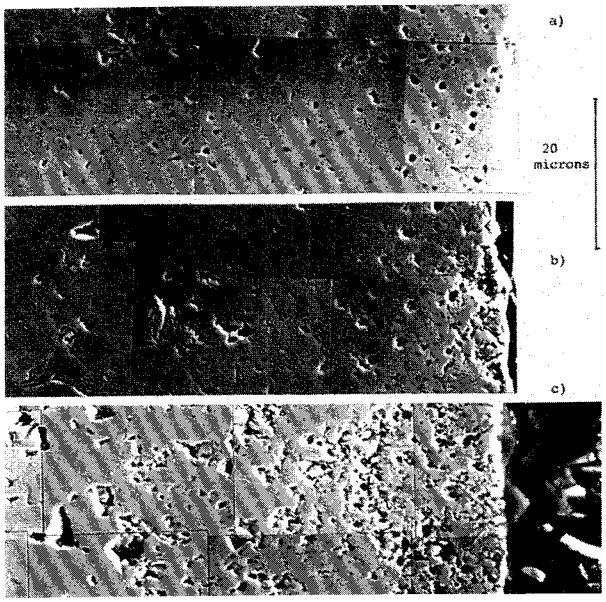


Figure 13-2. Scanning electron microscope mosaics of the rim of the BWR reference fuel:
a) Uncorroded
b) Corroded for 1427 days in 240 ppm bicarbonate groundwater.
c) Corroded for 1521 days in deionized water.

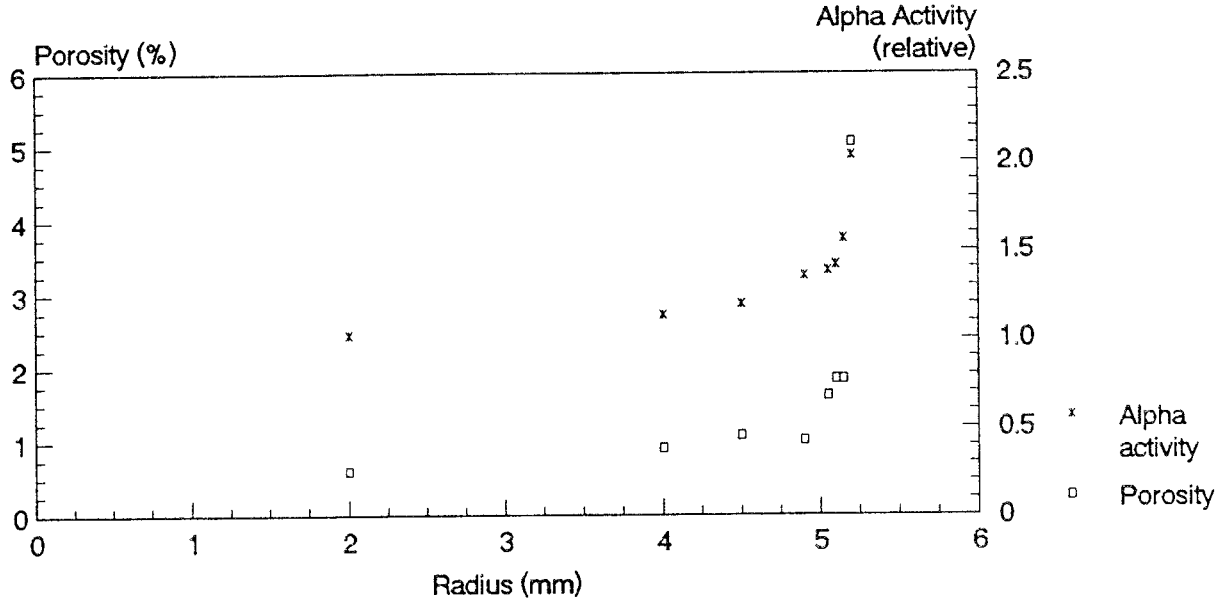


Figure 13-1. Radial variation of fuel porosity and actinide inventory for the BWR reference fuel.

attack is evidenced by the development of chains of porosity and grain pull-out. It can also be noted that on the far right in Figure 13-2c (distilled water) crystals of UO_3 hydrates, which have grown out from the fuel surface are present. It is, however, not yet clear if this corrosion attack, predominantly at the fuel rim, is caused mainly by the increased porosity, or if it also is assisted by the higher alpha and beta dose rates at the rim and in the pores in the rim.

13.1.2 Spent Fuel Corrosion Studies

The BWR fuel corrosion experiments, started in 1982, and the PWR fuel experiments, started in 1986, have continued during 1990. However, the emphasis in 1990 was put on an investigation of the effects of burnup and linear power on the corrosion properties. The source material for the experiments came from the bottom segment of a stringer rod irradiated for eight cycles in the Ringhals 1 BWR. The local burnup along the fuel column, excluding the end pellets, varies between 20 and 47 MWd/kg U. Only during the first irradiation cycle did the maximum-rated pellet experience a linear power as high as 25 kW/m. The integral fission gas release value for the rod is 1.1 %. A gamma scan of the stringer rod is shown in figure 13-3. The release fractions for ^{137}Cs and ^{90}Sr under oxic conditions are shown in Figures 13-4 and 13-5, respectively.

Inspection of the Figures leads to a number of observations:

1) That the results form a consistent set.
2) That for both ^{137}Cs and ^{90}Sr, a step-increase in leachability occurs at a rod position with a burnup of about 32 MWd/kgU.
3) That after this step-increase (about 39-40 MWd/kgU), there was no further increase in leachability with increased burnup and fuel operation temperatures under reactor operation. Indeed, the release behaviour over four contact periods suggests instead that water access to the fuel surface, or certain parts of the fuel surface, has been hindered.

Support for the hypothesis presented in 3) is afforded by the observed ^{99}Tc release behaviour. Although it is usually assumed that Tc release is effected by oxidative attack on the 4d metal inclusions situated at grain boundaries, and that formation of the inclusions is enhanced at higher burnup and fuel temperatures, the measured cumulative release fractions of ^{99}Tc were lower for the high burnup specimens (40 MWd/kgU) than for the lower. However, a fully satisfactory explanation for these effect will have to await future results from the on-going programme.

13.1.3 Modelling

As during previous years, the research activities during 1990 has been concentrated on oxidative dissolution, although studies of fuel dissolution under reducing conditions are currently being performed. The reason for this is that even if reducing conditions can be expected in deep granitic groundwater, local oxidizing conditions may well be at hand at the fuel surface due to radiolysis. Some experimental evidence for this hypothesis can be found in the observation that although the solution concentrations of uranium and plutonium are drastically reduced (several orders of magnitude) under reducing conditions, the ^{90}Sr release is only lowered by a factor of 10 to 20. If ^{90}Sr is homogeneously distributed in the matrix /13-4/, this would indicate an on-going oxidative dissolution also

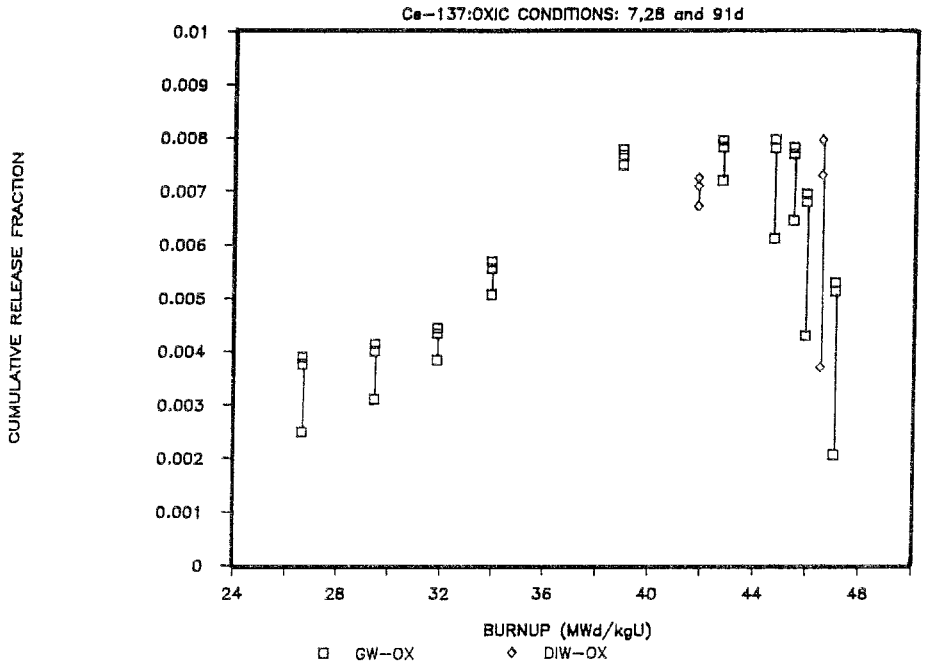


Figure 13-3. Gross gamma scan and sampling plan for stringer rod used for studying the relationship between burnup/linear power and corrosion properties.

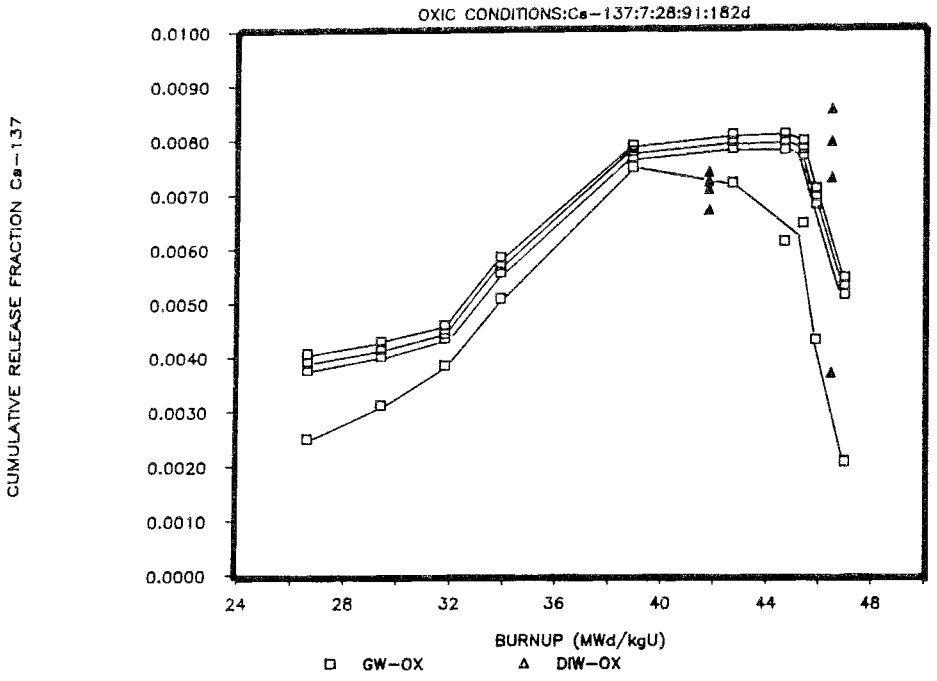


Figure 13-4. Cumulative release fractions (7, 28, 91 and 182 days) for ^{137}Cs from stringer rod under oxic conditions.

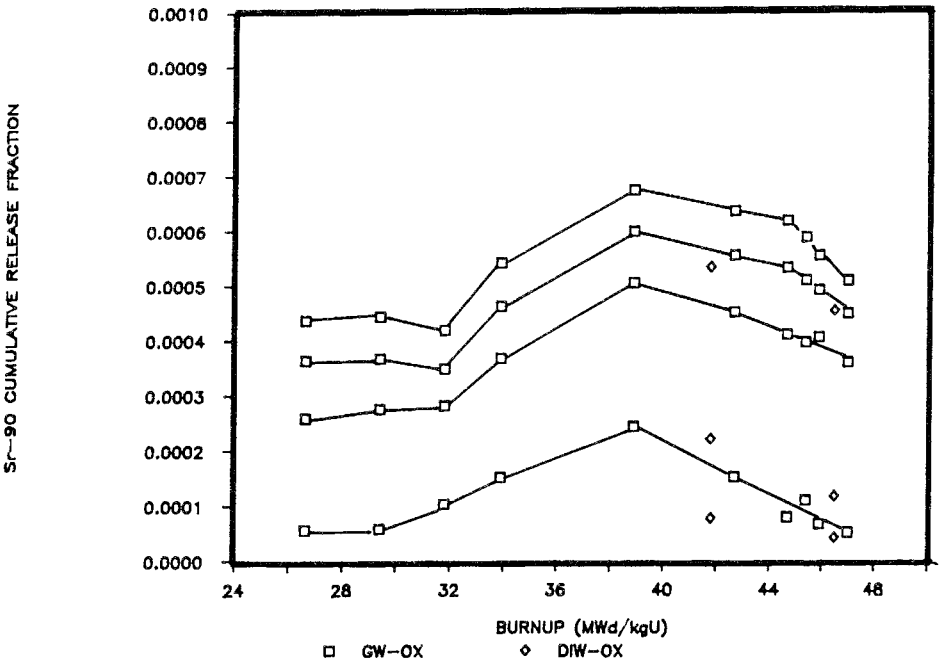


Figure 13-5. Cumulative release fractions (7, 28, 91 and 182 days) for ^{90}Sr from stringer rod under oxic conditions.

under nominally reducing conditions. Some of the results from the SKB programme /13-5, 13-6/, however, appear to indicate ^{90}Sr segregation: fuel specimens from different locations in the fuel column, showed consistently different release rates for ^{90}Sr over a period of several years, suggesting the effect of local power history variations. There are few literature reports of Sr-containing segregated phases in LWR fuel /see e.g. 13-7/, and search for such phases or zones in the reference fuel used in the SKB programme (burnup 41-42 MWd/kgU) has so far been unsuccessful. Nevertheless, for safety analysis purposes, it is conservative to assume that the Sr-release is an indicator of an on-going fuel matrix alteration.

A simple model for radiolytically controlled oxidative dissolution has been proposed /13-8/ with the intention that the model is used in the SKB-91 safety analysis. The model is based on the assumption that the fuel oxidation rate is proportional to the alpha dose rate. It is difficult to assess the actual contribution from radiolysis to the dissolution/alteration rates measured in the laboratory. Conservatively, it has assumed that the ^{90}Sr-release rates in experiments performed under reducing conditions marks the radiolytic oxidation rate. The fraction of fuel altered

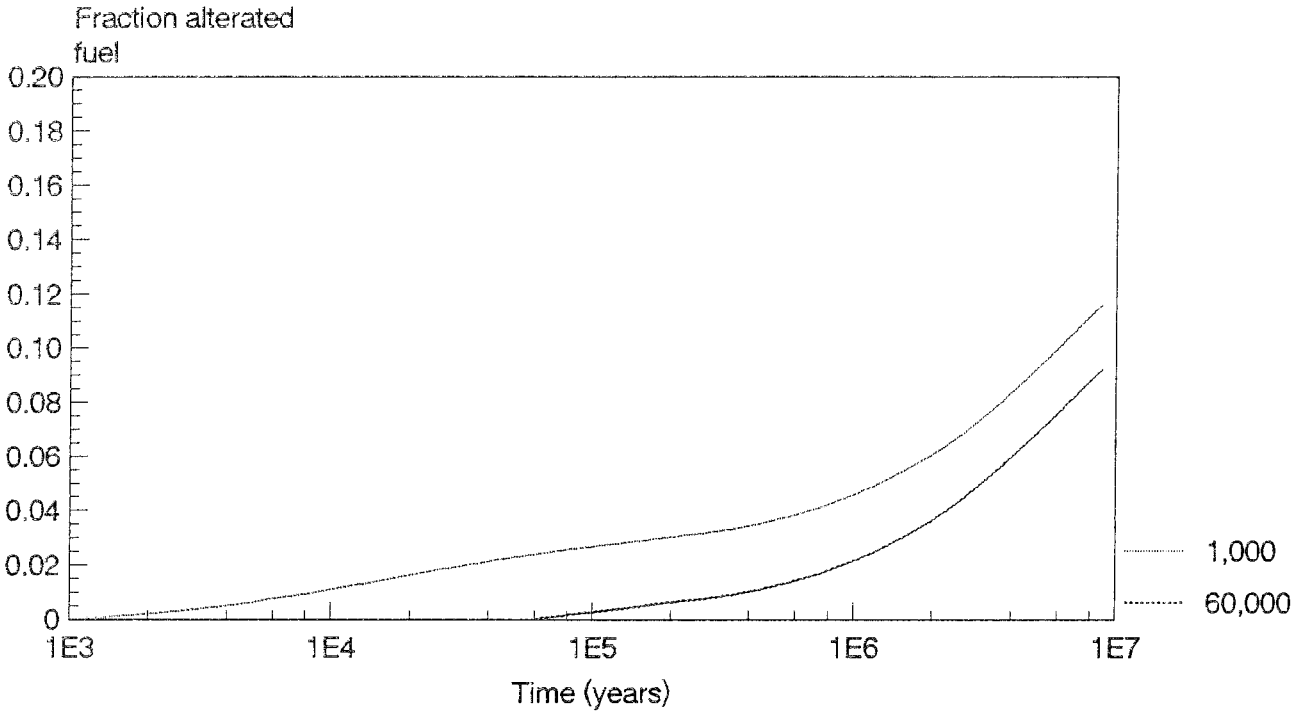


Figure 13-6. *Fraction of altered fuel as a function of time for canister life-times of 1,000 years and 60,000 years.*

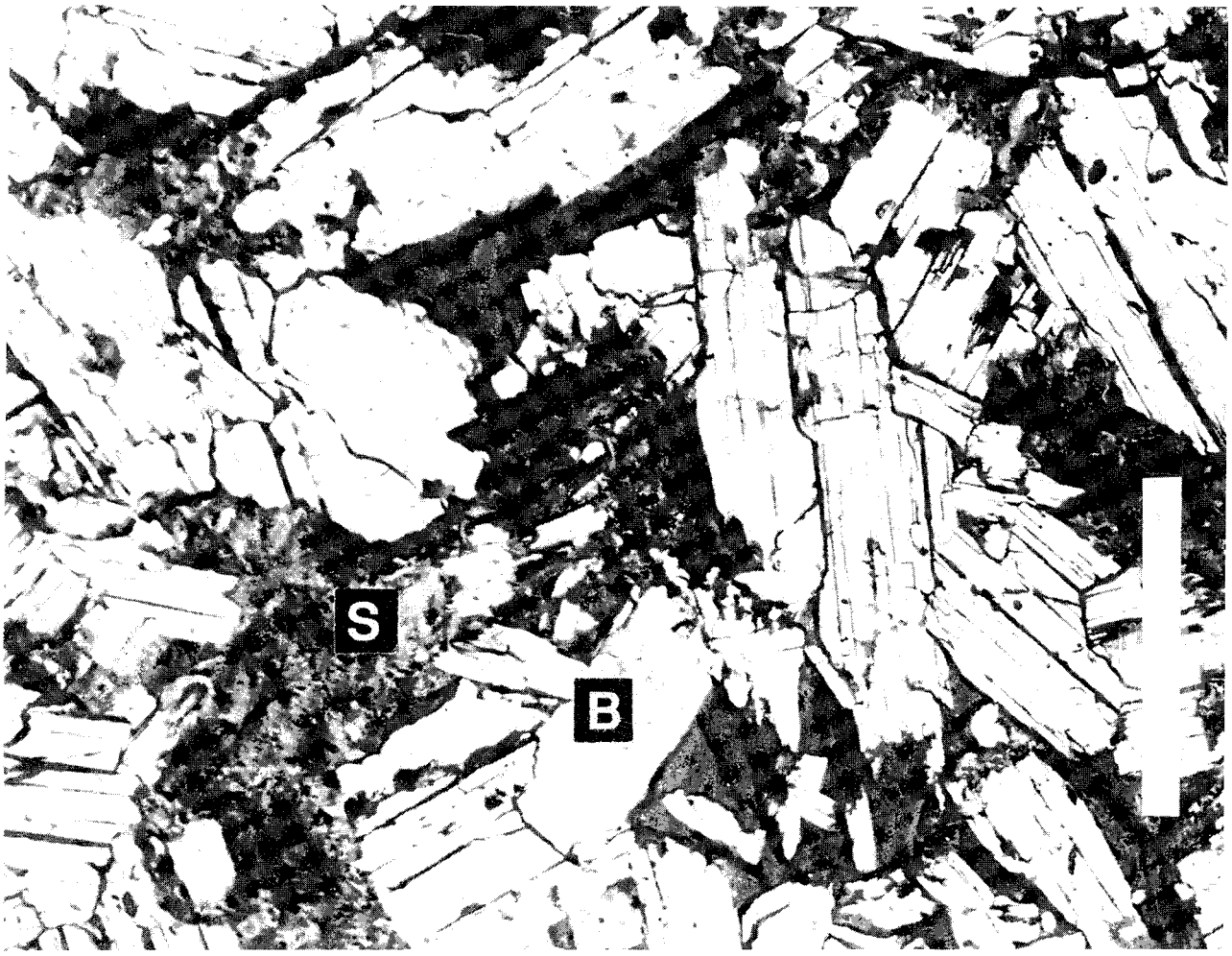


Figure 13-7. *Photomicrograph of uranyl silicate (S) replacing becquerelite (B) due to groundwater interaction. Scale bar equals 200 m.*

as a function of time for two canister failure times (1,000 years and 60,000 years) are shown in Figure 13-6.

13.2 NATURAL ANALOGUES

The studies of alteration products of natural uraninite (UO_{2+x}) in contact with oxidizing groundwater has continued during 1990. The first phase of the work is now finished and reported /13-8/. Further studies are in progress and will continue during 1991 and 1992.

A purpose of the natural analogue studies is to validate geochemical models used for predicting long term behaviour of spent fuel in a repository. This requires detailed mineralogical studies of the alteration products as well as an understanding of the paragenesis of the phases observed in nature. In an aqueous, oxic, environment, the oxidation of uraninite proceeds rapidly beyond $UO_{2.33}$ with concomitant hydration to produce the uranyl oxide hydrates. From these oxide hydrates, secondary phases are formed by incorporation of cations coupled with loss of hydrogen ions from the hydroxyl groups /13-9/. α-U_3O_7 may exist as a short-lived intermediate phase prior to the dissolution or hydration of uraninite, but its existence in nature is uncertain. Higher anhydrous oxides of uranium have never been reported in nature. This may be due to a kinetic barrier to the reconstructive transformation between $UO_{2.25}$ (cubic) and U_3O_8 (orthorhombic).

Pseudomorphic replacement of uraninite by uranyl oxide hydrates and the uranyl silicates indicates that these phases are formed early in a uranium ore body in contact with oxidizing groundwater. Figure 13-7 shows uranyl silicate replacing becquerelite due to groundwater reaction. The phosphates may form as pseudomorphous replacement products after the Pb-uranyl oxide hydrates, or they may precipitate from groundwater solutions /13-8/.

14. CANISTERS

During 1990, the studies have been concentrated on canisters with copper as the outer corrosion barrier. As a new concept, an advanced cold process canisters has been proposed. This canister consists of an inner load-bearing carbon steel canister, covered by an outer corrosion protecting copper shell.

In order to assist SKB in choosing appropriate canister type for each type of repository, a reference group for mechanical integrity of canisters has been formed. The group, which will meet several times per year during 1991 and 1992, will also give advice on the research programme for the next few years.

14.1 COPPER CANISTERS

14.1.1 Copper Creep Studies

The creep investigations during 1990 have been concentrated on high temperature studies. In the phase I of the creep studies, the creep properties of copper were investigated at repository relevant temperatures as well as slightly elevated temperatures (75°C to 145°C). For experimental reasons, these tests had to be performed at rather high stresses (75 MPa to 100 MPa) in order to go to failure in reasonable times. These tests showed a strain at failure of 5 to 20 %. However, the deformation mechanism in these tests did not necessarily correspond to the service deformation mechanism and, therefore, extrapolations to the expected service stress levels were considered as somewhat uncertain.

To enable extrapolation to lower stresses, creep tests were started at higher temperatures (180°C to 250°C) but at more realistic stresses (20 MPa to 100 MPa). These tests, which were started in 1989 showed creep failure at extremely low strains, less than 1 %.

After testing, the samples contained many grain boundary cavities along the gauge length as well as some cavities in the unstressed grip ends of the samples. The presence of cavities in the unstrained material together with the low ductility suggest possible hydrogen embrittlement. The OFHC copper presently used has a hydrogen content of 0.6 to 0.7 ppm. In order to resolve this problem, new tests were started in 1990 using copper with lower (0.1 ppm) hydrogen contents. Oxygen free copper, phosphorus deoxidized copper and copper containing 0.15% silver, were chosen for this study. However, embrittlement was still found for the OFHC copper, although fine grained material showed a higher ductility than material with coarser grains. The reasons for the embrittlement are still not fully understood but appears to be a high temperature effect. The work will continue during 1991.

14.2 CARBON STEEL CANISTERS

The experimental work within the first phase of the investigation of the corrosion behaviour of carbon steel containers for nuclear waste disposal, which started in 1986 and was concentrated on localized corrosion, was finalized in 1990. The study, which has been performed at Harwell Laboratories, UK, has addressed four issues: statistical analysis of pit growth data, stability and growth of deep pits, length of aeration period at the canister/backfill interface and appraisal of the corrosion allowance for pitting for a canister. The data are presently being analysed and a final report will be available in 1991.

The second phase of the study of corrosion on carbon steel, has been concentrated on anaerobic (hydrogen producing) corrosion. Within this programme, carbon steel specimens have been corroded at 90°C in anaerobic conditions under a hydrogen pressure 0.1, 1 and 10 MPa. At present exposure times of up to 18 months have been analysed and corrosion rates of 0.5 to 1 μm/a have been measured. No influence of the hydrogen pressure has been observed. In view of the findings to date, the programme has been revised and will during 1991 be supplemented electrochemical measurements in order to obtain information on the corrosion mechanisms and hence the processes limiting the overall anaerobic corrosion reaction.

14.3 COMPOSITE CANISTERS

A near-field performance evaluation of an Advanced Cold Process Canister for spent fuel disposal has been performed jointly by TVO, Finland and SKB, Sweden /14-1, 14-2/. The canister consists of a steel canister as a load bearing element, with an outer corrosion shield of copper. The canister design was originally proposed by TVO /14-3, 14-4/. In the analysis, as well internal (ie corrosion processes from the inside of the canister) as external processes (mechanical and chemical) have been considered both prior to and after canister breach. Throughout the analysis, present day underground conditions has been assumed to persist during the service life of the canister.

The major conclusions for the evaluation are:

Internal processes cannot cause the canister breach under foreseen conditions, ie localized corrosion for the steel or copper canisters can be dismissed as a failure mechanism.

The evaluation of the effects of processes outside the canister indicate that there is no rapid mechanism to endanger the integrity of the canister. Consequently the service life of the canister will be several million years. This factor will ensure the safety of the concept.

For completeness also evaluation of post-failure behaviour was carried out. Analyses were focussed on low probability phenomena from faults in canisters.

Some items were identified where further research is justified in order to increase knowledge of the phenomena and thus strengthen the confidence of safety margins. However, it can be concluded that the risks of these scenarios can be judged to be acceptable. This is due to the fact that firstly, the probability of occurrence of most of these scenarios can be controlled to a large extent through technical measures. Secondly, these analyses indicated that the consequences would not be severe.

As a summary, according to this evaluation the Advanced Cold Process Canister seems to meet at least the same safety targets as the KBS-3 canister.

During the analysis, a potential benefit of the presence of hydrogen gas and/or steel corrosion products was identified. If it can be demonstrated that after an early failure, the redox conditions inside the will be controlled by the hydrogen present, the releases will be very low throughout the period when corroding steel is present. This is illustrated in Figure 14-1, which shows the releases from the near-field (in Bq/a) from one canister assuming reducing conditions, controlled by the hydrogen over-pressure, to prevail inside the canister.

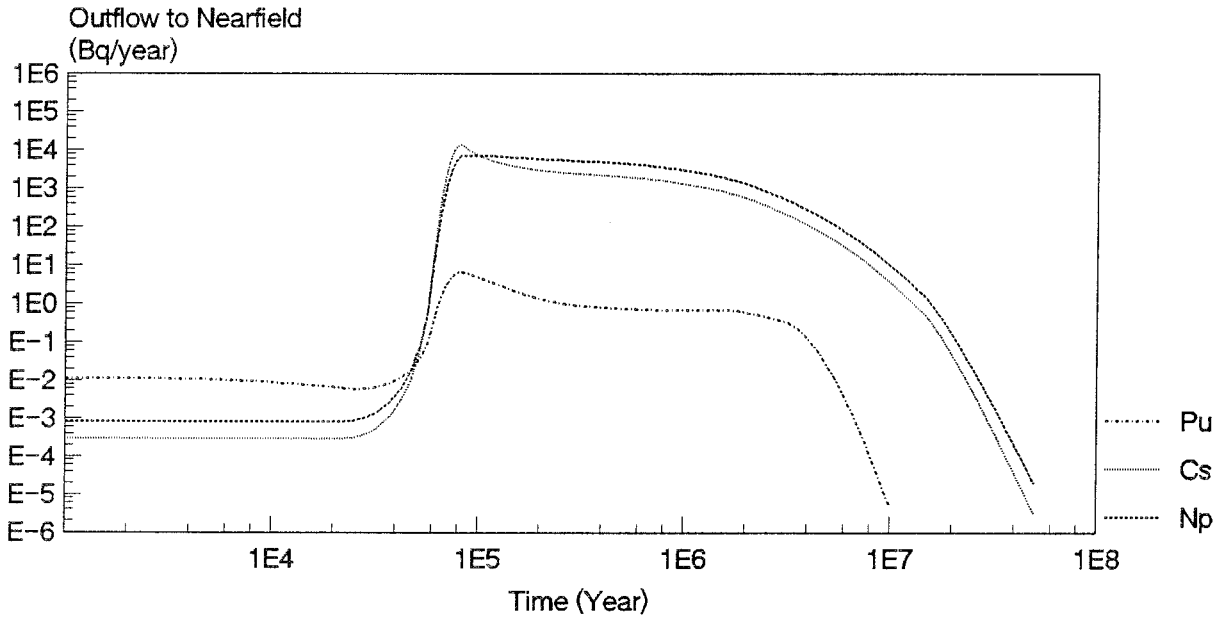


Figure 14-1. *Release from the near-field (in Bq/a) from one canister assuming reducing conditions, controlled by the hydrogen over-pressure, to prevail inside the canister.*

15. BUFFER AND BACKFILL

15.1 CLAY CHARACTERIZATION

In 1987 a standard procedure for characterization of clay materials was presented /15-1/. The experience from ongoing research with detailed characterization of several natural bentonites was the reason for a change of earlier standardized use of a developed XRD technique to four methods for quantification of the smectite content. The proposed laboratory test program and its application to a clay is presented in a report /15-2/ which also describes the redox conditions in yellow and blue bentonite, see Figure 15-1.

The heater test with highly compacted French smectite clay in a simulated deposition hole in the Stripa mine, with temperature up to 170°, was finalized in September 1990. The hole was overcored in rock and the samples are in examination. The results will be evaluated together with laboratory tested radiated samples of the French clay and our reference clay Mx-80.

A general microstructural model for qualitative and quantitative studies of smectite clay (GMM) is an improvment of the model first presented in /15-3/. The model provides a basis for quantitative determination of transport capacities and analysis of the rheological behaviour. The present knowledge of the physical state of porewater in dense clay and rheological testing have led to the microstructural model - the GMM which is presented in /15-4/.

The chemical stability or alteration of montmorillonitic bentonite buffer materials is addressed in ongoing testing. A model is presented in a new report /15-5/. The key mechanism in the alteration to hydrous mica at temperature below 130°C is neoformation of the latter material in the clay voids, where dissolved silica and aluminium are present, the controlling parameter being the access to potassium.

15.2 CLAY RHEOLOGY

The test in the Stripa mine which simulates possible movements of a canister in a deposition hole due to swelling, temperature effects and consolidation settlement was still running in 1990. It started on June 11, 1986 and is planned to run until the summer of 1991 with excavations of the upper part in the last step.

Fig 15-1. A piece of Bavarian bentonite clay (Moosburg) where oxidation has formed a redox front.

Laboratory testing was performed according to the plan to have data on the rheologic behaviour of buffer materials for required models at year 1993. During 1990 especially calcium clays were tested in drained and undrained conditions and complementary tests were made in order to verify the theory of effective stress. Preliminary material models were proposed and these were used in the analysis of the laboratory tests /15-6/.

15.3 MODELLING BUFFER PERFORMANCE

Theoretical calculations are used for quantitative descriptions of the geotechnical behaviour of the buffer material of importance for the performance of the isolation of canisters from moving ground water and movements of rock as well.

During 1990 some different models were applied and tested /15-6/. Conclusions are that the effective stress theory can be applied, thermomechanical behaviour can be modelled and the interaction between canister and clay in the process of shear due to rock movements as well. In the future the modelling should be improved by additional tests in order to better define some parameters in the models of plasticity and the effect of temperature.

16. GEOSCIENCE

16.1 OVERVIEW

The geoscience programme covers research and developments, in geology, geophysics and geohydrology and also includes development of new methods, models and instruments for measurements and evaluations.

The overall objectives and main activities of the geoscience programme 1987-1992 are expressed in the SKB R&D-Programme 86 /19-1/ and in the current programme 1990-1996 /10-1/ that was released in September 1989.

The geoscience research is to a great extent organized in projects that give opportunity for interaction between the specialized disciplines. Interdisciplinary approaches are used in several SKB activities as:

— the Äspö Hard Rock Laboratory

— the Comparison of Alternative Repository Designs (PASS)

— the Safety Assessment Programme, e.g. SKB 91

— the Siting of Final Repository

During 1990 the geoscience programme has involved the following tasks:

— Ground Water Movements in the Rock

— Bedrock Stability

— Post-Glacial Studies in the Lansjärv Area in Northern Sweden

— Structuring of Former Investigated Sites

16.2 GROUNDWATER MOVEMENTS IN THE ROCK

16.2.1 Overview

A thorough understanding of groundwater movements is essential for a detailed safety analysis of a repository. The groundwater flow affects the degradation of engineered barriers, the dissolution of the waste and the transport of solubles in the water.

The relative importance of the parameters that describe flow in the bedrock can be treated in performance assessments and safety analyses. One of the factors that has great importance for assessment of radionuclide transport of nonsorbing and sorbing species is the flow-rate of water. The flow-rate of water in the bedrock is dependent on conductivity, connectivity and the driving forces. The importance of small density contrast for the overall groundwater flow distribution has been recognized.

The conceptualization of the groundwater flow distribution is important for the overall assessment of radionuclide transport, both non-sorbing and sorbing. The hypothesis that groundwater flow occurs in more or less dependent channels or pathways needs thorough studies.

16.2.2 Groundwater Presence in Tunnels

Existing underground facilities in Sweden are mostly constructed in crystalline bedrock. A conceptual description of the presence of groundwater in tunnels is important when modelling the near-field which surrounds a generic repository site. Experiences from several tunnel works thus have been summarized in a report /16-1/.

The groundwater flow paths seen in tunnels in crystalline bedrock are usually restricted to small channels along only minor parts of the fractures or along the shear line of two fractures. The number of flow paths and the flow rate in general increase with the degree of tectonisation up to a given point. This is also true in fracture and crush zones, as well as in fracture clusters and fracture systems. When the bedrock is still more tectonised there is only very small space left for groundwater channels. Between the water bearing fractures and fracture zones there may be large sections of rock with no visible groundwater.

The drainage to a tunnel is, however, very much affected by the behaviour of the by excavation damaged zone of the rock mass just nearby the tunnel walls. Further effort has to be made in order to better understand the impact on the conductivity of stress release, blasting gases and unsaturated flow conditions, etc.

16.2.3 Groundwater Flow due to Heat Convection

If nuclear waste is buried in the rock the generated heat may force the groundwater to move. An interesting aspect of such thermally induced convection is concerned with stratified groundwater where the stratification is caused by a step in salinity. If the repository is located below the stratification the decrease in density caused by the temperature might compensate the additonal density caused by the salinity. This destabilization would however lead to a risk that the lower liquid, possibly contaminated, will

rise through the upper liquid and reach the surface, see Figure 16-1.

An analysis of the above problem is complicated due to the complex structure of the rock. Nevertheless, the fundamental character of the problem had been studied in laboratory scale. The basis for such a study has been the analogy between flow through a porous body and the flow through a narrow slot. A narrow slot simulating a porous body is a standard tool named a Hele Shaw cell. A new approach has been to make one of the walls of the cell of a material that conducts heat. In this way it has been possible to let heat be conducted as well as convected /16-2/.

16.2.4 Boundary Conditions of Models

The 3-D groundwater models are increasingly common which in turn imply that successively more complicated geometries may be analysed. A limited study on the influence of boundary conditions in the context of a watertable has been carried out /16-3/.

When modelling, one of the greatest practical interest is to be able to describe typical flow paths through a hypothetical repository located in a bedrock block at the -500 m level.

According to considerations of classic groundwater system theory, it seems entirely reasonable to expect that the -500 m level at any site may be within the realm of a deep regional groundwater system. If this is true then the groundwater flow through a repository may have little, if anything, to do with the watertable topography within the local site area. Flows at depth may be driven by a gradient resulting from regional rather than local topography. Further, if this is true, then it may be concluded that the question of accuracy in the watertable specified to a model of a site is moot. Accurate measurements of vertical variations in hydraulic heat at boundaries may be of greater importance in obtaining realistic flow fields, than precision in specification of the watertable elevation.

16.3 BEDROCK STABILITY

An in-depth analysis of the possible effects of geological processes on a final repository is under way. Essential questions are whether recent movements can lead to new fracturing and whether load changes or rock block movements can decisively alter the geohydrological situation around a final repository.

The objectives are to:

— quantify or set limits on the consequences of earthquakes, glaciation and land uplifts of importance in analyzing the safety of a final repository for spent nuclear fuel,

— process, evaluate and increase knowledge concerning the geodynamic processes in the Baltic Shield.

The present major efforts in the project have been directed to an Ice Age Scenario and a rock mechanical study regarding the response of a glaciation. Furthermore a field

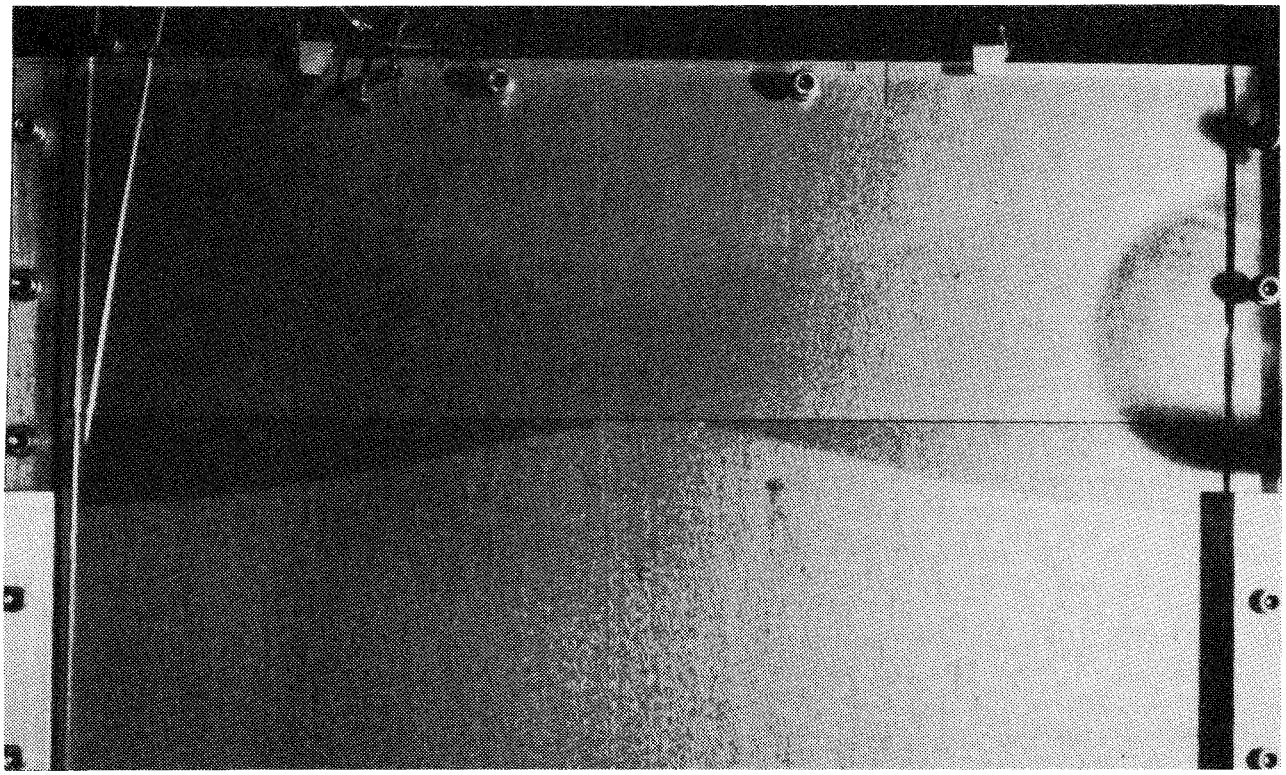


Figure 16-1. *Modified Hele Shaw cell showing the displacement of the interface between two immiscible liquids after a breakthrough due to thermal induced convection.*

study in Southeastern Sweden has been carried out. The latter study will be reported during June 1991.

16.3.1 Future Ice Age Scenario

An understanding of the stability of the bedrock of Fennoscandia is of importance to existing theories about final storage of spent nuclear fuel in crystalline rocks.

The ongoing safety assessment project will pay attention to a glaciation scenario and related phenomena. Therefore, SKB of Sweden and TVO of Finland in cooperation have initiated studies of the World's ice ages and changing environments and their importance for future glaciations in Fennoscandia /16-4/.

The world's climate will be dominated by glaciations for the next 100 000 years in the same way as it has been over similar periods for the past million years. This forecast is based on the last 20 years of research which have clearly demonstrated that glaciations have occurred periodically for at least the last 900 000 years. There is also an overwhelming evidence that the time of occurrence of glaciations are triggered by small periodic changes in the earth's orbit around the sun (Milankovitch orbital parameters) resulting in variations in the solar radiation reaching earth. Since these periodic changes are possible to calculate for the future, also predictions of future glaciations can be made.

The present scenario, even if reality turns out to deviate from the basic forecasts, aims to provide examples of basically realistic developments, serving as illustrations of what may be expected. It should, however, be noted that these forecasts are made without consideration of human effects on the climate. Based on the output from the ACLIN and the Imbrie & Imbrie models and known conditions during a glaciation cycle /16-5, 6/ reference scenarios have been selected in terms of iceloads, sealevels, hydrogeology etc. The maximum extensions of postulated future ice sheets are shown in Figure 16-2.

16.3.2 Modelling of the Rock Mass Response to Glaciation

The objective of a study conducted during 1990 was to illustrate quantitatively possible rock mass deformations due to glaciations with special emphasis on a future repository located at Finnsjön /16-7/.

Six rock mechanics models of a cross section of the Finnsjön test site were simulated by means of distinct element analysis and the computer code UDEC. The rock mass response to glaciation, deglaciation, isostatic movements and water pressure from an ice lake has been simulated.

Simulation of isostatic movements in combination with ice loading and melting gave several interesting results. Stress discontinuities and displacements appear at the major already existing fracture zones. Maximum displacements are in the order of 10-30 cm.

