SKB

TECHNICAL REPORT

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SKB ANNUAL REPORT 1991

Including Summaries of Technical Reports Issued during 1991

Stockholm, May 1992

SVENSK KÄRNBRÄNSLEHANTERING AB
SWEDISH NUCLEAR FUEL AND WASTE MANAGEMENT CO
BOX 5864 S-102 48 STOCKHOLM
TEL. 08-665 28 00 TELEX 13108 SKB S TELEFAX 08-661 57 19

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FOREWORD

The Annual Report on SKB's activities during 1991 covers planning, constructing 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 1992

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 1991.

Lectures and publications during 1991 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 1991.

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 1991 in total 1514 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 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 1991 a total of 7 900 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 1991 was 182.7 MSEK of which 15.9 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.
- Radionuclide transport in biosphere and dose evaluations.
- Development of performance and safety assessment methodology and assessment models.
- 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 55 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 1991 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 1991 successful public information activities have been carried out using mobile exhibitions in a tailor-made trailer and on the SKB ship M/S Sigyn.

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SKB ANNUAL REPORT 1991

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 10 000 MW net electric power. Main data and location of the 12 units are shown in Figure 1-1. The nuclear power plants generated about 52% of the total Swedish electric power produced in 1991.

Swedish reactors

Reactor		Power MW_e	Commercial operation	Energy availability in 1991 %
Oskarshamn 1	BWR	440	1972	89
Oskarshamn 2	BWR	605	1974	84
Oskarshamn 3	BWR	1160	1985	92
Barsebäck 1	BWR	600	1975	91
Barsebäck 2	BWR	600	1977	94
Ringhals 1	BWR	795	1976	85
Ringhals 2	PWR	875	1975	89
Ringhals 3	PWR	915	1981	80
Ringhals 4	PWR	915	1983	91
Forsmark 1	BWR	970	1980	91
Forsmark 2	BWR	970	1981	91
Forsmark 3	BWR	1155	1985	94

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 60 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 600 persons are involved in SKB waste handling and research 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.