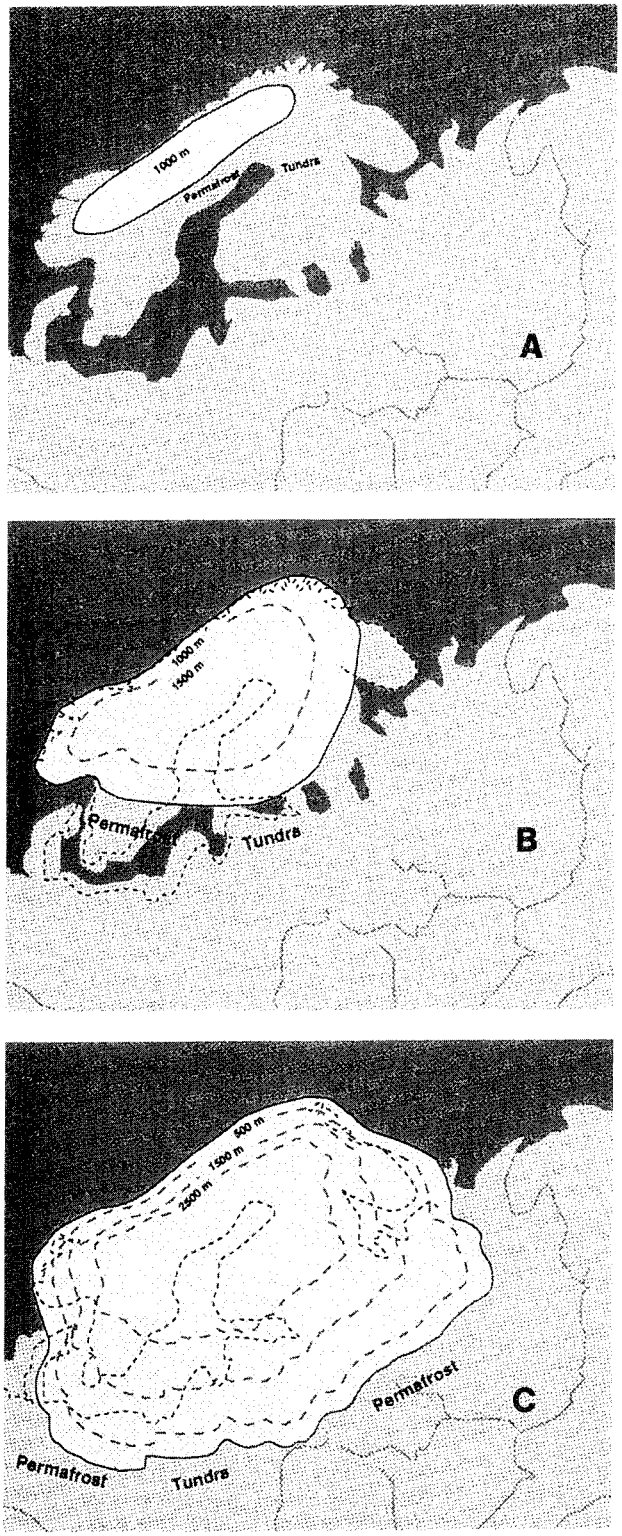


Figure 16-2. *SKB/TVO scenario. Illustration of the stadial periods.*
A=glacial conditions within the next 5000 years,
B= conditions around 20 000 years from now and
C= glaciation around 60 000 years from now. Estimates in changes of shoreline are highly speculative.

16.4 POST-GLACIAL STUDIES IN THE LANSJÄRV AREA IN NORTHERN SWEDEN

Post-glacial faults have been recognized in the northern Baltic shield for several decades. 1986 SKB initiated an interdisciplinary study of the post-glacial faults in the Lansjärv area. 1989 the results gained during the period 1986-88 were presented in an internal report.

In summer 1990 complementary investigations were concentrated to the Molberget locality, where a 4 m high veritical bedrock scarp earlier had been localized, see Figure 16-3. The main aim of the 1990 study was to make detailed investigations of the bedrock along two excavated trenches, across the fault scarp concerning petrology, structural features and fracture infillings /16-8/.

Three cored coreholes which cut the fault at different depths complemented the surface study. To control the strain distribution and displacements in the fault zone Sliding Micrometers have been installed in two percussion boreholes.

Complementary excavations in the Lansjärv area have been made during the summer 1990, in order to study seismically induced disturbances of the primary structures of Quaternary deposits.

In June 1991 SKB plan to arrange an excursion to the Lansjärv area in order to present and review the results of the project.

16.5 REPOSITORY SITING - GEOLOGICAL OVERVIEW

In preparation for the siting process a study is going on which aims to structure and summarize data and results from the already investigated study sites. The uncertainties of field data and models used will be described as well as the need for supplementary works. During 1990 the results from Fjällveden, Gideå and Sternö study sites have been compiled.

A methodology study regarding characterization of rock under the sea-bottom has been initialized during 1990. The aim is to analyse whether suitable rock blocks may be localized by means of bottom topography conditions in connection with geophysical results from airborne magnetic and seismic data.

16.6 DEVELOPMENT OF INSTRUMENTS AND METHODS

Regarding developments of instruments and methods, a number of activities has been ongoing, initiated or finished during 1990. Activities which directly relates to the

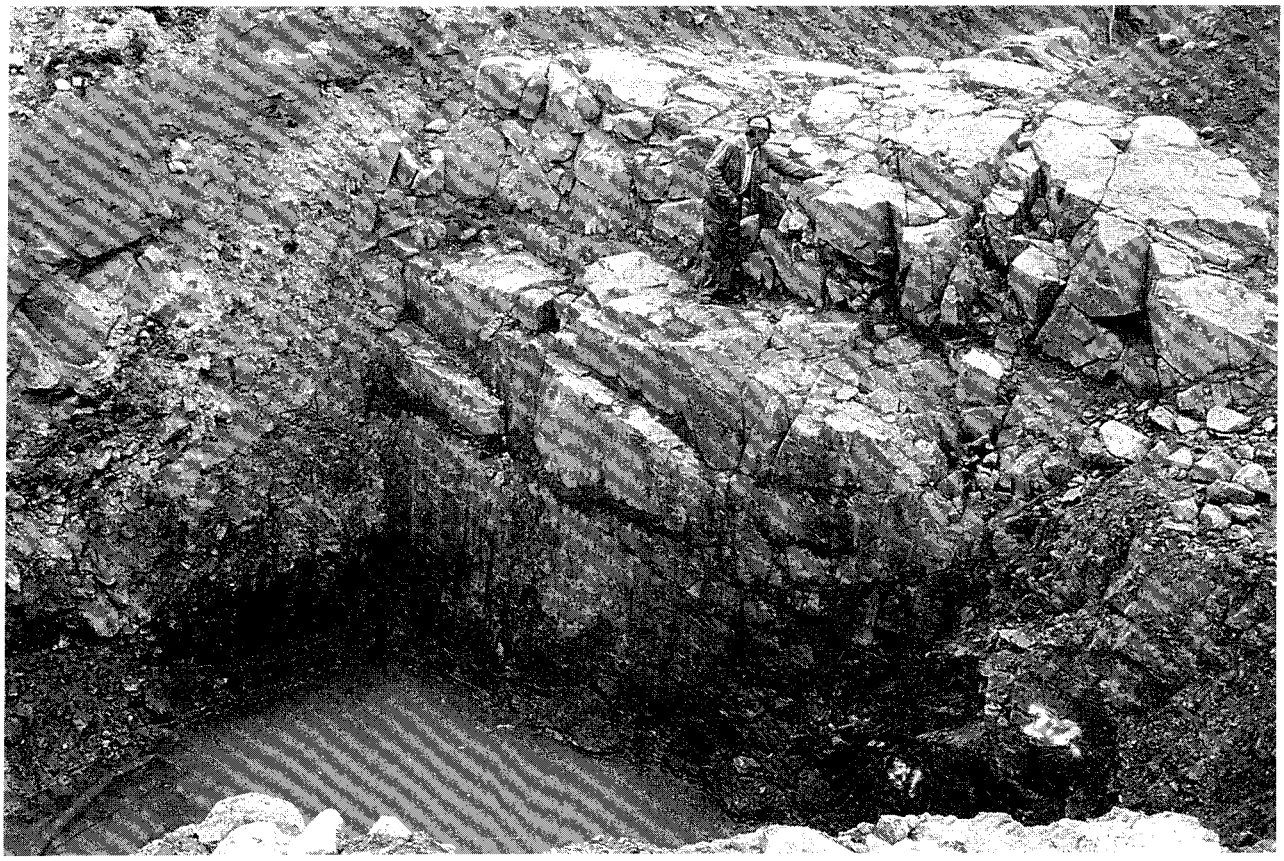


Fig. 16-3. Detailed investigations of the scarp at the Molberget locality, Lansjärv

Äspö Hard Rock Laboratory are described in section 19.5.4 of this report.

Radar technique

The directional borehole antenna for the radar system was in late 1989 improved for production measurements. The use of the directional antenna measurements, however, was not fully practiced until the package of interpretation software for this antenna was developed in early 1990. The very powerful software will, based on the collected radar-data, create radar reflectograms for any direction from the borehole. The operator will among these pictures determine the direction to a reflector by identifying the strenght of the reflector.

The development of the combined antenna for use at the ground surface and from tunnels or underground space was completed by the end of 1990. The project, which was funded by SKB and PNC in cooperation, have improved the radar system to be a very flexible system to be used in a wide area of applications.

Borehole-TV

The development of a new borehole TV-camera was finished during 1990. The borehole-TV, which can be used down to 1000 m depth in 56 mm boreholes was constructed around a CCD-camera device. The borehole-TV probe includes sufficient lighting and electronics for conversion of videosignals to optosignals, as which the "borehole-movie" will be transferred to surface and then reconverted to videomedia.

Flow-meter probe

The flow-meter logging method has in the Äspö Hard Rock Laboratory project been used in combination with pumping, in order to identify and characterize the water conducting structures in a borehole. In order to improve the measuring technique, by means of increasing the measuring range in the low velocity region, a new flow-meter probe has been developed. This new flow-meter probe is based on ultrasonic measuring principle. The prototype of the instrument has been used for test measurements, but still some minor modifications have to be done.

Ground water sampling pump

A new ground water sampling pump has been developed, primarily for use in conjunction with the Mobile Field Laboratory for hydrochemical investigations. The pump is operated by electricity, supplied from the surface, and can replace the hydraulically operated piston pump in cases when pressure draw down is not too large. To compare with the former piston pump the new pump is easier to operate and has higher flow capacity but on the other hand the head capacity is lower. The pump operates in 56 mm boreholes to a depth of 1000 m.

Drilling technique

In order to reduce the contamination of the formation water by drilling water and also reducing the entrance of cuttings into the fracture system an improved drilling technique, the "telescope drilling technique" has earlier been introduced (Annual Report 1987). In order to further reduce this contamination a field test of a reversed circulation coredrilling technique has been initiated. The project will continue during 1991.

17. CHEMISTRY

17.1 GEOCHEMISTRY

17.1.1 Quality Control and Database

Ever since the investigations of study sites for KBS-3 started in 1981 the groundwater chemical analyses have been checked by control analyses. When the complete set of data from a sampled section is available a judgement is made on which of these data are representative of the sampled section. The representative data are transferred to the GEOTAB database.

During 1990 this procedure for evaluation and storage of data has been changed in order to minimize the number of subroutines in the data handling. Only the data representative of the conditions prevailing in the sampling borehole section are stored in the data base. The data which have been sorted out are also stored. They are, however, not available directly through GEOTAB.

17.1.2 Groundwater chemistry

Sampling and analyses of deep groundwater at Äspö were completed in 1990. In order to classify the large amount of data, see Table /19-1/ a multivariat method called principal component analyses was used /17-1/. Four different classes could easily be differentiated, see Figure 17-1.

At Äspö the character changes from freshwater of Na, Ca-HCO_3 type at surface to a saline Na, Ca-Cl type water which at great depth (500 m) shifts to a Ca, Na-Cl type. Oxygen-18 data indicate that the Äspö groundwater has participated in a mixing process involving glacial water, marine water and present day freshwater. The complex mixing process is further supported by the tritium and carbon-14 data, which indicate proportions of very old and very young water. A complete evaluation of the groundwater chemistry of Äspö will be completed during 1991.

17.1.3 Fracture mineralogy

A reference borehole, KLX01, is located about one kilometer west of Äspö on the main land. Groundwater sampled in this borehole has the same character as in the Äspö boreholes. Calcites sampled in the fractures from the drillcore of KLX01 have been analysed for carbon-13 and oxygen-18 /17-2/. The interpretation of these data support the interpretation of the chemistry data of Äspö. A com-

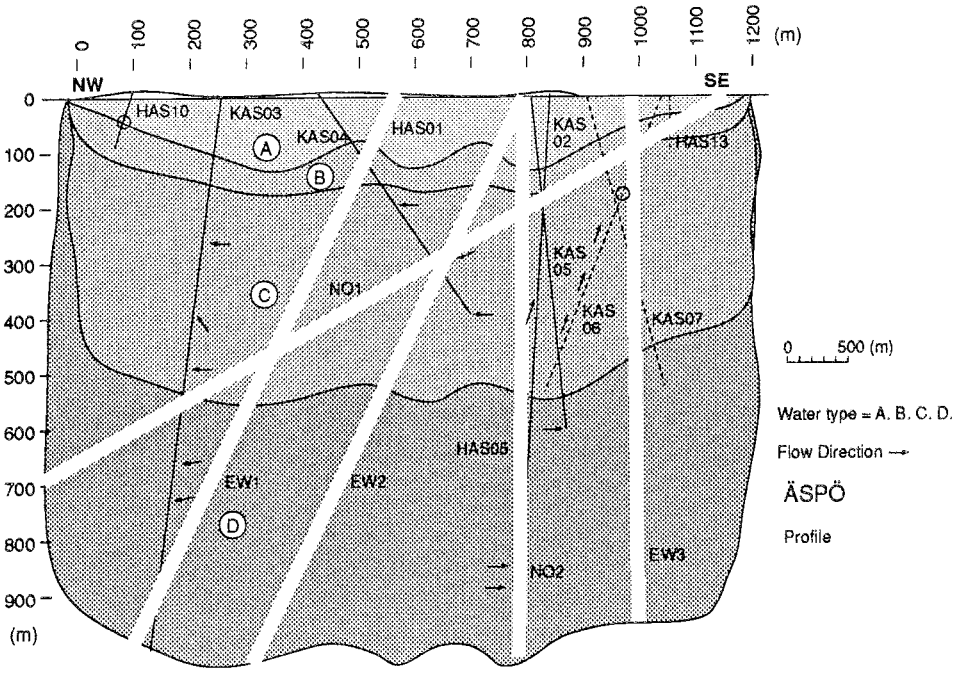


Figure 17-1. Distribution of different groundwater classes on Äspö.
A = freshwater.
B = mixed fresh and saline water.
C = Na-Ca, Cl type saline water.
D = Ca-Na, Cl type saline water.

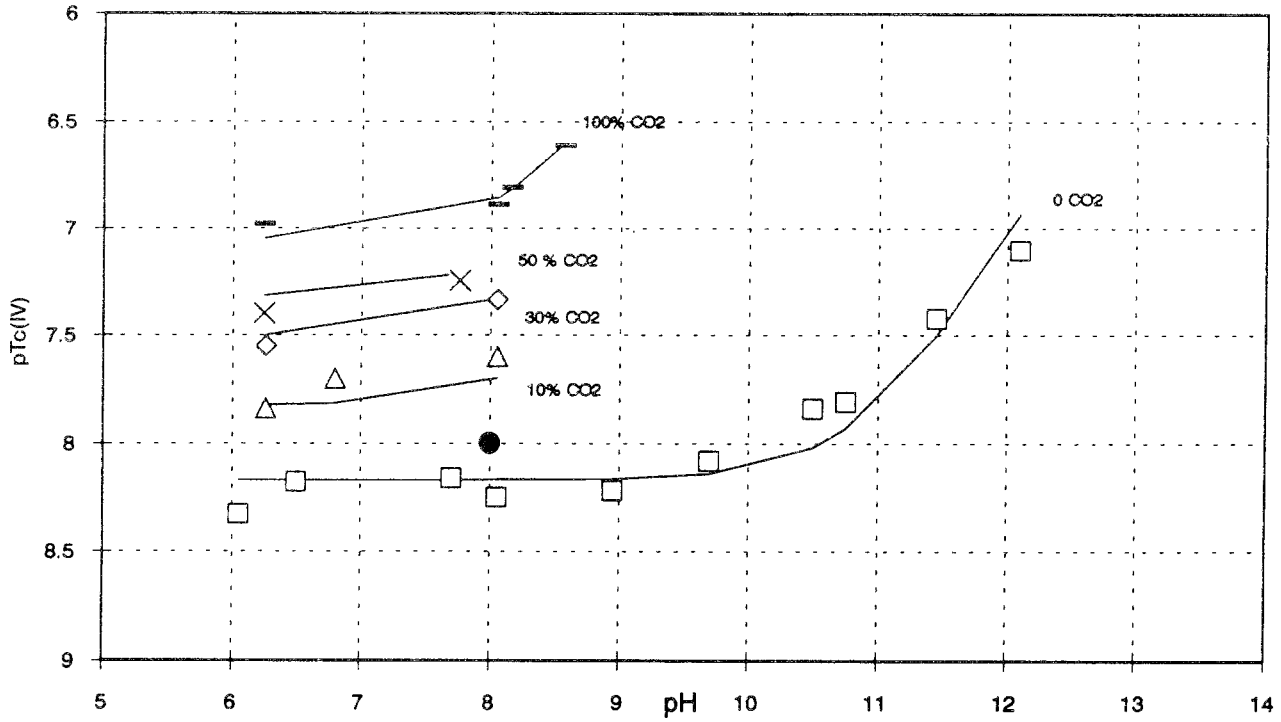


Figure 17-2. Measured (symbols) and fitted (lines) data of technetium solubility in carbonate containing solution. Ambient groundwater conditions are marked with a dot.

plex mixing process between marine water, glacial water, meteoric water and possibly also hydrothermal water has given the carbon and oxygen isotope pattern of the calcites. Also biogenic CO_2 production is possible.

From three different fracture zones at Klipperås both groundwater and fracture minerals have been sampled and analysed for uranium, thorium and rare earth elements /17-3/. The distribution factors, Kd, are calculated from their concentration in solid phase and solution. The resulting in situ Kd values are two to three orders of magnitude higher than the corresponding values of the laboratory measurements, except for uranium which are similar. A similar study is presently made on fracture minerals and water chemistry of Äspö.

17.2 RADIONUCLIDE CHEMISTRY

17.2.1 Solubility and speciation

Laboratory experiments are being performed in order to obtain reliable data on thermodynamic constants needed to predict solubility and speciation of radionuclides in groundwater. The investigations are concentrated on elements such as uranium, plutonium, neptunium, americium, thorium and technetium which are important for safety assessment and sensitive to geochemical conditions. SKB supported work on uranium reduction /17-4/ and on the formation of carbonate complexes with uranium /17-5/ and thorium /17-6/ have been presented as a PhD thesis by Bo Lagerman /17-7/.

In cooperation with the Ispra laboratory in Varese, Italy, thermal lensing spectroscopy has been used for studies or uranium(VI) carbonate species /17-8/.

The solubility of Tc(IV) in carbonate containing solution has been investigated, see Figure 17-2. Hydroxy carbonate complexes with technetium have been identified.

The solvent extraction technique AKUFVE-LISOL is used to measure the hydrolysis complexes of actinides

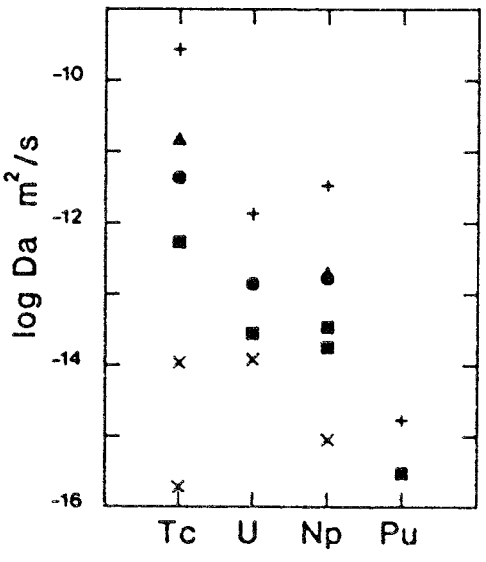


Figure 17-3. Summary of the apparent diffusivities, D_a, in compacted bentonite with addition of: 1 % Fe (x), 1 % FeO (■), 1 % Cu (●), 1 % CuO (▲); 10 % bentonite and 90 % sand (+).

/17-9/. Pre-tests have been accomplished with thulium-(III) as a model ion /17-10/.

SKB is supporting participation of Swedish experts in the international OECD/NEA project TDB to compile and evaluate databases of thermodynamic constants for uranium, plutonium, americium and technetium. SKB is also participating in the CHEMVAL project organized by CEC with the aim to validate geochemical codes used. Codes and databases for radionuclide solubility and speciation are also validated as a part of the natural analogue study projects, see Chapter 20.

17.2.2 Organic complexes, colloids and microbes

Investigations of quantities, chemical character and complex forming properties of humic substances in groundwater have been reported /17-11, 12 and 13/. Different techniques for studying metal-humate interactions have been tested such as ultra filtration /17-14/ and laser induced fluorescense /17-15/. The laser technique was applied to complexes between lanthanides and fulvic acids /17-15/.

Particles and colloids are being collected by filtration during groundwater sampling. The quantities and composition are analysed. Content and composition of colloids vary with depth. Calcite particles dominate in deep samples. Less abundant but also represented are iron hydroxides, gibbsite, iron sulphides and quartz.

Experiments are being performed with colloid carried radionuclide migration. This is partly done in cooperation with Oak Ridge National Laboratory and Los Alamos National Laboratory in USA.

Analyses of microbial content of deep groundwater have continued /17-16/. A sampling device, constructed for downhole sampling of water in packed off sections, have been used in boreholes in Ävrö, Äspö and Laxemar. A total of 17 sections in five boreholes have been sampled. The deepest samples were taken below 800 m. The presence of methanogenic and sulphate reducing bacteria have been indicated. This is compatible with the geochemical environment at depth where methane, hydrogen, carbon dioxide, sulphide and sulphate are present.

Experiments have been reported on the uptake of promethium on Shewanella bacteria /17-17/. The lanthanide promethium and the bacteria were selected as a model system. Reversibility of sorption and strong dependence on pH were demonstrated. The sorption of threevalent prometium on the bacteria decreased at pH above 7.

17.2.3 Sorption and diffusion

The surface complexation model is being tested as a way to calculate the uptake of radionuclides on mineral surfaces. Prepared pure goethite have been used in the experiments.

Diffusion experiments have been reported where bentonite with additives have been tested as barriers to radionuclide transport. /17-18/. These additives, also referred to as "getters", have consisted of iron, copper, iron(II) oxide, copper(I) oxide, vivianite (iron(II) phosphate), magnetite and iron minerals occurring as rock fracture fillings (mainly epidot and chlorite). The diffusivity of the actinides uranium, plutonium, neptunium and the fission product technetium was measured in bentonite samples with different "getters". The experiments were performed in an inert atmosphere. The results indicate the reduction of neptunium, uranium and technetium to lower less mobile oxidation states by iron and iron(II) oxide. The diffusivity is thereby diminished by several orders of magnitude, see Figure 17-3. For plutonium the diffusion was immeasurably slow; less than 3.10^{-16} m^2/s. The addition of the minerals did not change the diffusion rate, at least not at concentrations of 1% of the minerals.

It is concluded that iron and copper as canister materials and their corrosion products will have a beneficial influence on the radionuclide retention. However, the value of adding the above tested substances as "getters" to the bentonite backfill is disputable. The effect on diffusion of the "getters" tested is not enough to retain long lived nuclide so that they decline considerably by radioactive decay inside the clay barrier. The only exception is iron powder in bentonite which effectively retains ^{99}Tc and to some extent ^{237}Np. Any additive considered seriously for application will have to be tested for its long time effect on the chemical and physical properties of bentonite. The risk of any adverse effect on the bentonite may possibly be lowered by having two successive layers of clay, one with and one without "getters".

Long time diffusion experiments with radionuclides in concrete have been performed. The results are being evaluated.

17.3 VALIDATION OF TRANSPORT MODELS

The present concepts of water flow and transport in fractured rock with applications to radionuclide waste repositories have been summarized /17-19/. The data needs of the models are described and the use of information from laboratory experiments and large scale in situ tracer tests. Among the field investigations referred to are the Stripa 2D and 3D experiments, the diffusion experiment in Stripa, the Chalk river experiments and the Fannay Augère investigation. The laboratory experiments with drillcores containing natural open fractures are also referred to in the study. The importance of matrix diffusion and channeling of flow for the transport of dissolved radionuclides is pointed out /17-19/.

The laboratory experiments with overcored fractures have continued through 1991. Migration of redox sensitive radionuclides and flow conditions in the rock fractures are being tested.

17.3.1 Tracer experiments at Finnsjön

The dipole tracer experiment, the last one of the activities within the Finnsjön fracture zone project, has been reported /17-20/. The 19 injected tracers resulted in more than 50 breakthrough curves. Qualitative interpretation and calculations of tracer recovery and loss have been made.

Within the phase two of the INTRAVAL project the Finnsjön tracer experiments are one of the remaining test cases. Material for modelling has been compiled and presented at the INTRAVAL workshops.

At the GEOVAL symposium in Stockholm in May the radially convergent tracer test and the dipole tracer experiments were presented /17-20/. The emphasis was put on the modelling of the two tracer experiments and the hydraulic pumping tests.

17.3.2 Tracer tests at Äspö

Within the geohydrological investigation programme of Äspö a long term pumping test was conducted in 1989. During autumn 1990 the pumping test was repeated with the purpose of defining the major flow paths intersecting the pumping hole and the surrounding boreholes. Short-lived radioactive isotopes were used as tracers. The half-life ranged from four to fifty days.

Tracers were injected into totally six different borehole sections. A breakthrough was only observed for tracers coming from two of these sections. The evaluation of the tracer test will be made during 1991.

18. THE INTERNATIONAL STRIPA PROJECT

18.1 INTRODUCTION

The International Stripa Project is being performed under the sponsorship of the OECD Nuclear Energy Agency (NEA). The management is entrusted to the Swedish Nuclear Fuel and Waste Management Company (SKB). The project is now at the end of its third phase (Phase 3) where seven countries - Canada, Finland, Japan, Sweden, Switzerland and the United States - are participating. The research activities in Phase 3 are carried out under two headings:

— Fracture Flow and Nuclide Transport with Site Characterization and Validation (SCV) as the major subproject. The SCV-study is focussed on validating the diagnosticity of techniques and approaches, developed for and used, in site characterization. In close relation to the SCV-study are the developments of high resolution and directional radar antennas, improved techniques for high resolution borehole seismic measurements and, fracture network modelling.

— Groundwater Flow Path Sealing where the principal objective is to identify suitable grouts and grouting techniques for the long-term sealing of groundwater flow paths in the Stripa granite.

18.2 SITE CHARACTERIZATION AND VALIDATION

18.2.1 Introduction

The Site Characterization and Validation (SCV) Project focusses on the problem of validating the correctness of

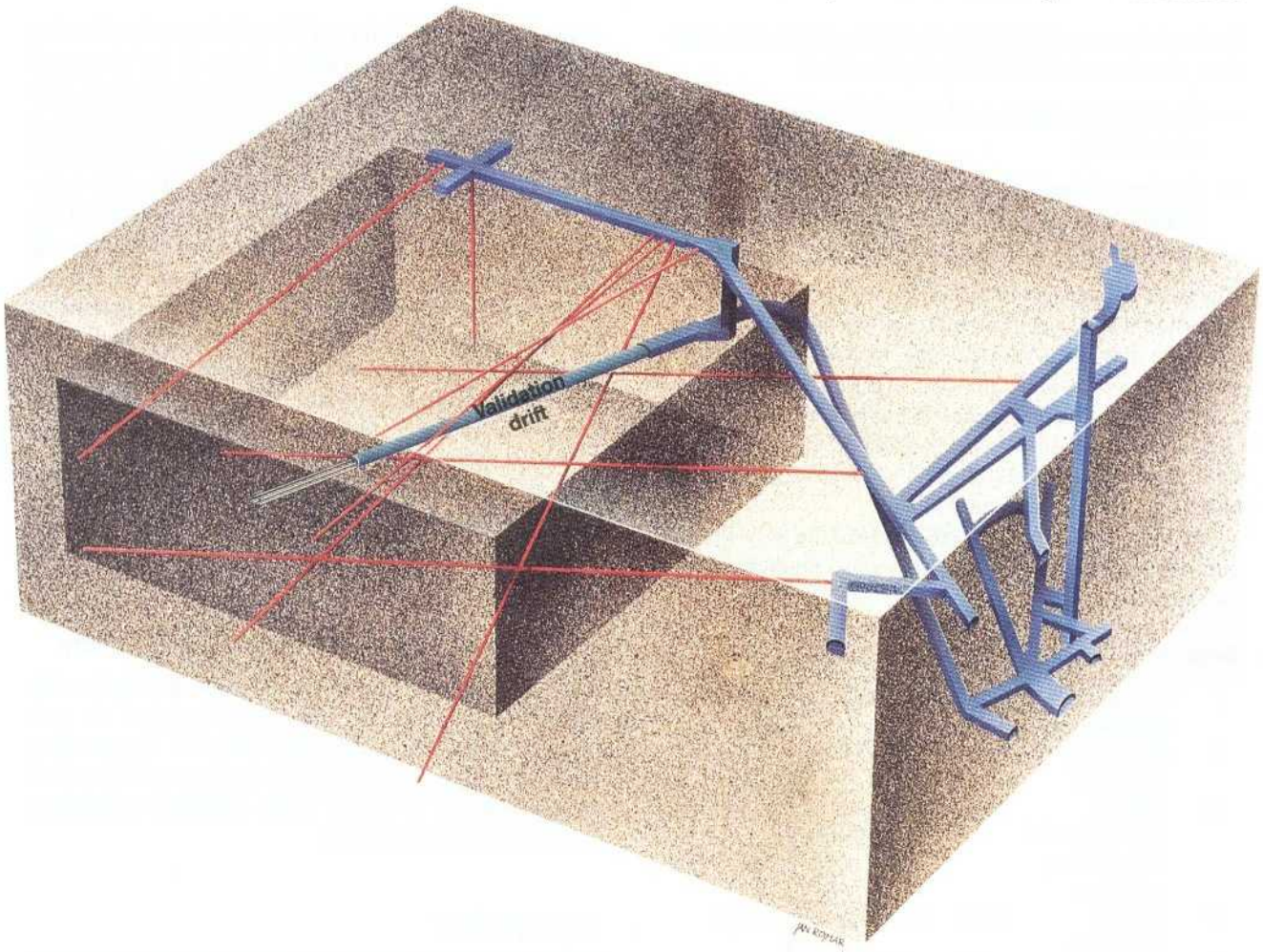


Figure 18-1. *Isometric view of the SCV block including boreholes for site investigations.*

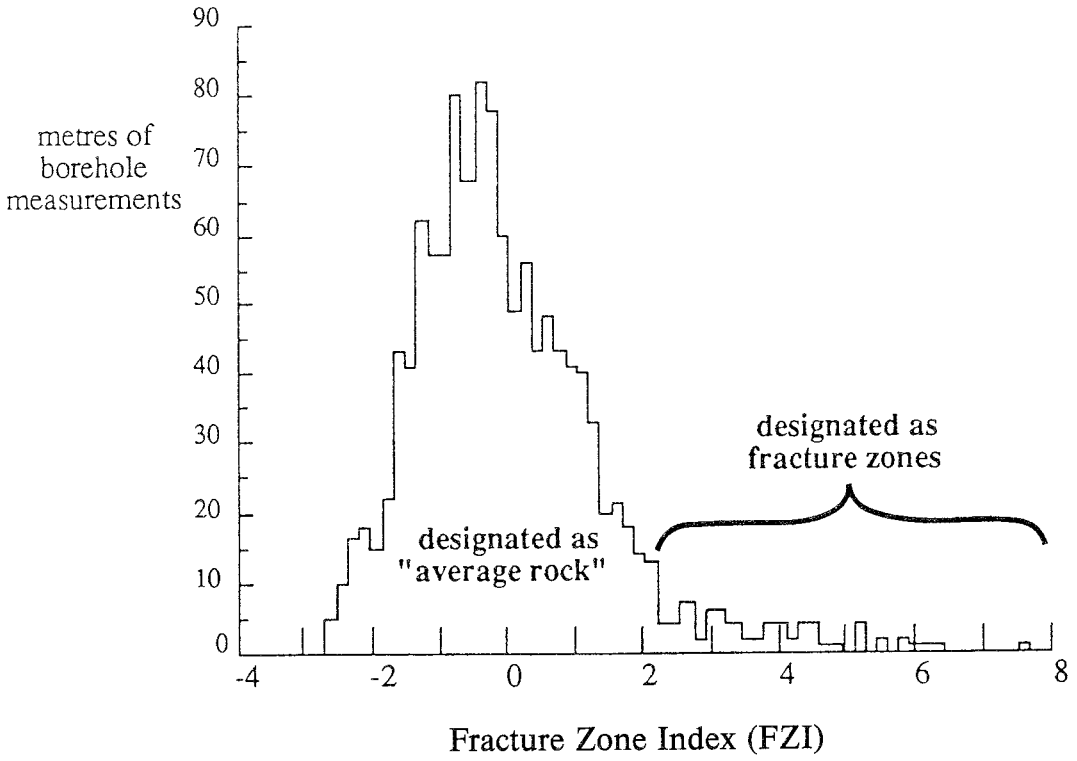


Figure 18-2. *Frequency distribution of "fracture zone index" based on all boreholes at the SCV-site.*

the techniques and approaches used in site characterization. The central aims of the program are to:

— develop and apply an advanced site characterization methodology

— develop and apply a methodology to validate that the models (both conceptual and numerical) are appropriate to the processes under examination

The basic experiment of the SCV Project is to predict the distribution of water flow into a potential drift (tunnel), excavate the drift, measure the inflows and compare measurements with prediction. In support of the basic experiment there are a number of subsidiary experiments such as an assessment of channeling, the small scale hydrogeological effects of drift excavation, and tracer tests associated with fracture zones.

The five year program (1986-1991) of the SCV Project contains two cycles of data gathering, prediction, and validation as follows:

Stage	Title of stage	Period	Type of work	Cycle
I	Preliminary site characterization	86-88	data gathering	first
II	Preliminary prediction	87-88	prediction	first
III	Detailed characterization & preliminary validation	88-89	validation/ data gathering	second
IV	Detailed predictions	89-90	prediction	second
V	Detailed evaluation	90-91	validation	second

Stage I comprised drilling of 5 boreholes and performing investigations in them. During Stage II the data were analyzed and a conceptual model of the site devised. This model was the basis for preliminary numerical predictions of the groundwater inflow to a set of boreholes (the D-boreholes) outlining the Validation Drift to be excavated during Stage V. During Stage III a number of boreholes were drilled in the central portion of the site and investigations made in them to provide data for detailed predictions of inflow to the drift and for validation of inflow predictions to the D-boreholes. Stage IV comprised an update of the conceptual model based on the additional data available and compilation of data needed for the numerical predictions of the inflow distribution into the Validation Drift.

Stage IV was completed during 1990 and Stage V is currently in progress. Figure 18-1 shows an overview of the SCV-site.

18.2.2 Conceptual Model of the SCV-site

As to enable the prediction of the inflow distribution into the Validation Drift, the conceptual model of the rock volume has been updated during Stage IV. The resulting model is briefly described below in terms of Major Features, Properties of Joints, Stress Boundary Conditions and Disturbed Zone Effects.

Major Features

During the course of the SCV Project it has been assumed that a binary representation of the rock mass as "major

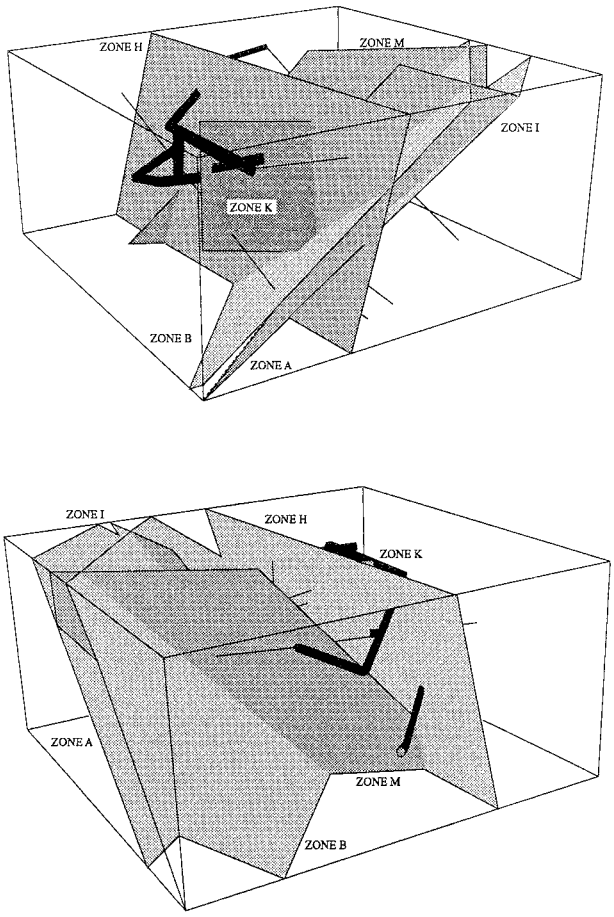


Figure 18-3. *SCV-site: The location of major features of the conceptual model in 3D space.*

features" (considered to be fracture zones) and "background rock" (or averagely fractured rock) is justified. The underlying assumption is that the "major features" should account for significant fractions of the flow across the site.

Based on principal component analysis of the results from sonic and resistivity logging, hydraulic conductivity, radar and open fracture measurements, a "fracture zone index" (FZI) has been constructed. The frequency distribution of the "fracture zone index" (FZI) values for all boreholes shows a skewed distribution, see Figure 18-2.

The conceptual model of the SCV-site contains three major features or fracture zones named A, B, and H. These features are considered to extend beyond the limits of the SCV-site. Features A and B are thought to be parts of the major feature which can be observed as a 3 km long morphological lineament on the surface. H is also considered to extend to the surface where it has an extent of about 1 km. The connection between the SCV-site and the surface provided by these features is thought to cause the high heads observed at the SCV-site. These major features are important for the groundwater flow system across the SCV-site in that they account for 75 % of the hydraulic transmissivity as measured by single hole hydraulic tests.

At the borehole intersections the features generally exhibit anomalous properties compared to "background rock". This is demonstrated by the fracture zone index which has an average of approximately 2.5 for these zones. Fracture zone index anomalies are generally smaller in the southern part of the site and larger towards the north. The borehole with the largest anomalies is W2 which is probably caused by the proximity of W2 to the intersections of A, B, and H.

Three minor features named I, K, and M with an extent of 50-100 m have also been identified. Though the associated fracture zone index anomalies are close to or just below 2, they have been included in the conceptual model. The reason is that they provide hydraulic connections between the major features A, B, and H. These minor features account for 4 % of the single hole hydraulic transmissivity measured in the boreholes.

The perspective view of the features is shown in Figure 18-3.

The consistency of the model and its relevance for groundwater flow through the site have been tested by crosshole hydraulic tests. The test results support the conceptual model which thus is concluded to give a realistic representation of the flow system at the SCV-site. The features identified provide the major pathways for groundwater flow. These features act as "leaky aquifers" linked to the background rock by minor zones and joints.

Properties of Joints

The conceptual model of the SCV-site, in addition to the major features, also includes the description of orientation, spacing, trace lengths, and hydraulic properties of individual joints. This description is by virtue of the large number of fractures or joints stochastic.

From earlier work two strong sub-vertical fracture clusters and one weaker sub-horizontal group or cluster have been identified. As the results, however, are biased by oversampling in the horizontal direction it is not evident if a strong sub-horizontal fracture system exists at the SCV site or not. Hence, for numerical modelling purposes, a larger number of clusters than the three or four indicated by the scanline data, may have to be accepted. The fracture trace length and spacing statistics show that the fracture intensity increases towards the northwest corner of the SCV site and that the North-South striking fracture set has a much higher density than the other sets or clusters.

The scanline fracture data were analyzed with respect to fracture mineralogy and termination mode. Epidote as primary coating or filling material in fractures is associated with the steeply dipping, north-south trending fracture set. Calcite is associated with the steeply dipping, northwest-southeast trending set, whereas fractures with chlorite as the primary coating or filling mineral is associated with all orientations.

Analysis of fracture terminations may give indications on the relative ages of the fracture sets.

The overall fracture characterization program in the Stripa project also included several interrelated fracture testing programs. Their principal aims were; to provide data for predicting or calculating the stress-permeability relationships for the different fracture sets, to provide stress versus permeability relationships for calibration of empirical stress flow models, and to determine the

coupled stress-flow behavior of a 1.4 m long section of a fracture plane in order to determine its in situ behavior and assess the effects of sample size on the stress-permeability relationships.

The studies and tests showed significant decreases of permeability with increase in stress. The experimental program showed a major difference between hydraulic and mechanical apertures, indicating that fracture porosities are much greater and fluid velocities are much slower than those predicted using flow and head measurements. The fracture planes tested also showed that the permeability tended to decrease slightly for small shear displacements, becoming dilatant at low normal stresses only after undergoing 0.1 mm or more of shear displacement.

Stress Boundary Conditions

The stress tensor presented by McKinnon and Carr (1990), as shown in Table 18-1, was used to provide the boundary conditions for the 3-D stress modeling of the SCV site.

Table 18-1. Interpreted virgin stress tensor for SCV block.

Principal Stress	Orientation (bearing/dip)	Magnitude by depth (MPa)
σ_1	105/00	7,5 + 0,044*D
σ_2	195/00	2,5 + 0,035*D
σ_3	Vertical	0,0 + 0,026*D

— D is depth below surface in meters
— dip is positive down
— bearing is positive clockwise from mine north

The 3-D numerical modelling was carried out by McKinnon and Carr (1990) in two stages in order to: a) determine the influence of the mine excavations on the stress field in the SCV block, and b) to examine in detail the state of stress around the Validation Drift, particularly at the locations of the fracture zones and in selected planes oriented perpendicular and parallel to the drift.

The 3-D stress modelling results suggested that the mine excavations have no effect on the stresses around the Validation Drift. Hence, only the drift itself was included in the model used to determine the effect of drift excavation on rock stresses near the Validation Drift. In addition to the generalized components of the stress tensor, the principal components of the stress tensor and their direction cosines were computed for six planes that were oriented perpendicular to the Validation Drift and for two orthogonal planes coaxial with the drift at the western end of the drift in order to examine stress concentrations near the end of the drift.

Because of the complexity of representing stress in three dimensions visually, contours of the stress difference (σ_{max}-σ_{min}) has been plotted for each plane. The contour intervals are in MPa. These plots show the important zone of stress concentration at the west end of the Validation Drift and the very high stresses at the top and bottom of the drift. The location of these zones of high stresses is controlled by the high horizontal stresses and high stress ratios. Figure 18-4 shows the general pattern of stress differences on a vertical plane, perpendicular to the drift, that is located approximately in the middle of the drift.

Disturbed zone effects

In addition to the 3-D continuum stress modelling, 2-D discrete fracture stress modelling was made using the UDEC (Universal Distinct Element Code) model. The initial purpose of this 2-D, discrete fracture, stress modelling was to determine if the rock-mass relaxation around the Validation drift, produces a stress distribution that was significantly different from that generated using the 3-D continuum stress model.

As a result of the numerical drift excavation, a variety of changes in the joint apertures occurred, some closing, others opening, some shearing and suffering dilation thereby potentially creating more openness. The stress redistribution, deformation, joint shearing and conducting apertures obtained from one of the models are shown in Figure 18-5.

Excavation induced deformations shown in Figure 18-6 showed maxima of 1.0 to 1.6 mm. Drift closures were therefore generally limited to 2 to 3 mm. The continuum result is, as expected, considerably different from the discontinuum results.

18.2.3 Detailed Evaluation - Stage V

Excavation of the drift

The excavation of the Validation Drift started in November 1989 and was completed before the end of January

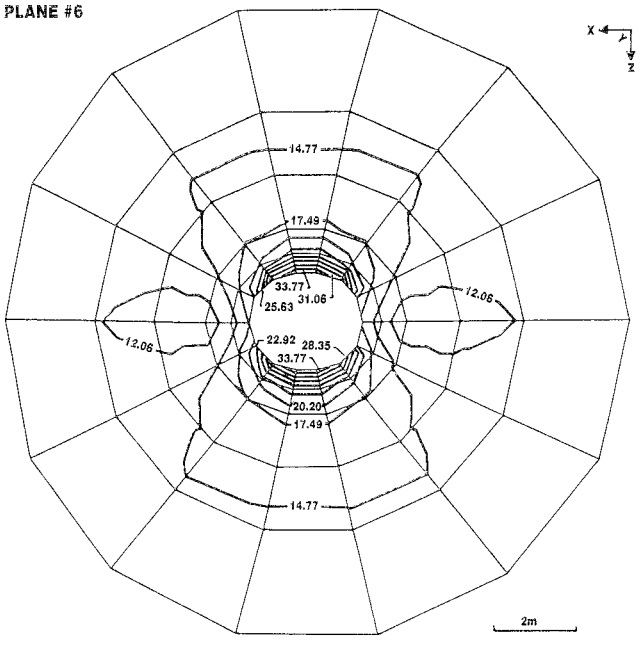


Figure 18-4. Validation drift: Stress difference contours in MPa for a plane perpendicular to the drift axis located approximately in the middle of the drift.

1990. The total length of the excavated drift is 50 m. The drift was made 3 m wide and 2.4 m high. A smooth blasting procedure was successfully used for excavation of the drift. The approximate shape of the drift perimeter and length profile is shown in Figure 18-7.

After cleaning of the drift a grid system was painted on the drift walls. Each grid cell has a size of approximately 1 m^2. The circumference of the drift is approximately 9 m varying somewhat due to the drill and blast procedure used. Hence, there are 9 grid cells around the periphery of the drift and about 50 cells along the extent of the drift, making a total of about 450 grid cells.

Fracture characterization of the Validation Drift

The entire surface of the Validation drift was mapped using the 1 m^2 reference grid. Figur 18-8 shows the entire drift map and the mapping grid that were plotted using the digitized data.

A total of 914 fractures were mapped in the Validation drift. Figure 18-9, a lower hemisphere contour plot of poles to the fracture planes, shows four fracture sets. The most prominent fracture set is sub-vertical and strikes in a north-south direction. A weaker, sub-horizontal set trends NNE-SSW. The two other groups are poorly developed, striking NE-SW and NW-SE with dips that are sub-horizontal and subvertical, respectively. Figure 18-10, consisting of contour plots for individual sections of the drift, shows that there is significant variation in frac-

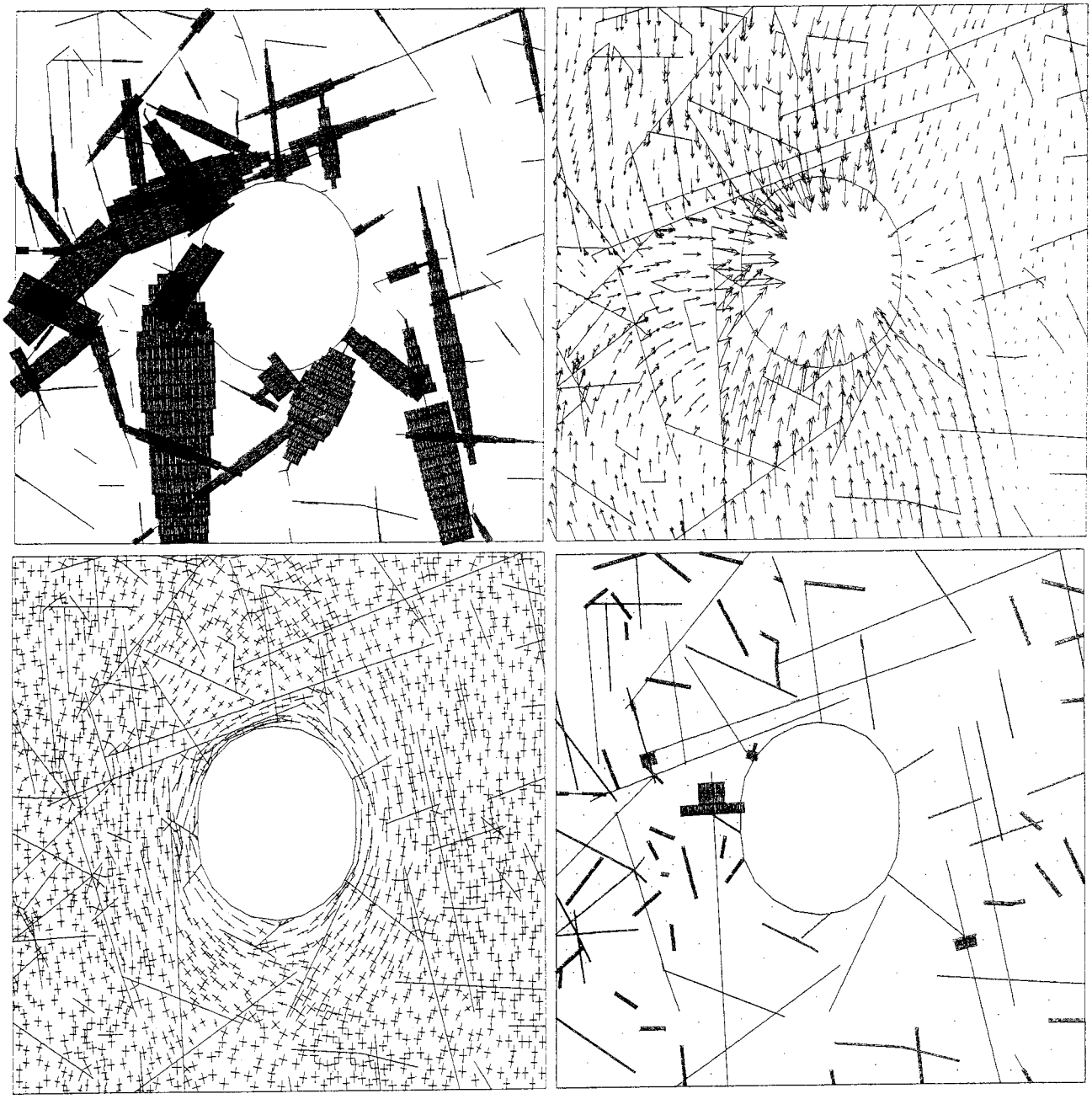


Figure 18-5. *Validation drift UDEC-BB model (no. 8) showing, in clockwize order; principal stresses (max. 61.9 MPa) joint shearing (max. 0.8 mm; 1 line = 10 μm) and in the lower two pictures major joint conducting fractures (max. 0.58 mm).*

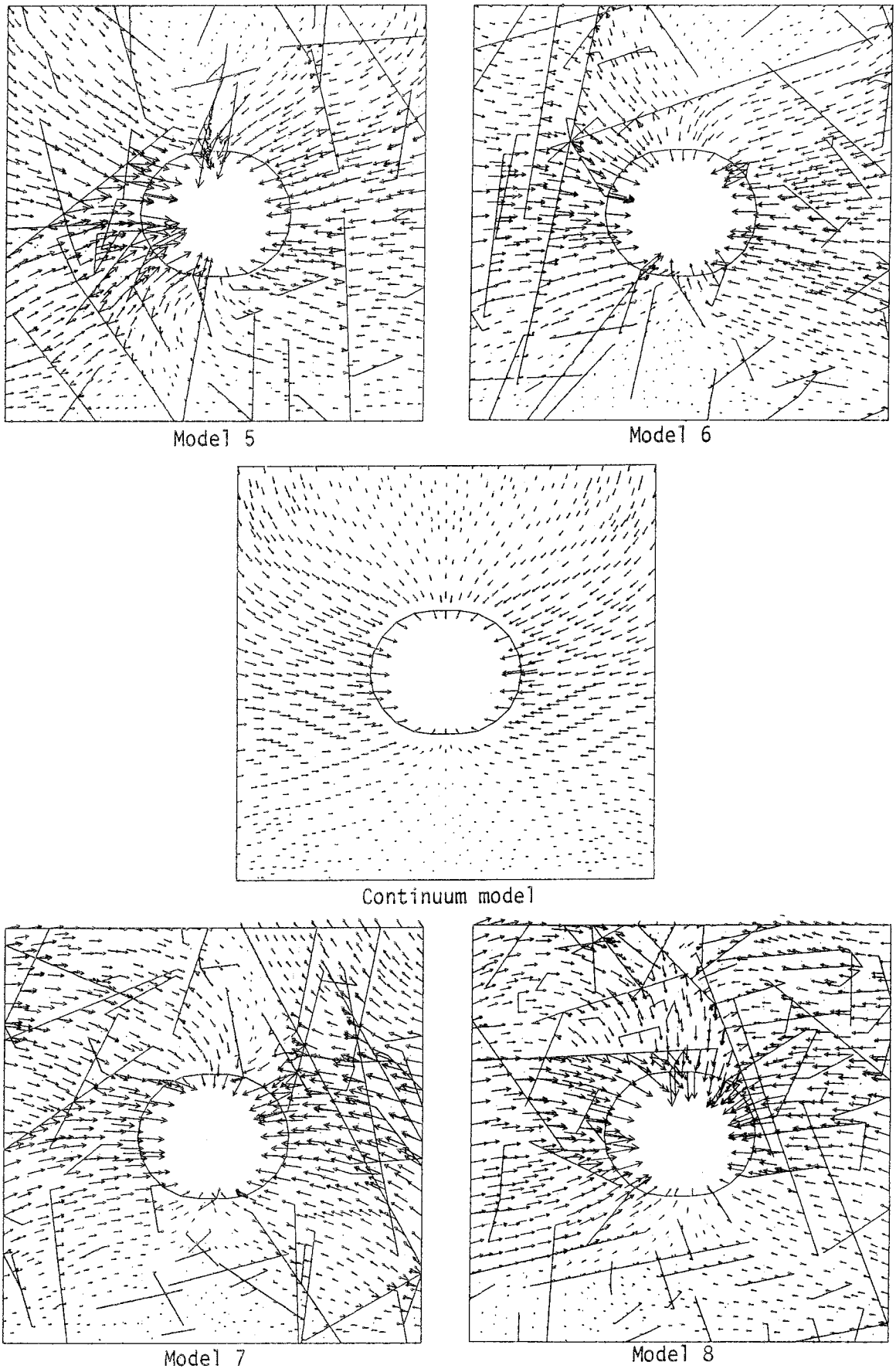


Figure 18-6. *Validation drift. Deformation vectors in the four jointed models compared with the continuum model. Maxima were 1.55, 1.03, 0.75, 1.18 and 1.32 mm.*

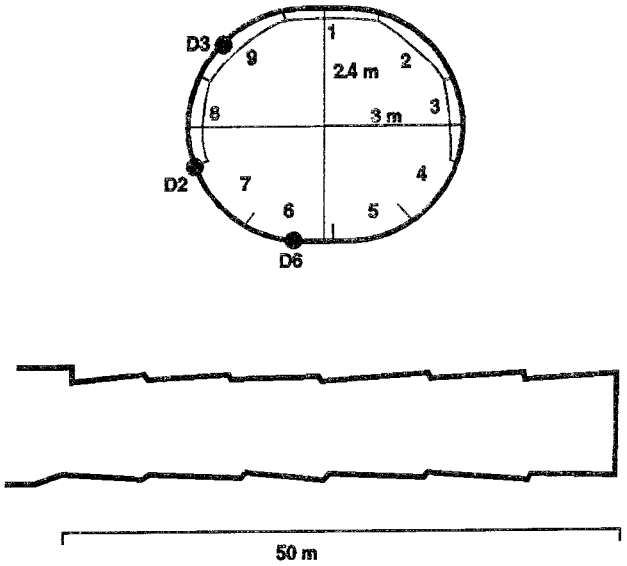


Figure 18-7. Approximate shape of the Validation Drift after excavation and division of perimeter into grid cells. Cells numbered 1, 2, 3, 8, and 9 are covered with plastic sheets.

ture orientations along the drift. This variability was not discernable in the fracture data from the D-boreholes.

Comparison of the fracture data from the Validation drift with the data from the Stage I and Stage III mapping efforts shows that similar groupings or sets of fractures can be found in all areas and each set or group has similar mean trace lengths and spacings in most areas. However, the orientation of a given set varies within the rock mass from area to area. Fracture orientations within the H fracture zone are similar to those mapped in the "good rock", but have different mean trace lengths and spacings. In general the orientation of large scale features tend to mimic mean orientations of the regular joint/fracture system. The converse is not necessarily true.

Water inflow measurements

The inflow of groundwater to the Validation Drift forms a focus for the Site Characterization and Validation Project. The inflows are due to be predicted by a series of numerical models based on measurements performed in Stages I and III and the conceptual model presented above.

A system for measurements of inflow to the Validation Drift was set up during 1990. The inflows are measured in a number of different ways based on location and inflow type. They are as follows:

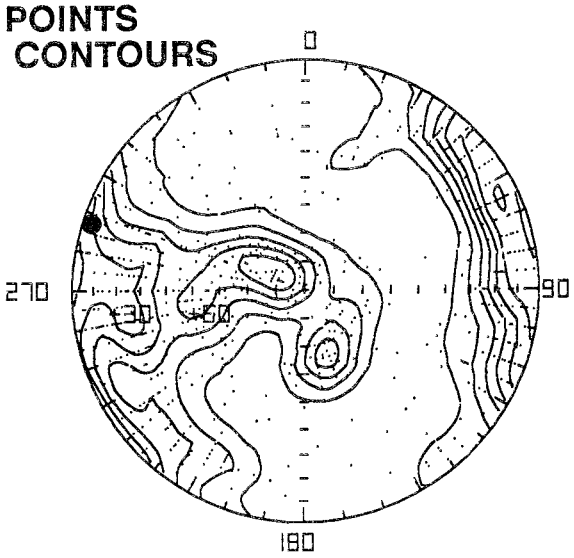


Figure 18-9. Contour plot of poles to fracture planes for all of the fractures mapped in the Validation Drift.

1 Flows into the upper part of the drift.

2 Flows into the lower part of the Validation Drift.

3 Evaporation from unsheeted areas.

4 Specific evaporation studies.

The distribution of flow into the plastic sheets and the sumps are summarized in Figure 18-11. The total flow into the sumps and plastic sheets is approximately 92.8 ml/min. This value has remained practically constant during the measurements. The amount of water transported by ventilation amounts to approximately 5 ml/min. This value is also fairly constant with time. The data are summarized in Table 18-2.

The numbers indicate a considerable reduction in the inflow to the drift compared to that of the boreholes. In this case the inflow to zone H is defined as the inflow to sheet rows 24 through 29. The reduction appears to be largest for the good rock. The reduction in the good rock has to be considered with some caution as the data on the "good rock" inflows from the SDE-experiment are not very reliable. For example, the distribution of inflow was

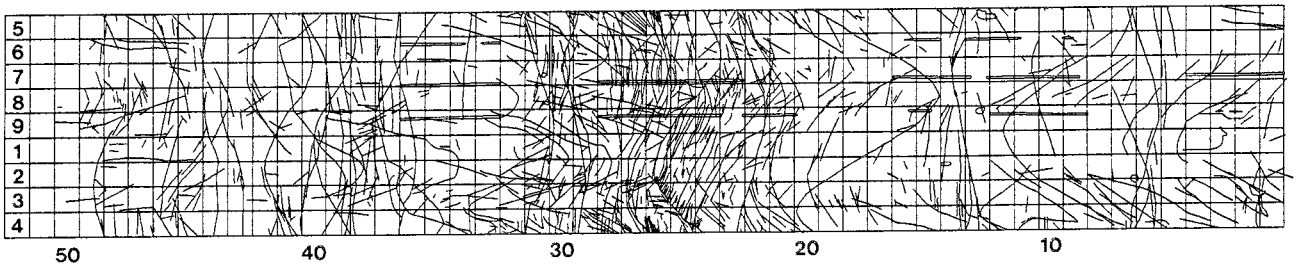


Figure 18-8. Plan view of the entire Validation Drift map. The map represents a surface that is approximately 9 meters in circumference and 50 meters long.

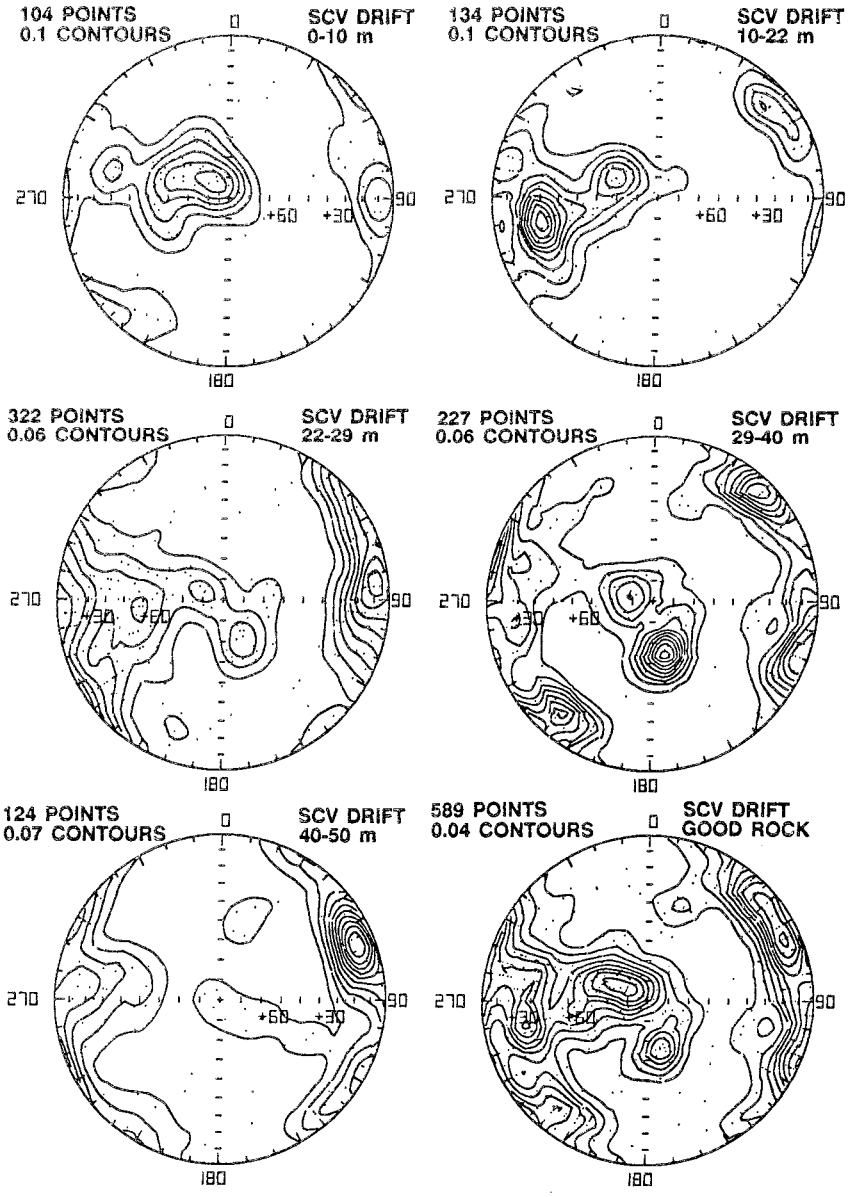


Figure 18-10. Contour plots of poles to fracture planes for individual sections of the Validation Drift.

not obtained and it is not possible to strictly define the division between zone H and the "good rock".

The evaporation measurements gave an estimate of the total inflow from the "good rock" of approximately 9 ml/min. The evaporation rate was highest in the inner part of the drift, between zone H and 50 m.

The spatial distribution of the measured evaporation rates are shown in Figure 18-12.

Radar/Saline Tracer Experiment

The objective of the radar/saline tracer experiment is to provide data on the geometry of flow paths from an injection point in fracture zone H. The flow paths have been monitored through radar difference tomography. In the first experiment saline tracer was injected in borehole C2 where it intersects zone H and the D-boreholes were used as a drain, see Figure 18-13. This first experiment was carried out in two phases. During the first phase the

Table 18-2. *Inflows to the Validation Drift (ml/min) based on data available 90-12-19.*

Source	Validation drift	SDE*-flow	Fraction drift/SDE
Sheets & sumps, zone H	92.8		
S & s, good rock	0.17		
Ventilation	5.0		
Total	*98.0*		
Zone H	92.8	650	14.3 %
Good rock	5.2	190	2.6 %
Total	*98.0*	*830*	*11.8 %*

* Simulated Drift Experiment

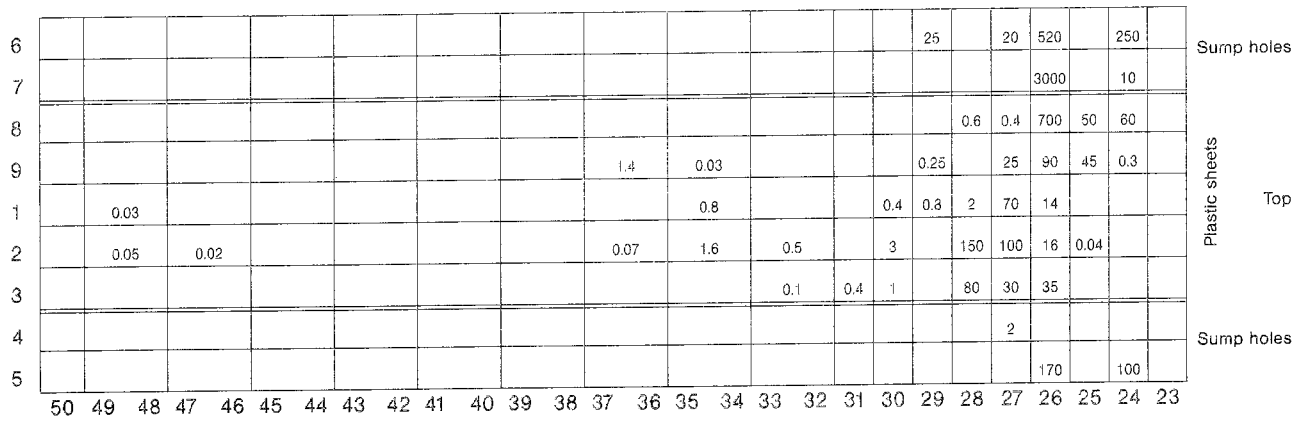


Figure 18-11. *Inflow of groundwater to sumps and plastic sheets in the Validation Drift.*

head in the D-boreholes was kept at 165 m relative to the 385 m level of the mine. During the second phase the head in the D-boreholes was reduced to zero. In the second experiment the excavated Validation Drift was used as a drain. The report on the first experiment is completed and analysis of data from the second experiment is in progress.

The injected tracer only caused minor increases in the radar attenuation. The maximum increase in attenuation due to saline tracer was 25 dB/km or approximately 5 % of the normal attenuation of the Stripa granite. The small increase (5 %) in attenuation observed is most likely due to that the injected tracer only occupies a fraction of the total pore space. Hence, the ratio of observed increase in attenuation to expected increase gives an estimate of the ratio of flow porosity to total porosity. These data give an estimate of the flow porosity approximately in the range $0.5\text{-}1\times10^{-4}$. This value is somewhat smaller than previous estimates based on values of flow porosity ($\approx2\times10^{-4}$) obtained by Andersson, Andersson, Gustafsson, and Olsson (1989) at the Crosshole Site in the Stripa Mine.

Figure 18-14 is an attempt to represent the evolution of the flow system with time in the first phase of the first experiment. The figure is based on data on the increase of attenuation with time in zone H. The blocks on the lines represent increase of attenuation in excess of 10 dB/km. The time at which the tracer appears is indicated by the pattern in the boxes. The approximate time after start of injection for the measurements are M2 ≈ 65 h, M3 ≈ 110 h, M4 ≈ 170 h, M5 ≈ 290 h, and M7 ≈ 650 h. The width

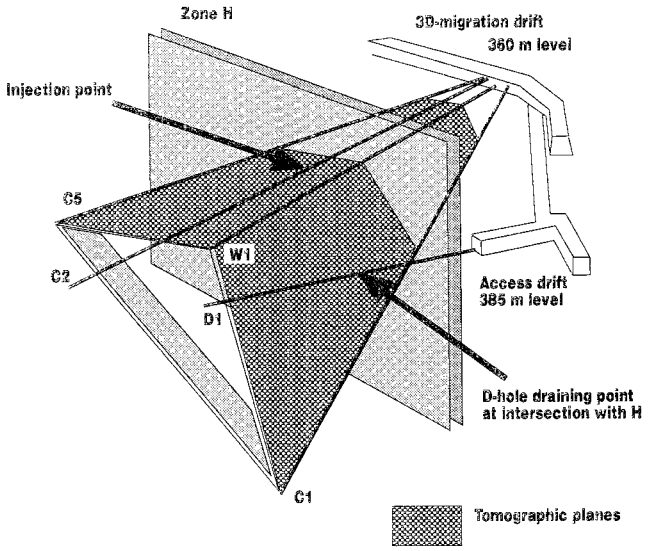


Figure 18-13. *Generalized geometry of the Radar/ Saline Tracer Experiment. Saline tracer was injected in borehole C2 where it intersects zone H. Radar tomography was made in the W1-C5, C5-C1, and W1-C1 planes.*

gives an estimate of where the attenuation has increased significantly for each measurement. As the boxes are stacked on top of each other the height gives an estimate of the time of arrival. A large height indicates an early arrival.

In summary, based on this experiment it can be concluded that the tracer appears to follow a few preferred

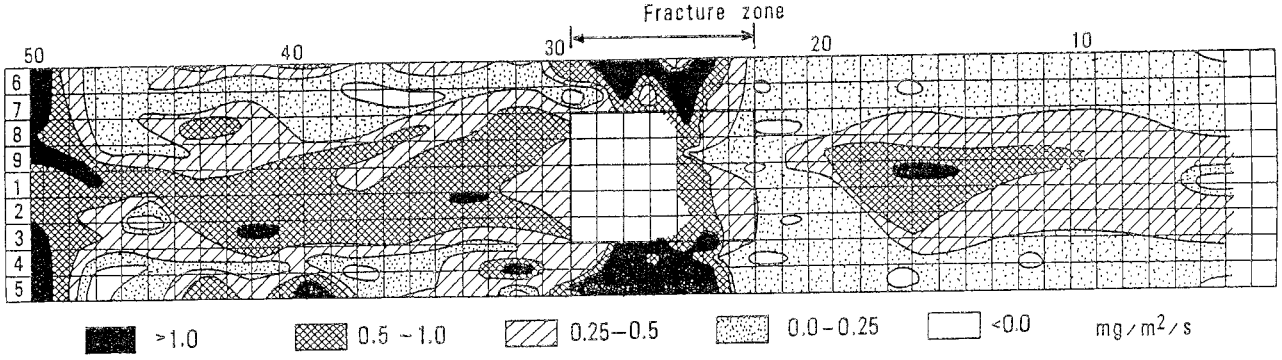


Figure 18-12. *Evaporation rate distribution in the Validation Drift measured in April 1990 (From Watanabe, 1991).*

flow paths where some of these paths are linked to the intersection of two minor features (fractures or fracture zones) with zone H. Tracer was also observed to be transported through these zones out of zone H. The radar data also indicated a change in flow pattern during phase 2 as a consequence of the change of head in the D-boreholes. The new flow paths believed to exist during phase 2 are indicated by thin arrows in Figure 18-14.

Tracer Test in the Validation Drift

The main activities during 1990 were;

— Drilling of boreholes T1 and T2.

— Installation of bentonite packer systems in boreholes T1, T2, C2 and C3.

— Design of tracer injection system.

— Start of tracer injections in 4 sections in early September. Two of these injections were terminated in early December while the other two are still running. Two other injections were started in mid December.

— Water collection and tracer analysis.

The objective of the tracer test is to make such measurements that a comparison can be made between the predictions of tracer movement in the rock around the Validation Drift and the actual tracer movement. Furthermore, the results will be used to further improve the understanding of water flow and tracer movement in fractured rock.

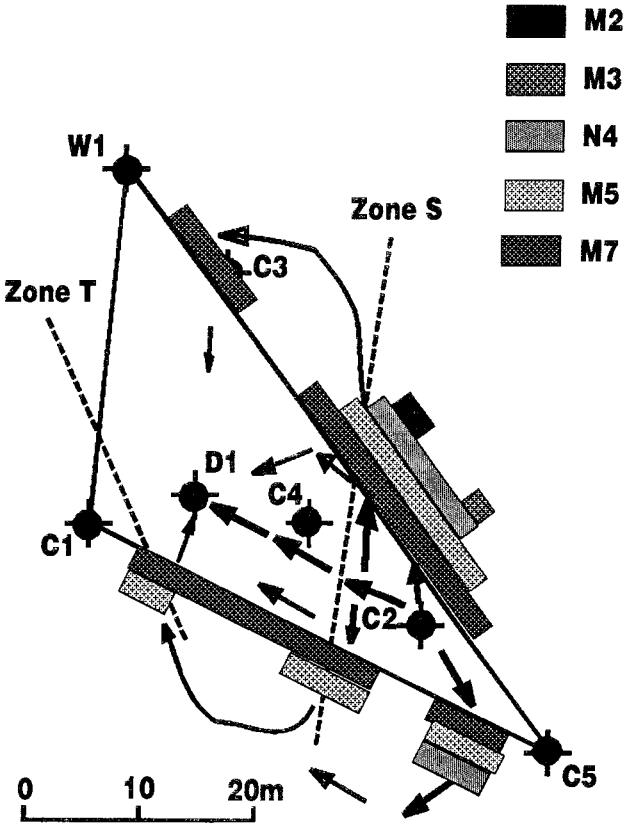


Figure 18-14. Conceptual model of saline tracer flow within zone H based on radar difference tomography. The boxes indicate when and where saline tracer is observed.

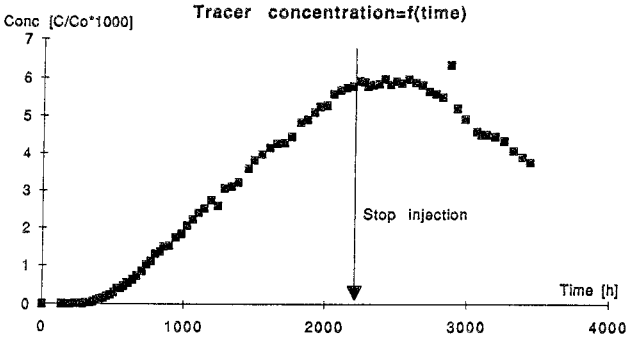


Figure 18-15. Tracer breakthrough curve for one of the tracers injected 20 m above the drift.

Tracers, mixture of metal complexes and dyes, are injected in a fracture zone as well as in the "good" rock. The distance from the injection sections to the Validation Drift is between 10 and 25 m. The tracers are collected in plastic sheets in the Validation Drift.

Tracer injection from four sections started in early September. Three of these tracers were found in the validation drift in detectable concentrations after about one week. The fourth tracer, injected in the good rock, has so far only been found in concentrations slightly above the detection limit. Two of these four tracers were found in high concentrations in the validation drift after a few months of injection. These injections were terminated in early December. The other two tracers are still being injected. Two other tracer injections were started in mid December and these tracers have already been found in low concentrations in the drift.

See Figure 18-15 for an example of a tracer breakthrough curve in one of the sampling areas in the validation drift. The figure shows the dye concentration from one of the injection sections in borehole T2, approximately 20 m above the drift .

CAD-modelling of the SCV-site

A CAD database has been produced of the Stripa Mine excavations, boreholes, and fracture zones. The objective has been to develop a database in an easily transferrable format to facilitate data exchange between research groups and in member countries. Another objective is to demonstrate how CAD systems can be used to present often very complex 3D geometries in a way perceptible to a larger audience.

An example of an output from the CAD database and the accompanying software is given in Figure 18-16. This figure shows a perspective view of the SCV-site including the location of fracture zones A, B, H, and I, and adjacent drifts and shafts.

18.3 DEVELOPMENT OF HIGH RESOLUTION AND DIRECTIONAL RADAR

The directional radar antennas have been constructed as a direct continuation of the RAMAC radar system developed during phase 2 of the Stripa Project. By using directional antennas one can obtain all the required data from a single borehole. This was demonstrated during the first measurements at the SCV site: directional antennas were used to determine the position of several weak and irregular zones characteristic of this area (Sandberg et al., 1989).

The efforts during 1990 were concentrated on the development of; calibration procedures to test the directional antennas, computer algorithms for presentation and interpretation of radar data, a high frequency radar.

The function of the directional antennas depends on the accuracy of each antenna component as well as on our ability to register the orientation of the antenna and to analyse the data properly. A set of calibrational procedures has consequently been developed to test the directional antennas. The calibration checks the function of the antenna directly in the laboratory without requiring a borehole, but it also involves all instruments registering the orientation of the antenna.

Directional data was previously computed and printed on paper for different rotation angles and the minima of the reflections were then determined by inspection. The new program RADINTER for radar interpretation allows the user to perform this rotation directly on the screen as shown in Figure 18-17. Reflecting objects, such as planes or point reflectors, can be defined and the geometrical curves corresponding to the theoretical models appear directly on the screen. This model can be moved around with a mouse allowing the user to determine quickly which parameters best fit the measured data. RADINTER is so simple to use that in practice all radar measurements are now analyzed in this way, though automatic routines have also been tested. The complete orientation of a fracture zone is in this way obtained in a matter of seconds.

A secondary goal of the radar project has been the development of a high frequency radar. The commercially available samplers have improved recently, especially at higher frequencies, and some tests were performed with resistively loaded antennas but as expected these antennas show considerable ringing because proper loading can not be imposed near the feeds. The best antenna at high frequencies is in fact the directional antenna which is by construction very broadband.

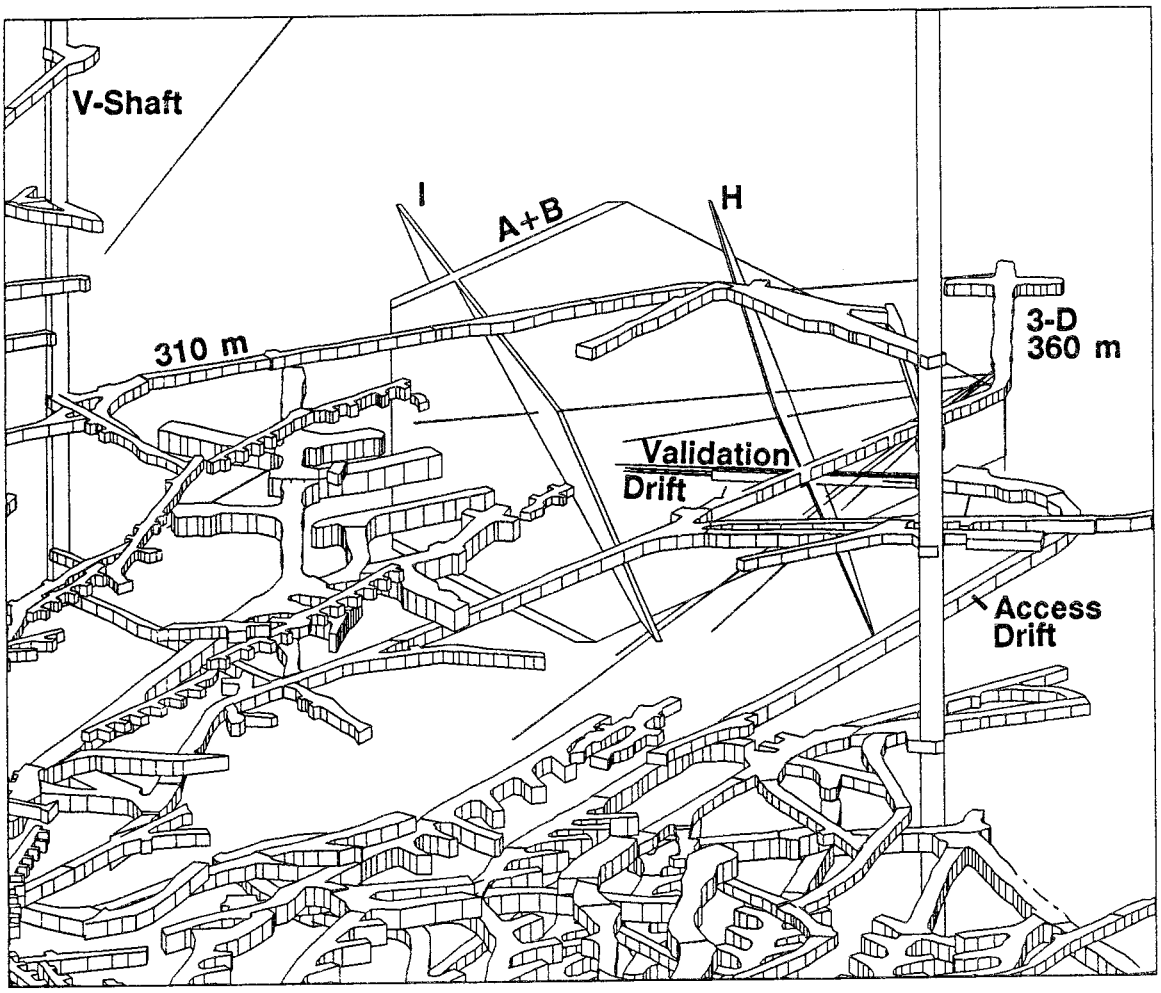


Figure 18-16. Perspective view of the SCV-site generated from the CAD-database developed within the Project.

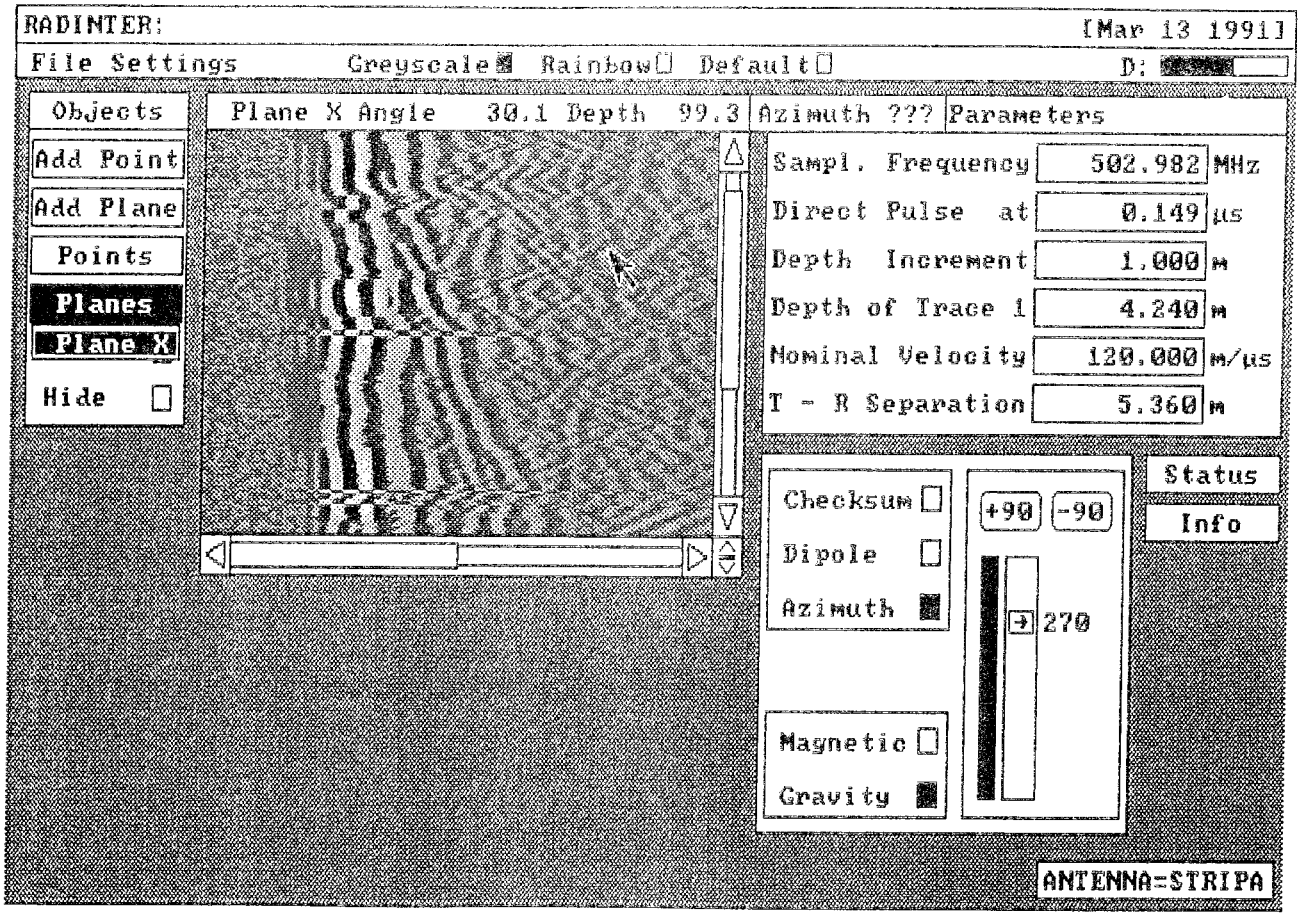


Figure 18-17. Interactive analysis of directional radar data using the program RADINTER.

18.4 IMPROVEMENT OF TECHNIQUES FOR HIGH RESOLUTION BOREHOLE SEISMICS

During 1990, the main topics of the seismic development project were:

A resonant seismic source working at lower frequency was constructed in order to extend the application range of the seismic method to softer rocks.

The program modules of the seismic reflection technique were organized in a processing sequence which, after testing many alternatives, was found to be the most suitable for data collected at Stripa. Reflection data was obtained also from other sites than Stripa, with various geological conditions, different site scales and collected with other acquisition systems. By applying the same procedures to various data sets we have improved the performance of the method and attempted to make it independent of the specific site conditions.

A high frequency piezoelectric resonant source has been developed for the project. In order to widen the spectrum of applications of the techniques developed within the Stripa Project, a source based on the same principle but producing lower frequencies was constructed by modifying the previous model. Compared with the previous version, the new source provides a more efficient overall energy transfer to softer rocks, hence a larger operational range in media less competent than the Stripa granite.

The two-dimensional transform which is currently applied for seismic signal processing is a novel technique aimed at enhancing the coherent events, acting thus as a two-dimensional noise filter. An example is given in Figure 18-18, with a profile obtained in the borehole C1 from a source placed in the borehole C3. The picture is dominated by the two sides of zone H, which is considered as the primary zone of the SCV site. Zone A, with two subzones ranks second in strength, as it is also generally accepted by other investigators. The power of this approach is that it can select only the most prominent events. Reflector procedures applied earlier produced a large number of potential reflectors but could not set a reflector strength hierarchy, which led to confusion.

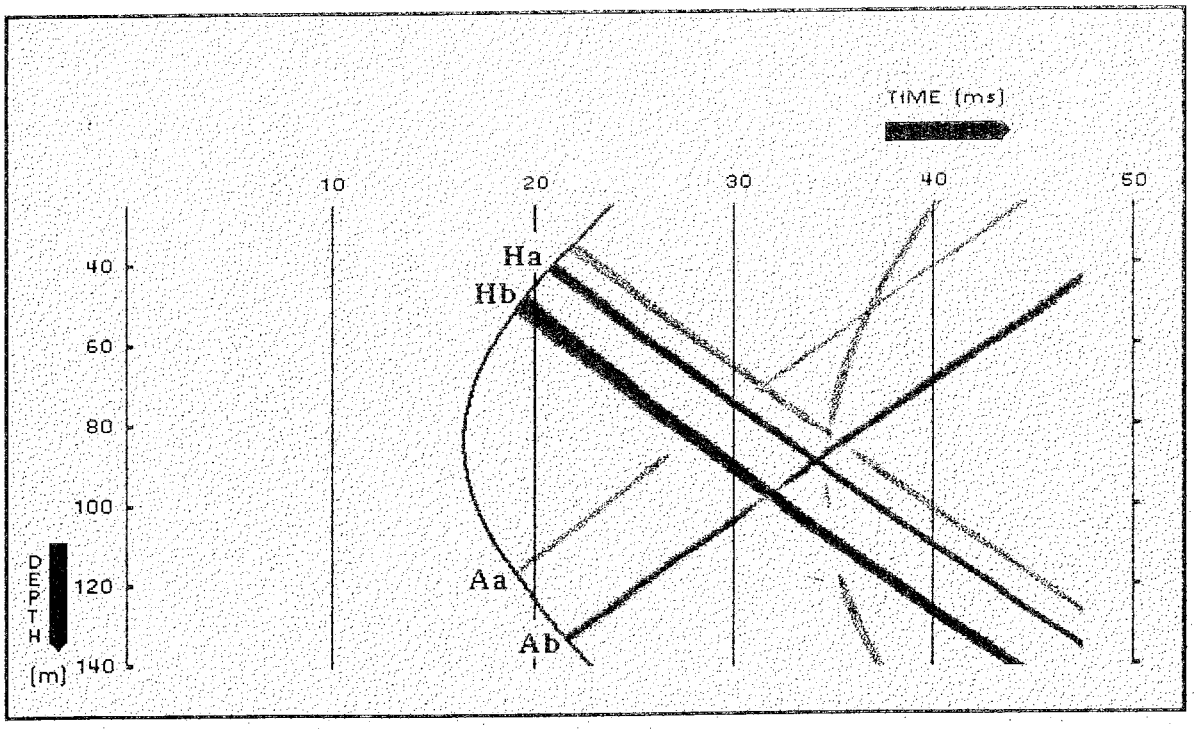


Figure 18-18. Reflection profile from borehole C1 using a VSP geometry (source in C3) after two-dimensional filtering. The less prominent reflectors are filtered out leaving in the plot only the major features.