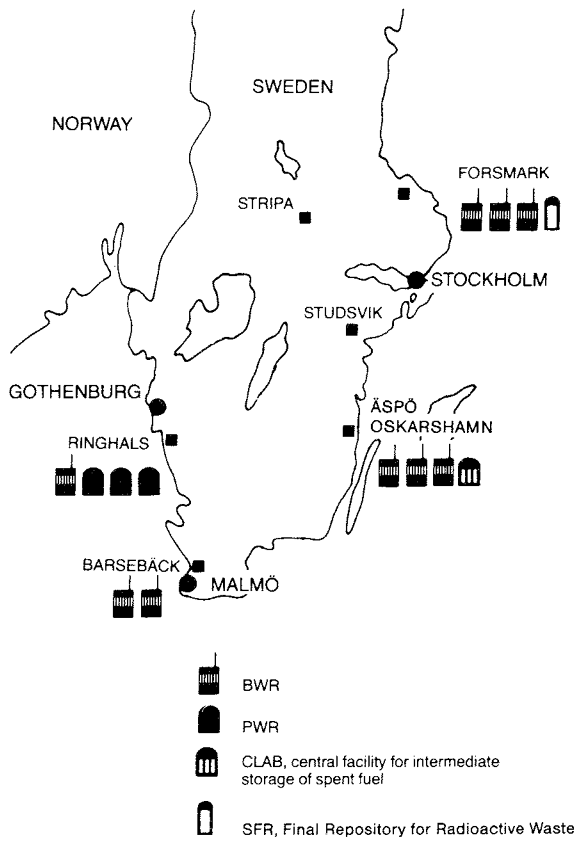

__Figure 1-1.__ The Swedish nuclear power programme.

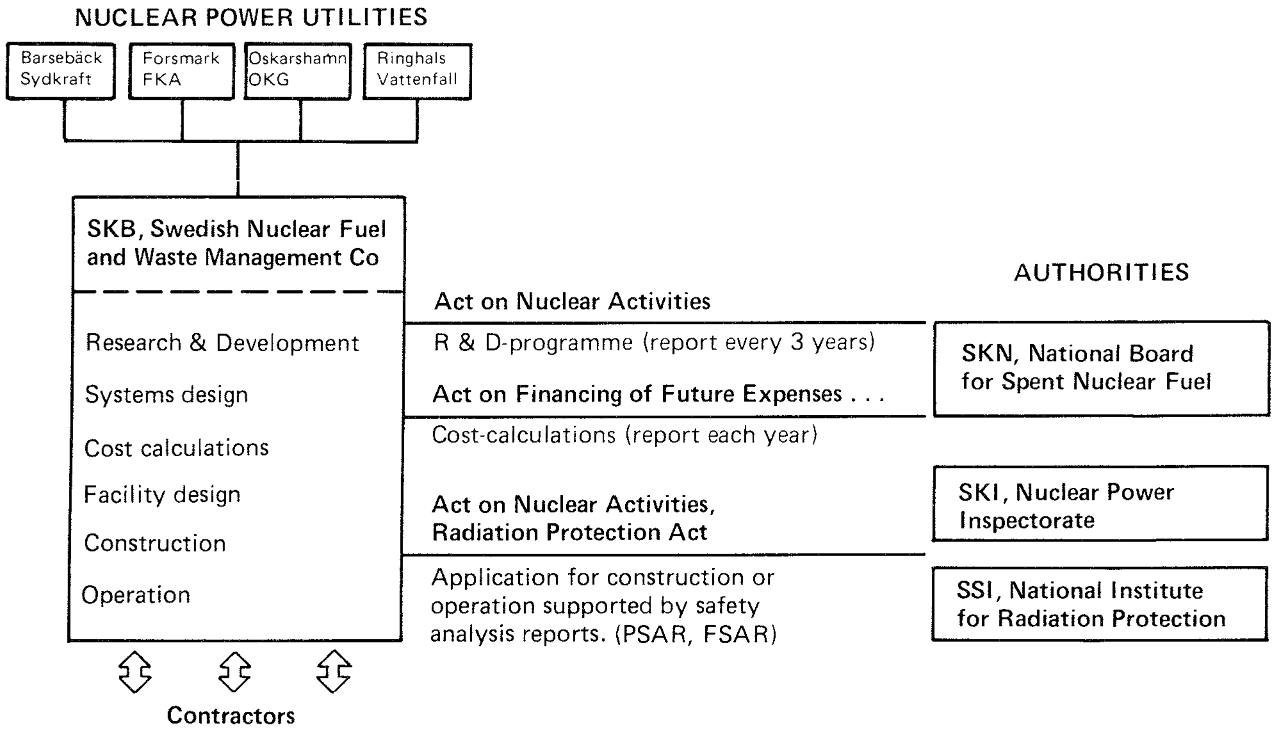

Figure 1-2. *Legal framework for activities of SKB.*

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 has ever since 1984 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	5 300 canisters (7 900 tU)
2 Transuranic-bearing waste	Waste from the Studsvik research facility	Solidified in concrete	Low- to medium-level. Contains long-lived nuclides	1 500 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 facilities 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 into 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, see 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.

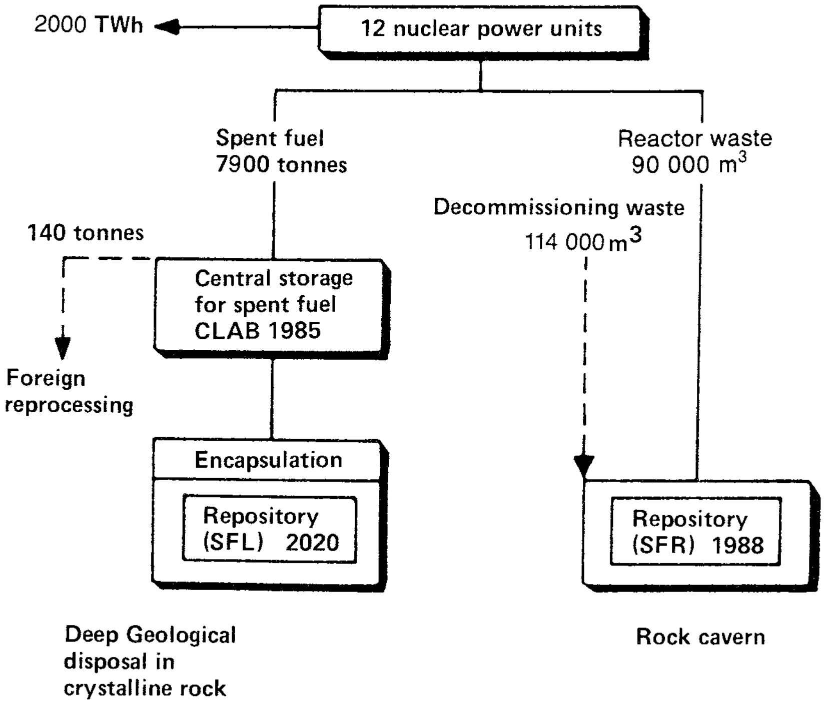

Figure 1-3. *Main system for management of radioactive waste in Sweden.*

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 of natural uranium. 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 1991 up to 2 000 is 15 400 tonnes. At the end of 1991, the Swedish utilities had contracts for supply of 10 900 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 1991, some spot quantities were purchased.

Natural uranium is delivered to Sweden mainly from Canada and Australia, but also from USA. Canada and Australia will deliver around 35% 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 1991.

The average price for long term deliveries in 1984-1990 to the European Community was considerably higher than the spot prices for the same delivery years.

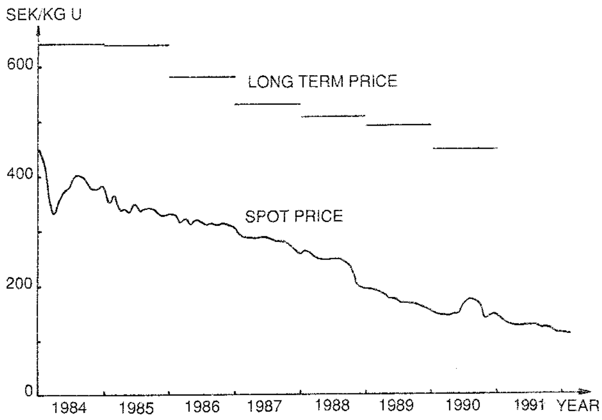

***Figure 2-1.** Long term and spot prices for uranium.*

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 43 000 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 1991-2000, 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 Russia with an enrichment plant near Jekaterinburg. 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.