18.5 FRACTURE NETWORK MODELLING

18.5.1 Introduction

One of the objectives of Phase III of the Stripa Project is to develop an improved understanding of groundwater flow and radionuclide transport through hard fractured rock. In such rocks, groundwater flows primarily through a network of connected fractures, and it is not clear that these flows can be fully explained using models based on continuum approximations such as Darcy's law. In this project we are developing more direct models of such flow systems, numerically generating fracture networks which exhibit the same statistical properties as those measured in the rock. We are incorporating this approach in the NAPSAC computer code, and we aim to show that approach is valid and feasible. It should improve our understanding of flow in Phase III at Stripa mine, and it should be generally applicable at other fractured rock sites.

During the first part of 1990 we were able to complete our assessment of the results of the predictive modelling of the 'D-hole' experiment. The Stripa project modelling the complementary studies by Golder Associates and Lawrence Berkeley Laboratory teams were reported and a summary report was prepared assessing the extent to which the models were validated. All three teams made good predictions and the Stripa project has benefited from the diversity of modelling approaches.

Whilst the three different modelling approaches predicted very similar bulk flows, the details of the inflow predictions were different. The original experiment did not resolve these details and therefore a new set of predictions and experiments is planned for the remaining sections of the D-holes early in 1991.

Following the success of the D-hole modelling, attention has been focussed on modelling of flow and tracer transport to the validation drift. These exercises involve considerable conceptual uncertainty. In particular, the properties of the fracture network will be distributed by the drift excavation, and the transport properties of fractures depend upon fracture storage as well as transmissivity. Neither of these two effects have been fully characterised experimentally, but must nevertheless be incorporated in our numerical models. During 1990 we developed facilities within NAPSAC to represent property changes near the drift due to the altered stress field. We also completed the development of the tracer transport model incorporated within NAPSAC.

There are many uncertainties involved in characterising a model of tracer transport into the Drift. In order to distinguish between different sources of uncertainty, the modelling program for tracer transport has been considerably expanded to incorporate three separate phases. The experiments are conducted within the H-zone feature rather than the averagely fractured rock since timescales for transport in the averagely fractured rock are too long. We therefore spent considerable effort during the second half of 1990 in developing and characterising separate fracture network models of the H-zone feature and the averagely fracture rock. Preliminary results in early 1991 suggest that we have been successful in this extension of the modelling programme.

Finally, towards the end of 1990, plans were made to construct a detailed porous-medium model of the SCV site

to incorporate our best understanding of the hydrology of the site. In addition to consolidating our hydrogeological understanding of the site, this model will provide a very useful contrast between the best conventional modelling of the SCV site and the fracture network approaches developed during Phase III of the Stripa project.

18.5.2 Continuing development of the NAPSAC fracture network

The NAPSAC steady-state flow model is essentially complete, and is being applied to simulate flow experiments at Stripa. Development of the NAPSAC code has therefore focussed on providing the capability to predict the outcome of the tracer transport experiments taking place at Stripa.

During the first part of the year we completed the development of the NAPSAC tracer transport option based on particle swarm tracking. The particle tracking algorithm is now integrated into the NAPSAC code. We have also started development of a number of output options. These will help identify the transport properties of the fracture networks characterised at Stripa, and identify the principal transport pathways through the numerical networks generated to represent the fracture networks.

The second area of development has been to enable fractures to be generated with locally varying apertures. The finely discretized finite-element meshes used to calculate the flow field across each fracture plane means that we can specify or calculate apertures for each element separately. We have used this capability to study two specific problems. First, we have used a compliance model to investigate the influence of the stress changes around the excavated Validation Drift. The second problem where we need to consider the detailed flow structure over fracture planes is to explain channelling experiments and the discrepancy between measurements of effective 'flow apertures' and of 'transport apertures'.

The final area of NAPSAC development concerns the progress of NAPSAC verification and documentation. In both these areas we are working closely with Intera Sciences. We have made progress towards flow verification with good agreement between all the codes used at Stripa for all but the large, stochastic, flow test-case. Here there is a significant difference between NAPSAC and FRACMAN results. There is no exact solution for this test-case and we are investigating the details of our solutions in order to resolve the discrepancy. We have also begun transport verification with two test cases specified and good agreement for preliminary calculations. A documentation plan has been created for NAPSAC and a first draft of the NAPSAC technical description is now available.

18.5.3 Application of NAPSAC to simulation of flows in the Stripa mine

For the modelling of the Validation Drift Inflow Experiment, the Harwell group has built upon the success of the models used to simulate the inflows to the D-holes (the Simulated Drift Experiment). Our models are direct forward models predicting large-scale properties and fluxes from measurements of individual fracture properties. The fracture network flow field is modelled directly in a cylinder of radius 12.5 m around the Validation Drift axis, which we have shown to be of a representative volume, with boundary conditions inferred from porous-media models of the SCV site as discussed in the next section. A typical realisation of these networks is illustrated in Figure 18-19. We have used the full coated-fracture-density as measured at Stripa and have relied upon the experimental Principal Investigators for their interpretation of the raw data. By restricting our models to simple concepts with measureable parameters much of this data can be incorporated directly. Where further interpretation is required or additional physics is incorporated to our basic model, we can clearly identify its importance and consequences.

In addition to updating the input data, the models have been improved in two main respects. First we have modelled the fracture system of the H-zone directly as a fracture network. Secondly, we have concentrated on demonstrating the consistency of our interpretations.

For averagely fractured rock we show good consistency and predict D-hole flows to within 50% of the measured values. The H-zone is less well characterised, and involves a very dense network with a wide range of length-scales. For the D-hole experiment our inflow prediction for the H-zone is low by a factor of about 5. This would probably be best improved by using single-fracture transmissivities directly: our log-normal fitting procedure for H-zone transmissivities showed poor convergence.

The important difference between the D-hole flows and the drift inflows is the effect of the disturbed zone. We believe our D-hole inflow predictions are acceptable and the different geometry of the experiments has only a small effect on the flow-rate per metre.

We conclude that whilst our underlying fracture network model gives good flow predictions, the stress compliance model is not a valid description of the disturbed zone. We consider a number of neglected physical processes to be potentially important. Two-phase flow effects may reduce fluxes to the drift and be important in a very narrow skin, but these are unlikely to reduce flows by a factor as large as 8. Disturbance of fracture infill may be more important, but is not quantifiable. Finally, dynamic stress effects, such as permanent deformation during the high stresses experienced during blasting, may be significant. This last hypothesis is supported by the fact that the formation of the skin can be seen in the pressure monitoring of nearby holes: the skin reduced the influence of the D-hole sink immediately and progressively as the drift excavation proceeded.

18.5.4 Porous modelling of flows in the Stripa mine

Three-dimensional equivalent-porous-media modelling of the SCV site was completed using the CFEST code.

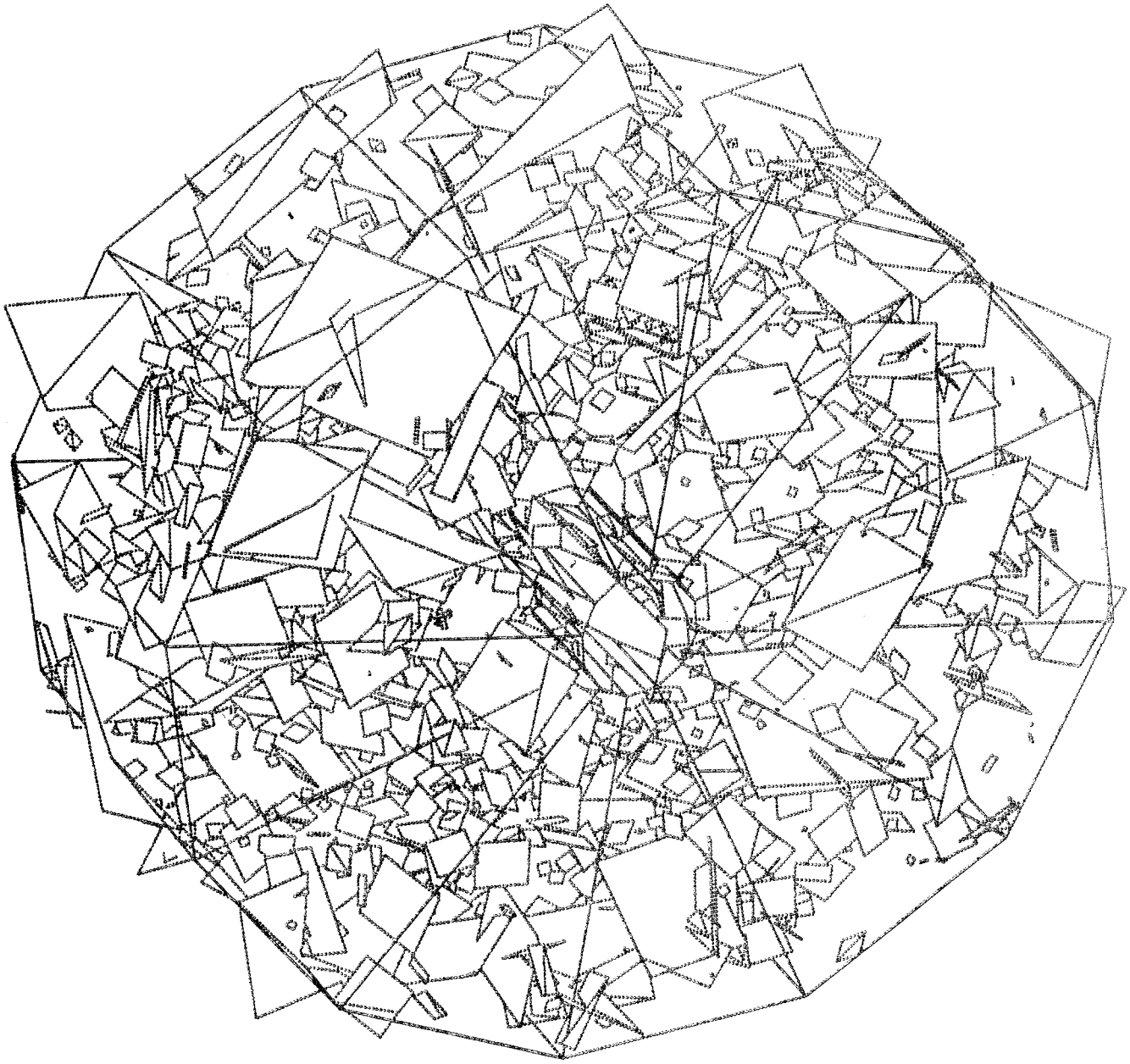


Figure 18-19. *NAPSAC fracture network model used to calculate inflow to the Validation Drift. Only 10% of the modelled fractures are plotted to clarify the illustration.*

Comparison of computed heads in the form of contour plots with contour plots of field measurements suggest that fracture zones I and A-B may have been extended too far to the southwest in the numerical model. In addition, the steeper hydraulic gradients measured in the field probably reflect the effects of stress concentrations around the drifts and the pinching and swelling of the fracture zones along strike, and hence a strong variation in hydraulic properties that has not been reproduced in the model. However, the overall agreement between the measured and computed hydraulic heads suggest that additional refinement in the distribution of hydraulic properties within the 3-D model may enable one to complete a first order calibration of the 3-D model against the measured hydraulic heads.

The importance of building stress concentration effects into the elements surrounding the simulated SCV drift, and other drifts, is apparent when we compare the effects of opening the SCV drift on the hydraulic head distribution, see Figure 18-20. The measured head changes are much more localised than the computed head changes, suggesting a low-permeability zone around the SCV drift.

18.6 ROCK SEALING TEST

18.6.1 Introduction

The general objective of the Rock Sealing Test is to identify suitable grouts and grouting techniques for seal-

ing fine rock fractures in repositories. The grouts have to be sufficiently erosion-resistant and chemically stable to make them serve for long periods of time and part of the project is therefore focussed on the testing of candidate materials not only with respect to their initial sealing ability but also to their potential to survive in repository environment.

The objective to seal fine fractures is met by use of "dynamic" injection technique, i.e. by applying vibrations of suitable amplitude and frequency to the grout in addition to the conventional static injection pressure. The project comprises development of suitable field-adapted equipment for such grouting, and application of the technique in the mine for determination of the sealing effect and for evaluation of the validity of a grout flow theory.

The work in 1990 consisted of three major parts: 1/ Field work concerning the evaluation of the hydraulic conductivity of the "disturbed zone" of the BMT Drift (Test 2), 2/ Field work concerning the characterization of the natural fracture zone in the eastern arm of the 3D cross (Test 4), 3/ Laboratory work comprising hydrothermal tests of clay in different chemical environment, and theoretical and experimental investigations of cement-based grouts.

18.6.2 Field tests

Figure 18-21 shows the general test arrangement of Test 2, which is conducted in two steps, i.e. a first one in which the inner slot and borehole curtain were pressurized while recording the inflow into the rock and the flow from the outer borehole curtain, and a second one of identical form after "hedgehog grouting".

The flow measurements, which were made at water injection pressures of 0.25, 0.45, 0.75 and 0.95 MPa, showed that the rock next to the periphery of the blasted drift has a hydraulic conductivity of around 10^{-8} m/s, assuming the disturbed zone to extend 1 m from the periphery. The conductivity of the rock next to this zone, reaching 6 m further into the rock, is concluded to have become about five times as high as the conductivity of the virgin rock, which is taken as 10^{-10} m/s.

The walls of the drift had to be tight for carrying out the test and it turned out that even a carefully made rubber-based liner was not good enough. The preparation of the drift for the experiment therefore required filling the drift with a bentonite slurry that could be pressurized by use of a central rubber bladder.

In the fall the drift was emptied as a preparation of the "hedgehog" grouting, i.e. injection of cement grout into

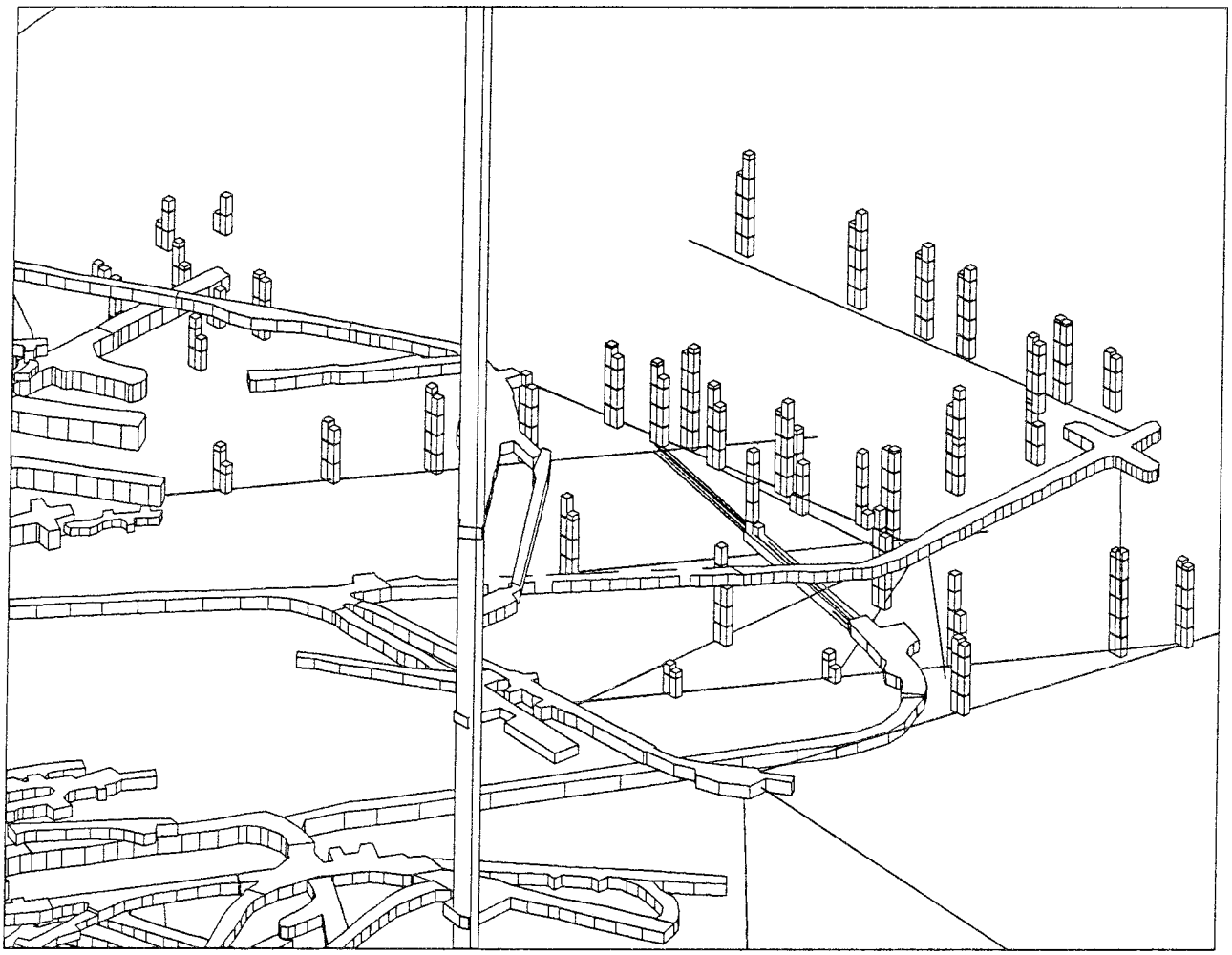


Figure 18-20. *CAD diagram showing comparison of measured versus computed pressure heads for selected monitoring points around and in the SCV Block. The pressure heads are shown as columns with 50m sections. The measured pressure heads are given by the left column and the computed pressure heads are shown as the right hand column.*

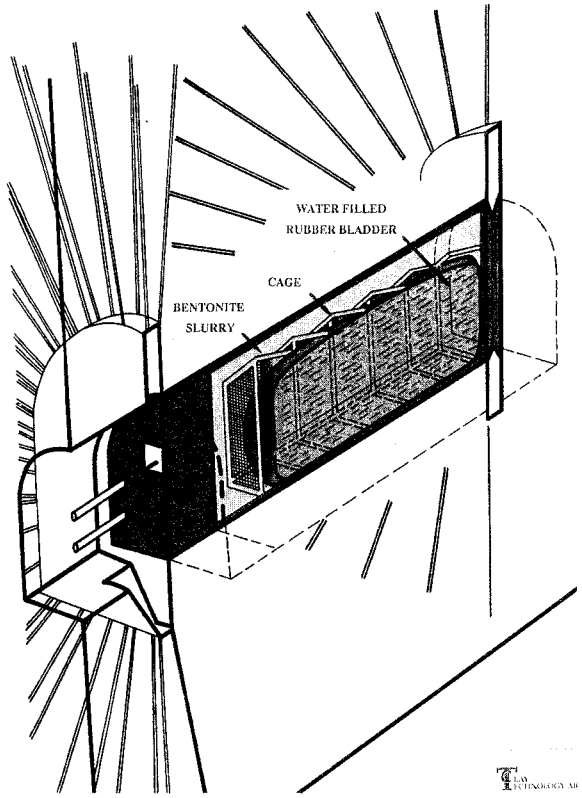


Figure 18-21. *General arrangement of Test 2. K represent water-pressurized boreholes extending radially from 0.75 m deep slots cut around the inner and outer ends.*

densely spaced, short holes. The grouting was completed at the end of the year.

Field Test 4 concerned the characterization of the natural fracture zone in the eastern arm of the 3D cross. Comprehensive drilling and hydraulic characterization of the rock has been made and a first grouting phase completed.

Water inflow measurements and tracer tests revealed the major water-bearing structure that controls the inflow and it was characterized by core drilling, "Lugeon testing" and tracer experiments.

FEM calculations, in which the rock is modeled as porous zones with specific hydraulic conductivities, have been conducted. Asuming that the fracture can be sealed so that its conductivity drops to 10^{-10} m/s, the inflow pattern will be very significantly altered and the inflow capacity reduced to 50-60% of the initial value.

A comprehensive set of hydrothermal tests of smectite clay was started and certain test series were stopped after 10 and 30 days, respectively in order to get a first picture of the kinetics. A major conclusion is that a temperature of around 130°C represents a critical level with respect to the dissolution of smectite. Transformation to yield mixed layer and hydrous mica seems to require access to magnesium or iron and 120-130°C temperature, while neoformation takes place at any temperature exceeding about 70°C, the process being entirely dependent on the access to potassium.

The cement study has been pursued by considering chemical degradation, of which leaching/dissolution of more soluble constituents like $Ca(OH)_2$ or reaction with aggressive species like sulphate and chlorite are the major ones. The independent and combined effects of these processes have been investigated experimentally and seem to indicate that high performance cement grouts are virtually impermeable. Surface leaching is likely to be the major degrading process, meaning that fracture widening may be the controlling factor of cement longevity. The parallel thermodynamic modelling has concerned flow and diffusion through the cement matrix and in the later part of the year the work has been focussed on successive changes in diffusivity of the grout due to chemical reaction with the grouts. Preliminary results suggest that cement grout seals should provide acceptable performance for very long times.

19. ÄSPÖ HARD ROCK LABORATORY

19.1 GENERAL

The scientific investigations within SKB's research programme are a part of the work of designing a final repository and identifying and investigating a suitable site. This requires extensive field studies regarding the interaction between different engineered barriers and host rock.

A balanced appraisal of the facts, requirements and evaluations presented in connection with the preparation of R&D-Programme 86 /19-1/ led to the proposal to construct an underground research laboratory. This proposal was presented in the aforementioned research programme and was very positively received by the reviewing bodies.

In the autumn of 1986, SKB initiated field work for the siting of an underground laboratory in the Simpevarp area in the municipality of Oskarshamn. At the end of 1988, SKB made a decision in principle to site the facility on southern Äspö about 2 km north of the Oskarshamn station, see Figure 19-1. Construction for the Äspö Hard Rock Laboratory started October 1, 1990 after approval was obtained from the concerned authorities.

The work with the Äspö Hard Rock Laboratory, HRL, is divided into three phases: the pre-investigation, the construction and the operating phase, see the time schedule in Figure 19-2.

The pre-investigation phase aimed at site selection for the laboratory, description of the natural conditions in the bedrock and predictions on changes that will occur during

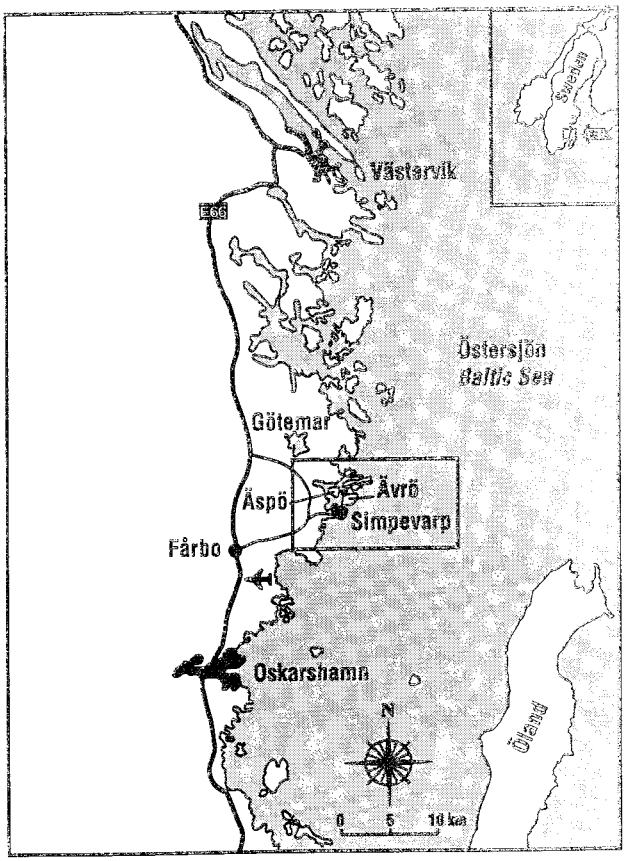


Figure 19-1. Äspö island with environs.

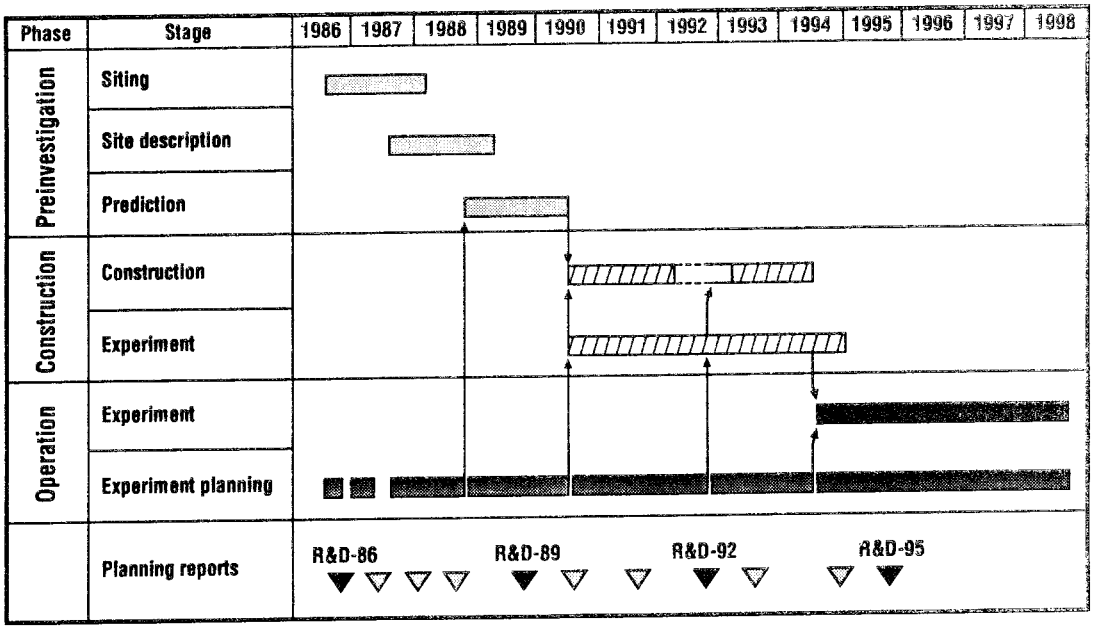


Figure 19-2. Master time schedule.

construction of the laboratory. The construction of the access ramp to a depth of 500 m will be used to check the predictive models set up from the pre-investigation phase, to develop methodology for construction/testing integration and to increase the database on the bedrock in order to improve models on groundwater flow and transport of solutes. A preliminary programme for the operating phase has been set up, /19-2/.

19.2 OBJECTIVES FOR THE ÄSPÖ HRL

The main goals of the R&D work in the Hard Rock Laboratory are:

— To test the quality and appropriateness of different methods for characterizing the bedrock with respect to conditions of importance for a final repository,

— To refine and demonstrate methods for how to adapt a final repository to the local properties of the rock in connection with planning and construction,

— To collect material and data of importance for the safety of the final repository and for confidence in the quality of the safety assessments.

The last goal is general for SKB's entire research programme.

To meet the overall timetable for SKB's research work, the following stage goals have been set up for the activities at the Hard Rock Laboratory.

Prior to the siting of the final repository for spent fuel in the mid-1990s, the activities at the Hard Rock Laboratory shall serve to:

1 Verify pre-investigation methods

2 Finalize detailed investigation methodology

As a basis for a good optimization of the final repository system and for a safety assessment as a basis for the siting application, which is planned to be submitted a couple of years after 2000, it is necessary to:

Test models for groundwater flow and transport of solutes

In preparation for the construction of the final repository, which is planned to begin in 2010, the following shall be done at planned repository depth:

3 Demonstrate construction and handling methods

4 Test important parts of the repository system

These tests shall be able to be carried out on a sufficient scope as regards to time and scale to provide the necessary support material for Government approval of the start of construction. Certain tests may therefore have to be started in the mid-90s.

19.3 SITING AND LAYOUT OF THE LABORATORY

In R&D-Programme 86 /19-1/, it was stated that the new Hard Rock Laboratory should preferably be located in a place where existing services and the kind of infrastructure needed for research work already existed. One of the nuclear power sites should be considered first, such as Simpevarp in the municipality of Oskarshamn.

Investigations in the Simpevarp area were begun in the autumn of 1986 and have since continued on a relatively large scale. On the basis of the results obtained up to 1988, SKB made a decision to locate the laboratory on the southern part of the island of Äspö, see Figure 19-3.

The exact site of the Äspö Hard Rock Laboratory will not be considered as a site for the final repository. However, if appropriate geological conditions are found to exist in the vicinity, this could be one of the candidate sites that will be subject to detailed investigations prior to the final siting of the final repository.

Studies of alternative layouts of the underground portion of the Äspö Hard Rock Laboratory were performed during 1987. An access ramp was found to be preferable to the sinking of a shaft to a depth of about 500 m. The ramp alternative was chosen primarily because it provides

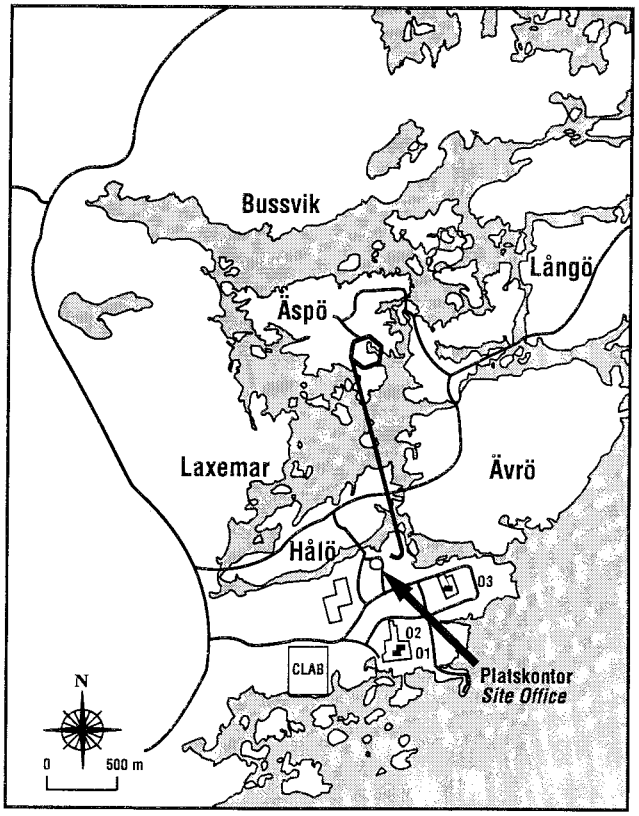


Figure 19-3. Location of the Äspö Hard Rock Laboratory.

better flexibility and a greater opportunity for collection of data and characterization of the rock mass. The layout of the facility is shown in Figure 19-4. The entrance is located on the Simpevarp peninsula.

19.4 OVERVIEW OF WORK 1986 - 1989

Investigations of the bedrock have been undertaken both from the ground surface and in boreholes. Data was compiled in conceptual models as a basis for siting of the laboratory, layout of the facility and numerical calculations of groundwater flow on different scales.

The pre-investigation phase was divided into the stages siting, site description and prediction.

The results from the siting stage have been reported in /19-3/. The regional-scale rock description shows that the Simpevarp area consists primarily of granitic bedrock (Småland granite) with intrusions of basic rock types, greenstones. The information from the geological and geophysical surveys shows a tectonic picture of the Simpevarp area dominated by a nearly orthogonal system of first-order fracture zones in the N-S and E-W directions. Aside from this system, there are second-order zones

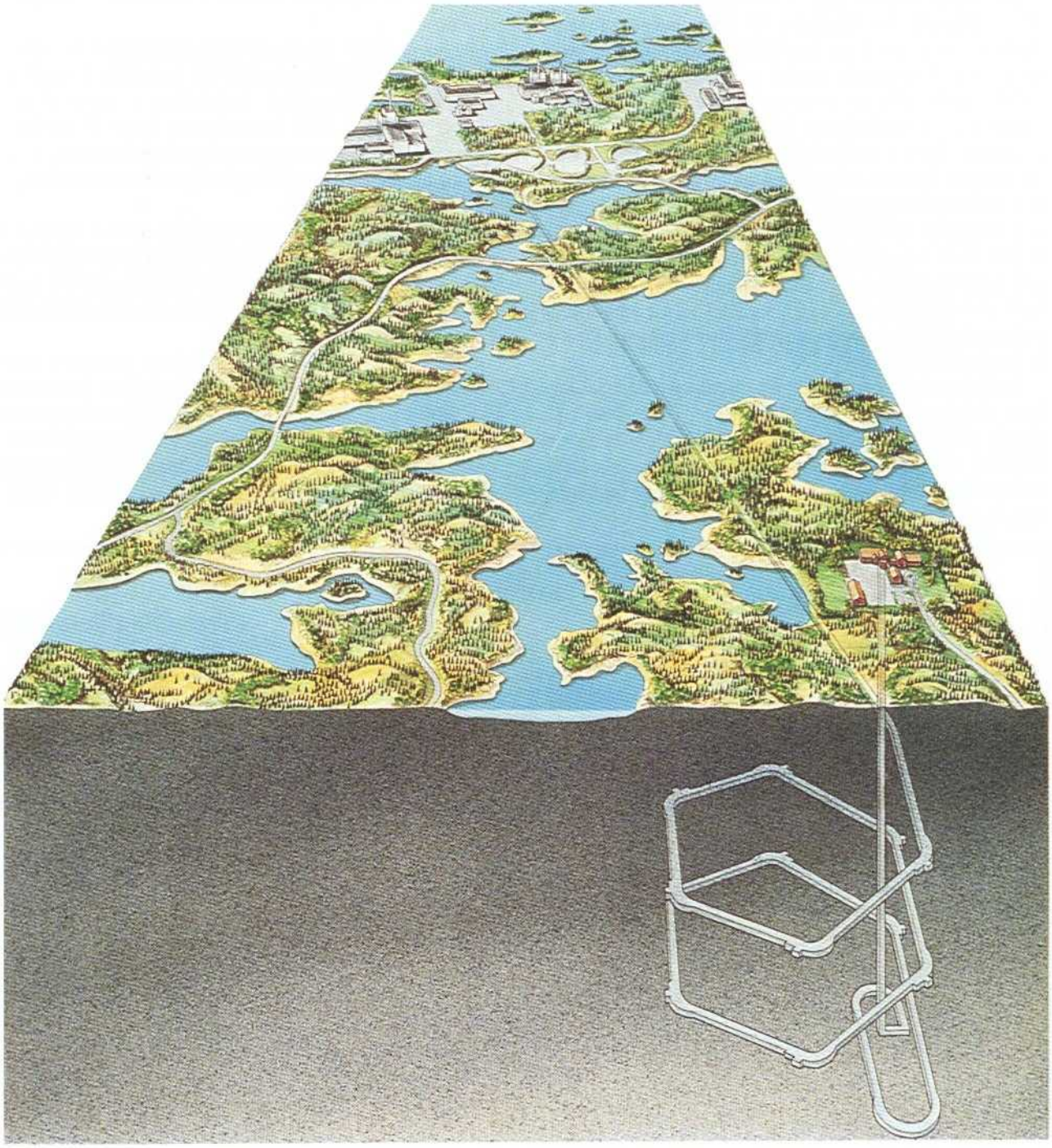


Figure 19-4. *Design of the laboratory.*

running in the NW and NE directions that also form a nearly orthogonal system. There are probably also low-dipping, subhorizontal zones.

Of importance for numerical models of groundwater flow has been the fact that the Simpevarp area is surrounded by younger, granitic diapirs, which are also assumed to underlie the Simpevarp area at great depth. Regional well data show that these younger rock types are more permeable. The siting stage also included percussion drilling programmes on three sites to gather data for a chemical characterization of the superficial groundwater. It was judged that both Äspö and Laxemar were suitable sites for a Hard Rock Laboratory, see Figure 19-1.

The site description stage has been described in /19-4/. The continued investigations for siting were focussed primarily on Äspö. Laxemar will be used as a reference area where, for example, natural variations in groundwater levels can be followed and compared with the disturbed conditions that will exist on Äspö after the laboratory has been built. Four holes KAS 01--03 and KLX01 was cored, the deepest down to a depth of 1 000 m in connection to a percussiondrilling programme. In addition to high-quality core mapping, extensive geophysical measurements have been carried out, along with hydro tests on several scales and hydrochemical analyses. Thorough surface investigations was carried out on Äspö, including seismic profiles, outcrop mapping, geophysical measurements and cross--hole interference tests.

Evaluation of the siting stage led to the conclusion that four additional cored holes, KAS05-08, were drilled to depths of about 500 m in addition to the percussion holes HAS 13 - 17. Measurements have been carried out, both in these holes and between the holes. A long-time pumping test, in total 3 months, was carried out.

This test was preceded by predictive modeling utilizing two different approaches. The first approach used three-dimensional finite elements. The second used a three-dimensional finite volume code incorporating the saline/fresh water interface. The major flow paths were described deterministically whereas the rest of the rock mass was treated as a stochastic continuum. After evaluation of the approaches it was decided that predictive modeling in site scale will continue using the finite volume code PHOENICS. Based on surface mapping and borehole measurements fracture network models have been applied. The objective of the modelling was basically to simulate heterogeneity on the scale of canisters and at the scale of elements whithin a stochastic continuum model.

In August 1989 the government decided that the laboratory should be reviewed under the Act on the Conservation of Natural Resources. A government approval was obtained in April 1990. In connection herewith SKB decided to make changes in the layout of the laboratory. Due to the new layout, new drillings and surface investigations were launched late 1989.

Up to 1989 results were presented in two SKB Technical Reports, and 65 Progress Reports. All data from boreholes are collected in separate Borehole Reports, one for each hole. Data has been stored in SKB's computerized data base GEOTAB.

Along with the site characterization, activities were carried through to plan the construction phase. Important activities was to obtain permits accordingly to Act on the Conservation of Natural Resources, Planning and Building Act and Act on Water. The planning also included organization, construction/testing integration and tender documents for the excavation works.

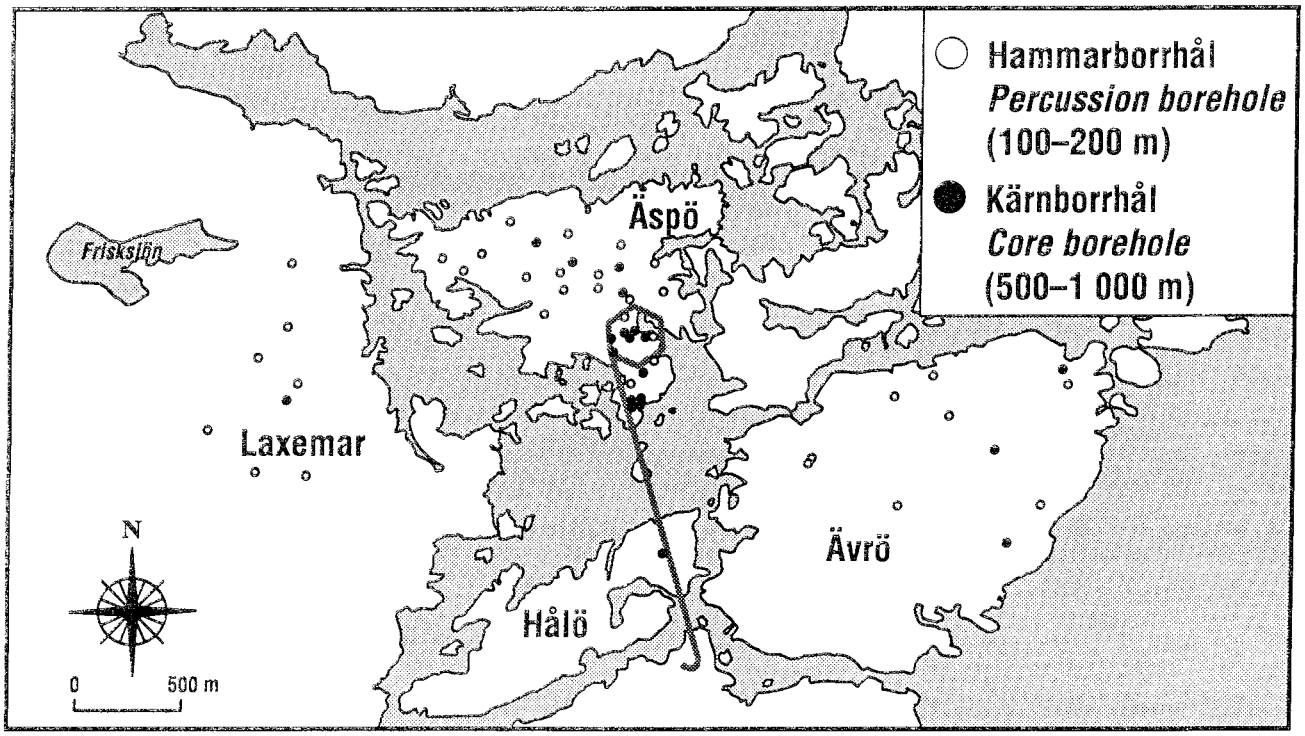


Figure 19-5. Borehole location map at Äspö.

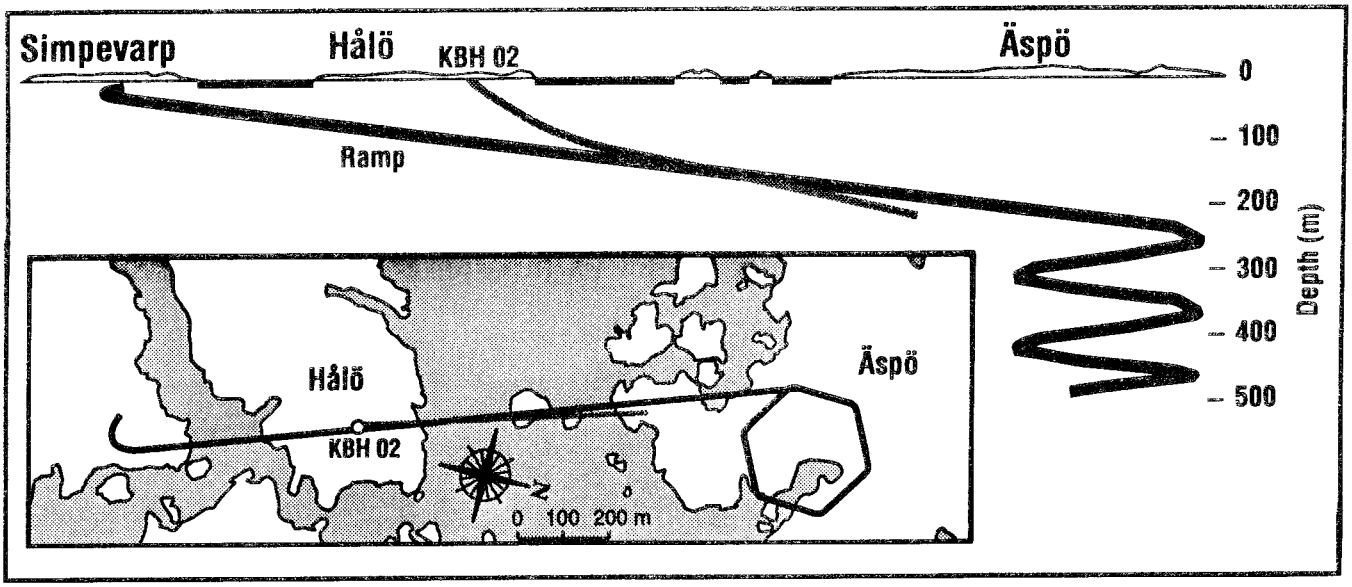


Figure 19-6. Section along borehole KBH02.

19.5 OVERVIEW OF WORK 1990

The following section highlights a few of the main targets obtained during 1990:

The field work in the pre-investigation was extended with additional drillings. Figure 19-5 shows the boreholes on Äspö island. Notably is one of the cored hole, KBH02, which was guided along the planned access ramp, a new and highly interesting development, see Figure 19-3 and Figure 19-6.

The radioactive tracer test originally planned to 1989 was carried out late 1990. Evaluation of the test is under way. An important task during the year has been to decide on a synopsis of predictions prior to excavation and a process of their validation. The set of predictions presented were a basis for the minimum documentation to be done during the excavations.

The principal investigators received many different opinions on how the first integrated presentation of the complete pre-investigation work should be organized. It was later decided that the results should be reported in a "pure" Prediction Report and a second report explaining all evaluations and background. These reports will be published 1991. During 1990 work carried out was reported in 16 Progress Reports.

An effort was made during the year to plan in detail how to integrate data collection at the tunnel face and the excavation sequence. Many of the persons assigned to this work are now working at the site office set up during autumn 1990.

Establishment of the site office was preceeded by permits by authorities and a decision of investment by SKB.

On April 19 the government decided that the siting of the laboratory on southern Äspö was permissible according to the Act on Conservation of Natural resources. The Development Plan accordingly to the Building and Planning Act was approved by the Oskarshamn County Board. The decision was appealed but finally adopted by the Government in September 1990. The Water Rights Court handed down their ruling in September 1990.

The Board of SKB decided May 2 to continue with the second phase of the Äspö Hard Rock Laboratory that is to do research and investigations during excavation of the laboratory to a depth of 500 m and to plan for the succeeding operational phase as well. The budget for the project was set to 150 MSEK for research and investigations and 267 MSEK for the construction in total 418 MSEK. Adding the incurred costs for 1986 to 1989 the total cumulative costs up to medio 1994 is estimated to 500 MSEK.

After evaluation of tenders for the excavation works, the contract was awarded to Siab, the third biggest Swedish contractor. They started to establish the site in August. October 1 was the day for the first excavation of the access ramp. At the end of the year 353 m had been excavated. Drillings will be done with a computerized Tamrock drilling rig. Loading is done with an electric front-wheel TORO loader.

The integration of documentation, investigations and construction has so far been successful in the access ramp. The first 800 m of this ramp is considered as a "learning" stretch in order to work out this integration in detail.

19.5.1 Research and Investigations

Geology

The geological pre-investigation for the Äspö HRL was finished during 1990. The extended drilling programme that started 1989 was completed with a number of boreholes (KAS 09-14, HAS 18-20) in spring 1990 mainly in order to improve the knowledge of the rock mass in the site area and the major fracture zones south of Äspö.

Due to the new layout a cored 700 m long borehole (KBH 02) was inclined almost parallel to the access tunnel, see Figure 19-6.

The Vertical Seismic Profile survey, carried out 1989 in borehole KAS 07, was supplemented with a 3-D interpretation using a new image space processing technique.

A tectonical model and an evaluation of the rock mechanics of the site area was also presented.

A first geological prediction of the Äspö-Hålö area, on different scales, has been made.

The cored borehole KLX 01, sited in the Laxemar reference area, was deepened from 702 m to 1078 m. A preliminary examination of the recovered core was carried out on-site giving a brief overview of the lithology and the fracturing in the borehole.

Geohydrology

In the cored holes KAS 09-14 and KBH 02 and the new percussion holes HAS 18-20 several hydraulic tests were performed during the spring 1990. The tests confirmed some of the already defined conductive structures and revealed some new conductive structures interpreted as probable or possible hydraulic structures. These field investigations were focussed on the southern part of Äspö.

KLX 01 was also deepened down to 1078 m during 1990 and a few hydraulic tests were also performed.

During the summer, dilution tests under natural gradient were made in several of the packed off sections in the coreholes, and in the autumn 1990 the second longtime pumping test (LPT2) was started, ending in December. Tracers were injected in a few of the packed off sections and breakthrough was detected in the pumping hole, KAS 06. Evaluation of the test is under way.

In the ramp, the first hydraulic tests and geohydrological documentations were performed late 1990. The routines for the documentation and the hydraulic testings have been established.

The numerical modelling have been continued with the finite volume code PHOENICS by preliminary calculations based on the spring 1990 conceptual model. Typical calculations regarded the inflow to the tunnel, changes in the piezometric levels in the rockmass during the excavation of the Äspö Hard Rock Laboratory and scoping calculations of LPT2. In the autumn 1990, when the final conceptual model was available, work with the calculations for the final predictions prior to excavation HRL were carried out.

Discrete fractures flow modelling has also been performed. The fracture distribution and the hydraulic properties of the fractures was generated from statistical distributions, and the flow through a 50 m cube was calculated under two boundary conditions. The calculations show that the modelling technique is a useful tool when examining the flow conditions for groundwater in crystalline rock. The modellings however also show that there are needs for better routines to simulate the boundary conditions.

19.5.2 Groundwater chemistry, tracer tests

The groundwater chemistry at Äspö has included sampling and analyses of the groundwater from a large number of packed off borehole sections. The percussion drilled

Table 19-1. Sampled sections of groundwater at Äspö.

CCC = Complete chemical characterization
SPT = Sampling during pumping tests
SDD = Sampling during drilling

Borehole	Sampled section/m		
	CCC	SPT	SDD
KAS02	202-215		
	314-319	308-344	
	463-468		
	530-535		
	860-924	802-924	
KAS03	129-134		
			196-223
			248-251
			347-374
			453-480
			609-623
	860-1002	690-1002	
KAS04	226-235		
	334-343		
	440-481		
KAS05			155-388
			387-550
KAS06			106-217
		204-277	217-317
		304-377	319-396
		389-406	396-505
		439-602	505-602
KAS07			106-212
			212-304
			372-604
			462-604
KAS08			106-208
			208-306
			306-447
KAS09			303-450
KAS11			99-249
KAS12			204-303
			303-380
KAS13			104-211
			210-314
			312-407
KAS14			105-212
			153-211
KBH02			100-183
			192-304
HAS02			44-93
HAS03			46-100
HAS05			45-100
HAS06			40-100
HAS07			71-100
HAS13		0-100	

holes have also been sampled in an early stage of the investigations, see Table 19-1. During 1990 data were collected and evaluated. The final outcome of the evaluations are the predictions put up prior to the excavation of the tunnel and due to be reported in 1991.

Fracture minerals have been collected from water conducting single fractures in two deep boreholes. This sampling did, however not, include all the conducting fractures but only those that were encountered in the borehole sections from where water samples have been collected and analyzed.

A radially converging tracer test was conducted at southern Äspö during the autumn 1990. Six different borehole sections, representing identified fracture zones were used for the injection of tracers. The tracers were short-lived radioactive isotopes selected so that they could be detected by a gammalog in the hole.

The pumping was made at a constant flow rate in the borehole KAS 06. The total duration of the pumping was ten weeks.

19.5.3 Development of measuring methods and instruments

In December 1990 the preinvestigation stage of the Äspö Hard Rock laboratory was ended. During the year the extensive field investigation program included single hole measurements in a set of complementary boreholes as well as interference tests and tracer tests. Installations of multipacker system in the complementary boreholes was carried out as well, according to a technique which was described in the Annual Report for 1989. In total, approximately 110 measuring points of ground water head are monitored in the boreholes on the Äspö island. In some of the sections dilution tests can be conducted while in others also the fluid resistivity are recorded. Ground water samples can be taken from most of the borehole sections. In addition, some 30 measuring points are recorded in boreholes at the reference sites Ävrö and Laxemar. Improvements of the monitoring system, multipacker system, measuring sensors and data aquisition units has been made in order to increase the level of accuracy and reliability.

The final experiment in the preinvestigation stage was a large scale tracer experiment. The test was carried out as a large scale pumping test, in principle using the same technique as in the earlier conducted long-term Pumping test, which means high capacity pumping from an open hole. The equipment used was the Pipe String Equipment, modified with a high capacity pump. For the tracer experiment four different tracers were injected in four different packed-off sections in the surrounding monitoring boreholes. Radioactive tracers were used and a gamma detector was monitoring the arrival time in the pumping water. When tracers were detected a multilevel sampling device was lowered down to collect water from levels where the boreholes are penetrating water conducting structures. Thereby the tracer arrival point could be detected.

Prior to the beginning of the tunnel excavation, the planning for a monitoring network system was started. The basic principle of the monitoring system is to connect all measuring points in already existing boreholes and all the additionaly measuring points which successively will be initiated in the tunnel to a host measuring station in the site office. The system will allow on-line recording of any measuring point. The system will include calibration facilities, all measured data will be tagged regarding the status of calibration in order to fullfill a high degree of quality control.

During the construction of the tunnel, each drill and blasting cycle also will include a period of documentation work, such as mapping of the last section of tunnel surfaces, and for every fourth cycle also drilling of pilot holes and pressure build-up tests are performed. In order to facilitate the mapping of geology; lithology and structures, points of leakage etc, a CAD system has been set up and adopted for our special purposes. With use of this CAD system the tunnel map with all collected information will successively be extended within a few hours after each tunnel documentation step.

For the performance of the pressure build-up tests in the pilot holes, a packer system has been developed as well as a datalogger has been modified in order to facilitate an easy handling and time-effective performance of the measurements.

19.5.4 Site office

In October 1, 1990 the construction of the tunnel started. A new organization was set up at the site. An overview of

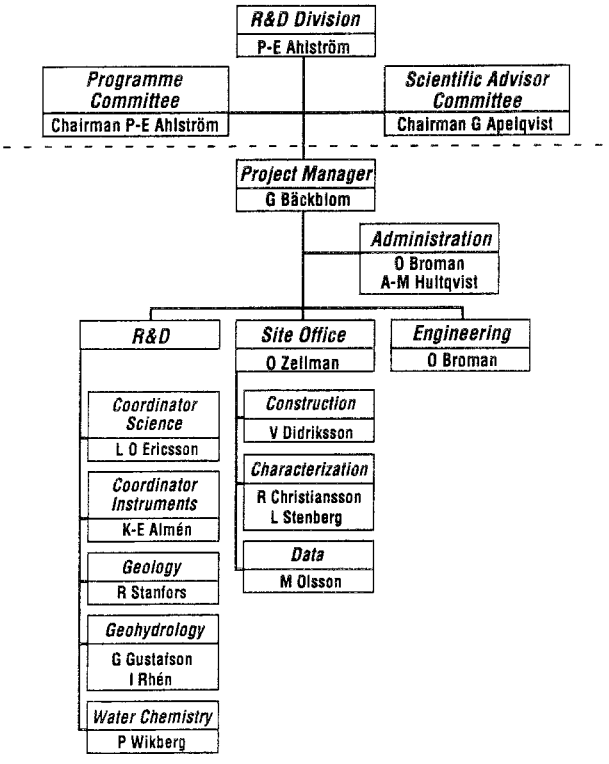


Figure 19-7. Overview of the project organization.

the organization, including the site office is shown in Figure 19-7. The documentation group consists of seven qualified geoscientists. The construction supervisor is responsible for the direct relation to the contractor, Siab. All together twelve people are at the site office, situated at the portailing of the access ramp.

Drilling and blasting is the technique used for excavation. The contractor, Siab, has a crew of 25 people at the site. The construction excavations are done in two shift. Drilling is performed by a computerized drilling rigg with two drilling machines. The ramp area is 25 m^2 except in the bends where it is 43 m^2. Reinforcement is made either by spot bolting, shotcreting or steel meshing. The blasted rock is loaded with an electric loader. Haulage is done with conventional trucks. The rock waste is transported on a barge to the harbour of Oskarshamn in order to extend the current quays.

After each blasting round the tunnel face (including roof and walls) is mapped in detail. Photographs are also taken after every round. All the collected data are immediately stored in a CAD system connected on-line to the geodatabase at the SKB headoffice in Stockholm. Every fourth round two 20 meter long probing hole are drilled. The inflow of water is measured and pressure buildup tests are performed. From 140 sections in boreholes in the surroundings, groundwater pressure data are collected every fourth hour. Two sections in every borehole are also equipped with electrical conductivity probes in order to measure the changes in salinity in the water due to natural variations or due to the excavations. The data are stored in a logger at every borehole. During 1991 new equipment will be installed at the boreholes so that the monitoring data are accessible on-line at the site office.

19.5.5 Design works

The target for the design works 1990 was to submit drawings and specifications to:

— Receive permits necessary prior to start of construction October 1.

— Procure construction works for excavation and establishment of service facilities.

These targets were fulfilled.

The drawings and specifications for the excavation contract were completed March 1990. Six tenders arrived and a contract was awarded to Siab June 14. After the start of construction, working drawings are delivered in accordance with a delivery schedule.

Invitations to tender for turnkey contracting of the ventilation and hoist system were sent out during spring 1989. It was later decided to postpone the procurement until the end of 1991.

Master drawings for the buildings on Äspö are ready. Building permit has been obtained for the works on Äspö. Detailed planning of the Äspö village will be completed during the autumn of 1991.

19.5.6 Planning for Operational period 1994-

An overview of the preliminary programme for the Operational period is given in /19-2/.

It was envisaged that some activities related to the Radionuclide Migration Test were to be carried out during 1990 in order to develop a new chemical probe. Preliminary contacts with CEA, Cadarache, have indicated that the SKB design will be possible to construct and operate. The development is planned to be a joint effort between CEA, France and SKB.

20. NATURAL ANALOGUE STUDIES

20.1 THE POÇOS DE CALDAS PROJECT

Processes governing the release and transport of radionuclides with groundwater flow have been studied in and around two separate locations close to the town of Poços de Caldas in Minas Gerais, Brazil. One site, Morro do Ferro, is a thorium lanthanide mineralization, and the other, Osamu Utsumi, is a uranium mine. Participants in the project are Sweden (SKB), Great Britain (UK DOE), Switzerland (NAGRA), USA (US DOE) and Brazil (Federal University of Rio de Janeiro, Pontificial Catholic University of Rio de Janeiro (PUC), University of Saõ Paulo, CNEN and URANIO DO BRASIL).The project was managed and coordinated by SKB.

The project started in May 1986. It was originally planned for three years but later extended to the end of March 1990. The project is now officially closed and the final results were presented at the fourth CEC National Analogue Working Group Meeting in Pitlochry, Scotland, 18-22 June 1990 /20-1/. The results are available in a series of technical reports /20-2 to 20-17/. One of the technical reports is a summary of the project /20-16/. Progress reports, publications and presentations have been made in the course of the project from May 1986 to March 1990 /20-18 to 20-45/. Further publications are being prepared and will be submitted as a special issue of Chemical Geology during 1991. Since the first project year of feasibility investigations the study has proceeded in accordance with the following list of technical objectives:

1. Assist in the validation of equilibrium thermodynamic codes and databases used to evaluate rock-water interactions and solubility-speciation of elements.

2. Produce a model of the geochemical evolution of redox fronts, specifically aimed at understanding long-term, large-scale movements of redox sensitive natural series radionuclides.

3. Determine interactions of natural groundwater colloids, radionuclides and mineral surfaces with respect to radionuclide transport processes and colloid stability.

4. Model the migration of lanthanides and uranium thorium series radionuclides during hydrothermal acitivity similar to that anticipated in the near-field of some spent-fuel repositories.

20.1.1 Poços de Caldas caldera

A large volcanic caldera with a diameter of about 30 km was formed 75 Ma ago in the Poços de Caldas region, see Figure 20-1. Intrusive alkaline volcanic nepheline syenites and phonolites rich in potassium formed the most common rock types within the caldera complex.

Uranium, thorium and lanthanides were in general above background for these rock types. Hydrothermal activities have concentrated these elements in certain locations and led to the formation of ore deposits. The Morro do Ferro thorium lanthanide mineralization and the Osamu Utsumi uranium mine is situated within the caldera region.

The Poços de Caldas caldera region is today a plateau 1500 meters above the sea level. Very early in its evolution it had a comparatively low relief of less than 500 m above the present surface. The rate of erosion, averaged over a 50 Ma is about 6 to 7 m/Ma. Drainage patterns on the Poços de Caldas plateau have not changed very much over the last 50 Ma when an average denudation rate of 12 m/Ma has been estimated. Weathering rate should have been similar over the last 10 Ma.

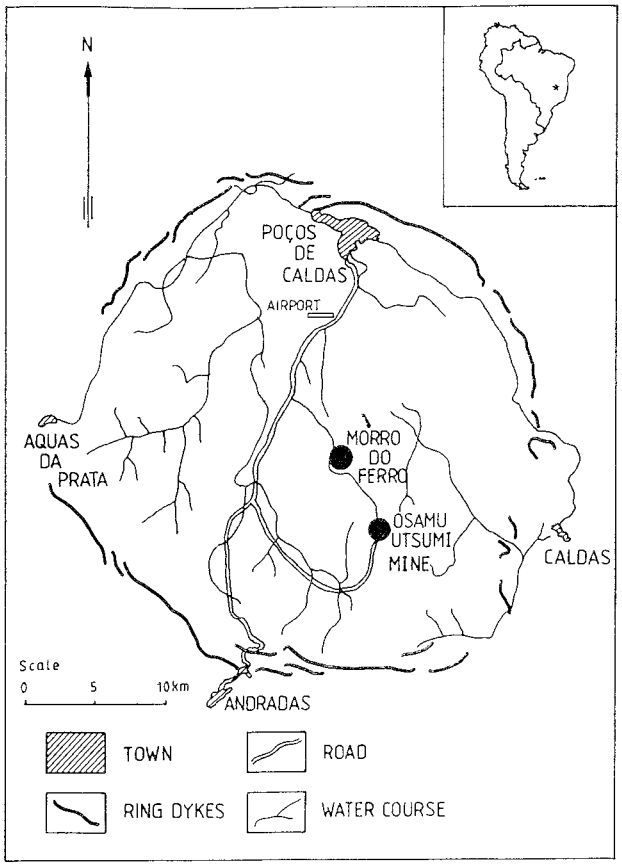


Figure 20-1. *Location of the Osamu Utsumi mine and Morro do Ferro natural analogue study sites.*

20.1.2 Morro do Ferro

The Morro do Ferro thorium lanthanide deposit is situated near the summit of a rounded hill which is 140 m above the base, and about one kilometer in diameter. The hill is drained by two small streams. The ore body had been investigated in the fifties and sixties by ground surveys, drilling, trenching and gallery construction. A cored borehole down to a vertical depth of 450 m was made during that phase.

The Poços de Caldas project work has included the drilling of the four boreholes MF10, 11, 12 and 13 down to depths ranging from 40 to 75 m, see Figure 20-2. Morro do Ferro is completely weathered down to a depth of 100 m and intensively altered below that. Resistant veins of magnetite are extending through the weathered and altered rock.

Studies indicate that this has been a carbonatite complex intruded into the phonolite rocks. Weathering has produced a very deep laterite layer.

In borehole MF12, which was drilled near the bottom of the hill, "fresh" phonolite was encountered at a depth of 27.5 m. A redox front was encountered at 35.7 m within the phonolitic rock.

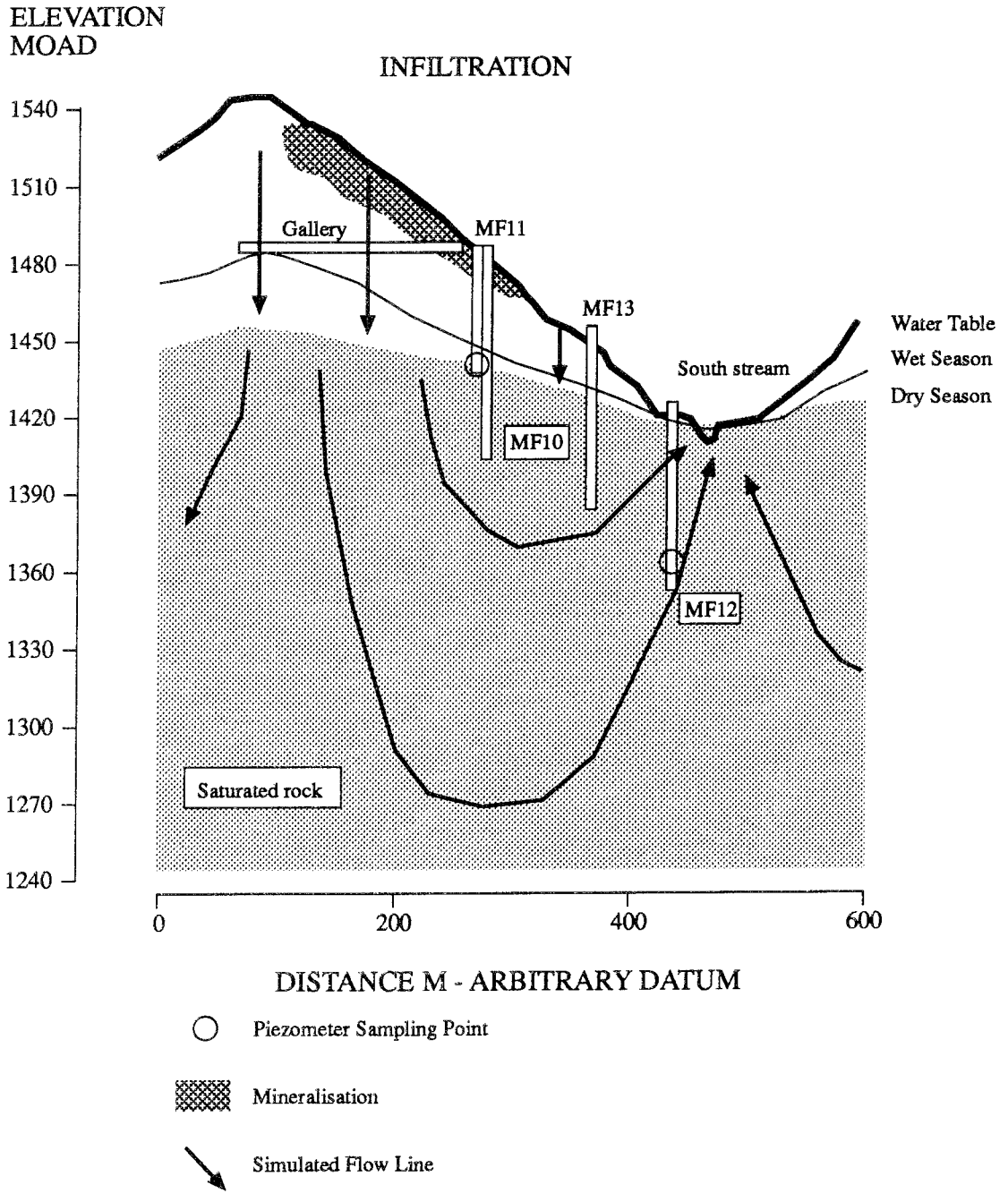


Figure 20-2. Cross-section through Morro do Ferro.

The thorium lanthanide mineralization is situated in the laterite and is most concentrated from the surface down to between 30 and 100 m. The ore body is about 150 m wide and 320 m long. It contains roughly 30 000 metric tonnes of thorium (cut off grade 1% ThO_2) and 50 000 metric tonnes of lanthanides (cut off grade 4% REE).

Samples taken from the ore body contain 0.5-10 g thorium/kg, comparable quantities of lanthanide and 20-60 mg uranium/kg. Thorium bearing minerals such as thorite, thorianite, cerianite, cheralite and thorbastnaesite are present in the 6.3-20 grain fraction. Lanthanides and uranium are also associated with these mineral phases. In the less than 2 grain fraction, thorium and uranium are associated with iron hydroxides and clay particles coated with iron hydroxides.

At the top of the hill the groundwater table is at least 80 m below the ground surface. At the bottom of the valleys the water table is near the ground surface and groundwater discharges as seepages or springs. Hydraulic tests in the boreholes indicate permeabilities in the range 10^{-5} to 10^{-6} m/s in the weathered rock and 10^{-7} to 10^{-9} m/s in the surrounding phonolite. The lowest value was recorded at depth in the MF12. Two-dimensional hydraulic modelling was carried out assuming a bulk permeability of $5 \cdot 10^{-6}$ m/s.

Table 20-1. *Representative groundwater analyses of samples from boreholes in Osamu Utsumi mine (F1, F2 and F4) and Morro do Ferro (MF12). Concentrations in mg/l and Eh in mV*

	Osamu Utsumi			Morro do Ferro
	F1	F2	F4	MF12
Code	[Select]	PC-GW-78	PC-GW-80	PC-GW-50
Date	870707	890320	890413	880614
T °C	22	21	24	21
pH (field/lab)	4.87/4.06	5.90/6.42	5.83/6.38	5.99/6.19
Eh	338	191	462	212
Alkalinity	2.0	10	23.5	22
Ca	0.47	2.65	7.88	8.48
Mg	0.07	0.07	0.46	0.70
Sr	0.043	0.009	0.20	0.346
Ba	0.125	0.13	0.12	< 0.001
Na	0.20	0.2	0.63	0.84
K	12.7	13.5	11.8	11.2
Fe(II)	1.30	1.67	6.13	0.74
Fe(III)	1.33	1.70	6.27	0.79
Al	< 0.05	0.319	0.183	0.21
Mn	0.19	0.318	0.13	1.68
Zn	0.083	0.211	2.17	0.27
SO_4	16	14	28	9.5
F	0.41	2.57	6.0	5.3
Cl	3.0	< 2	< 2	< 0.1
Br	0.04	< 0.05	< 0.05	< 0.05
SiO_2	35	29	34	33.4

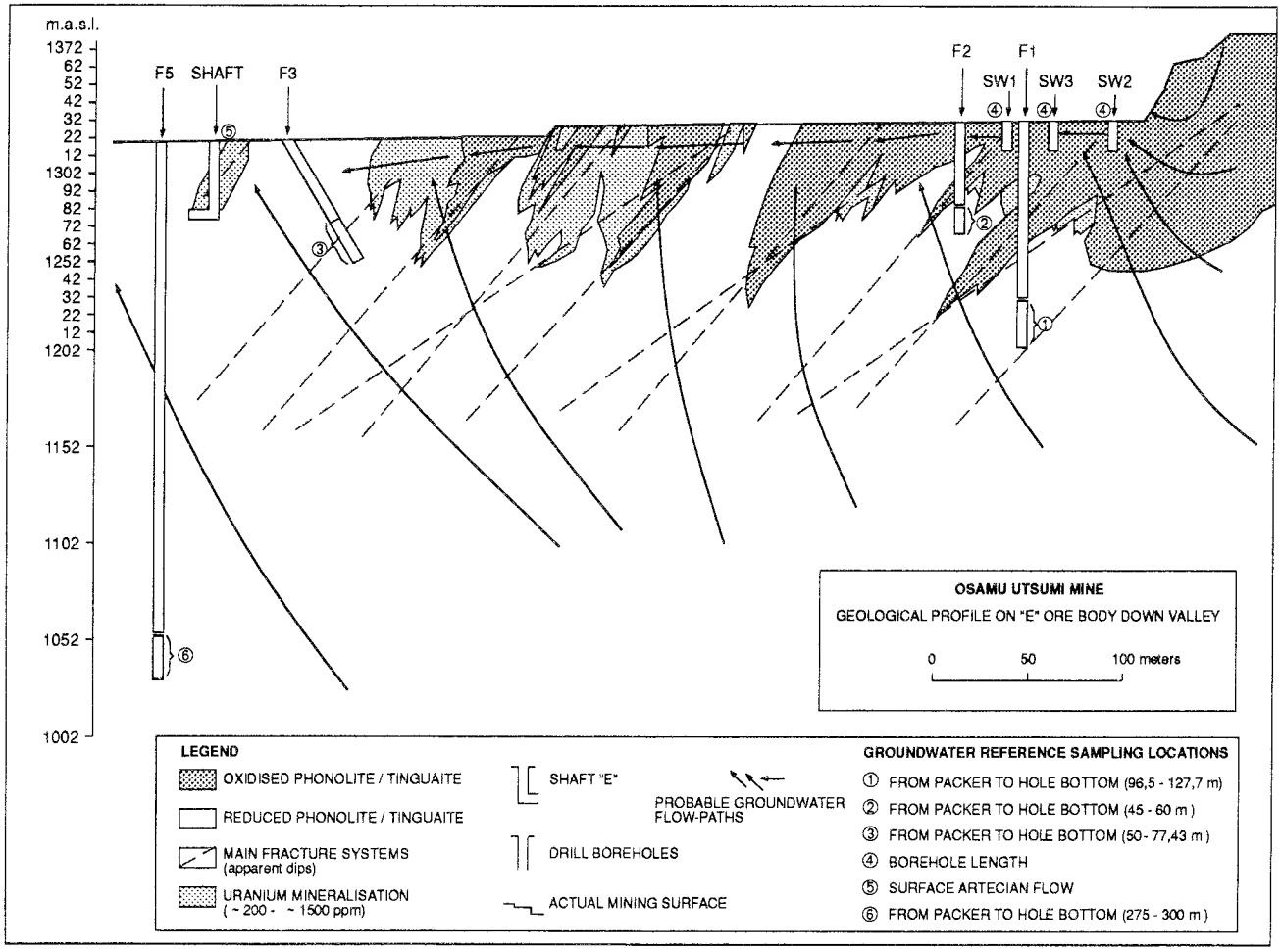


Figure 20-3. *Geological properties and borehole locations at Osamu Utsumi mine.*

Groundwater samples were taken from boreholes MF10, 11, 12, 13, the north and south stream and a piezometric hole PZ2 adjacent to MF12. The results are summarized in Table 20-1. The groundwater has a relatively low ionic strength. Samples taken below the hill from MF12 have tritium contents 0.10 to 0.24 TU suggesting an age of 40-50 years. The redox properties of the groundwater is ranging from oxic near the surface to anoxic at depth.

20.1.3 Osamu Utsumi uranium mine

The Osamu Utsumi open pit mine has been in operation since 1975. The mine covers an area of two square kilometers. The host rock consists of phonolites and nepheline syenites which have been hydrothermally altered. The hydrothermal alteration and the primary mineralization are related to the intrusion of two large breccia pipes. Elements associated with uranium in the ore are thorium, lanthanides, molybdenum and zirconium.

Weathering under semi tropical conditions has altered the upper parts of the rock. Oxidizing groundwater has caused a downward moving redox front, which is seen as a very sharp transition from yellowish brown (oxidized) to bluish grey (reducing) rock. The yellowish brown colour is caused by the formation of iron oxhydroxides by the oxydation. The bluish grey rock is rich in pyrite. Uranium is enriched at the redox fronts, occurring sometimes visibly as nodules of pitchblende (uranium dioxide) on the reducing side of the redox front. Single nodules of relict pitchblende may also be found on the oxidized side. Uranium is also present as sorbed to the iron oxyhydroxides.

Three shallow boreholes SW01, 02, 03 and five deep boreholes F1, 2, 3, 4 and 5, the deepest down to about 300 m, were drilled in the mine for the project, see Figure 20-3. Borehole F4 was made for the high temperature hydrothermal studies.

Hydraulic testings have been performed in the boreholes F1, 2, 3 and 4. The conductivity of the upper 10-15 m under the quarry floor is high, 10^{-4} m/s, due to the excavations. Below 30 m the conductivities range from 10^{-5} to 10^{-8} m/s. Three dimensional ground water flow before and after mine excavation was simulated by computer calculations. The excavations have, of course, changed the flow pattern completely, see Figure 20-4.

Groundwater samples for chemical and isotope analysis have been obtained routinely from packed off sections of all project boreholes F1, 2, 3, 4, 5 and from the artesian occurrences such as the Piezometer Station 22 and an old exploratory shaft. The results of the analyses were evaluated. Representative data are presented in Table 20-1.

The groundwaters are meteoric in origin. Upwelling discharge groundwater is relatively low in tritium (0.5 TU). Mixing with recent recharge (about 4.5 TU) is indicated as deep as 50 m. Below that the waters have lost their oxygen content and nearly all the dissolved iron occurs as Fe^{2+} which indicates mildly reducing conditions. The pH stabilizes and the uranium concentrations, which are relatively high in the acidic water in the mine, drops to the microgram per liter range at depth.

20.1.4 Geochemical model testing

Thermodynamic codes are used to calculate element solubilities and speciation in order to predict release and mobility of radionuclides in the geosphere. This is a powerful tool for safety assessment but also sensitive to data and assumptions used such as thermodynamic constants, solid phases and the existence of phenomena not considered by the models. Five different groups were therefore engaged to blindly predict concentrations of relevant elements in the groundwater knowing only the mineralogic composition of the rock and ore and general groundwater composition. The modelling results for some elements are summarized in Table 20-2. There is in general a fair agreement in results between the groups except for nickel where in one group the control of a low soluble solid nickel phase was erroneously assumed. Comparing the calculation with the observations it is reassuring to conclude that again with the exception of the single nickel result, all predicted solubilities are close to or above those observed.

The observed uranium concentration is in the microgram per liter range which is well in agreement with numerous other observations of uranium concentrations in deep groundwater reported in the litterature. At many

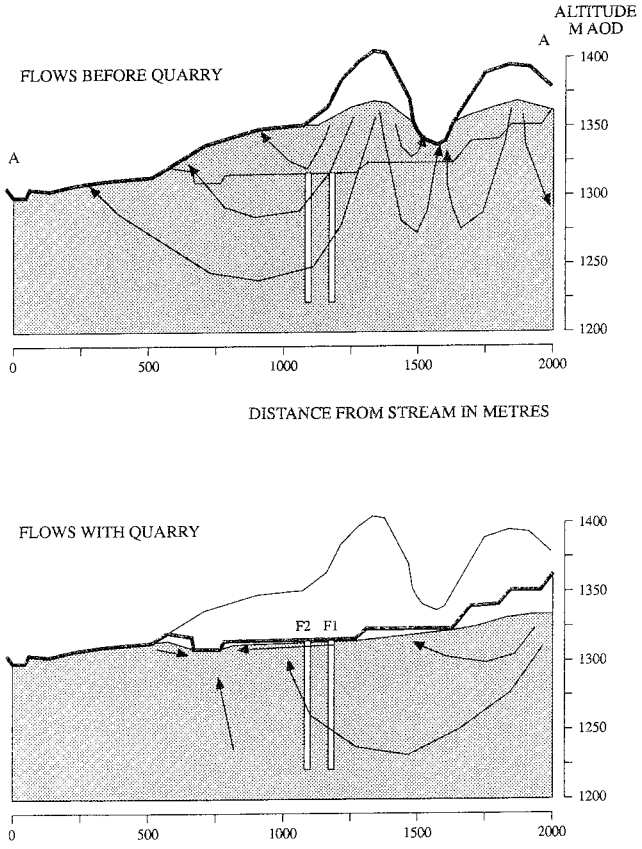


Figure 20-4. Cross-section of the Osamu Utsumi mine area showing water flow prior to and post-excavation.

Table 20-2. Observed and predicted concentrations of trace elements in groundwater from Osamu Utsumi (F5) and Morro do Ferro (MF12). The intervals cover the results of five independent groups from SKB, RIT, PSI, Harwell and Atkins. All concentrations in µg/l.

Element	Observed concentrations		Predicted solubilities
	F5	MF12	
U	7.5	2.4	10000 - 240
Th	0.04	0.06	0,5 - 0,02
Pb	1000	820	40000 - 650
Ni	30	0.3	$3 \cdot 10^{6}$ - $3 \cdot 10^{-6}$
Sr	5.6	350	10^{6} - $2 \cdot 10^{4}$

places this can be explained by the redox state of the groundwater but not in this case. Because calculated uranium concentrations are in the milligram per liter range, see Table 20-2, it demonstrates the existence of other solubility limiting processes such as sorption, coprecipitation or mineral surface mediated redox processes.

Sorption and coprecipitation can also explain the lower than calculated nickel and strontium concentrations. So far coprecipitation has not been extensively used in safety assessment.

Predictions of element speciation was tested to some extent against field ion-exchange separation results. Reasonable consistency was obtained for several elements and further development and testing of the technique were emphasized.

20.1.5 Redox front modelling

The geochemical conditions have been investigated across the redox fronts in the Osamu Utsumi mine. The reactions at the front can be summarized by the following formulas:

$$FeS_2 + O_2 \rightarrow Fe(OH)_3 + H^+ + SO_4^{2-}$$

$$\text{K-feldspar} + H^+ \rightarrow \text{kaolinite} + K^+$$

Oxidizing groundwater has infiltrated and pyrite has become oxidized to iron(III) hydroxides and sulphate. This generates sulphuric acid which attacks the K-feldspars. Potassium ions are thereby liberated and clay minerals formed. The velocity of the front varies between less than a meter to about 10 meters per million years. Uranium is enriched at the front and pitchblende has precipitated on the reducing side subsequently becoming dissolved when passed by the front. Formation and dissolution rates of pitchblende nodules are similar and in the range of centimetre per million years as determined by isotope methods. Uranium is also enriched by sorption on the iron oxhydroxides.

A simple mass balance calculation has been performed, assuming infiltration of 100 mm of oxygen saturated water per year at the front. Further assuming complete pyrite oxidation, a front velocity of 25 m per million years was obtained.

Assuming that groundwater flow is concentrated to the conductive parts of vertical open fractures and, using advection-diffusion models for transport of oxygen, the observed marked "fingering" of the front can be simulated. The existence of transport phenomena such as "matrix diffusion" and "channeling" is thereby demonstrated, see Figure 20-5. Detailed modelling of redox front processes was carried out using the CHEQMATE and CHEMTARD coupled equilibration-transport codes. This enables the observed processes to be better described than by the simple mass balance approach. The sharp front was simulated as well as the precipitation of uranium minerals on the reducing side, see Figure 20-6. The calculated front velocity agreed with that observed.

Another approach tested was kinetic modelling. In this model the groundwater-mineral reactions are described by pseudo-kinetic rate expressions. The sharp front, the precipitation of uranium minerals and the formation of secondary pyrite were successfully simulated.

A number of other elements were also like uranium enriched at the redox front. This could not at present be simulated with any model. One reasonable explanation for the trace element enrichment at the redox front is coprecipitation, notably coprecipitation on secondary iron minerals.

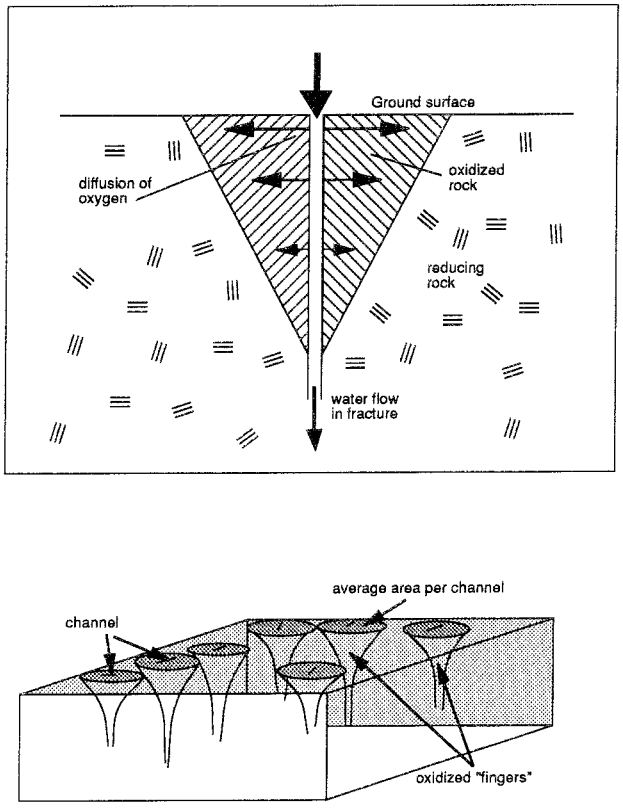


Figure 20-5. Development of the geometry of the redox front.

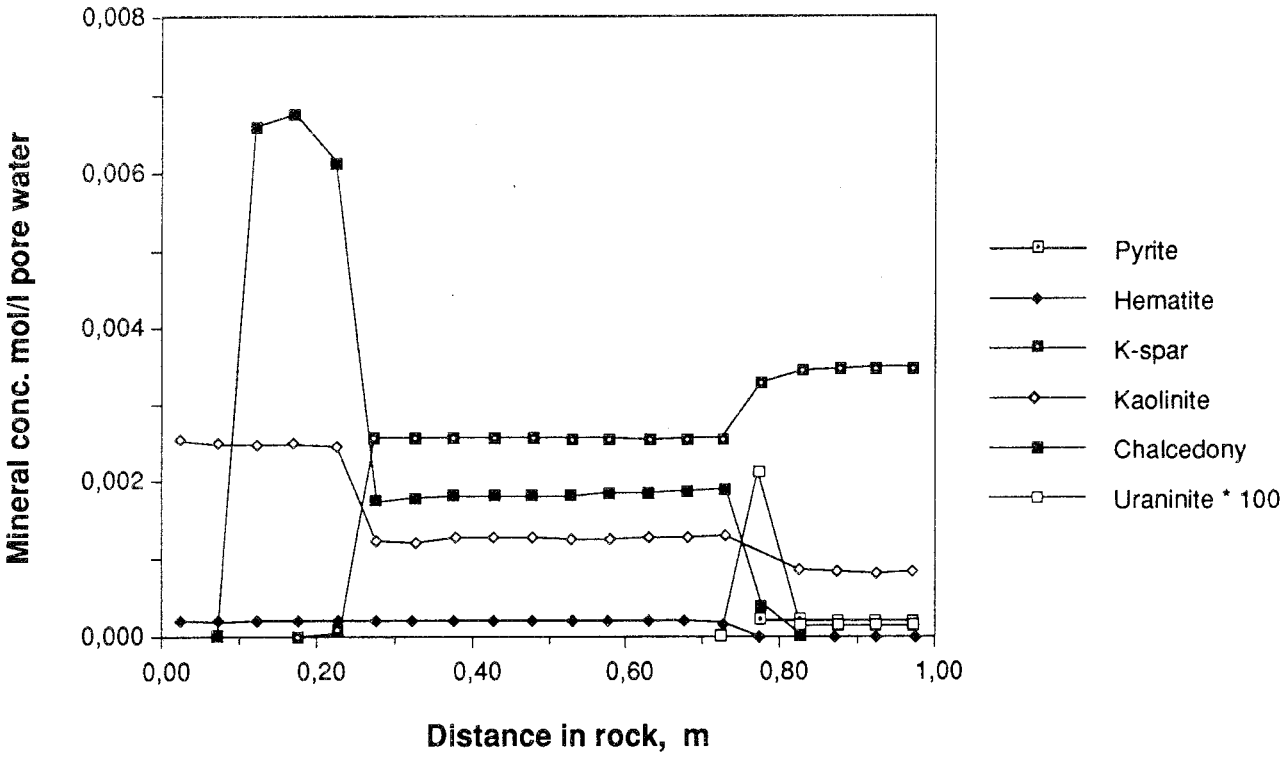


Figure 20-6. Calculated mineral concentrations across the redox front in the uranium mine Osamu Utsumi.

20.1.6 Colloids

Colloidal particles are abundant in surface and near surface waters in Morro do Ferro and Osamu Utsumi. The colloidal material partly consists of inorganic compounds and partly of organic, humic substances. Most of the dissolved thorium and lanthanides and a significant portion of uranium are bound to the particles and colloids.

Favourable conditions for colloid formation and transport are:

— Intense weathering with high clay contents in the weathered rock,

— Low ionic strength groundwaters promoting colloid stability,

— High content of iron and silica in the groundwater,

— Redox and pH transitions along the flow paths,

— Rapid groundwater flow.

Colloidal particles are indeed found at depth. However, the concentrations are considerably lower as compared to surface or near surface groundwater in the area. In addition to that it should be noted that concentrations of less than 1 mg/l are not much different to what is found in normal deep groundwater at our study sites in Sweden.

Ferric oxyhydroxides and humic species dominate at depth. Clay particles are less abundant. This is also similar to Swedish study sites where iron oxyhydroxide colloids are found at depth but very little clay particles.

In the deep groundwaters at Morro do Ferro the dominating fraction of polyvalent metals especially thorium and lanthanides are associated with colloids and particles. However, relative concentrations of lanthanides, see Figure 20-7, and uranium isotope ratios, indicate that colloids and particles at depth are not derived from the surface. Their lanthanide and uranium content is rather related to the groundwater content of these elements at depth. It is therefore concluded that although particulate materials act as sorbents for many elements, especially three- and tetravalent ions, they are apparently not transported across the rock barrier.