Russia also delivers enriched uranium which means that the corresponding quantity of natural uranium is of CIS origin.

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.

2.4 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 1991. 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 1991 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.

2.6 COSTS

The costs for the front end supply and services of the nuclear fuel cycle in 1991 in Sweden were as shown in Table 2-1 (the production of nuclear electricity was 73.5 TWh in 1991):

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

	SEK/kWh	Million SEK in 1991
Natural uranium	0.007	510
Conversion	0.001	70
Isotope enrichment	0.008	590
Fuel fabrication	0.008	590
Strategic stockpile	0.001	70
Total front end	**0.025**	**1 830**

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 1983-1991.

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
1991	0.025

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 fuel 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

By the end of 1991 CLAB had been in operation for 6.5 years. The performance of the facility has been excellent. Improvements have gradually been introduced along with the experiences gained. In total 1514 tonnes of uranium from the 12 Swedish reactors have been shipped to the facility and placed in storage.

In 1991 53 casks containing spent fuel have been received, 52 of which contained fuel from Swedish BWR reactors and 1 cask PHWR fuel from the old dismantled Ågesta reactor. The Ågesta fuel has been stored at the Studsvik nuclear research centre for more than 15 years. 4 casks containing residuals from post irradiation examination of fuel at Studsvik have also been received. The total fuel quantity shipped to CLAB during the year amounted to about 157 tU. In addition two casks with core components have been transferred to CLAB.

Fuel handling in the receiving building was temporarily halted during about 2 weeks by the end of 1991, while an extra safety analysis of a handling incident was performed.

The total occupational dose in 1991 (77 mmanSv) was about 37% of what was expected according to the final safety report.

The release of radioactivity to the environment during the 6 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 1991 to about 72% of those of 1986 in real terms.

A major contribution to the savings is due to the installation in 1990 of a simple system allowing the residual heat from the fuel to be used for heating the entire plant.

Another important factor is the improved operating procedures, which made it possible to unload casks in one shift instead of in two shifts.

The flexibility of the plant has been demonstrated by the fact that other transport casks than the normally used standard cask have been used for shipments to CLAB at several occasions. E.g. a cask built in the 1960's is used for the transfer of the Ågesta fuel and post irradiation examination residues from Studsvik. The operating procedures and involved equipment have been quite easily adapted to the different casks.

3.3 INCREASED STORAGE CAPACITY

The storage capacity of the existing pools, 3000 tU, will be fully utilized by year 1996, see Figure 3-1. 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%. 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 5000 tU. The government gave its permission in December 1989. Due to this increase, the new cavern will not be needed until after year 2003.

Tests with a prototype of the new compact BWR canister, see Figure 3-2, were successfully finished in February 1991 and an order of serial canisters was placed with ABB Atom AB in March. The first serial BWR canister was delivered in December 1991.