20.1.7 Hydrothermally induced transport

Temperatures as high as 200 to 300°C in a repository will cause mineralogical alterations and induce temperature and fluid convection in the host rock. It will also influence the leaching of the waste form, in the event of becoming exposed to the fluid. This applies to the US nuclear waste program and is of interest for us when evaluating alternative disposal concepts.

As an analogue to the influence of high temperatures in a repository the chemical, isotopic and mineralogical alterations which occurred during primary ore deposition in a breccia pipe of about 0.5 km diameter at the Osamu Utsumi mine were studied and modelled. Borehole F4 was drilled through the breccia pipe, see Figure 20-8. The hydraulic permeability was measured and the drillcore studied.

A coupled fluid convection-temperature model was used to model the fluid flow and development of the temperature field. Flow was found to have been concen-

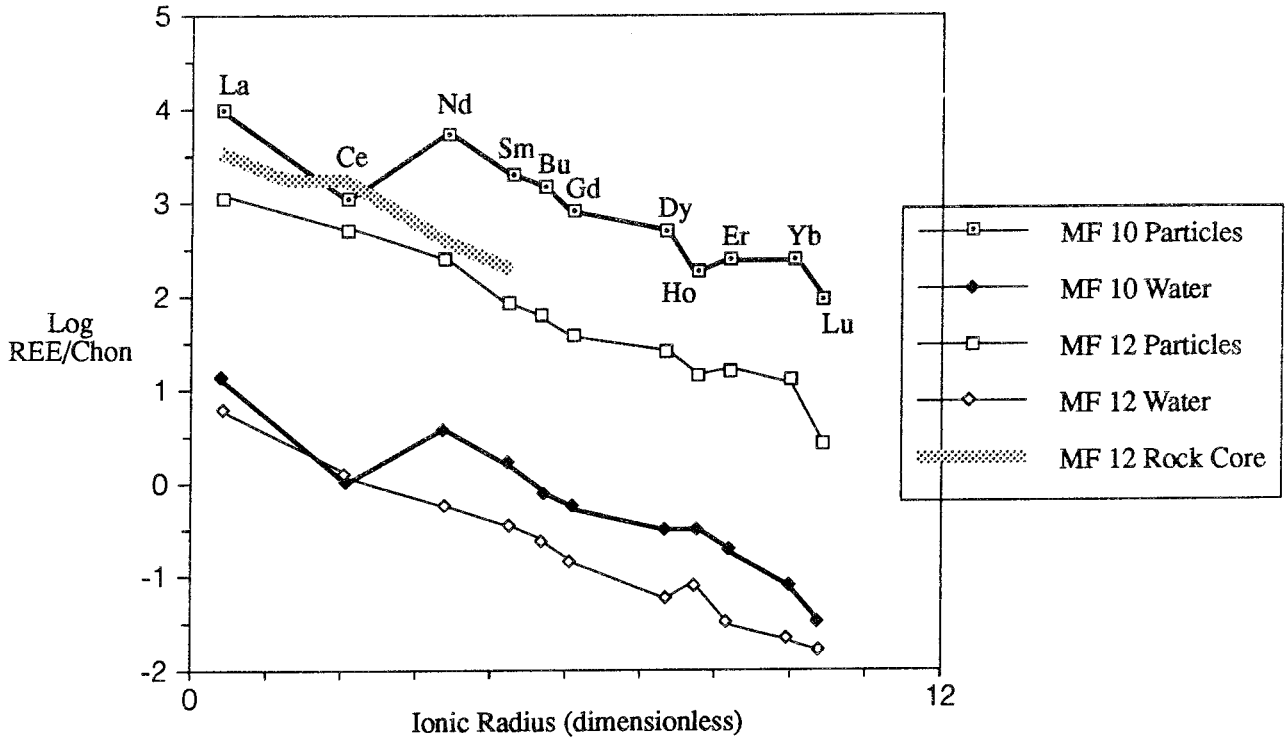


Figure 20-7. *Chondrite normalised REE patterns in typical rocks, groundwaters, and corresponding suspended particles from Morro do Ferro.*

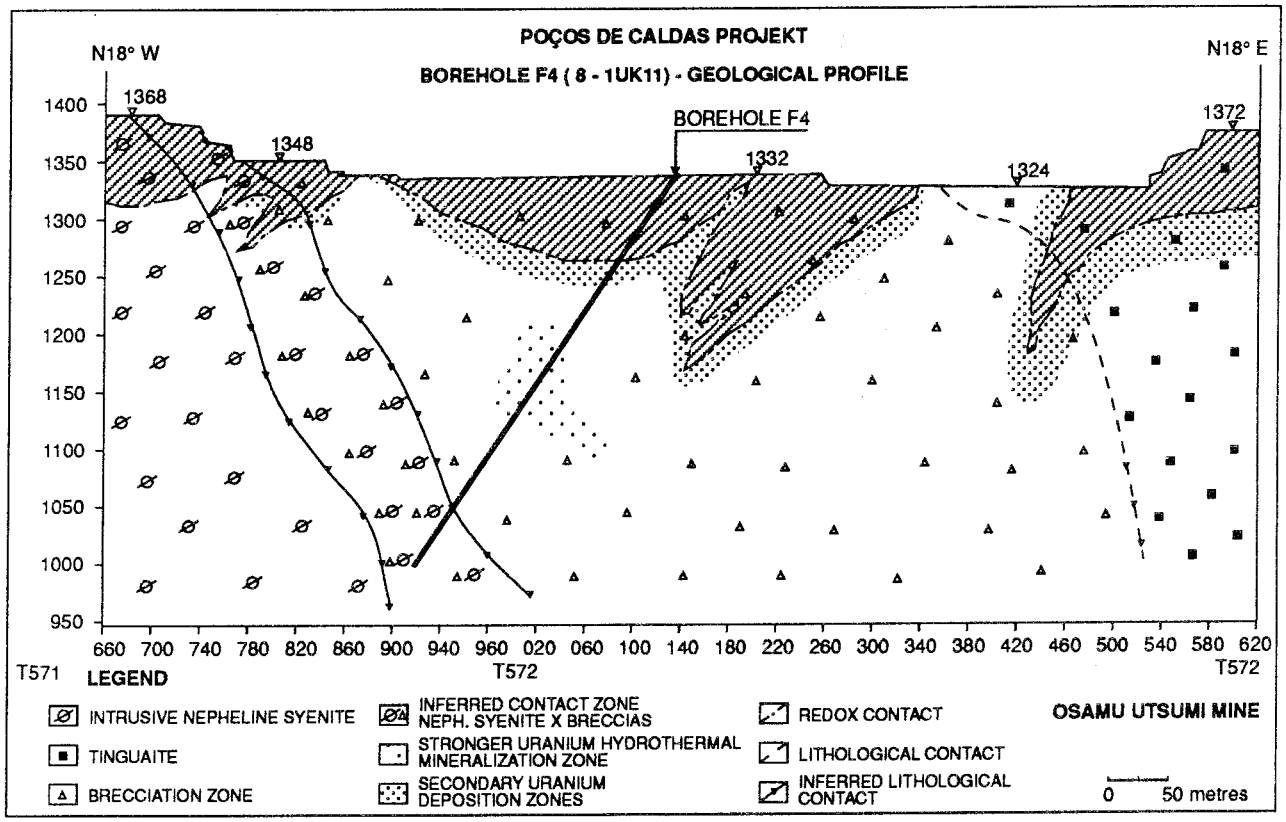


Figure 20-8. *North-south cross-section of the Osamu Utsumi mine showing the relationship of borehole F4 with the breccia pipe and associated uranium mineralization.*

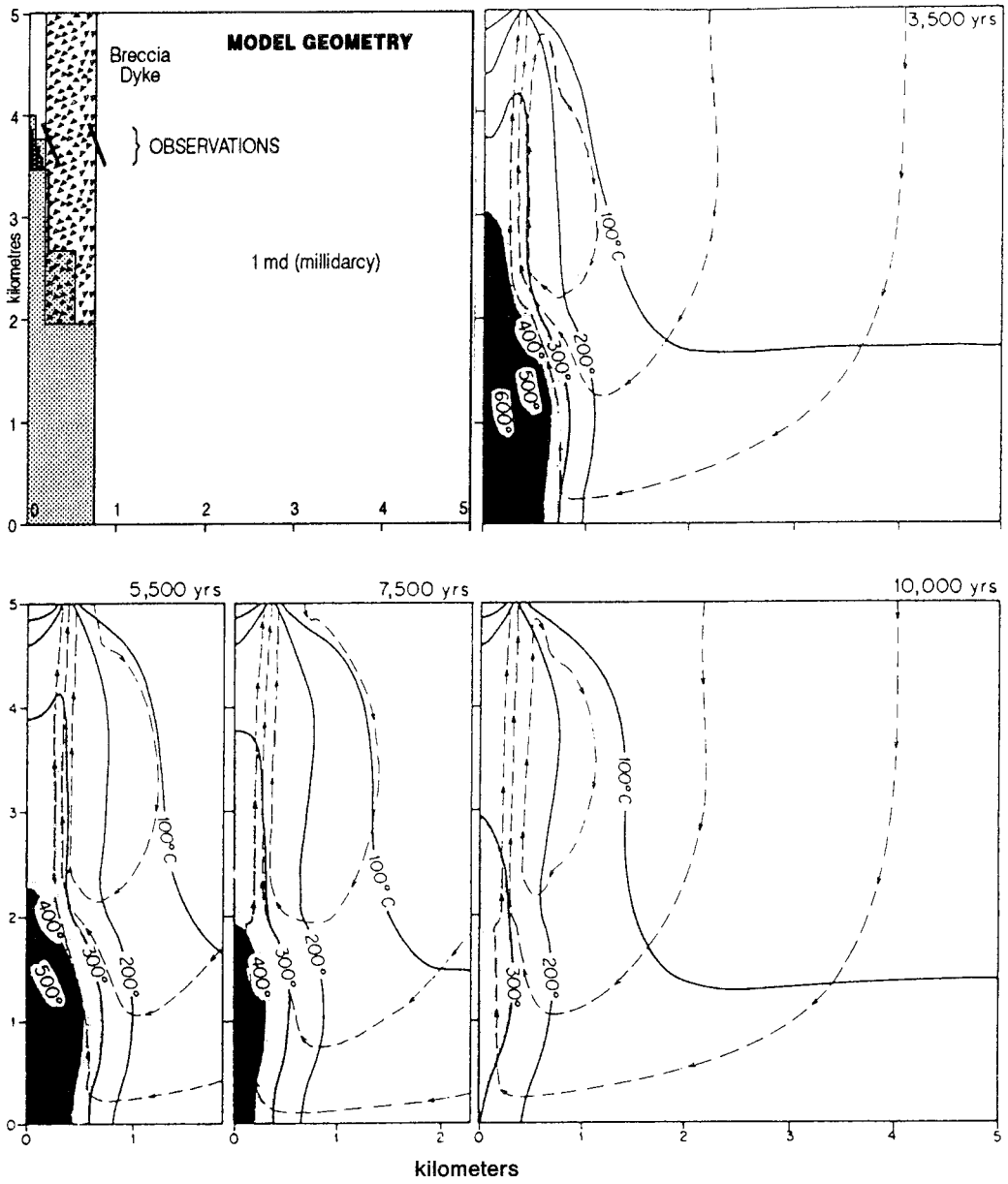


Figure 20-9. *Calculated induced groundwater flow and progressive cooling of the magmatic intrusion in Osamu Utsumi. The temperature of the initially 700°C intrusion is indicated by solid contours. Streamlines indicating the direction of fluid flow are shown with dashed lines and arrows. The general permeability is 1 millidarcy, except for the breccia pipe which has a permeability of 5 millidarcies and the intrusion whose permeability decreases exponentially with temperature for temperatures higher than 300°C.*

trated to the more permeable breccia pipe with temperatures up to about 300°C, 1000 years after the magmatic intrusion. By 20 000 years the intrusive was largely depleted in heat, see Figure 20-9. The observed uranium concentration of 50 mg/kg was caused by the hydrothermal circulation. Literature data on uranium solubility at 330°C, although recent, varies by as much as 5 orders of magnitude. The effect of hydrothermal circulation on uranium distribution can, however, be judged by the observations.

The field observations and modelling of hydrothermal alterations were validated by a laboratory experiment. A nepheline syenite rock sample from Poços de Caldas was placed in an autoclave, centrally heated to 350°C and water passed through at 5 l/min at 238 bars for 200 hours. The results agreed with the observations and supported the model.

The same model as that used for the Poços de Caldas analogue was applied to a hypothetical high-temperature repository. A similar circulation system with a maximum temperature of 300°C developed in the calculations. However, the effects on hydrothermal alteration and uranium transport was much less. At Poços de Caldas as much as 100 metric tonnes of hydrothermal solution have passed per cm^2 (in the breccia) as compared to the calculated value of 100 kg/cm^2 in the repository rock hotter than 200°C. The reason for this difference is that the Poços de Caldas breccia pipe has focused much of the hydrothermal

circulation, whereas the model high-temperature repository causes a more diffuse circulation. As a result of the comparison, the amount of hydrothermal alteration in the repository is expected to be about 0.1% of that observed in the Osamu Utsumi mine breccia. With no other barriers, the uranium transported and precipitated around the repository would only be 0.05 mg/kg rather than the 50 mg/kg observed in Osamu Utsumi.

20.2 THE CIGAR LAKE PROJECT

The Cigar Lake uranium mineralization is being investigated as a natural analogue to a high-level waste repository. The Cigar Lake deposit has many features in common with a repository. The ore has a very high grade of uranium in the form of uraninite (uranium dioxide) with local concentrations in excess of 55% of weight uranium. The ore is embedded in dense illitic clay at a depth of about 430 m. The overlaying host rock is sandstone which is relatively permeable in contrast to the clay. The dense clay and the benign geochemical conditions seem to have played a key role in the successful isolation of the ore for 1.3 billion years.

Since April 1989 AECL and SKB have been engaged in a joint Cigar Lake natural analogue project. Phase I of the project was concluded in April 1990 with a workshop in Pinawa. Present data were presented and discussed /20-46/. The second phase was planned.

The investigation programme contains the following tasks:

— Geochemistry/mineralogy

— Hydrogeochemistry

— Colloids

— Hydrogeology

— Organic material and microbes

— Radiolysis

— Nuclear reaction products

— Modelling

The main objectives are to describe and model the water-mineral interactions in the deposit and the trace element migration around it, with the ultimate aim to validate those models used for the assessment of possible release and transport of radionuclides from a spent fuel repository.

So far it may be concluded that the groundwater in Cigar Lake is similar in composition to what is found at our study sites. Colloids are being analysed. The concentrations of humic and fulvic acids are relatively low. The clay minerals have been carefully investigated. Hydrogeologic measurements and model calculations have been performed.

Oxidation of the near field by radiolysis has been indicated. However, the uranium dioxide in the ore seems not to have been affected by this process.

20.3 MISCELLANEOUS

SKB have become engaged as an external participant in the CEC sponsored natural analogue project in Oklo. The project is managed by CEA in France.

Oklo is a uranium mine in Gabon in Central Africa. In Oklo and the adjacent Okelobondo a number of zones have been discovered where natural nuclear criticality has occurred about two billion years ago. These natural reactors operated for time periods of about 100 000 years. Most of the fission products and actinides generated apparently stayed in the reactor zones or in the near vicinity.

21. THE BIOSPHERE

The biosphere studies shall describe the transfer of radionuclides from the deep groundwater to biota and the subsequent dose to man. As the exact knowledge of systems and processes is not at hand, rather coarse compartment models are used to describe this nuclide transport. As direct validation of the models is impossible, the confidence in these models can only be increased by applying them to other problems like atmospheric fallout or Hg pollution and by comparing the results from different groups. This has been the basis for the Chernobyl studies and the participitation in BIOMOVS.

21.1 THE TIME ASPECT

The biosphere studies has to bridge not only the spatial distance between bedrock and man, but also the timescales involved.

The end point of any assessment study is annual dose to man, where dose rate (Sv/h) also should be considered. A human being can be expected to exist for no more than 100 years and his living habits probably changes each 10 years. Changes in land exploitation can occur from 10 to 1000 years. More dramatical changes in nature, as lakes drying up, eventuates in 1000 to 10000 years, iceages and changes in sea level in 10000 to 100000 years while geological changes operates in timescales of several million years. The timescale covers more than nine orders of magnitude (hours to million years).

The assumption that all processes are in a semi steady state would simplify the treatment of biosphere modelling. It is possible though, that some reservoir could accumulate radionuclides (not necessarily with higher concentration) during a long time period. Due to some change in for instance land exploitation these nuclides can be released during a relatively shorter time period, giving a higher dose during that short time. One example of this is the ageing lake, where the sediment of a lake evolutes into farmland. Other examples may exist but no systematic study has been accomplished. The ageing lake example /21-1, 5/ shows that these processes can occur but that the effect on the assessment is limited.

21.2 VALIDATION OF MODELS: BIOMOVS

BIOMOVS (BIOspheric MOdel Validation Study) was an international cooperative study initiated in 1985 by the Swedish National Institute of Radiation Protection, SSI, to test models designed to calculate the environmental transfer and bioaccumulation of radionuclides and other trace substances. To SKB this has been an opportunity to test the widely utilized modelling tool BIOPATH and the uncertainty tool PRISM in several applications. The study was run for five years and ended in 1990.

The primary objectives of BIOMOVS were threefold, namely:

- to test the accuracy of the predictions of environmental assessment models for selected contaminants and exposure scenarios;
- to explain differences in model predictions due to structural deficiencies, invalid assumptions and/or differences in selected input data; and
- to recommend priorities for future research to improve the accuracy of model predictions.

The study has provided an international forum for testing and critically evaluating models commonly used to predict the transfer of radionuclides through the biosphere. BIOMOVS has been the first organization devoted to model testing in the field of radioecology and to:

1. Require that each model prediction be accompanied by a quantitative estimate of uncertainty, and evaluate the uncertainty procedures and results.

2. Test the use of models developed for radiological assessment purposes to predict the biosphere migration and accumulation of a non-radioactive trace element (mercury).

3. Utilize world-wide data sets on Chernobyl fallout to evaluate model predictions through the process of a blind test.

BIOMOVS has revealed the potential for exposing people to doses arising from buildup of radionuclides in soils and lake sediments that could exceed in magnitude those arising from the introduction of equivalent amounts of radioactivity into streams and lakes used for drinking water /21-5/. It has focussed attention on the problems arising when modelling transport across the geosphere and the biosphere interface and the transport of radionuclides in groundwater to surface soils in discharge areas /21-6, 7/.

BIOMOVS utilized two different approaches to fulfill its objectives, namely:

Approach A in which scenarios were formulated based on suitable observational data and model predictions were compared against independent data sets; observations were not made known to the modelers until predictions had been submitted.

Approach B in which model predictions and related uncertainty estimates for specific test scenarios were compared and the differences explained.

User judgement plays a significant role in determining the outcome of a model prediction because of decisions required to interpret the description of the scenario, derive relevant parameter values, and estimate uncertainty. Thus, similar models with similar data bases often produced different results when these models were used by different groups. This has highlighted the need for more than one independent modelling group to be involved with critical environmental assessment activities so that differences in predictions can be identified and resolved. In doing so, quality of the assessment results is enhanced and the defensibility of the results is improved.

The following is a list of summary conclusions derived from the BIOMOVS study.

— In trying to assess and improve confidence in model predictions of biospheric transport of radioactive and other trace substances the participants were made aware of the potential for very large uncertainties to be associated with any given prediction and for large discrepancies to occur among predictions submitted by different modelling groups.

— Once model predictions were corrected for common mistakes in programming and data entry, analyses of the results of the individual test scenarios revealed that confidence in model predictions was highest for well studied radionuclides (I-131 and Cs-137) and pathways of biospheric transfer (e.g. forage-cow-milk-pathway). In these cases uncertainties were usually well within one order of magnitude. For releases of long-lived radionuclides into the far distant future the uncertainties were generally much larger than one order of magnitude, indicating low confidence in model predictions for scenarios involving these conditions /21-6, 7/.

— The presence of large uncertainties for the predictions of concentrations of specific radionuclides in specific environmental media may not necessarily cause a lack of confidence in the overall assessment of dose or risk to man. The contributions of those nuclides and pathways to the total dose to a group or population would have to be considered. The B8 /21-2, 13/ scenario was expressly designed to explore this matter.

— The problem for which a model run is needed must be most carefully and completely described otherwise discrepancies due to interpretations and the appropriate selection of model and parameter will dominate overall uncertainties /21-6/.

— In general, model complexity increases a model's flexibility for dealing with a variety of assessment questions. However, if site specific data is unavailable to take advantage of this flexibility, generic or default values must be substituted and the increased complexity in model structure may not lead to more accurate predictions.

— While individual modelers may seem reasonably confident of their own predictions for some pathways and nuclides, the collective view that emerges from BIOMOVS is much less sanguine.

BIOMOVS has forcefully demonstrated the shortcomings of our present capabilities for biosphere modelling /21-7/. Older models involving well studied pathways and relatively shortlived radionuclides (e.g. Cs-137 and I-131) need improvement, but the newer models for the longer lived radionuclides and less well studied pathways inspire little confidence. With values assigned to basic parameters differing between modelers by 3, 4 and even 5 orders of magnitude, with estimates of uncertainties about these parameters by the individual modelers covering a similar range, and with, in the worst cases, little to no overlapping of the uncertainty ranges, the situation clearly demands a remedy. Ideally, any modelling group given a specific scenario should calculate levels of activity in any commodity that agree to well within a factor of 2. BIOMOVS has shown that such a target is a long way off even for the older well studied pathways.

Nowhere is the effect of the user more pronounced than in the uncertainty analyses. BIOMOVS has shown that there are such wide difference in the way individual modelers go about assessing the uncertainties, that nothing useful can be said about model uncertainty and uncertainty estimation. BIOMOVS revealed this situation which could not have been gained from a study of the text books on the subject.

The following parameters has been identified as the ones for which the largest uncertainties arise:

(i) Adsorption coefficients for soils and long-lived radionuclides (e.g. Tc-99, Np-237, Scenario B2 /21-4/).

(ii) Bioaccumulation factors for fish, particularly for radium and thorium (Scenario B3 /21-3/).

(iii) Concentration ratios between plants and soils (Scenario B2 /21-4/).

(iv) Interception factors for spray irrigation (Scenario B2 /21-4/).

(v) Resuspension factors from soils and other surfaces (Scenario B2 /21-4/).

(vi) Distribution of radionuclides between dust and soil particles /21-5/.

(vii) Assessment of effects of climatic and geomorphological changes on calculated doses and improved ways to model them (Scenarios B2 /21-4/ and B5 /21-5/).

21.3 SITE SPECIFIC STUDIES OF RECIPIENTS AT ÄSPÖ

This project is divided into the following three phases:

Phase I - Prestudy on which data are available, a preliminary fieldstudy and planning.

Phase II - Recipient studies regarding surface and ground water and water flows through the sounds, estuaries and coastal area.

Phase III - Recipient evolution - modelling of the likely evolution of the coastal region in the time perspective of 1000 to 10000 years.

In analyzing the mineral composition and natural radiation in sediments and soil samples at the site, it will hopefully be possibly to draw some conclusions about the history of long term radionuclide transport. Comparisons with future situations when flow patterns may have changed, may also be valuable.

During 1990 phase I and the first part of phase II were completed. Sediment samples (0.5-6 m sediment depth) from the waters around Äspö have been taken at 22 sites. 15 of these are concentrated to the area SE Äspö. Soil samples (0.4-2 m depth) from 4 sites on Äspö have been characterized. In some cases neutron activation analysis was used. Measurements with gammameter have been made along two well determined profiles, supplementing previous measurements.

Phase II and phase III will continue during 1991 to be reported in 1991 and 1992.

21.4 THE CHARACTERISTICS OF SEDIMENTS IN INFLOW AREAS

All the release pathways of radionuclides from a repository to man assume that the deep groundwater will reach the biosphere either in a well or in a groundwater outflow area like a lake or a stream. Should a substantial groundwater outflow take place in a lake, it will probably influence the sedimentation rate, the chemical composition of the sediments and the biologic activity in the local area. These are all factors that can be of importance to the transfer of radionuclides to man.

Two lakes have been selected for the experimental studies. The major constituents, some heavy metals (As, Cr, Co, Zn) and the uranium content of both sediments and the sedimental pore water are measured. Samples are taken at different depths in areas affected by the inflow and "normal" sediments. In the solid phase rare earth elements and thorium are also measured and grain size and organic fraction is determined.

The study will be reported in 1991.

21.5 THE DISTRIBUTION OF RADIONUCLIDES IN SOILS AND SEDIMENTS

The modelling of transport in soils and sediments have been heavily relying on the sorption assumption expressed as a single K_d-value. There is a strong need for improved techniques to model this important part of the biosphere models /21-9, 10, 11/.

Thus, a project was initiated in 1989 to better understand the processes of the accumulation of nuclides in sediments and soils. This can be achieved by:

— extending the understanding of sorption phenomena relevant to both the biosphere and the geosphere.

— using thermodynamic data and sorption data to explain and hopefully reduce uncertainty within the biosphere modelling (as the big intervals of uncertainty today mostly are the sequel of the highly variable K_d-values found in the litterature).

The study is expected to be reported in 1991.

21.6 THE CHERNOBYL FALLOUT

In order to utilize the Chernobyl fallout for validation of nuclide migration models in the shallow groundwaters and the upper soil layer, samples have been collected and measurements have been made in two Swedish areas since 1986 /21-8, 12, 14—19/. Model evaluations are currently performed using both compartment models /21-8/ and continuous flow models /21-12/. An other main issue is the chemical properties of the observed radionuclides, currently studied by migration in soil /21-19/.

Measurements of radionuclides originating from the Chernobyl accident in samples of deep and superficial ground water, soil profiles and dwell sediments from the Gideå and Finnsjön areas have been performed. The radionuclides studied are: Mn-54, Co-60, Ag-110m, Ru-106, Sb-125, Cs-134 and Cs-137. As expected there is a strong correlation between groundwater table fluctuations and precipitation and temperature fluctuations at different periods during the year.

The measurements of water from the deep core drillhole KGI02 over 3 years indicates an activity pulse of long-lived radionuclides, present in the Chernobyl fallout, at all sections (28-96 m, 97-106 m and 107 m-), which is surprising since the water flow at these depths is very low (approx. 0.05 l/min). The flow is not affected by the fluctuations in precipitation /21-12/ indicating that there is no short circuit and that the radionuclides are transported quite fast through the bedrock. The Ru-106 peak arrives 263 days after the fallout to the 96-107 m level, while the peak of Co-60 and Cs-137 arrives at 599 resp 516 days.

The migration of radionuclides in the soil profiles shows that the transport in till is relativly slow compared to sand and peat (the profiles were sampled each year since 1986). Other conclusions from this study is that:

— Co-60 moves relativly fast with 50% of the activity found in the upper 5 cm of sand and till.

— Ru-106 seems to move very fast and 50% of the activity is found in the upper 7 cm in sand.

— Ag-ll0m has moved very moderately but it should be observed that this nuclide is difficult to measure because of the low activity.

— Sb-125 seems to move very fast with 50% of the activity found in the upper 7 cm in till.

— Cs-134/137 can be found with 50% of the activity in the upper 3 cm in sand and till.

Measurements of radionuclide content in sediment profile samples taken in a dwell indicate a very fast migration through the sediment, shown by an almost straight radionuclide concentration profile versus depth.

21.7 CARBON-14 MODEL REEVALUATED

The well/lake scenario for C-14 release from SFR was modified to allow all C-14 (8.4 GBq) to be released from the repository, disperse and retard in the geosphere and enter the biosphere /21-20/. The individual doses peaked at about 24,000 years after repository closure at 5 nSv for local zone and 0,8 nSv for the regional zone.

In the local zone vegetables an water consumption contributed 41 resp 37%, while fish consumption dominated the dose in the regional zone.

22. INTERNATIONAL COOPERATION

An important part of SKBs programme is to follow the corresponding research and development work conducted in other countries and to participate in international projects within the field of nuclear waste management.

These efforts gives positive results in many ways e.g.:

— contributions to method– and model development

— broadened and strengthened databases

— exploration of alternatives for repository and barrier design, material selection etc.

— insights in programmes to broaden the public confidence in waste management systems

The international work gives a perspective to the domestic programme and is an aid to the SKB strive for maintaining state-of-the art in relevant scientific areas of nuclear waste management.

22.1 SKBs BILATERAL AGREEMENTS WITH FOREIGN ORGANIZATIONS

SKB has signed formal bilateral agreements with the following organizations in other countries:

— USA – US DOE (Department of Energy),

— Canada – AECL (Atomic Energy of Canada Ltd),

— Switzerland – NAGRA (Nationale Genossenschaft für die Lagerung Radioaktiver Abfälle),

— France– CEA (Commissariat à l'Energie Atomique) including DCC, IPSN and ANDRA,

— EC – EUROATOM,

— Finland – TVO and IVO,

— Soviet Union – SCUAE (State Committee on the Utilization of Atomic Energy),

— Japan – JNFI (Japan Nuclear Fuel Industries Company, Inc.).

The formal agreements are similar in their construction and cover information exchange and cooperation within handling, treatment, storage and final disposal of radioactive waste. Exchange of up-to-date information (reports), as well as results and methods obtained from research and development, are main points in the agreements. Arranging joint seminars and short visits of specialists to other signatories' facilities are other examples of what is included within the framework of the agreements. General reviews of the signatories' waste programmes and activity planning are held at approximately one-year intervals.

In the case of exchanges of personnel of long duration or extensive direct project cooperation, special agreements are generally concluded within the framework of the general agreement.

SKB also has information exchange without formal agreements with organizations in the other Nordic countries, Germany, Belgium and Great Britain.

22.2 COOPERATION WITH TVO, FINLAND

A regular exchange of experience and technology for site investigation is taking place. Furthermore, Finnish representatives are included in the reference groups for the Lansjärv study and for the Hard Rock Laboratory.

TVO and SKB are jointly compiling existing knowledge on the importance of ice ages and related phenomena for the assessment of the repository's safety.

Regarding waste canisters SKB and TVO have made an joint evaluation of an Advanced Cold Process Canister with an inner steel canister and an outer corrosion shield of copper, see Chapter 14.

Aside from this organized cooperation, information has been exchanged regarding repository design, deposition methodology, safety assessment and quality evaluations.

22.3 COOPERATION WITH CEA, FRANCE

22.3.1 Clay

SKB is currently cooperating with CEA in clay studies. The cooperation has included coordination of research projects and information exchange regarding relation-

ships between the microstructure, mineralogy etc of smectite clays and the influence of temperature and irradiation. Hydrothermal tests and irradiation have been carried out during year-long experiments in the laboratory. The test conducted at Stripa with highly compacted French smectite clay in a simulated deposition environment at approx. 170°C was finalized in September 1990. The results will be evaluated together with laboratory tested radiated samples of the french clay and SKB reference clay Mx-80. The cooperation has provided good opportunities for comparisons between the two countries' reference clays for buffer materials, methods for measurement of properties, swelling pressure, hydraulic conductivity, thermal conductivity etc, and technical methods for deposition.

22.3.2 Chemistry

SKB and CEA has during 1990 discussed the possibility and technical details of joint development of an in-situ experimental probe for radionuclide chemistry measurements.

22.4 COOPERATION WITH AECL, CANADA

22.4.1 Characterization of the 240 level of URL

AECL and SKB signed in April 1987 an agreement on cooperation for characterization of the 245 Level in the Underground Research Laboratory situated in a granitic batholite in Manitoba, Canada. The agreement expires 1991. SKB regularly attach staff or designated representatives to follow and participate in the work.

During 1990 the URL Characterization Program has continued. The program comprises a broad spectrum of activities such as: geological mapping, testing of rock properties, geomechanical and geophysical measurements, acoustic emission monitoring, microseismic monitoring, hydrogeological monitoring etc. The operating phase experiments include studies of solute transport in highly as well as moderately fractured rock. Furthermore rock strength, rock stress and rock yield are major engineering issues relevant to excavation stability and sealing system integrity. A mine-by experiment has commenced in order to improve underground characterization methods including monitoring instrumentation and data management systems. A buffer/container experiment is in progress and some technical accomplishments have been achieved such as: water-jet drilling technology, in-situ buffer compaction and heater fabrication and testing.

22.4.2 Natural analogues

Concerning the joint AECL/SKB work at Cigar Lake see Chapter 20.

22.5 COOPERATION WITH EURATOM, CEC

22.5.1 COCO

The working group COCO (Colloids and Complexes) was formed by CEC to explore the importance of colloids and organic complexes for the migration of radionuclides. An important part of the cooperation is comparative experiments with different methods used at different laboratories. SKB is supporting the participation of a Swedish specialist active within the field.

22.5.2 CHEMVAL

The CEC project CHEMVAL for verification and validation of chemical equilibrium calculation programs and coupled models for geochemistry transport was finalized and reported during 1990 /22-1/.

SKB had during 1990 a group participating in the project.

A new phase of the CHEMVAL project called CHEMVAL2 was initiated with participants from the EC countries, Sweden, Finland and Switzerland. The project will run from 1991-1994 and will comprise temperature effects, ion strength effects, organic complexes, sorption, coprecipitation and coupled geochemical transport.

22.5.3 Natural Analogue Working Group

Natural Analogue Working Group (NAWG) is an international group working with natural analogues and their use in the safety assessment modelling. It's organized by CEC.

SKB has been represented in this group since its start in 1985.

22.5.4 Radionuclide Chemistry

Thermal lensing spectroscopy has been used for studies of uranium (VI) carbonates in cooperation with the Ispra laboratory in Varese, Italy.

22.6 COOPERATION WITHIN OECD NUCLEAR ENERGY AGENCY

22.6.1 RWMC

One of OECD/NEA's principal areas of cooperation is radioactive waste management in the member countries. These questions are dealt with by the Radioactive Waste Management Committee (RWMC), where SKB is represented through Per-Eric Ahlström. Some work is carried out in joint international projects, and working groups are formed to facilitate information exchange or prepare material as a basis for joint opinions or coordination.

Seminars and workshops are arranged within important areas to document and discuss the state of development and the direction of future work.

The groups and projects within the area of radioactive waste management where SKB during 1990 was providing personnel or funding are listed below.

PAAG (Performance Assessment Advisory Group) functions in an advisory capacity to RWMC in matters pertaining to cooperation on means and methods for performance and safety analyses of final disposal systems.
Member from SKB: Tönis Papp

SEDE (Site evaluation and design of Experiments for Radioactive Waste Disposal) functions in an advisory capacity to RWMC in matters pertaining to the activities of experimental work in the member countries. The group will organize a workshop in 1992 on the use of palaeohydrogeological evidence in site characterization.
Member from SKB: Bengt Stillborg

PSAG (Probabilistic Safety Assessment Group) is a cooperation group between those who develop and those who use mathematical models for probabilistic analyses of repository systems. The emphasis lies on coordinating the development and comparing the quality of the models.
Member from SKB: Nils Kjellbert

Cooperative Programme for the Exchange of Scientific and Technical Information Concerning Nuclear Installation Decommissioning Projects is a forum for information exchange and cooperation on various decommissioning projects all over the world.
Member from SKB: Hans Forsström. SKB is also sponsoring a programme coordinator, Shankar Menon, Studsvik Energiteknik AB.

Expert Group on Geochemical Modelling and Data deals with matters of common interest within geochemistry, including the buildup of a common thermodynamic database TDB and augmentation of the database for sorption data, SDB.
Member from SKB: Fred Karlsson

The Stripa Project. See Chapter 18.
Members from SKB: P-E Ahlström (chairman of Joint Technical Committee), Hans Carlsson, SGAB (member of Joint Technical Committee) and Bengt Stillborg (Project Manager) and Karl-Erik Almén (assistant Project Manager)

Working Group on the Assessment of Future Human Actions at Radioactive Waste Disposal Sites will deal with different aspects on human intrusion into waste repositories. The group was initiated in 1990.
Member from SKB: Torsten Eng.

22.6.2 TDB

The TDB Project (Thermochemical Data Base) is under the direction of OECD/NEA. The goal is to develop a chemical thermodynamic database for a number of elements that are of importance for the safety assessment of the final disposal of radioactive waste. The development of the database entails not only collecting and storing published data, but also critical review. Review is carried out by a group of international experts selected for each element. At present the work is concentrated on uranium, neptunium, plutonium, americium and technicium.

The TDB Project is a very important effort to develop a well-documented, reviewed and internationally accepted database. SKB is supporting the activity and Swedish experts are participating in the review work. For SKB, as well as for other participants, it will naturally be necessary to have an operational database available before TDB for different calculation purposes. However, the results from TDB will be incorporated as they become available. A good example of this is the Uranium Database at SKB.

22.6.3 INTRAVAL

INTRAVAL is an international project whose purpose is to validate calculation models for radionuclide transport in the geosphere. The project is a follow-up of the previous projects HYDROCOIN and INTRACOIN. All of these projects were initiated by SKI, which also appointed the secretariat that coordinates the work within INTRAVAL.

A total of 14 test cases were included in the project phase I, which involved evaluation of results of selected laboratory tests, field tests and studies of natural analogues. In many of the cases, it was possible for different model groups to perform predictive modelling before the measurement results had become available.

Five of the fourteen test cases were SKB-linked:

— laboratory tests of migration in overcored fractures/KTH,

— tracer tests at Finnsjön within the fracture zone project/SGAB,

— Stripa 3D migration/KTH,

— Poços de Caldas Project,

— colloid transport/BGS,

— redox front/KTH.

—

The detailed results of INTRAVAL phase I are now being documented. The reports are planned for publication during 1991.

Phase II of INTRAVAL started in 1990. This phase will emphasize on validation efforts based on field studies and natural analogues. The number of test cases will be less than in phase I and will cover validation issues like scale dependency, heterogeneity and coupled processes.

22.7 COOPERATION WITHIN IAEA

Cooperation has during 1990 also been conducted within the International Atomic Energy Agency, IAEA, concerning the management of radioactive waste.

The cooperation is conducted in different ways, including the publication of reports consisting of:

— proceedings from international symposia,

— guidelines and standards within established areas of activity,

— status reports and methodology descriptions within important areas undergoing rapid development.

IAEA has an expert advisory group for its waste management programme (the International Waste Management Advisory Committee, INWAG) and arranges for information exchanges within different special areas through Joint Research Programmes. IAEA publishes an annual catalogue on current research projects within the waste management field in the member countries.

An important new IAEA initiative is the RADWASS programme to work out international safety standards and guidelines. SKB will participate in the Standing Technical Committee for Disposal within the RADWASS programme.

23. DOCUMENTATION

The scientific work in the SKB programme is documented at different levels:

— in reports requested by law and submitted to the Swedish Government or its authorities such as KBS-3, R&D-Programme 89 and Plan 89,

— in the series of SKB Technical Reports,

— in contributions to scientific journals, symposia and conferences in different subject areas,

— in SKB Working or Progress Reports (Arbetsrapporter),

— in internal SKB memos,

— in technical memos and notes.

Further, the bulk of basic data from geological site characterization activities, spent fuel studies etc. are collected and stored in the electronic data base systems at SKB.

23.1 TECHNICAL REPORTS

SKB Technical Reports and many main reports, like for instance the KBS-3 report, are written in or translated to English. They are given a broad distribution to the scientific community in the nuclear waste management field in order to get feedback to the program by the comments, discussions and contacts between specialists that they may give rise to. SKB Technical reports are filed as microfiche at IAEA in Vienna and are available through them. Abstracts of the 1990 Technical Reports are included in part IV of this Annual Report.

23.2 CONTRIBUTIONS TO PUBLICATIONS, SEMINARS ETC

The contributions to conferences, symposia and scientific journals have been extensive during 1990, see Appendix 2.

Both SKB own staff as well as the contractors of SKB have been involved in this work.

23.3 SKB GEOLOGICAL DATA BASE SYSTEM

The data from the geological site investigations, including the Äspö hard rock laboratory, is managed by and brought together in GEOTAB, a common database system. The aim of this database system is threefold, namely to

— facilitate retrieval and combination of data from different disciplines.

— provide an archive, independent of the different data collecting contractors.

— assure the quality of measurements and calculations performed.

This database is a so called relational database, giving the investigator the possibility to freely select and combine information. The stored data can be kept at the high initial quality due to the implied data structure.

Data are structured in subject areas and the data acquisition techniques for each subject is documented in technical reports /23-1, 2, 3, 4/. As new measuring methods and data acquisition techniques are applied the documentation is completed with working reports. All documentation is in English.

The database now contains surface data from 42 sites and data from 346 boreholes in many of these. Data are structured in 9 subject areas, 98 different measuring methods and 658 tables containing 5595 columns. Total data volume is only about 190 Mbyte. New data is continuously fed into the system with a time lag varying between one day and some weeks, depending on which quality-assurance routines that must be applied. In some cases the primary data is collected in dBase format, checked and directly transferred into GEOTAB. After entry in GEOTAB the stored data is checked again by the investigator.

The codes in GEOTAB are written in the language C, using the database manager MIMER and is currently running on a VAX-11/750 with operating system VMS. Typical response times are 10 seconds to 10 minutes for a selected retrieval from two combined tables with 1.000 records in each. Plans exist to port it to some of SKBs newer computers, running UNIX. These plans now have even more been brought to the fore, as the MIMER company in 1989 was bought by an other company selling the database manager INGRES. This means that the MIMER system probably cannot be used after 1992.

Despite large efforts to make the programs user friendly, retrieval is still mostly done by the same personnel that stored the data. Some working documents have been

prepared to give an overview of GEOTAB /23-5/. An "USERS GUIDE" /23-6/ has also been distributed. All documentation is in English. The small amount of direct user retrieval is partly due to the relatively high complexity in some of the measuring methods and data evaluation.

Statistical and graphical presentation is currently better provided on PCs or workstations. The output from GEOTAB can be correctly formatted for direct use by a large number of programs and automatically transferred to the PC.

23.4 COMPUTER SYSTEM AT SKB

23.4.1 Computer Network - LAN and WAN

The computers owned by SKB are placed in three locations; the office at Brahegatan, the computer room at Birger-Jarlsgatan (both in Stockholm) and at the office of Äspö Hard Rock Laboratory, north of Oskarshamn. The computers at all three sites have been connected to local area network (LAN) of the physical type "ethernet". The three LANs are connected via two pairs of ethernet bridges, operating over 64kbps lines, making the three segments appear as one.

Two standard protocols are used in the network - TCP/IP and DECNET. TCP/IP is used by all 67 connected computers (nodes) and used for PCnetworking, terminal sessions, mail and file transfer. The mail systems in all multiuser machines (including the VMS/VAX) are integrated and externally connected to the E-mail international mailing system, covering 90% of all UNIX machines worldwide. The more proprietary but well known DECNET is used by the 5 nonPCs for terminal sessions and file transfer.

The networking software used for PC networking is PCNFS from SUN Microsystems. The main use is to keep a common file system, making document transfer very easy and the common software and standards consistent throughout the company. The servers can be one or several UNIX computer with NFS and currently 3 SUN386i workstations with 2.4 Gbyte on 5 disks, two 2.3 Gb Exabyte and two QIC tape stations are used. A PC in this LAN is served by several file servers simultaneously and, to improve performance, one server has been sited at Äspö.

As SKB is contracting several companies for different work in the computer system a wide area network (WAN) for terminal lines has emerged during the years. Currently 58 lines are connected to the computers in the computer room. Of these 2 are local, 9 are used as dialup lines (2 in Gothenburg) and the rest connected via multiplexors and leased lines to 9 different sites in Stockholm and to Luleå and Gothenburg. The system is very open in the sense that an user at any node can log into any other node (except PCs), depending on his rights.

23.4.2 Minisupercomputer

Since 1989 SKB owns a CONVEX C210 for use internally and by its contractors. It has been very easy to operate, running 24 hours a day with no major problems and with the expected vector capacity of about 12 Mflops (floating point operations per second). Some computations runs 200 times as fast as on the old VAX 11/750. The operating system is a BSD UNIX 4.3 system with system V extensions. To facilitate communication and migration into this system the CONVEX also provides VAX commands, DECNET, the VAX editor EDT and direct batch queues operated from the VAX 11/750. This software enables all consultants with access to the VAX system to directly access the CONVEX as well. The current hardware configuration is 64 Mbyte main memory, 4 Gbyte on 3 disks, a 6250 bpi tape drive, 2 ethernet transceivers and 16 asyncronous ports.