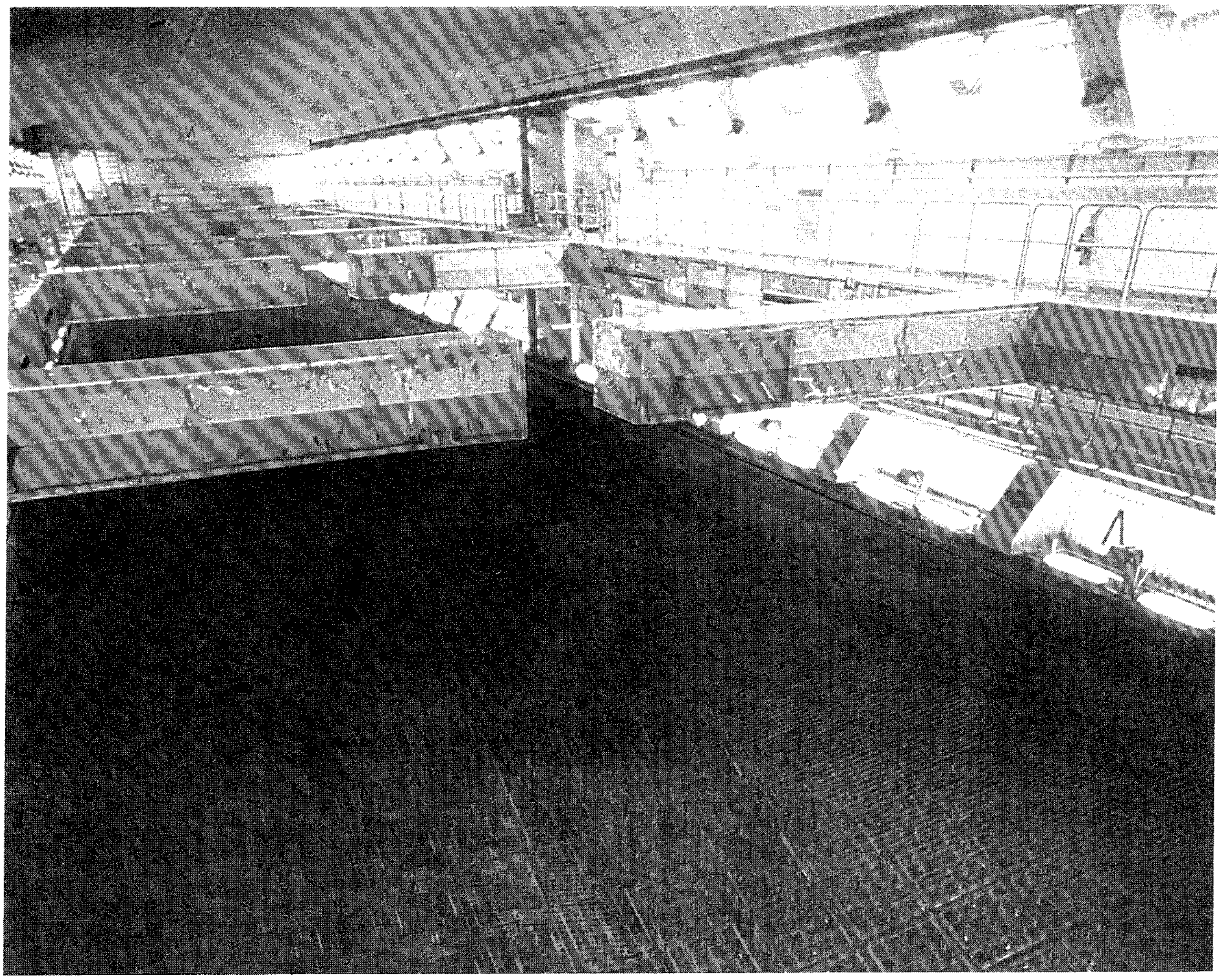

Figure 3-1. *Storage pools with PWR and BWR canisters.*

The final Safety Analysis Report for the new canisters and for the necessary modifications of the plant hardware and operating procedures has been submitted to the competent authorities. The new canisters are expected to be used routinally from March 1992.

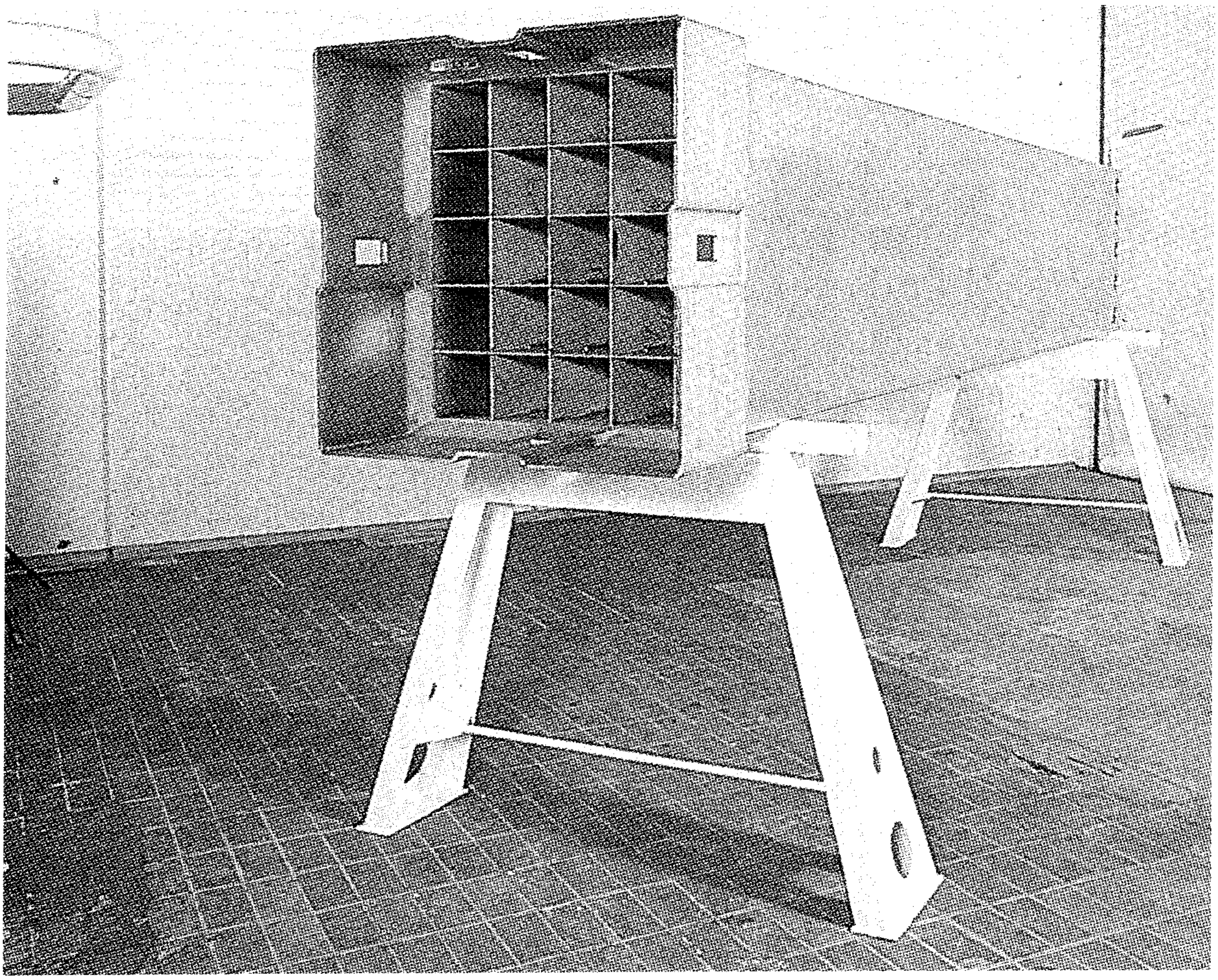

Figure 3-2. *BWR compact storage canister with borated stainless steel insert.*

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.

SKB has engaged the shipping line Rederiaktiebolaget Gotland to operate Sigyn.

4.2 OPERATING EXPERIENCES

In 1991 the ship, M/S Sigyn, sailed around 20 500 n.m. during 78 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 59 transport casks with spent fuel, 2 transport casks with core components and 87 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.

A complete new satellite navigation system has been installed at the ship making the operation of navigation system even more reliable.

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 18 cities including the capital, Stockholm.

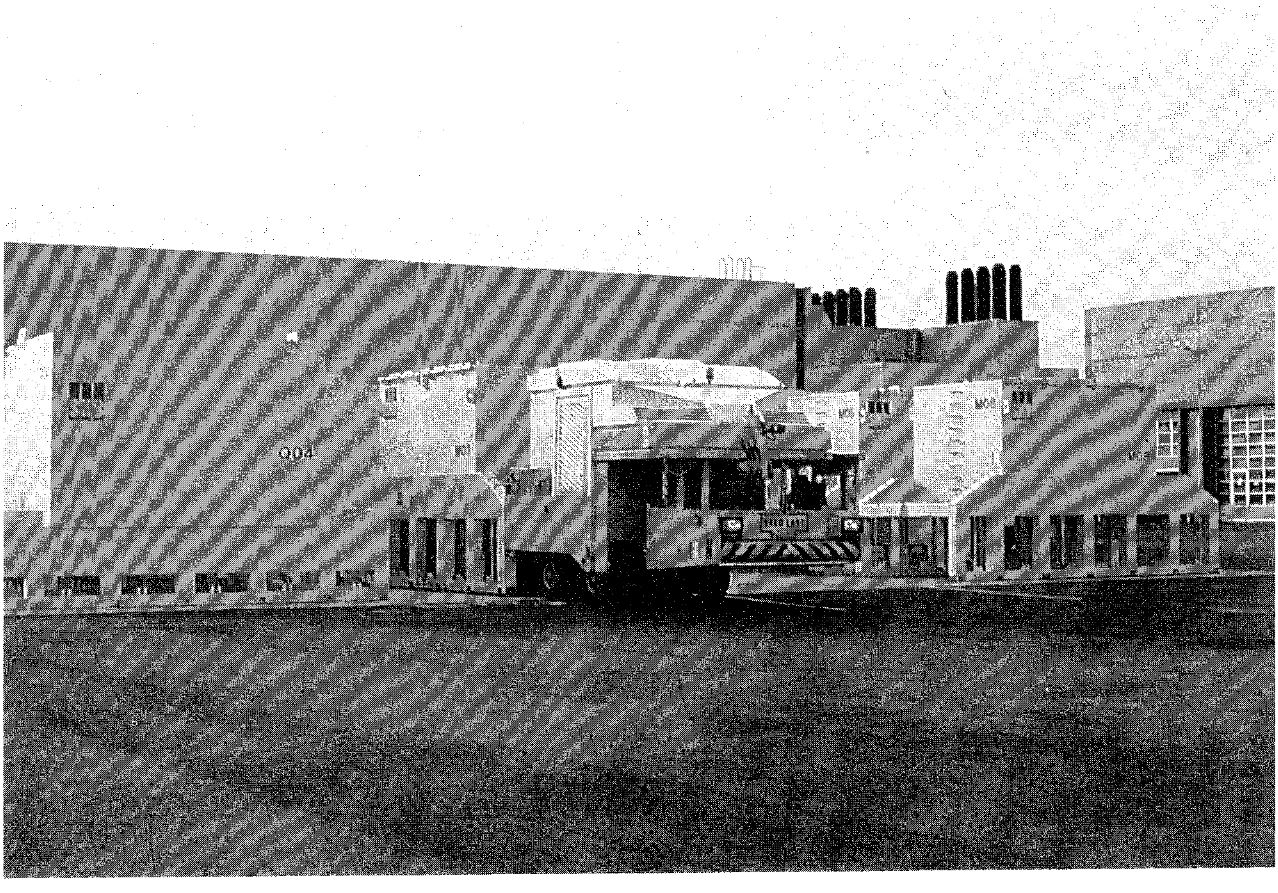

Figure 4-1. *ATB-containers and the specially designed SFR terminal vehicle at the SFR receiving area.*

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 mainly 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.

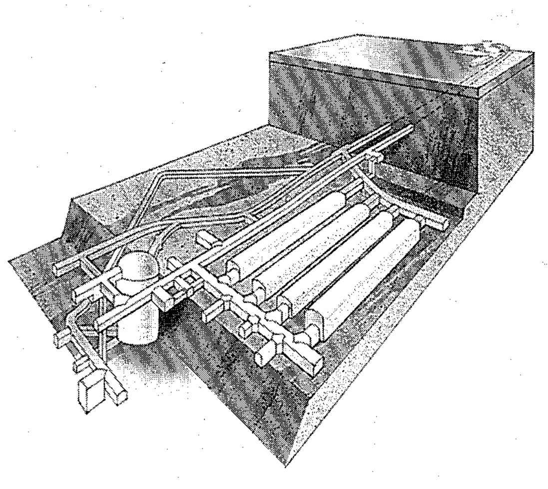

Figure 5-1. Overview of tunnels and storage chambers in the first construction stage of SFR.