23.4.3 Minicomputer

The VAX 11/750 is now conceptually more than 12 years old and does not cope very well with the computing demands of today. However it is reasonably good in reading and writing to disks and is currently intensively used for storing data and archiving backups from the other machines. The machine configuration now includes 12 Mbytes main memory, 2.3 Gbytes on 5 disks, a 2.3 Gbyte Exabyte and a 1600 bpi tape station, ethernet transceiver and 40 asyncronous ports. The software is rather conventional but includes a TCP/IP suite from Carnegie Melon to make the VAX communicate with the UNIX world.

23.4.4 Workstations and measuring system

Currently the 3 SUN workstations are mainly used as PC network servers but they are of course also used as personal workstations. Due to increased demands on presentation of results from the large computations on the minisuper, some more workstations are planned for 1991.

The main machine in the automatic measuring system at Äspö is also a UNIX-like system, connected to the network, sharing disk and backup device with the SUN workstation and accessible from the all the terminals in the WAN.

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Part III

Appendices

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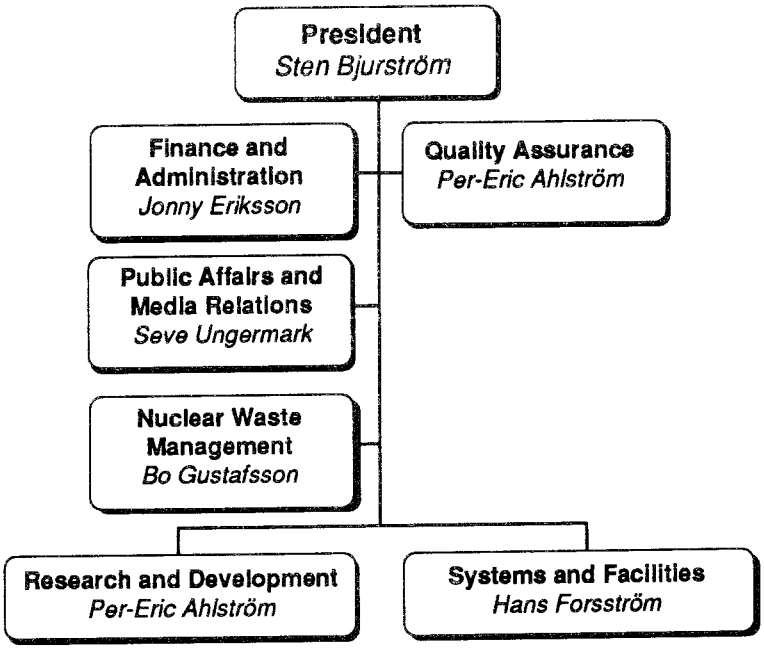
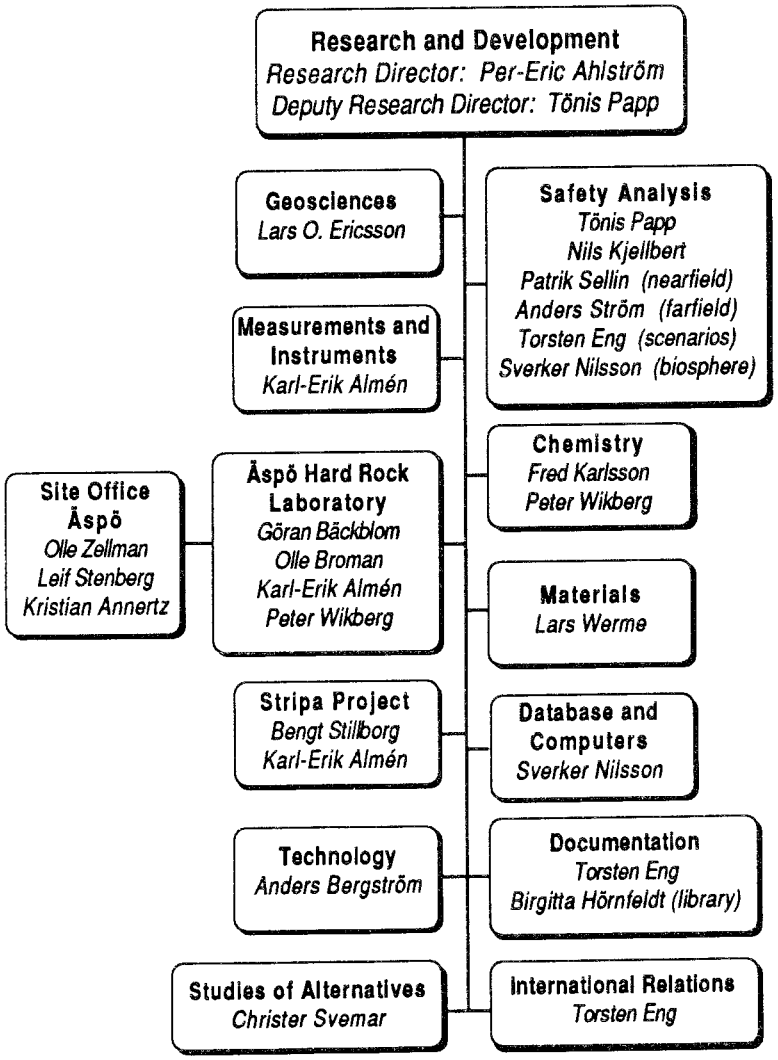
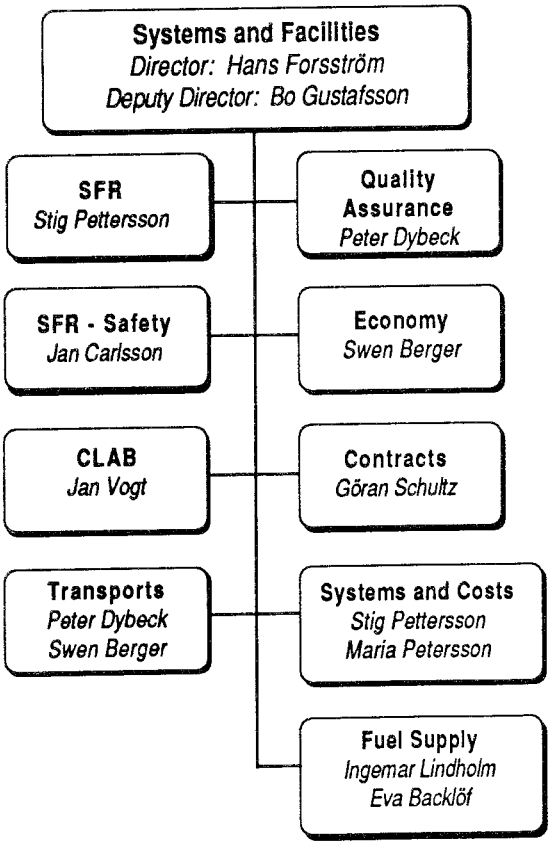
Organization charts for SKB and its divisions







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Universidade de Sao Paulo, Instituto de Geociências - DMP, Sao Paulo, Brazil 1); University of Chicago, Department of Geophysical Sciences, Chicago, Illinois, USA 2)

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Mineralogisch-Petrographisches Institut, Universität Bern, Bern, Switzerland 1); Universidade de Sao Paulo, Instituto de Geociências, Sao Paulo, Brazil 2)

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University of Chicago, Department of Geophysical Sciences, Chicago, Illinois, USA

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British Geological Survey, Keyworth, Nottingham, UK 1); Intera Exploration Consultants Ltd., Henley-on-Thames, Oxon, UK 2)

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US Geological Survey, Menlo Park, CA, USA 1); Conterra AB, Uppsala, Sweden 2); GSF - Institut für Hydrologie, Neuherberg, Germany 3)

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Scottish Universities Research and Reactor Centre, Glasgow, UK 1); New York University Medical Center, Institute of Environmental Medicine, Tuxedo, New York, USA 2); Department of Chemistry, Pontifical Catholic University, Rio de Janeiro, Brazil 3); Geology Department, Florida State University, Tallahasse, Florida, USA 4); Los Alamos National Laboratory, Los Alamos, New Mexico, USA 5)

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Dept. of Chemistry, Pontifical Catholic University, Rio de Janeiro, Brazil 1); New York University Medical Center, Institute of Environmental Medicine, Tuxedo, New York, USA 2); Dept. of Geology, Florida State University, Tallahassee, USA 3);

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Dept. of Chemistry, Pontifical Catholic University, Rio de Janeiro, Brazil 1); Paul Scherrer Institute, Villingen, Switzerland 2);

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West, J 1); Vialta, A 2); McKinley, I G 3)
British Geological Survey, Keyworth, Nottingham, UK 1); Urânio do Brasil, Poços de Caldas, Brazil 2); Nationale Genossenschaft für die Lagerung radioaktiver Abfälle (NAGRA), Baden, Switzerland 3)

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Department of Inorganic Chemistry, Royal Institute of Technology (KTH), Stockholm, Sweden 1); Chemistry Division, B10.5, Harwell Laboratory, UKAEA, Harwell, Oxon, UK 2); Paul Scherrer Institute (PSI), Villingen, Switzerland 3); NAGRA, Baden, Switzerland 4); Atkins ES, Epsom, Surrey, UK 5); Swedish Nuclear and Waste Management Co (SKB), Stockholm, Sweden 6)

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Chemistry Division, Harwell Laboratory, UKAEA, Harwell, U.K. 1); Mineralogisch-Petrographisches Institut, Universität Bern, Bern, Switzerland 2); Scottish Universities Research and Reactor Centre, Glasgow, U.K. 3); Department of Chemical Engineering, Royal Institute of Technology, Stockholm, Sweden 4); U.S. Geological Survey, Menlo Park, CA, USA 5); Atkins ES, Epsom, Surrey, U.K. 6)
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Cornell University, Department of Geological Sciences, Ithaca, New York, USA 1); University of Chicago, Department of Geophysical Sciences, Chicago, Illinois, USA 2)

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Nordstrom, D K 1); Puigdomènech, I 2); McNutt, R H 3)
US Geological Survey, Menlo Park, CA, USA 1); Studsvik AB, Nyköping, Sweden 2); Department of Geology, McMaster University, Ontario, Canada 3)

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University of Göteborg, Department of General and Marine Microbiology, Gothenburg, Sweden 1); Chalmers University of Technology, Department of Nuclear Chemistry, Gothenburg, Sweden 2)
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Allard, B 1); Arsenie, I 1); Borén, H 1); Ephraim, J 1); Gårdhammar, G 2); Pettersson, C 1)
Department of Water and Environmental Studies, Linköping University, Linköping, Sweden 1); Department of Chemistry, Linköping University, Linköping, Sweden 2)
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TR 90-28
Complex forming properties of natural organic acids. Part 2. Complexes with iron and calcium
Ephraim, James H 1); Mathuthu, Andrew S 2); Marinsky, Jacob A 3)
Department of Water in Environment and Society, Linköping University, Linköping, Sweden 1); Chemistry Department, University of Zimbabwe, Harare, Zimbabwe 2); Chemistry Department, State University of New York at Buffalo, Buffalo, NY, USA 3)
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Royal Institute of Technology, Department of Land and Water Resources, Stockholm, Sweden
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Landström, Ove 1); Tullborg, Eva-Lena 2)
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December 1990

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Neretnieks, Ivars
Department of Chemical Engineering, Royal Institute of Technology, Stockholm
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Romero, Leonardo; Moreno, Luis; Neretnieks, Ivars
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Rosengren, Lars 1); Stephansson, Ove 2)
Itasca Geomekanik AB, Falun, Sweden 1); Division of Rock Mechanics, Luleå University of Technology, Luleå, Sweden 2)
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Clay Technology AB, Lund
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Pusch, Roland; Karnland, Ola; Hökmark, Harald
Clay Technology AB, Lund
December 1990

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Pusch, Roland; Karnland, Ola
Clay Technology AB, Lund
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Börgesson, Lennart
Clay Technology AB, Lund
December 1990

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SKB ANNUAL REPORT 1990

Part IV

Summaries of Technical Reports Issued During 1990

SKB Technical Report No 90-01

FARF31 - A far field radionuclide migration code for use with the PROPER package

Norman, Sven 1); Kjellbert, Nils 2)

Starprog AB 1); SKB AB 2)

January 1990

ABSTRACT

The far field radionuclide migration computer code FARF31 has been developed as a submodel to the probabilistic package PROPER, and can be considered a refined and less CPU-time consuming version of the far field models used in the KBS-3 study.

FARF31 constitutes the numerical equivalent of a dual porosity model for radionuclide migration along a stream tube in fractured rock. It calculates the migration rate of the radionuclide chains at the exit of the tube given the input rates at the entrance. Advection, dispersion and one dimensional matrix diffusion is taken into account as well as chain decay.

The underlying equations are formulated in terms of groundwater travel time and Peclet number, thus allowing for the groundwater travel time to be computed outside FARF31 by a separate submodel fitted to handle Darcy velocities and kinematic porosities which vary in space.

Input migration rate boundary conditions are arbitrary.

SKB Technical Report No 90-02

Source terms, isolation and radiological consequences of carbon-14 waste in the Swedish SFR repository

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Studsvik Nuclear

January 1990

ABSTRACT

The source term, isolation capacity, and long-term radiological exposure of ^{14}C from the Swedish underground repository for low and intermediate level waste (SFR) is assessed. The prospective amount of ^{14}C in the repository is assumed to be 5 TBq. Spent ion exchange resins will be the dominant source of ^{14}C. The pore water in the concrete repository is expected to maintain a pH of >10.5 for a period of at least 10^6 y. The cement matrix of the repository will retain most of the $^{14}CO_3^{2-}$ initially present. Bacterial production of CO_2 and CH_4 from degradation of ion-exchange resins and bitumen may contribute to ^{14}C release to the biosphere. However, CH_4 contributes only to a small extent to the overall carbon loss from freshwater ecosystems. The individual doses to local and regional individuals peaked with $5 \cdot 10^{-3}$ and $8 \cdot 10^{-4}$ $\mu Sv \cdot y^{-1}$ respectively at about $2.4 \cdot 10^4$ years. A total leakage of 8.4 GBq of ^{14}C from the repository will cause a total collective dose commitment of 1.1 manSv or 130 manSv TBq^{-1}.

SKB Technical Report No 90-03

Uncertainties in repository performance from spatial variability of hydraulic conductivities - Statistical estimation and stochastic simulation using PROPER

Lovius, Lars 1); Norman, Sven 1); Kjellbert, Nils 2)

Starprog AB 1); SKB AB 2)

February 1990

ABSTRACT

An assessment has been made of the impact of spatial variability on the performance of a KBS-3 type repository. The uncertainties in geohydrological related performance measures have been investigated using conductivity data from one of the Swedish study sites. The analysis was carried out with the PROPER code and the FSCF10 submodel.

SKB Technical Report No 90-04

Examination of the surface deposit on an irradiated PWR fuel specimen subjected to corrosion in deionized water

Forsyth, R S; Eklund, U-B; Mattsson, O; Schrire, D

Studsvik Nuclear

March 1990

ABSTRACT

A yellow deposit was observed to form on the surface of a spent PWR fuel specimen exposed to corrosion in

deionized water. In a parallel experiment with only groundwater leachant, no such deposit was observed.

The extent and thickness of the deposit appeared to increase over a period of 5 months of air storage. Subsequent examination, including XRD analysis, showed that the deposit consisted of dehydrated schoepite, $UO_3O_8H_2O$.

SKB Technical Report No 90-05

Potential effects of bacteria on radionuclide transport from a Swedish high level nuclear waste repository

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January 1990

ABSTRACT

Microorganisms can influence radionuclide migration if their concentration are high in comparison with other organic particles. Data on the numbers of microorganisms in undisturbed ground-water have been collected. The average number of cells in the samples from 17 levels in 5 boreholes was $3 \cdot 10^5$ cells ml^{-1}. A biofilm experiment indicated an active microbial rock surface population. Radiographic uptake experiments suggest inactive bulk water populations. The bulk water microbial cells in deep ground water might then be inactive cells detached from active biofilms. Enrichment cultures for anaerobic bacteria demonstrated the presence of anaerobic bacteria capable of growth on C-1 compounds with hydrogen and carbon dioxide, presumably methanogenic bacteria. Further, growth in enrichment cultures with sulphate as electron-acceptor and lactate as carbon source proved dissimilatory sulphate reducing bacteria to be present.

SKB Technical Report No 90-06

Transport of actinides and Tc through a bentonite backfill containing small quantities of iron, copper or minerals in inert atmosphere

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April 1990

ABSTRACT

In the Swedish concept for final disposal of high-level radioactive waste, compacted bentonite has been proposed as a suitable backfill. In order to study the possible effects of different additions to the clay on the transport of REDOX-sensitive nuclides an investigation has been performed where small quantities of iron or copper in different oxidation states or minerals have been added to the clay.

The apparent diffusivity (D_a) of the actinides U, Pu, Np and the fission product Tc in compacted bentonite mixed with 1% Fe(0), Fe(II), Cu(0) or Cu(II) and for Np and Tc with 1 or 10% respectively of vivianite ($Fe_3(PO_4)_2$), magnetite or fracture fillings (mainly epidot and chlorite) has been measured in an inert nitrogen atmosphere. The results indicate, especially in the case of Fe(0) or Fe(II), reduction from the higher oxidation states Np(V), U(VI) and Tc(VII) probably to Np(IV), U(IV) and Tc(IV). D_a is reduced by several orders of magnitude, and for Tc with Fe(0) addition no migration could be measured (e.g. $D_{a(Tc,Fe(0))} < 2 \cdot 10^{-16}$ m^2/s, $D_{a(Tc,FeII))} = 5 \cdot 10^{-13}$ m^2/s, $D_{a(Tc,Cu(0))} = 5 \cdot 10^{-12}$ m^2/s) while in the case of Cu(I) the effect is not so pronounced, $D_{a(Tc,Cu(I))} = 2 \cdot 10^{-11}$ m^2/s. U and Np show the same trend $D_{a(U,Fe(0))} = 1.2 \cdot 10^{-14}$ m^2/s, $D_{a(U,Fe(II))} = 2.8 \cdot 10^{-14}$ m^2/s, $D_{a(U,Cu(0))} = 1.4 \cdot 10^{-13}$ m^2/s, $D_{a(Np,Fe(0))} = 9.2 \cdot 10^{-16}$ m^2/s, $D_{a(Np,Fe(II))} = 3.5 \cdot 10^{-14}$ m^2/s, $D_{a(Np,Cu(0))} \approx D_{Np,Cu(I)} = 1.4 \cdot 10^{-13}$ m^2/s. For plutonium no diffusion can be measured in the time scale used, $D_{a(Pu,FeO)} < 3 \cdot 10^{-16}$ m^2/s.

For the minerals no change in diffusion rate was achieved in the case of 1% addition of the minerals. However, for Tc with addition of 10 % of the minerals and long preequilibration time, especially for magnetite and fracture fillings, indication of reduction is pronounced. Further experiments with Pu are still in progress due to long contact times.

SKB Technical Report No 90-07

Examination of reaction products on the surface of UO_2 fuel exposed to reactor coolant water during power operation

Forsyth, R S; Jonsson, T; Mattsson, O

Studsvik Nuclear

March 1990

ABSTRACT

A limited experimental programme has been performed to examine the reaction products on the surfaces of fuel fragments from a BWR fuel rod which had operated in the defective condition for about 100 days.

A yellow crust which was observed mainly on the fuel surfaces directly exposed to the reactor coolant water was identified by XRD as the sub-monohydrate of schoepite, the same material which had been found previously in spent fuel corrosion tests in deionized water.

Other corrosion products with varying morphology and size, also probably UO_3 hydrate(s), were observed on surfaces some distance from the position of clad fracture.

SKB Technical Report No 90-08

Radiolytically induced oxidative dissolution of spent nuclear fuel

Werme, Lars 1); Sellin, Patrik 1); Forsyth, Roy 2)

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May 1990

ABSTRACT

The possible effects of radiolysis on the oxidative dissolution of spent nuclear fuel are discussed. A simple model for radiolytically controlled oxidation is proposed and numerical examples are given based on empirical data. The effects of solubility limits for some specific nuclides are also illustrated.

SKB Technical Report No 90-09

Individual radiation doses from unit releases of long lived radionuclides

Bergström, Ulla; Nordlinder, Sture

Studsvik Nuclear

April 1990

ABSTRACT

The turn-over in a standard biosphere of radionuclides, disposed in a repository for high level waste was studied from a dose point of view. A multi-compartment model with unit releases to the biosphere was designed and solved by the BIOPATH-code. The uncertainty in the results due to the uncertainty in input parameter values were examined for all nuclides with the PRISM-system.

Adults and five year old children were exposed from 10 different exposure pathways originating from activity in well and lake water. The results given as total doses per year and Bq release (conversion factors) can be used in combination with leakage rates from the geosphere for safety analysis of a repository. The conversion factors obtained (arithmetic mean values), are given below.

Nuclide	Adults	Children
C-14	1.6E-14	1.2E-14
Se-79	1.1E-13	4.5E-14
Tc-99	2.6E-15	6.8E-16
Sn-126	5.5E-14	2.2E-14
I-129	8.3E-13	5.0E-13
Cs-135	4.7E-14	1.9E-14
Pb-210	9.6E-12	2.5E-12
Ra-225	1.3E-13	4.3E-14
Ra-226	2.6E-12	8.9E-13
Ac-227	2.4E-11	6.1E-12
Th-229	6.3E-12	1.7E-12
Th-230	1.1E-12	2.9E-13
Pa-231	1.5E-10	3.9E-11
U-233	2.4E-12	6.6E-13
U-234	2.3E-12	6.6E-13
U-235	2.2E-12	5.9E-13
U-236	2.2E-12	6.1E-13
U-238	2.1E-12	5.6E-13
Np-237	3.3E-12	8.5E-13
Pu-239	6.2E-12	1.8E-12

SKB Technical Report No 90-10

The regional geology, mineralogy and geochemistry of the Poços de Caldas alkaline caldera complex, Minas Gerais, Brazil

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ABSTRACT

The Poços de Caldas Alkaline Complex, the largest in South America, is circular-shaped with a mean diameter of about 33 km. It is one of the Mesozoic alkaline occurrences of South Eastern Brazil that developed from the Upper Jurassic onwards, during continental break-up and drift. It comprises a suite of alkaline volcanic and plutonic rocks (mainly phonolites and nepheline syenites) with normal background amounts of U, Th and rare-earth elements (REEs). The evolutionary history began with major early volcanism involving ankaratrites and phonolite lavas, and volcanoclastics, followed by caldera subsidence and nepheline syenite intrusions forming minor ring dykes, various intrusive bodies, and circular structures. Finally, the addition of strongly incompatible elements led to the formation of enriched eudialyte nepheline syenites and phonolites.

Magmatic evolution included deuteric processes indicating a volatile-rich parent magma. These processes extended over a large temperature range and resulted in the formation of pegmatitic veins, of pneumatolitic and auto-hydrothermal mineral assemblages including rare metal silicates such as giannettite, various zeolites, fluorite, and hematite, together with mineral alterations. These alterations developed from magmatic pseudoleucite through alkali-exchange reactions to a "clouding" of the main alkali feldspars under auto-hydrothermal conditions (with fluid inclusion formation, incipient kaolinization, and hematitehydrous ferric oxide pigmentation). Geochemically, the resulting rocks are enriched in potassium when compared to global nepheline syenites and phonolites. Mobilization and concentration of U, Th and REEs could not be detected at this stage.

At least at one place (Morro do Ferro) the intermediate nephelinic suite was affected by a carbonatite intrusion and the formation of a stockwork of magnetite veins.

Very intensive hydrothermal K- and S-rich alteration, associated with pene-contemporaneous formation of magmatic breccias, occurred locally.

These processes led to the formation of several important radioactive and REE-rich anomalies. Two of these, the Th-REE occurrence of Morro do Ferro and the U-Zr-REE-Th occurrence of the Osamu Utsumi uranium mine, comprise the study sites of the Poços de Caldas Analogue Project.

Later major evolutive stages of the Poços de Caldas Complex involved the emplacement of mafic-ultramafic dyke rocks and the onset of lateritic and allitic weathering resulting (at the uranium mine) in supergenic geochemical redistribution, and formation of redox fronts related to uranium enrichments.

The regional rock studies were focussed towards the "status quo" properties of the intermediate nephelinic suite with respect to the subsequent more local hydrothermal and final weathering related processes. They included petrographic, mineralogical, geochemical and isotopic studies, in addition to petrophysical parameters. Results showed very little variation for the studied intrusive, subvolcanic and volcanic nepheline syenites and phonolites. The lack of a major differentiated series may be seen as an argument for a short emplacement history of the intermediate nephelinic suite. Previous and present radiometric age measurements suggest a time span of about 15 Ma for emplacement, much too long if compared to modern volcanoes. The end of the magmatic and hydrothermal-mineralizing events is likely fixed by the Ar-Ar dating of an unmineralized lamprophyre dyke intrusion at the site of the uranium mine (76 Ma).

SKB Technical Report No 90-11

Mineralogy, petrology and geochemistry of the Poços de Caldas analogue study sites, Minas Gerais, Brazil. I. Osamu Utsumi uranium mine

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ABSTRACT

The lithology of the Osamu Utsumi mine is mainly composed of a sequence of volcanic and subvolcanic phonolites and nepheline syenite intrusions similar to those of the Poços de Caldas caldera complex; volcanic breccia pipes of about 80 m in diameter also occur characterised by U-Th-Zr-REE mineralisation concentrated in the matrix. A strong hydrothermalism, related to the formation of the breccias, has resulted in the potassic alteration and pyritisation of the phonolites and syenites, with a low-grade mineralisation of disseminated pitchblende. The potassic alteration has transformed all feldspars into pure potash feldspars, nepheline into illite and kaolinite, and clinopyroxenes, which are the primary REE-bearers, into mixtures of TiO_2-rich minerals, clay minerals and pyrite. The

enrichment of K, S, U, Th, Pb, Rb, Ba and Mo was accompanied by a strong depletion in Ca, Na, Mg and Sr. Fluid inclusion data indicate temperatures around 250°C and a KCl-H_2O mixture with approximately 7 equiv. wt.% KCl for the hydrothermal fluids. For fluids in the breccia pipes that transported additional Zr, Hf and F, the inclusions indicate boiling and give temperatures of 210°C with 40-45 equiv. wt.% KCl for a KCl-NaCl-H_2O brine containing $FeSO_4$ and KF. Ultramafic dykes (dated to 76 Ma) with carbonatitic affiliation put a younger age limit on the hydrothermal event.

As a result of supergene weathering below a lateritic soil of 20 to 40 m and a saprolite zone of 15 to 60 m, the pyrites in the rocks have been oxidised to varying depths of 80 to 140 m below surface, resulting in a redox front marked by a contrasting colour change from oxidised (yellow/buff) to reduced (grey/green). In the vicinity of water-bearing fissures these redox fronts have penetrated to greater depths. Due to mobilisation in the oxidised zone and precipitation immediately below the redox front, a secondary pitchblende mineralisation, partly occurring as nodules associated with secondary pyrite, has been developed. This secondary pyrite is sometimes related with CdS and has a S of -13 o/oo compared to S values of -3.63 to +1.24 o/oo for hydrothermal pyrites; the low S values of the former are attributed to bacterial action. In the immediate vicinity of the redox front, dissolution of the potash feldspar becomes apparent and the kaolinite content begins to increase. The marked colour change at the redox front is caused by the presence of hydrous ferric oxides that with time evolve from amorphous Fe-hydroxides to goethite and hematite. On the oxidised side alunite-jarosite minerals are frequent. The porosity increases by 5 to 8% (almost doubled) at the redox front.

Gibbsite is present when potash feldspar has been removed at the saprolite-laterite contact. Many of the REEs are associated with phosphate-rich clays (including the crandallite group minerals) and seem to be hardly mobilised by the oxidising weathering fluids. Only a slight general loss of REEs was observed between oxidised and reduced rock, with the degree of loss being greater for the light REEs. Certain indications for a fractionation of Ce and Eu from the other REEs are present.

SKB Technical Report No 90-12

Mineralogy, petrology and geochemistry of the Poços de Caldas analogue study sites, Minas Gerais, Brazil. II. Morro do Ferro

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ABSTRACT

The Th-REE deposit at Morro do Ferro is of supergene origin formed under lateritic weathering conditions. The orebody forms shallow NW-SE elongated argillic lenses that extend from the top of the hill downwards along its south-eastern slope. The deposit is capped by a stockwork of magnetite veins which have protected the underlying, highly weathered argillic host rock from excessive erosion. The surrounding country rocks comprise a sequence of subvolcanic phonolite intrusions that have been strongly altered by hydrothermal and supergene processes.

From petrological, mineralogical and geochemical studies, and mass balance calculations, it is inferred that the highly weathered host rock was originally carbonatitic in composition, and initially enhanced in thorium and rare-earth elements compared to the surrounding silicate rocks. Intrusion of the carbonatite produced a fenitic alteration of the surrounding phonolites, consisting of an early potassic alteration followed by a vein type Th-REE mineralization with associated fluorite, carbonate, pyrite and zircon. Subsequent lateritic weathering has completely destroyed the carbonatite forming a residual supergene enrichment of Th and REEs.

Initial weathering of the carbonatite might have been conducive to carbonate and phosphate complexing of the REEs and may have appreciably restricted the dissolution of the primary Th-REE phases. Strongly oxidic weathering has resulted in a fractionation between cerium and the other LREEs. Ce^{3+} is oxidized to Ce^{4+} and retained together with thorium by secondary mineral formation and adsorption on poorly crystalline iron- and aluminium-hydroxides. In contrast, the trivalent LREEs are retained to a lesser degree and are thus more available for secondary mineral formation and adsorption at greater depths down the weathering column. Seasonally controlled fluctuations of recharge waters into the weathering column may help to explain the observed repetition of Th-Ce enriched zones underlain by trivalent LREE enriched zones.

SKB Technical Report No 90-13

Isotopic geochemical characterization of selected nepheline syenites and phonolites from the Poços de Caldas alkaline complex, Minas Gerais, Brazil

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ABSTRACT

This paper presents and discusses the isotopic data from the hydrothermal studies of the Poços de Caldas Natural Analogue Project. The purpose of this study was to elucidate the mass transport of relevant elements and isotopes associated with hydrothermal mineralization and alteration at the Osamu Utsumi uranium mine, particularly as applicable to radwaste isolation concerns in the U.S. nuclear waste program.

Research efforts were focussed on studying the thermal, chemical and hydrologic nature of the palaeohydrothermal regime associated with a breccia pipe at the Osamu Utsumi mine, and related to the geochemical, geochronological and petrological characterization studies of unaltered regional nepheline syenite and phonolite.

The regional rocks studied have a vertically elongated D, ^{18}O pattern, which possibly indicates meteoric water/rock interaction. Regression of Rb-Sr whole-rock data for the regional nepheline syenite and phonolite samples did not produce isochrons. An internal, mineral separate isochron regression from a nepheline syenite sample, considered representative of unaltered nepheline syenite of the Poços de Caldas plateau, yields an age of 78 Ma, and an initial $^{87}Sr/^{86}Sr$ ratio of 0.70511. The moderate initial $^{87}Sr/^{86}Sr$ ratios of the regional nepheline syenites are possibly indicative of a mantle source for the alkaline magmatism, with some incorporation of old, high Rb/Sr crustal material. The greater-than-mantle values of ^{18}O, if not due solely to surficial processes, also appear to require some assimilation of crustal material. Sm-Nd data for the regional rocks do not define any isochrons, although the nepheline syenite samples conform very well to a calculated model isochron for 78 Ma and an initial $^{143}Nd/^{144}Nd$ of 0.512359. The regional phonolite samples lie markedly off this isochron. This open system behavior is probably due to the phonolite samples having different initial $^{143}Nd/^{144}Nd$ values. Even so, all regional samples lie within the "Mantle Array" trend. Their location within the Nd-Sr space indicates an asthenospheric Mid Ocean Ridge Basalt (MORB)-type source magma also contaminated by continental igneous and metamorphic rocks (e.g. the Precambrian schist surrounding the Poços de Caldas plateau).

The rocks studied at the Osamu Utsumi mine from the F4 drillcore have experienced varying degrees of hydrothermal mineralization and metasomatism, and deep weathering. The hydrothermally altered rocks have a quite pronounced D shift, with only a slight ^{18}O shift.

The D-^{18}O trend of the hydrothermally altered F4 samples most likely reflects the variability of temperature, hydrologic flow and, therefore, water/rock interaction and isotopic exchange in the palaeohydrothermal regime.

Regression of Rb-Sr whole-rock data for subsamples from a nepheline syenite xenolith sample yields an age of 76 Ma and an initial $^{87}Sr/^{86}Sr$ ratio of 0.70530. Due to the marked hydrothermal alteration and metasomatism of this sample, the Rb-Sr isotopic system is interpreted as being reequilibrated and thus the regressed age is the age of the hydrothermal event. Using a $(^{87}Sr/^{86}Sr)i$ versus 1/Sr mixing diagram, distinct trends are seen for hydrothermal alteration, mineralization and weathering.

Again, the nepheline syenite subsamples do not define an Sm-Nd isochron, but conform very well to a calculated model isochron for 78 Ma and an initial $^{143}Nd/^{144}Nd$ of 0.512365. The Sm-Nd isotopic data also exhibit a likely disturbance by the hydrothermal, metasomatic alteration.

A lamproite dyke which crosscuts the hydrothermal alteration in the Osamu Utsumi mine gives an age of 76 Ma, which is essentially the same as the Rb-Sr age of the nepheline syenite subsamples.

SKB Technical Report No 90-14

Geomorphological and hydrogeological features of the Poços de Caldas caldera and the Osamu Utsumi mine and Morro do Ferro analogue study sites, Brazil

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ABSTRACT

The Osamu Utsumi mine and Morro do Ferro study sites lie within the Poços de Caldas plateau which is roughly circular in outline with a diameter of 35 km and an area of approximately 800 km^2. Its general altitude lies between 1300 and 1600 m. The plateau is the eroded form of a caldera which was initially intruded some 80 million years ago.

Geomorphologically, both sites occupy watershed areas adjacent to small streams in the centre of the plateau. The climate of the area has a marked wet season from November to April and is dry the rest of the year. The streams are ephemeral in their upper reaches, tending to dry up in the dry season as they are fed by a declining base flow. In the

wet season they exhibit flash floods fed by high-intensity rainfall causing overland flow. The wet season also provides recharge to the groundwater. Natural slopes are steep and the original vegetation was thin forest cover which is now restricted to the valley bottoms; usable slopes have poor quality grass cover used for cattle grazing. The plateau is a stable feature and its surface has been eroding at an average rate of 12 m per million years over a period of 50 million years.

The mine geology is dominantly volcanic to subvolcanic phonolites that have been hydrothermally altered. Fracturing of the rock is extensive. Downward diffusion of oxygen in groundwaters during deep weathering has produced a distinct redox zone seen as a colour change from green/grey to brown/yellow. Morro do Ferro has a more weathered version (laterite/clay) of the same geology penetrated by magnetite breccia dykes. Whilst the area surrounding Morro do Ferro remains untouched, that around the mine has been seriously disturbed by mining activity which has penetrated the water-table. The existing mine has modified groundwater flow patterns and disturbed the movement of oxidising and reducing waters.

SKB Technical Report No 90-15

Chemical and isotopic composition of groundwaters and their seasonal variability at the Osamu Utsumi and Morro do Ferro analogue study sites, Poços de Caldas, Brazil

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ABSTRACT

Groundwaters and a few surface waters were collected over a period of 3 years from two natural analogue sites near Poços de Caldas, Brazil: the Osamu Utsumi uranium mine and the Morro do Ferro thorium/rare-earth deposit. These were analysed for major constituents, several trace elements, tritium, deuterium and ^{18}O, to provide hydrochemical data for the modelling objectives as defined within the natural analogue study programme. The groundwaters are a K-Fe-SO_4 type, which classifies them as a highly unusual composition related to the weathering of a hydrothermally altered, mineralised complex of volcanic to sub-volcanic phonolites.

A subset of selected constituents (Fe(II), Fe(total), SO_4, pH, Eh, alkalinity, F and U) was monitored to gain detailed information on the seasonal variability. Seasonal patterns were only apparent from the very shallow groundwater data, but a trend of continuously increasing dissolved solids for the furthest down-gradient sampling point in deep groundwater indicates a growing plume of water affected by pyrite oxidation but without the residual acidity. Tritium and stable isotope measurements indicate that all groundwaters are of meteoric origin and are not affected significantly by evaporation or by water-rock interactions. Recharging groundwaters at both study sites demonstrate infiltration of water of less than about 35 years in age, whereas deep groundwaters are below 1 TU (tritium unit) but still contain detectable tritium in most cases. These deeper groundwaters may be interpreted as being 35-60 or more years in age, resulting mainly from an admixture of younger with older groundwaters and/or indicating the influence of subsurface-produced tritium.

SKB Technical Report No 90-16

Natural radionuclide and stable element studies of rock samples from the Osamu Utsumi mine and Morro do Ferro analogue study sites, Poços de Caldas, Brazil

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ABSTRACT

This report describes a study of the distribution and behaviour of natural radionuclides and selected stable elements at the Poços de Caldas and Morro do Ferro natural analogue study sites. At Poços de Caldas, the study was focussed upon investigation of the behaviour of natural decay series radionuclides and stable elements at the redox fronts which exist in the mine. Uranium nodules from the mine were also analyzed for natural decay series radionuclides in order to characterize their ages and growth rates and for natural plutonium. At Morro do Ferro, the objective was to provide additional information on the geochemical behaviour of thorium, uranium and the light rare earth elements and to relate this to the groundwater flow pattern in an attempt to evaluate the degree of mobilization of these species.

A summary review of those aspects of the geochemistry of natural decay series radionuclides relevant to the interpretation of radioactive disequilibrium is provided along with a detailed treatment of mathematical modelling of

natural decay series disequilibria in rock-water interactions. The overall study comprised a number of discrete subprojects carried out in five different laboratories and each of these is described in detail. In addition to constituting a self contained study, the results and conclusions of this work were also used as an input for modelling studies and other aspects of this integrated research programme.

The natural decay series studies at the Osamu Utsumi mine confirmed the generally greater mobility of U^{6+} and Ra than U^{4+}, Th and Pa in groundwater. The results further confirmed that at the position of the drillcore studied, the long term direction of groundwater flow had been downwards, along the line of the main fissure system, rather than upwards as is presently observed.

Dissolution of uranium and other elements at the redox fronts followed by diffusive movement into both the oxidized and the reduced rock is identified as the mechanism giving rise to the observed concentration profiles about the redox fronts. Deposition of uranium, either as thin, dispersed coatings on other minerals, or as discrete nodules, occurs in the reduced rock as a consequence of the reduction of U^{6+} to U^{4+}. Deposition of uranium, almost certainly by uptake on iron oxides, is also identified as a significant retardation process in the oxidized rock. Some of the uranium nodules are young (on a 10^5 - 10^6 y timescale) and exhibit growth rates of 1.8 - 2.6 cm in 10^6 y, whereas others are old on this timescale and exhibit equilibrium within the natural decay series. The time required for growth of nodules in the reduced rock is estimated to be of the order of 10^5 y at least, while a time of the order of 10^4 - 10^5 y is required for dissolution of micronodules stranded in the oxidized rock following the passage of the redox front.

The natural ^{239}Pu content of a nodule from the reduced rock was measured as $2.3 \pm 0.7 \cdot 10^8$ atoms per gram, consistent with a state of secular equilibrium between ^{238}U and ^{239}Pu. The study thus reveals that uranium (plus daughters) and plutonium are chemically stable in the form of nodules in the reduced rock for a time of at least 10^5 years.

One of the redox fronts studied was concluded to have been effectively static (on a cm scale) for a time of at least $7 \cdot 10^5$ y, while the natural decay series data for the other fronts were consistent with rates of movement in the range 2 - 20 m in 10^6 y, in good general agreement with the estimated rate of regional erosion.

Redistribution of thorium was observed at the redox fronts, with preferential deposition on the reduced sides of the fronts. The degree of this redistribution of thorium is estimated to be at least two orders of magnitude less than the corresponding redistribution of uranium. Separation of uranium from thorium is observed as the redox fronts move downwards and the degree of separation increases with increased length of flow path of the groundwater.

Summary data are provided for a range of stable elements, including the rare earths, which support the observations made above for uranium and indicate that the zone around the redox fronts contains generally elevated concentrations of most elements in conjunction with active dissolution at the front. This results in a variety of distributions of different elements about the redox fronts. The redox fronts thus represent an initial zone of retardation which would be a positive factor in far-field radionuclide migration considerations. However, a negative aspect of this situation is that the zone of enhanced concentrations moves in response to movement of the redox front and, given a sufficient distance of travel, could result in a breakthrough of high concentrations of radionuclides into the near surface environment.

SKB Technical Report No 90-17

Natural series radionuclide and rare-earth element geochemistry of waters from the Osamu Utsumi mine and Morro do Ferro analogue study sites, Poços de Caldas, Brazil

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ABSTRACT

Data are presented on natural series radionuclides and rare-earth elements (REEs) in pre-filtered (<450 nm) near-surface and deep ground waters from the Osamu Utsumi uranium mine and Morro do Ferro (thorium-REE-deposit) analogue study sites.

In the Osamu Utsumi uranium mine, very high concentrations of uranium (up to 10 mg/l) were measured in near-surface waters. In deep groundwaters (60 - 120 m), concentrations of this element are typically between 3 and 10 µg/l. The reduced concentrations of uranium in the Morro do Ferro host rock are reflected in the considerably lower concentrations of this element in waters from this environment.

The concentrations of ^{232}Th in groundwaters from both sites are very low and generally < 0.1 µg/l. However, they can be higher by a factor of 100 or more in superficial waters rich in humic compounds (Morro do Ferro) or acidic in character (Osamu Utsumi mine).

Pronounced disequilibria were measured between ^{234}U and ^{238}U isotopic activities in groundwaters which are characterised by an excess of ^{234}U due to preferential leaching of this isotope and/or recoil effects. The $^{234}U/^{238}U$ activity ratio is lower in the superficial waters

(1.0 - 1.2) than it is in the deeper groundwaters (1.4 - 2.7). This is because in moving toward the surface the groundwater picks up a greater, non-fractionating, leach component of uranium in the zone of higher redox potential. Due to the extremely low solubility of thorium and its strong tendency to sorb on suspended particles (mainly composed of hydrous ferric oxides), the $^{230}Th/^{234}U$ activity ratios in groundwaters are also very low (0.01).

Rare-earth element concentrations in groundwaters from both sites are typically in the range between 1 - 50 µg/l for the light rare-earth elements (LREEs; La, Ce, Nd) and 0.001- 0.1 µg/l for the heavy rare-earth elements (HREEs; Ho-Lu), but can be much higher in surface waters with high complexation capacities, as observed for thorium. The chondrite normalised distribution patterns of the REEs in water samples (and in suspended particles) are similar to those observed in the bedrock, indicating congruent dissolution and sorption of these elements. An exception, however, is cerium which shows a very characteristic depletion in oxidising, shallow groundwaters of both sites, probably related to its preferential oxidation and the much lower solubility of Ce(IV) species in natural waters.

With respect to the mobilisation of thorium and the rare-earth elements via a "solution" phase, the data obtained in this study provide further support that solubility limitations (Th) and strong affinities for sorption (Th and the REEs) on particulate and colloidal matter are efficient mechanisms for restricting the dispersion of these elements (and possibly also that of their transuranium analogues) over small distances in porous media. This is best seen by the absence of any significant contribution of the Morro do Ferro ore deposit, with its 30,000 t of Th and nearly 100,000 t of LREEs, to the concentrations of these elements in surface drainage waters (<450 nm) collected within 100 m distance from the mineralisation zone.