At the end of 1991 a total of 7 900 m^3 of waste have been deposited in SFR. All waste producers, except Studsvik, 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. 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 are disposed of in a concrete silo structure. Surrounded with a low permeable buffer material, bentonite. The space between the waste packages and the concrete construction in the silo are subsequently filled with a porous concrete.

Waste containing a minor part of the activity content are disposed of in 160 m long caverns with various cross sections. The cavern with the largest cross section, BMA, is equipped with machines for remotely controlled handling, similar to those used in the silo, see Figure 5-2.

LLW is handled with an ordinary forklift truck.

5.3 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.

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. In 1991 19 waste types (of a total of about 40) were accepted for disposal. In 1991 disposal has been carried out in the rock chambers and in the silo.

5.4 SAFETY ASSESSMENT

According to the operation permit of 1988, SKB is requested to provide additional information on some areas of the safety assessment before large quantities of waste can be emplaced in the silo and concrete grouting is permitted. This additional information was presented to the authorities as a deepened safety assessment in August 1991. Some areas that are covered in detail are the effects of gas production, the effect of complexing agents from the degradation of cellulose and the change in the hydrological regime due to land rise. Also a systematic scenario analysis is included. The results of this deepened safety assessment confirms the results of the Final Safety Report.

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 1991 a total of 7 900 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. To overcome some remaining problems with high moisture content in the repository air an air drying system has been installed in 1991.

During 1991 the first two sections at BMA was sealed.

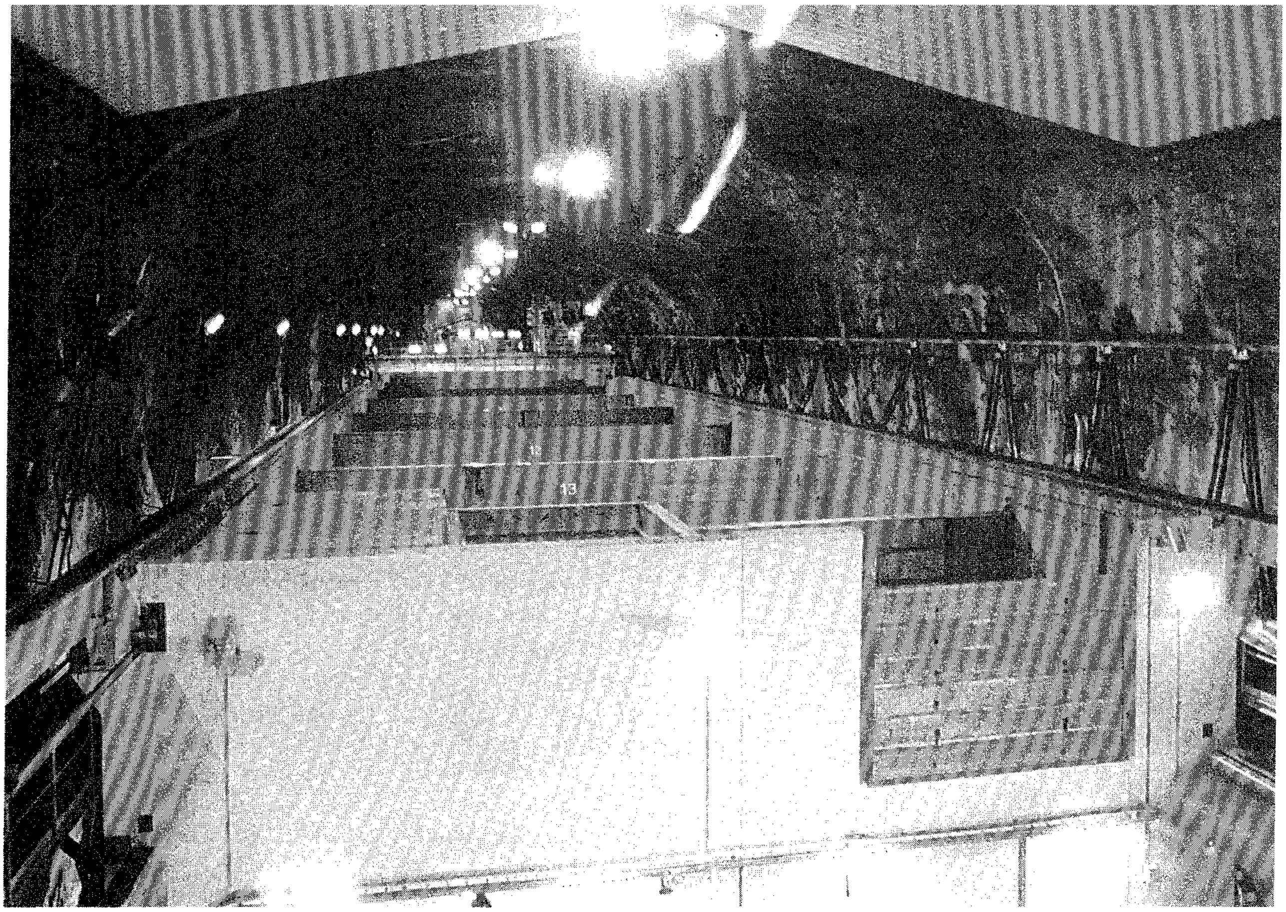

Figure 5-2. *View over the cavern with the largest cross section, BMA, where handling of the waste is remotely controlled.*

6 RESEARCH AND DEVELOPMENT

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 for the research and development and other measures that are needed i 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 – SKN – every three years starting 1986. The second programme was submitted by SKB to SKN in September 1989 /6-1/ and approved by the government in December 1990.

The work done during 1991 has in general followed the 1989 programme with some amendments requested by the government on SKN's suggestion. This chapter only gives a few highlights of the results obtained in 1991. For a more comprehensive account the reader is referred to Chapters 10-22.

The programme is executed under the leadership of SKB's division for research and development. The staff of the division was 24 persons in 1991. 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 63 technical reports in the SKB-TR-series, 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 1991 were 166.8 MSEK as compared to 126.4 MSEK in 1990. The increase was due to the first full year of construction work at the Äspö Hard Rock laboratory and increasing efforts in preparation for siting of a deep geological repository for spent fuel.

SKB is also the managing participant in the international Stripa Project. The expenditures for this project was 25.0 MSEK of which 9.1 MSEK were SKB contributions and 15.9 MSEK came from participants outside Sweden. The total turnover of the R&D-division was thus 182.7 MSEK.

6.2 REPOSITORY DESIGN STUDIES

The reference design for spent fuel disposal for SKB's various R&D activities and other studies has been the KBS-3 method published in 1983. The method was extensively evaluated and found acceptable with respect to safety and radiation protection. It formed the 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 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.

During 1991 the ranking methodology has been defined. Various canister designs have been defined for the three alternatives. The technique for emplacement of canister and bentonite buffer has been studied in some detail for the VLH concept. Additional geological data for the assessment of the VDH concept have been obtained from the Russian boreholes at Kola (12 260 m deep), Tyrauz Caucasus (4 001 m deep) and Krivoy Rog Ukraine (4 549 m deep). These data support the conclusions based upon the borehole data from Gravberget Sweden (6 600 m deep).

The studies in the PASS project have so far lead to the conclusion that the VDH both from a technical and from an economic point of view will be less favorable than the KBS 3 concept. Even if the VDH has a high potential for safe isolation of spent nuclear fuel this may not outweigh the disadvantages concerning technology and cost as also KBS 3 will give a very safe isolation.

6.3 SAFETY ANALYSES

The activities with regard to safety analysis during 1990 and 1991 have been focused on SKB 91, an assessment of the role of the site geology to the total safety of the repository for spent nuclear fuel. Although the report was sent to print in May 1992 almost all the work had been done by the change of the year, so it is reported in the 1991 Annual Report.

The assessment shows that the encapsulated fuel will, in all likelyhood, be kept isolated from the ground water for millions of years. In order to be able to study the role of the rock for the safety of the repository, calculations have been carried out under the assumptions that some initially defect canisters have been deposited.

The SKB 91 safety assessment shows that a repository constructed deep down in Swedish crystalline basement with engineered barriers possessing long-term stability fulfils the safety requirements suggested by the authorities with ample margin. The safety of such a repository is only slightly dependent on the ability of the surrounding rock to retard and sorb leaking radioactive materials. The primary function of the rock is to provide stable mechanical and chemical conditions over a long period of time so that the long-term performance of the engineered barriers is not jeopardized.

SKB 91 has shown that the safety-related requirements on a site where a final repository is to be built are such that they are probably met by most sites SKB has investigated in Sweden. The assessments also show that there are a number of factors that can strongly determine how the bedrock performs as an extra safety barrier. An example is the presence and location of flat fracture zones and their hydraulic conductivity.

The SKB 91 constitutes an example of how performance assessments can be used to shed light on the importance of various geological structures in a possible repository area and to clarify factors that are essential from a safety point of view. The methodology can, in the continued siting work, be utilized to adapt the repository in such a way that the ability of the rock to contribute to the safety of the repository is optimally utilized. However, this requires access to site-specific data and an opportunity to augment these data continuously as the safety assessments progress.

Beside the activities directly related to SKB 91, work has mainly been done to further develop alternative models for nearfield transport of radionuclides and the farfield hydrology.

In a Nordic cooperative project the value of and the possibilities for preserving information on repositories for radioactive waste is studied.

6.4 SITING OF A FINAL REPOSITORY FOR SPENT FUEL

The siting of a deep geological repository for spent nuclear fuel and other long-lived waste is one of the main remaining tasks within the Swedish Nuclear Waste Management programme. Siting of this repository will be done in stages over the next 10 years, involving site-investigations and site characterization activities. This siting process can build on more than 15 years of research, development and field studies and it will be supported by the results and experiences continuously obtained within the ongoing programmes for research, system studies, safety assessments and Äspö HRL.

The first stage of the siting process is a systematic assessment of all important aspects concerning the future proposal of suitable candidate sites for further investigation. This work to identify, compile and analyze information about important siting factors has now been started.