Chemical and physical characterisation of suspended particles and colloids in waters from the Osamu Utsumi mine and Morro do Ferro analogue study sites, Poços de Caldas, Brazil

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ABSTRACT

Data are presented on suspended particles and colloids in groundwaters from the Osamu Utsumi mine and the Morro do Ferro analogue study sites. Cross-flow ultrafiltration with membranes of different pore sizes (450 nm to 1.5 nm) was used to prepare colloid concentrates and ultrafiltrates for analyses of major and trace elements and U- and Th-isotopic compositions. Additional characterisation of colloidal and particulate material was performed by ESCA, SEM and X-ray diffraction. The results obtained indicate the presence of low concentrations (mg/l) of colloids (1.5-450 nm) in these waters, composed mainly of iron/organic species. Minor amounts of U and some other trace elements (Si, Ca, Mg, Mn, Cu, Zn, Pb and occasionally Zr and Sn) and significant amounts of Th and REEs were associated with these colloids. U-isotopic measurements indicate element exchange equilibrium between aqueous, colloidal and suspended particle phases. Suspended particles (450 nm) in the waters show the same trends as the colloids with respect to U, Th and REE associations, but elemental concentrations were typically higher by a factor of 1,000 or more. Calculated association ratios (in $ml \cdot g^{-1}$) are in the order of 10^4 to 10^5 for U, 10^5 to 10^6 for the REEs and 10^6 to 10^7 for Th. In waters with low pH and high sulphate content, these ratios are considerably lower. Due to the low concentrations of suspended particles in groundwaters from the Osamu Utsumi U-mine (< 0.5 mg/l), these particles carry only a minor amount of U and REEs (% of the total concentration of the unfiltered groundwater), but a significant, usually predominant, fraction of Th (30-70%). The suspended particle load in groundwaters from the Morro do Ferro environment is typically higher than in those from the mine by a factor of 5 to 10. This suggests that U and the REEs could be transported predominantly by particulate matter. However, there is chemical and mineralogical evidence that these particles, composed mainly of Fe(III) oxyhydroxides and humic-like compounds, have a low capacity for migration.

SKB Technical Report No 90-19

Microbiological analysis at the Osamu Utsumi mine and Morro do Ferro analogue study sites, Poços de Caldas, Brazil

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ABSTRACT

The Poços de Caldas project is a wide-ranging natural analogue study focussed on a number of areas of concern in the performance assessment of the disposal of radioactive waste. Part of the work has involved characterising microbial populations and their influence in various processes. Core material and groundwaters have been sampled for microbiological content at various depths from boreholes at the Osamu Utsumi open pit uranium mine and Morro do Ferro Th/REE ore body. Microbes were found in all samples but numbers do not appear to be related to depth. Analyses of groundwaters gave higher numbers than with solid material and demonstrated the presence of sulphur cycle bacteria.

These observations have been compared with predictions of a model used in performance assessment to calculate the maximum biomass/microbial activity based on constraints set by available nutrients and energy. The main conclusions of this analysis are:

i) Low microbial activities can be supported by the energy and nutrients supplied by alteration processes at or around the redox front. The maximum annual production of 0.01 - 0.1 g biomass (dry)/m^2 of redox front is in reasonable agreement with observed standing populations.

ii) The presence of high concentrations of sulphate reducing bacteria around the redox front indicate a complex sulphur geochemistry which may be predominantly microbially catalysed and could explain the nodular form of pitchblende concretions and the presence of secondary pyrite.

iii) There is little trace element mobilisation by organic byproducts and the main role of microbes in this system is to catalyse specific redox reactions.

SKB Technical Report No 90-20

Testing of geochemical models in the Poços de Caldas analogue study

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ABSTRACT

In order to test the geochemical models used in repository performance assessment, modelling groups were provided with selected major element analyses of Poços de Caldas groundwaters and asked to predict 'blind' the solubility, speciation and limiting solid for a number of trace elements. This report documents these predictions and compares them to field analyses. These tests illustrate particular strengths and weaknesses in current models/databases and allow recommendations for amendments/improvements to be made.

SKB Technical Report No 90-21

Testing models of redox front migration and geochemistry at the Osamu Utsumi mine and Morro do Ferro analogue study sites, Poços de Caldas, Brazil

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ABSTRACT

Redox fronts occur at a number of locations in repository systems and models have been established to describe their chemical evolution and spatial development. Such models can be tested against detailed observations of the well-developed redox fronts at the Osamu Utsumi mine.

Simple scoping calculations can explain the formation of redox fronts in very general terms but greatly simplify the processes known to be occurring at such fronts. Coupled transport/chemistry models can provide a better simulation of the fronts, but these are primarily interpretative models which have not yet displayed any convincing predictive abilities. They tend to be rather poor, in particular, in simulating trace element chemistry in either solution or solid phases.

Interpretative modelling of microbial activity, natural series profiles and trace element distributions gives strong indications of the reasons for the limitations of the chemical modelling. The role of microbial catalysis seems to be very significant in such systems, particularly affecting the redox chemistry of sulphur. Natural series measurements indicate very slow redox front movement at particular sites which could be due to precipitation processes limiting accessible porosity, a point not considered in any of the models. Finally, the trace element distributions strongly suggest immobilisation of many elements as co-precipitates or solid solutions in secondary iron minerals, again a process not considered by current models.

SKB Technical Report No 90-22

Near-field high-temperature transport: Evidence from the genesis of the Osamu Utsumi uranium mine, Poços de Caldas alkaline complex, Brazil

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ABSTRACT

The chemical, isotopic and mineralogical alteration which occurred during primary uranium ore deposition at the breccia pipe-hosted Osamu Utsumi mine, Poços de Caldas, Brazil, was studied as a natural analogue for near-field radionuclide migration. Chemical and isotopic alteration models were combined with finite difference models of the convective cooling of caldera intrusives. The modelling indicates that the intense chemical, isotopic and mineralogical alteration of the Osamu Utsumi breccia pipe requires the circulation of 10^5 kg of boiling hydrothermal fluid 220°C through each square centimeter cross-section of the pipe. The circulation can be driven by heat from a 6 km diameter intrusion extending to 10 km depth. Even with this large amount of circulation concentrated in the permeable breccia pipe, uranium solubilities must be 2 1/2 orders of magnitude greater than indicated in the most recent experiments (and more in line with previous estimates) to produce the primary uranium mineralization at the Osamu Utsumi mine.

The same models applied to a hypothetical high-temperature waste repository show that heat from radioactive decay will produce a hydrothermal circulation system remarkably similar to that studied at the natural analogue site at Poços de Caldas. The depth of fluid convection induced by the hypothetical repository would be 5 to 10 km, the maximum temperature ~300°C, the lifetime of the high-temperature phase a few 1000s of years and boiling would cause most of the alteration of the waste repository. The physical analysis emphasizes the importance of permeability on a $10 \times 10 \times 10$ km scale in controlling the potential amount of circulation through the hypothetical repository.

Application of the chemical models successfully used to interpret mineralization and alteration at the Osamu Utsumi mine to the hypothetical waste repository shows that, even in a worst case scenario (waste emplaced in a permeable host rock with no measures taken to inhibit flow through the repository), the amount of hydrothermal alteration in the hypothetical repository will be ~0.1% of that in the breccia pipe at the Osamu Utsumi mine. Assum-

ing no barriers to uranium mobility, uranium precipitation above the hypothetical repository would be 0.05 ppm (rather than 50 ppm), hydrothermal alteration 0.03 wt.% (rather than 30 wt.%), etc.

The analysis indicates that mineralogical alteration is extremely sensitive to thermodynamic data. Prediction of mineralogical alteration (which may be necessary to predict the migration of radionuclides other than uranium, for example) probably cannot be based directly on even very carefully collected laboratory thermodynamic data. Mineralogical complexities of the system, as well as database uncertainties, will require calibration of the thermodynamic framework against mineralogical alteration observed in the laboratory or field by procedures briefly described.

SKB Technical Report No 90-23

Geochemical modelling of water-rock interactions at the Osamu Utsumi mine and Morro do Ferro analogue study sites, Poços de Caldas, Brazil

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ABSTRACT

Geochemical processes involving water-rock-gas interactions have been modelled using groundwater compositions, mineralogical data, ion plots and computations of speciation, non-thermodynamic mass balance and thermodynamic mass transfer for two natural analogue sites near Poços de Caldas, Brazil: the Osamu Utsumi mine and Morro do Ferro. The main rock type is an alkaline igneous complex composed of volcanic and sub-volcanic phonolites that have been hydrothermally altered and highly weathered. This altered rock mass grades from a laterite at the surface to a saprolite and finally to unweathered, hydrothermally altered bedrock at depth. The mine site contains high concentrations of uranium and Morro do Ferro contains high concentrations of thorium and rare-earths. The reaction models can reproduce the water chemistry and mineral occurrences and they were validated by predicting the masses of minerals precipitated and the pH of the final water. The model computations can also reproduce the pH and iron concentrations of the water samples during CO_2 degassing and iron(II) oxidation from exposure to air. The results from the geochemical reaction models reveal that the dominant processes are production of CO_2 in the soil zone through aerobic decay of organic matter, dissolution of fluorite, calcite, K-feldspar, albite and manganese oxides, oxidation of pyrite and sphalerite and precipitation of ferric oxides, silica and kaolinite. Recharge waters are undersaturated with respect to barite and discharging waters and deeper groundwaters are saturated to supersaturated with respect to barite, demonstrating a strong equilibrium solubility control. Strontium isotope data demonstrate that sources other than calcium-bearing minerals are required to account for the dissolved strontium in the groundwaters. These may include K-feldspar, smectite-chlorite mixed-layer clays and goyazite.

SKB Technical Report No 90-24

The Poços de Caldas Project: Summary and implications for radioactive waste management

Prepared by the Project Technical Committee

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ABSTRACT

INTRODUCTION: Over very long time periods buried radioactive wastes will behave as an integral part of their surrounding geological environment. Predicting what this future behaviour will be is considerably facilitated by comparison with the evolution of parallel natural geochemical systems, particularly those that are rich in radioelements. The geochemical processes that are included in performance assessment models for waste repositories can thus be found in nature, where they have been active over long periods of time. It should be made clear that no nature system represents an entire repository concept. However, detailed characterization of such occurrences helps to refine the models and give confidence in their predictions. This approach, by seeking similar circumstances in nature (so-called natural analogues), has developed considerably in profile since 1984 when the first guidelines were sketched out (Chapman et al., 1984; Côme and Chapman, 1984).

Although many important natural analogue findings have arisen from detailed studies of specific occurrences of a particular process or material, it was clear that interpreting radionuclide mobilization and transport from ore deposits would involve so many technical aspects that a complete picture could only be gained by a large-scale international effort. In 1984, the Poços de Caldas region of the state of Minas Gerais in Brazil was identified as potentially highly instructive with respect to the geochemical behaviour of U/Th-series radionuclides and rare-earth elements (REE's: chemically analogous in some respects to transuranic elements). At that time the potential importance of the geochemical behaviour of redox fronts in fractured rocks, and of colloid/particulate materials as radionuclide complexing or transport agents

in groundwaters was being recognized in safety assessments of high-level waste and spent fuel disposal.

The Poços de Caldas area had been the subject of long-term studies, particularly focussed on the Th/REE ore deposit of Morro do Ferro, since the early seventies. The Poços de Caldas region, and Morro do Ferro in particular, had been identified as amongst the most naturally radioactive places on the surface of the Earth. In 1977 an international conference on areas of high natural radioactivity was held in Poços de Caldas. (Cullen and Penna Franca, 1977).

A considerable amount of research on the biological uptake of U/Th series daughter elements was done by the New York University Medical Center's Institute of Environmental Medicine (see, for example, Linsalata et al., 1986). This work had looked in detail at the thorium deposit of Morro do Ferro, and the uptake of Ra-228 by plants, cattle, and humans in the vicinity and downstream areas of the catchment/drainage area.

Later work in this project looked specifically at the mobility of thorium in solution and particulate form in near-surface waters (Eisenbud et al., 1984). In early 1984, representatives from NYU and SKB (Sweden) met in Poços de Caldas to evaluate the geological potential of Morro do Ferro as an analogue for the burial of high-level radioactive waste. This resulted in a report compiled by a research group at the University of São Paulo (IPT Report, 1984). In late 1984 a group representing SKB, NAGRA (Switzerland) and the Department of Energy (USA) visited the area to assess the possibilities for extending the work, under international sponsorship, to look at other aspects of direct relevance to repository performance assessment. In addition to considering further work at Morro do Ferro, this pilot group noted that the very prominent natural oxidation fronts (redox fronts) displayed in the nearby Osamu Utsumi uranium mine could provide information vital to near-field repository models where such fronts were thought likely to occur in either the near-field (Nagra, 1985) or in the far-field (KBS, 1983). The fact that the redox fronts in the mine so clearly influence the mobility and distribution of uranium in the fractured rock mass made this an obvious site for study.

Over the next 12 months a project was formulated in outline to look at trace element chemistry, evolution of the redox fronts, colloid, and elevated temperature hydrothermal element transport aspects in particular, and the UK Department of the Environment also became involved as a co-sponsor. A three-year project was devised, of which the first year (June 1986 - June 1987) was to be a feasibility study, designed to obtain sufficient information to test the viability of the analogues and, if necessary, to revise or redirect the subsequent work programme. This early work involved drilling and rock/water sampling at both Morro do Ferro and the Osamu Utsumi mine, and involved considerable support from Nuclebrás (now Urânio do Brasil), the mine operators.

At the end of the feasibility study year, both the data gathered, and the growing awareness of other critical issues in performance assessment, enabled the project technical committee to define a list of four technical objectives:

1. Assist in the validation of equilibrium thermodynamic codes and databases used to evaluate rock/water interactions and solubility/speciation of elements.

2. Determine interactions of natural groundwater colloids, radionuclides and mineral surfaces with respect to radionuclide transport processes and colloid stability.

3. Produce a model of the geochemical evolution of redox fronts specifically, aimed at understanding long-term, large-scale movements of redox-sensitive natural series radionuclides (including, if possible, natural Pu and Tc).

4. Model the migration of REE/U-Th series radionuclides during hydrothermal activity similar to that anticipated in very near-field of some spent-fuel repositories.

These objectives have remained as the focus of the project throughout its existence, and the results presented in this summary, and the associated technical reports, are structured to present the advances made in these areas.

It should be emphasized that only certain components of the "performance assessment model chain" have been tested in the project and that these tests vary in rigour. Objectives (1) and (3) have involved quantitative testing (partial validation) of mathematical models (and databases) which are used regularly by performance assessors. The code used in (4) is similar in structure to assessment codes but has not yet been used in such applications. No comprehensive mathematical model of the effects of colloid transport exists and hence objective (2) involves a qualitative test of the conceptual models which are currently under development.

The project, from the outset, profited by the involvement of a range of laboratories and technical investigators covering many disciplines, including hydrogeology, radiochemistry, rock and water analysis, geomorphology, microbiology, and chemical modelling. One of the great successes of the project has been to bring together an excellent spectrum of expertise to study a common set of problems and achieve consensus on the geochemical evolution of the two study sites. This, in itself, constitutes a form of multidisciplinary group development with an internal peer review that would have useful parallels in repository site characterization. A list of all the laboratories and individuals involved, together with the technical management structure of the project is provided in Appendix 1, and a list of presentations/publications presently resulting from the project is given in Appendix 2.

Tune restrictions and the volume of data to be reported gave rise to logistic problems. The technical reports thus uncorporate the interpretations of the authors based predominantly on their own data, and there may naturally exist some inconsistencies between various reports. It is the intention of this summary report to provide an overview of all the information available, although it is ex-

pected that further analysis of the project database will give rise to a series of future publications.

This report is a detailed summary of the whole of the Poços de Caldas project. It begins by describing the area, and then focussing-in on detailed descriptions of the two study sites. In order to put the sites into context a limited programme of regional petrological, geochronological and geomorphological studies was carried out, and these are described in the next chapter. Chapters 3 and 4 describe the detailed geology and geochemistry of the Osamu Utsumi mine and Morro do Ferro, respectively, concentrating on the operative geochemical processes. Chapters 5-8 cover the four performance assessment related technical objectives of the project, and draw conclusions specific to these topics.

Finally, Chapter 9 presents a more general overview of the information derived in this project, with emphasis on how it could be applied in particular waste management programmes. This chapter also highlights areas which may be worth further study, and suggests ways in which the experience gained could be used to improve similar studies in the future.

SKB Technical Report No 90-25

Kinetics of UO_2(s) dissolution under reducing conditions: Numerical modelling

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May 1990

ABSTRACT

A numerical model is presented that describes the dissolution and precipitation of UO_2(s) under reducing conditions. For aqueous solutions with pH4, the main reaction is:

$$UO_2(s) + 2H_2O \rightarrow U(OH)_4(aq)$$

The rate constant for the precipitation reaction is found to be $\log(k_p)=-1.2 \pm 0.2$ $h^{-1}m^{-2}$, while the value for the rate constant of the dissolution reaction is $\log(k_d)=-9.0 \pm 0.2$ $mol/(l\ h\ m^2)$.

Most of the experiments reported in the literature show a fast initial disolution of a surface film of hexavalent uranium oxide. Making the assumption that the chemical composition of the surface coating is U_3O_7(s), we have derived a mechanism for this process, and its rate constants have been obtained.

The influence of HCO_3^- and CO_3^{2-} on the mechanism of dissolution and precipitation of UO_2(s) is still unclear. From the solubility measurements reported, one may conclude that the identity of the aqueous complexes in solution is not well known. Therefore it is not possible to make a mechanistic interpretation of the kinetic data in carbonate medium.

SKB Technical Report No 90-26

The effect from the number of cells, pH and lanthanide concentration on the sorption of promethium on gramnegative bacterium (Shewanella Putrefaciens)

Pedersen, Karsten 1); Albinsson, Yngve 2)

University of Göteborg, Department of General and Marine Microbiology, Gothenburg, Sweden 1); Chalmers University of Technology, Department of Nuclear Chemistry, Gothenburg, Sweden 2)

June 1990

ABSTRACT

The aim of this work was to investigate the sorption of the lanthanide promethium on bacteria and the distribution ratio, K_d, of the lanthanide between bacteria and water at different cell numbers, pH and lanthanide concentrations. There was a negative linear relationship between the number of cells and the amount of the Pm sorbed, and also between the number of cells and the K_d. The sorption decreased from a stable level at 90% as pH was raised above 7. There was a linear quantitative relation between the Pm concentration and the amount of Pm sorbed on the cells while the the relation to K_d was relatively constant. The results indicate the sorption of trivalent actinides and lanthanides on bacteria to be a reversible surface adsorption.

SKB Technical Report No 90-27

Isolation and characterization of humics from natural waters

Allard, B 1); Arsenie, I 1); Borén, H 1); Ephraim, J 1); Gårdhammar, G 2); Pettersson, C 1)

Department of Water and Environmental Studies, Linköping University, Linköping, Sweden 1); Department of Chemistry, Linköping University, Linköping, Sweden 2)

May 1990

ABSTRACT

A method has been developed for quantitative recovery of humic substances from aqueous systems based on ion exchange on DEAE-cellulose. A scheme is suggested for the characterization of dissolved humic substances (UV-, IR- and 1H NMR-spectroscopy, elemental analysis, molecular weight determination, ^{14}C-age, functionality, carbohydrate content and acid-base properties) as a routine in the chemical analysis of natural waters.

SKB Technical Report No 90-28

Complex forming properties of natural organic acids. Part 2. Complexes with iron and calcium

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July 1990

ABSTRACT

An ultrafiltration technique combined with ion-selective-electrode and atomic absorption methods have been employed to obtain information on the complex forming properties of fulvic acid with iron and calcium. A model for interpreting complexation of metal ions to fulvic acid at any pH, medium ionic strength and metal to fulvic acid ratio developed earlier /1/ has been used in an attempt to predict the nature of iron and calcium interaction to Armadale Horizon Bh fulvic acid. Binding of calcium to fulvic acid which is enhanced at pHs greater than 6.0 has reasonably been predicted by the model taking into consideration complications due to the polyelectrolyte nature and the heterogeneity of the fulvic acid. The lack of agreement observed between the model predicted binding behavior and the experimentally observed results for the fulvic acid-iron system has been attributed to the formation of metal-induced aggregation. Reduction of Fe(III) to Fe(II) by the fulvic acid as reported by other workers is corroborated.

SKB Technical Report No 90-29

Characterization of humic substances from deep groundwaters in granitic bedrock in Sweden

Pettersson, C; Ephraim, J; Allard, B; Borén, H

Department of Water and Environmental Studies, Linköping University, Linköping, Sweden

June 1990

ABSTRACT

Humic substances were isolated from deep groundwaters sampled at depths between 100 and 800 m at Finnsjön, Fjällveden, Forsmark, Gideå, Lansjärv, Stripa and Äspö. The humic fraction, which largely consisted of fulvic acid in all the samples, was characterized with respect to elemental composition, molecular weight, acid capacity (COOH and OH) as well as age (^{14}C). The differences in composition and capacity between old (1270-9675 y) and fresh (reference fulvic acid from surface water, Bersbo) were minor.

SKB Technical Report No 90-30

The earthquakes of the Baltic shield

Slunga, Ragnar

Swedish National Defence Research Institute

June 1990

ABSTRACT

More than 200 earthquakes in the Baltic Shield area in the size range ML 0.6-4.5 have been studied by dense regional

seismic networks. The analysis includes focal depths, dynamic source parameters, and fault plane solutions. In southern Sweden a long part of the Protogene zone marks a change in the seismic activity. The focal depths indicate three crustal layers: upper crust (0-18 km in southern Sweden, 0-13 km in northern Sweden), middle crust down to 35 km, and the quiet lower crust. The fault plane solutions show that strike-slip is dominating. Along the Tornquist line significant normal faulting occurs. The stresses released by the earthquakes show a remarkable consistency with a regional principle compression N60W. This indicates that plate-tectonic processes are more important than the land uplift. The spatial distribution is consistent with a model where the earthquakes are breakdowns of asperities on normally stably sliding faults. The aseismic sliding is estimated to be 20000 times more extensive than the seismic sliding. Southern Sweden is estimated to deform horizontally at a rate of 1mm/year or more.

SKB Technical Report No 90-31

Near-field performance of the advanced cold process canister

Werme, Lars

Swedish Nuclear Fuel and Waste Management Co (SKB)

September 1990

ABSTRACT

A near-field performance evaluation of an Advanced Cold Process Canister for spent fuel disposal has been performed jointly by TVO, Finland and SKB, Sweden. The canister consists of a steel canister as a load bearing element, with an outer corrosion shield of copper. The canister design was originally proposed by TVO. In the analysis, as well internal (ie corrosion processes from the inside of the canister) as external processes (mechanical and chemical) have been considered both prior to and after canister breach. Throughout the analysis, present day underground conditions has been assumed to persist during the service life of the canister.

The major conclusions for the evaluation are:

Internal processes cannot cause the canister breach under foreseen conditions, ie localized corrosion for the steel or copper canisters can be dismissed as a failure mechanism.

The evaluation of the effects of processes outside the canister indicate that there is no rapid mechanism to endanger the integrity of the canister. Consequently the service life of the canister will be several million years. This factor will ensure the safety of the concept.

For completeness also evaluation of post-failure behaviour was carried out. Analyses were focussed on low probability phenomena from faults in canisters.

Some items were identified where further research is justified in order to increase knowledge of the phenomena and thus strengthen the confidence of safety margins. However, it can be concluded that the risks of these scenarios can be judged to be acceptable. This is due to the fact that firstly, the probability of occurrence of most of these scenarios can be controlled to a large extent through technical measures. Secondly, these analyses indicated that the consequences would not be severe.

As a summary, according to this evaluation the Advanced Cold Process Canister seems to meet at least the same safety targets as the KBS-3 canister.

SKB Technical Report No 90-32

Radionuclide transport paths in the nearfield - a KBS-3 concept study

Pusch, Roland

Clay Technology AB and Lund University of Technology

July 1990

ABSTRACT

The general scope of the study has been to identify and define major paths for radionuclide transport from KBS3 canisters, focussing on the nearfield rock.

A primary purpose was to document the hydraulic properties of the "disturbed zones" around blasted tunnels and it is concluded from compilation of theoretical data and field experiment recordings that stress relief and blasting effects combine to form a pervious zone that extends to about 1 m from the tunnel periphery. It has an average, isotropic hydraulic conductivity of no less than 10^{-8} m/s.

A second major purpose of the study was to generalize the structure of granitic rock with respect to water-bearing fractures. Forsmark, Finnsjön, and Stripa data have been considered and found to support the idea of rather regular "orthogonal" fracture systems with relatively large spacings. The hydraulically active part of the fractures, which can be characterized by simple statistical distributions of persistence, spacing, and aperture, is formed by channels, which can be taken as plane, straight stripes with constant width and aperture. The width can be assumed on the basis of field observations while the aperture is estimated from the bulk conductivity and the geometry of the fracture network.

The major transport paths of the rock have been concretized and combined to form a general simplified model intended for calculation of radionuclide transport through water flow and through diffusion through continuous water passages. This model comprises of a circumscribing pervious zone of "wall disturbance" around the deposition holes in addition to the fracture channels.

SKB Technical Report No 90-33

Plan 90. Costs for management of the radioactive waste from nuclear power production

Swedish Nuclear Fuel and Waste Management Co (SKB)

June 1990

ABSTRACT

The Swedish nuclear power utilities are responsihle for adopting such measures as are necessary in order to ensure the safe management and disposal of spent nuclear fuel and radioactive waste from the Swedish nuclear power reactors. In order to fulfil this responsibility, the nuclear power utilities have commissioned SKB, the Swedish Nuclear Fuel and Waste Management Co, to plan, build, and operate the necessary facilities and systems.

This report presents a calculation of the costs for implementing all of these measures. The cost calculations are based on a scenario for management and disposal of the radioactive waste products, which has been prepared by SKB and is described in this report.

Since disposal of the high-level (long-lived) waste will not commence until some time into the 21st century, continued RD&D activities may reveal new methods, that can affect both system design and costs. This is expected to lead to overall simplifications in the design.

The facilities and systems that exist are:

Transportation system for radioactive waste products.
Central interim storage facility for spent nuclear fuel, CLAB.
Final repository for radioactive reactor waste, SFR 1.

Future facilities under planning are:

Encapsulation station for spent nuclear fuel.
Final repository for long-lived waste.
Final repository for decommissioning waste.

The cost calculations also include costs for research and development and for decommissioning and dismantling the reactor plants etc.

The total future costs of the Swedish waste management system, starting in 1991, have been calculated to be SEK 45.5 billion in January 1990 prices. These costs will be incurred over a period of about 60 years. SEK 8.0 billion has been spent up to the end of 1990.

This cost calculation is presented annually to SKN, the National Board for Spent Nuclear Fuel, which uses it as a basis to propose a fee on the nuclear electricity production in order to cover all future expenses. The fee for 1990 is on average 1.9 öre/kWh (0.019 SEK/kWh).

SKB Technical Report No 90-34

GEOTAB: User's guide - Version 1.8.2.

Magnusson, Stefan

Ergodata

October 1990

ABSTRACT

This manual describes the general outlines, the everyday use and how to maintain and make changes in the Geodatabase system.

SKB Technical Report No 90-35

Dose conversion factors for major nuclides within high level waste

Bergström, Ulla; Nordlinder, Sture

Studsvik Nuclear

November 1990

ABSTRACT

Individual doses to critical groups from a continuous unit release of nuclides to a standard biosphere were calculated. The selection of nuclides for this study was based on experience of their importance from a radiological point of view. The standard biosphere consisted of a well and a lake with adjacent farming-land. It was assumed that 1 % of the activity reached the well directly, while the remaining fraction was directly diluted into the lake water.

Ten exposure pathways for activity from the well and the lake water to man were considered. The ecosystem was assumed to be similar to present conditions in Sweden. This was also the case concerning diet and living habits. In addition the doses from naturally occurring nuclides in the uranium decay chains were calculated, based on natural levels in water and soil. The calculations were carried out with the BIOPATH and PRISM codes. The latter code was used to obtain the uncertainty in the results due to the uncertainty in the input parameter values.

SKB Technical Report No 90-36

Sensitivity analysis of groundwater flow. Licentiate thesis

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December 1990

ABSTRACT

Sensitivity is usually defined as a derivative of a specific performnance measure with respect to the system parameters. Sensitivity analysis is an effective tool for analysing the responses of some selected performance measure of a groundwater flow problem to perturbations of the parameters. It is used to study the behaviour of flow systems and to assess the importance of the various governing flow parameters.

A sensitivity analysis of general linear and nonlinear simulation equation sets is developed in this study in order to facilitate the application of the sensitivity analysis to groundwater flow problems. Two methods are considered for the sensitivity calculation: the "direct method" and the "adjoint method". In the former method the sensitivity equations have been obtained by direct differentiation of the primary flow equation, and in the latter method variational theory is used to formulate an adjoint sensitivity equation. A comparison between the two methods from a computational point of view revealed that when the number of parameters exceeds the number of performance functions, the adjoint method is more efficient than the direct method, otherwise, the direct method is preferable.

Sensitivity theory was used to establish a sensitivity analysis model for general three dimensional transient groundwater flow. The equations of sensitivity was derived in detail in the continuous equation form. Several performance functions, such as the local piezometric head, the Darcy velocity at certain points in the flow domain, the outflux through a boundary etc. have been derived. Three different methods for calculation of the sensitivity coefficient are presented.

The sensitivity equations and the groundwater flow equations were numerically solved by the Galerkin finite element method in the model. A verification exercise of the model was performed for a two-dimensional non-steady state flow problem with an analytical solution found in the literature. Sensitivity coefficients were carried out both numerically with the developed direct method and with the known analytic solution. Very good agreement between the two solutions was obtained.

The developed sensitivity model was applied to three dimensional (axi-symmetric) groundwater flow in a tunnel system, which was supposed to be located at a depth of 500 meters below the ground surface in a four-layered rock formation. In this case, the sensitivity distribution of the piezometric head was calculated with the direct method and the sensitivity of multiple performance functions to perturbations of the permeability were analyzed by using the adjoint method.

The calculation results showed that the peaks of the sensitivity coefficients appear mostly in the area around the tunnel. The piezometric head at the studied points (nodes) was quite sensitive to perturbations of the permeability in the layer where the points were located, but practically insensitive to perturbations of the permeability in the bottom layer. The flux into the tunnel and the velocity performance were mostly sensitive to perturbation of the permeability in the layer next to the top layer, but practically insensitive to perturbation of the permeability in the bottom layer.

SKB Technical Report No 90-37

The influence of fracture mineral/groundwater interaction on the mobility of U, Th, REE and other trace elements

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December 1990

ABSTRACT

Trace element analyses including U, Th and REE have been carried out on groundwater samples, fracture coatings and rock samples from drill cores. The influence of fracture mineral/groundwater interaction on the mobility of these elements is discussed. Compared to the host rocks the levels and ranges of element contents in the fracture fillings are usually much higher, reflecting the wide range in sorption capacities of different fracture-filling minerals.

In order to use the elements analysed as chemical analogues to predictions of actinide migration, the following cases are discussed:

1) Redistribution of elements in connection to clay forming alteration processes and preferential sorption of elements on clay minerals.

2) Occurances of Fe-oxyhydroxide associated with high concentrations of Th, U and LREEs at great depths.

3) Recent trace element distribution in a reactivated crush zone.

4) Use of Ce-anomalies and Eu-anomlies for tracing REE migration paths.

5) Validation of laboratory measured K_d's on crushed granite and mineral separates by determining distribution coefficients between fracture coatings and corresponding groundwater ("in situ" K_d's).

The examination of the relation between "in situ" K_d's and laboratory-determined K_d's shows that the "in situ" K_d's are on average a factor of 100 higher for Sr, Cs, Co, Eu and about 10 for U.

It is suggested that fracture minerals such as Fe-oxyhydroxide, carbonates and clay minerals have sorption capacities significantly different from those of crushed granite. This is one of the explanations for the higher "in situ" K_d's compared with the laboratory-determined ones.

SKB Technical Report No 90-38

Solute transport in fractured rock - Applications to radionuclide waste repositories

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December 1990

ABSTRACT

Flow and solute transport in fractured rocks has been intensively studied in the last decade. The increased interest is mainly due to the plans in many countries to site repositories for high level nuclear waste in deep geologic formations. All investigated crystalline rocks have been found to be fractured and most of the water flows in the fractures and fracture zones. The water transports dissolved species and radionuclides. It is thus of interest to be able to understand and to do predictive modelling of the flowrate of water, the flowpaths and the residence times of the water and of the nuclides.

The dissolved species including the nuclides will interact with the surrounding rock in different ways and will in many cases be strongly retarded relative to the water velocity. Ionic species may be ion exchanged or sorbed on the mineral surfaces. Charged and neutral species may diffuse into the stagnant waters in the rock matrix and thus be withdrawn from the mobile water. These effects will be strongly dependent on how much rock surface is in contact with the flowing water. It has been found in a set of field experiments and by other observations that not all fractures conduct water. Furthermore it is found that conductive fractures only conduct the water in a small part of the fracture in what is called channels or preferential flowpaths. The channels form a conductive network in rock with strong variations in flowrates and velocities between different channels.

This report summarizes the present concepts of water flow and solute transport in fractured rocks. The data needs for predictive modelling are discussed and both field and laboratory measurements which have been used to obtain data are described. Several large scale field experiments which have been specially designed to study flow and tracer transport in crystalline rocks are described. In many of the field experiments new techniques have been developed and used.

SKB Technical Report No 90-39

Modelling of the movement of the redox front in the uranium mine in Poços de Caldas, Brazil

Romero, Leonardo; Moreno, Luis; Neretnieks

Royal Institute of Technology, Stockholm

June 1990

ABSTRACT

Oxygen containing water which infiltrates reducing rock will be reduced by reaction with reducing agents in the rock. The rock will be depleted of its reducing agents and a redox front will develop. Redox sensitive elements such as uranium and some other radionuclides will precipitate in the reducing rock if they are transported into this region. This process has been suggested to take place in a repository for radioactive waste.

In an open pit uranium mine at Poqos de Caldas in Brazil, the upper portions of the rock have been oxidized by infiltrating oxidizing groundwater. The redox front is very uneven and "fingering" is in evidence to depths ranging down to several hundred meters. The redox "fingers" are found in fractures and fractures zones. An

attempt has been made to model the development of such redox fingerings along flow channels and to relate the structure to independent observations of flow channels in other crystalline rocks.

The rate of movement of the front has been calculated using a coupled chemical and transport model for cases which describe diffusive transport of the oxygen, advective transport of the oxygen as well flow in fractures and channels with diffusion perpendicularly from the channel walls into the rock.

SKB Technical Report No 90-40

Distinct element modelling of the rock mass response to glaciation at Finnsjön, Central Sweden

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Itasca Geomekanik AB, Falun 1); Division of Rock Mechanics, Luleå University of Technology, Luleå 2)

December 1990

ABSTRACT

Six rock mechanics models of a cross section of the Finnsjön test site have been simulated by means of distinct element analysis and the computer code UDEC. The rock mass response to glaciation, deglaciation, isostatic movements and water pressure from an ice lake have been simulated.

Four of the models (Model 1-4) use a boundary condition with boundary elements at the bottom and sides of the model. This gives a state of stress inside the model which agrees well with the analytical solution where the horizontal and vertical stresses are almost similar. Roller boundaries were applied to two models (Model 5 and 6). This boundary condition cause zero lateral displacement at the model boundaries and the horizontal stress are always less than the vertical stress. Isostatic movements were simulated in one model (Model 5).

Two different geometries of fracture Zone 2 were simulated. Results from modelling the two different geometries show minor changes in stresses, displacements and failure of fracture zones.

Under normal pore pressure conditions in the rock mass the weight of the ice load increases the vertical stress in proportion to the thickness of the ice sheet. The horizontal stresses in the models differ depending on the boundary condition. An ice thickness of 3 km and 1 km and an ice wedge of 1 km thickness covering half the top surface of the model have been simulated. For each loading sequence of the six models a complete set of data about normal stress, stress profiles along selected sections, displacements and failure of fracture zones are presented.

Major stress discontinuities exist in the vicinity of the fracture zones and fracture Zone 2 in particular. When the pore pressure from an ice lake is simulated in the models the effective stresses acting in the models tend to make the stress state more isotropic and the stress discontinuities of the fracture zones diminish.

The strength of the fracture zones are evaluated based on the Coulomb slip criterion. Models with boundary elements (Model 1-4) showed minor failure along the steeply dipping fracture zones.

Simulation of isostatic movements in combination with ice loading and melting gave several interesting results. Stress discontinuities and large displacements appear at the major fracture zones. Major changes in failure appear when ice thickness is reduced. Fracture Zone 2 fails and other failures are located to the uppermost ~1000 m of the crust.

Based on the results of this study a protection zone of ~100 m width from the outer boundary of stress discontinuity to the repository location is suggested. This value is based on the result that the stress disturbance diminishes at this distance from the outer boundary of the discontinuity. Further, a repsitory located between the steeply dipping fracture zones 1, 14 and 5 should be located below fracture Zone 2 at a depth of about 600-650 m. This value will be less (i.e. 500-550 m) if the interpretation of a horizontal fracture Zone 2 is accepted.

SKB Technical Report No 90-41

Groundwater in crystalline bedrock

Palmqvist, Kai

BERGAB - Berggeologiska Undersökningar AB

June 1990

ABSTRACT

The aim of this project was to make detailed descriptions of the geological conditions and the different kinds of leakage in some tunnels in Sweden, to be able to describe the presence of ground water in crystalline bedrock. The studies were carried out in TBM tunnels as well as in conventionally drilled and blasted tunnels. Thanks to this, it has been possible to compare the pattern and appearance of ground water leakage in TBM tunnels and in blasted tunnels. The extent to which the differences are attributable to disturbed leakage patterns because of increased fracturing and opening of old fractures through the blasting process is discussed.

On the basis of some experiments in a TBM tunnel, it has been confirmed that a detailed mapping of leakage gives a good picture of the flow paths and their aquiferous

qualities in the bedrock. The same picture is found to apply even in cautious blasted tunnels.

It is shown that the ground water flow paths in crystalline bedrock are usually restricted to small channels along only small parts of the fractures. This is also true for fracture zones. It has also been found that the number of flow paths generally increases with the degree of tectonisation, up to a given point. With further tectonisation the bedrock is more or less crushed which, along with mineral alteration, leaves only a little space left for the formation of water channels. The largest individual flow paths are usually found in fracture zones. The total amount of ground water leakage per m tunnel is also greater in fracture zones than in the bedrock between the fracture zones.

The individual leaks are classified into different types according to appearance, width and aperture. Some of the types are very common and are found in all the tunnels studied, while some types mainly occur in one geological region.

In mapping visible leakage, five classes have been distinguished according to size. Where possible, the individual leak inflow has been measured during the mapping process. The quantification of the leakage classes made in different tunnels are compared, and some quantification standards suggested.

A comparison of leakage in different rock types, tectonic zones, fractures etc is also presented.

SKB Technical Report No 90-42

Development of clay characterization methods for use in repository design with application to a natural Ca bentonite clay containing a redox front

Karnland, Ola; Pusch, Roland

Clay Technology AB, Lund

December 1990

ABSTRACT

Natural smectite clays in the form of "true" bentonites formed from volcanic ash, or resulting from in-situ weathering of rock, are available in very large quantities in southern Europe as well as in the rest of the world, and they are suitable for a number of sealing options in repositories, both as tightening component of sand/clay backfills and as highly efficient buffer for embedment of canisters, as well as for fracture sealing. The price and quality, in terms of smectite content and type of smectite, vary considerably and an optimum choice of clay for use in repositories has to be based on quantitative quality data. This requires characterization of the clay material for which a test scheme has been worked out. It comprises determination of the granulometrical, chemical, and mineralogical compositions, as well as of certain physical properties.

Recent research shows the importance of the type of smectite for the longevity of buffers in repository environment, beidellite being less favorable and saponite superior to montmorillonite, which is the most common smectite species. The test-scheme hence includes means of distinguishing between various smectite minerals. The influence of accessory minerals on the chemical integrity of both the smectite and the canister material requires identification also of such minerals, for which the scheme is useful as well.

The report summarizes the various test procedures and gives data from application of the scheme to samples from a natural Ca bentonite containing a redox front. This study suggests that a significant part of the iron in the clay fraction is in the form of Fe^{2+} in octahedral positions of the montmorillonite of unoxidized natural clay and that it is converted to Fe^{3+} on oxidation. Part of the iron is probably in the form of $Fe^{2+}Fe^{3+}$ hydroxy compounds that give the unoxidized clay its bluish color, while they can be assumed to be transformed to yellowish FeOOH forms on oxidation.

SKB Technical Report No 90-43

GMM - A general microstructural model for qualitative and quantitative studies of smectite clays

Pusch, Roland; Karnland, Ola; Hökmark, Harald

Clay Technology AB, Lund

December 1990

ABSTRACT

A few years ago an attempt was made to accomodate a number of basic ideas on the fabric and inter-particle forces that are assumed to be valid in montmorillonite clay in an integrated micro-structural model and this resulted in an SKB report on "Outlines of models of water and gas flow through smectite clay buffers". This model gave reasonable agreement between predicted hydraulic conductivity values and actually recorded ones for room temperature and porewater that is poor in electrolytes. The model also contributed to the understanding of mechanisms involved in the development of swelling pressures and gas percolation. A major feature of the model, which concerned clay formed from bentonite granules being hydrated by taking up water from the surroundings, was that the basic microstructural units are stacks of smectite

flakes with interlamellar water that has different properties than bulk water.

The present report describes an improved model that also accounts for effects generated by salt porewater and heating, and that provides a basis for both quantitative determination of transport capacities in a more general way, and also for analysis and prediction of rheological behavior in bulk. It has been understood very early by investigators in this scientific field that full understanding of the physical state of porewater is asked for in order to make it possible to develop models for clay particle interaction. In particular, a deep insight in the nature of the interlamellar water and of the hydration mechanisms leading to an equilibrium state between the two types of water, and of force-fields in matured smectite clay, requires very qualified multi-discipline research and attempts have been made by the senior author to initiate and coordinate such work in the last 30 years. Despite this effort it has not been possible to get an un-animous understanding of these things but a number of major features have become more clear through the work that we have been able to carry out in the current SKB research work. Thus, NMR studies and precision measurements of the density of porewater as well as comprehensive electron microscopy and rheological testing in combination with application of stochastical mechanics, have led to the hypothe-tical microstructural model - the GMM - presented in this report.

It is self-evident that further improvements of the model are possible and they are expected to be required when using the model in practice, especially respecting functions that have not yet been tested.

SKB Technical Report No 90-44

Preliminary report on longevity of montmorillonite clay under repository-related conditions

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ABSTRACT

This report summarizes current work on developing complete models for predicting the chemical stability of montmorillonitic bentonite buffer materials in HLW repositories. The major degrading mechanism is the conversion of montmorillonite to hydrous mica ("illite"), the basis of the derivation of tentative models being offered by ongoing systematic hydrothermal tests, which indicate that such conversion takes place by dissolution, yielding very mobile silica, and aluminum that tends to stay in the clay voids.

The key mechanism in the transformation to hydrous mica at temperatures below about 130°C is concluded to be neoformation of the latter mineral, the controlling parameter being the access to potassium.

For temperatures ranging between 130 and 200°C, excess silica is released by beidellitization and this yields I/S mixed layer minerals on uptake of potassium, and precipitation of cementing silica in the form of amorphous silica and cristobalite. The rate of transformation of montmorillonite to hydrous mica is still controlled by the access to potassium, i.e. by the rate at which potassium enters the clay. 10 Å minerals that can be mistaken for hydrous mica can be formed by cementing collapsed stacks together.

The models appear to give montmorillonite transformation rates that are in agreement with lab results and geological examples but further calibration, primarily by using the results of ongoing hydrothermal tests in the Stripa study, are required to make them applicable to repository conditions.

SKB Technical Report No 90-45

Interim report on the laboratory and theoretical work in modeling the drained and undrained behavior of buffer materials

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ABSTRACT

This report describes the continuous work of modeling the geotechnical properties of buffer materials. Some results of laboratory work with drained and undrained tests are described as well as the material models that these tests have yielded. The effective stress concept and its relevance is discussed. The technique to apply the models in calculations using the finite element program ABAQUS is described. Some calculations of laboratory verification tests are shown and the results compared. Finally two examples of scenario calculations are shown.

The work has led to three material models that can be used in ABAQUS calculations. All parameters for these models are not fully known and a continuation of the work is required. These models are not suitable for all situations and the relevance and need for further developments are presently investigated.

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