Present planning is to complete stage 1 (overview studies and assessment of siting factors) by mid 1993. It is estimated that pre-investigations (stage 2) and detailed site investigations (stage 3) will require in total about 10 years.

6.5 WASTE FORMS

The waste form research is concentrated on fuel characterization studies, fuel corrosion, modelling and natural analogue studies.

The fuel characterization studies have during 1991 been focused on the identification of corrosion sites. Spent fuel has been examined in scanning electron microscope before and after corrosion in water. An increased attack has been found in the fuel rim, where the porosity and the alpha dose rate are the highest.

The spent fuel corrosion studies have now been in progress for over ten years. The release rates of fission products and actinides are studied as a function of redox conditions, water chemistry and fuel irradiation history. While the releases of the actinides are controlled by their solubilities, the releases of some fission products reflect their behaviour in the fuel during irradiation.

The modelling studies are concerned mainly with the effects of radiolysis on fuel dissolution under reducing conditions. A substantial part of this work is performed in cooperation with AECL, Canada.

The natural analogue studies aim at elucidating the long term alteration processes of fuel by studying the alteration products of natural uraninites under oxidizing as well as reducing conditions.

6.6 CANISTERS

The programme for studies of canister materials have been switched from corrosion studies to having the emphasis on mechanical integrity.

During 1991 the main effort has been to investigate the creep properties of pure copper and of micro-alloyed copper. It has been found that although pure oxygen free copper shows very low creep ductility at elevated temperatures, a similar behaviour can not be found for the alloys.

A study of pitting corrosion on steel was finalized in 1991. It was shown that the rate of pit propagation was lower than previously suggested and that the time period during which pitting was possible in a repository is only a small fraction of the canister service life and, consequently, not seriously limiting the service life of a steel canister.

Production methods for the advanced cold process canister have been evaluated. There are several manufacturing routes available already today, such as hot extrusion or hot rolling and bending followed by electron beam welding. The latter method proved to be the most economical one for a full scale production of canisters.

6.7 BUFFER AND BACKFILL

The ongoing research on buffer and backfill materials is aiming at characterizing the properties of bentonite, and developing models for predicting different qualities' mechanical and chemical behaviour under repository conditions.

Two major studies reported during 1991 are the SKB/CEA joint experiment at Stripa with French clay heated to about 170°C during about 4 years, and laboratory experiments with salt water uptake by sodium as well as calcium-rich bentonite.

The Stripa experiment showed that the clay closest to the steel heater in the hottest zone hade been altered into claystone with total loss of swelling capacity and significant increase in hydraulic conductivity. This alteration is explained by the observed dissolution of minerals and precipitation of new ones.

The laboratory experiments with saline water uptake by non-saturated bentonite showed that the swelling pressure of sodium bentonite is not affected for temperatures up to 130°C and salt contents of up to 3.5% sodium chloride. The swelling pressure of calcium bentonite dropped by 50% compared to experiments at 20°C and with distilled water. The hydraulic conductivity increased about the same, up to ten times, for both sodium and calcium bentonite.

6.8 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 1991 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. Besides these major works some special effects studies have been made. SKB has also joined the international DECOVALEX project initiated by the Swedish Nuclear Power Inspectorate. The project aims at development and validation of coupled thermal-hydro-mechanical models.

In 1986 SKB initiated an interdisciplinary study of the post-glacial faults in the Lansjärv area in northern Sweden. The Lansjärv project was ended by a scientific excursion in the summer of 1991 by a group of invited international experts. According to the summarized comments from the experts the postglacial faults are mainly reactivated older fracture zones, but the occurrence of new fracturing to some extent can not be excluded. The causes of the post-glacial movements are probably a combination of rapid changes in vertical load with possible large earthquakes associated with deglaciation and horizontal crustal shortening related to continental plate boundary forces.

The SKB programme on bedrock stability also includes studies of the stress field variation in the Baltic Shield, of the so called Protogine Zone, of stability in South-eastern Sweden, of the isostatic uplift and of shoreline displacements in the county of Värmland.

In preparation for the forthcoming siting process a review of previously collected field data from the study sites investigated since 1977 has continued. 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.

Supplementary studies of gabbro as a host rock have been initiated partly in cooperation with TVO in Finland.

The spent fuel disposal programme includes the possibility of constructing a repository in the bedrock beneath the sea. This option has a low priority but some efforts have been made to compile the knowledge on the application of high resolution off-shore geophysical surveys in the Baltic.

6.9 INSTRUMENTS AND METHODS

As for the last couple of years most of the SKB field investigations have been carried out within the Äspö Hard Rock Laboratory Project. Since the tunnel excavation started in late 1990 most field investigations are related to investigations from the tunnel and monitoring of the groundwater responses, caused by the tunnel excavation.

In 1991 all measuring points of piezometric levels in the formation, i.e. more than 150 borehole sections, were included in a new Hydro Monitoring System (HMS). Most of the measuring points are connected on-line, which enables real-time observations of excavation responses from a host computer at the site office.

Tunnel radar and tunnel seismics were tested in the tunnel to examine their usefulness for characterizing the rock around the tunnel and ahead of the tunnel. Another geophysical project was the testing of a light, portable vibroseismic equipment for reflection seismics from the ground surface.

Outside the Äspö project a new point dilution borehole probe is under development. The probe will measure the groundwater flow across a borehole section, at depths down to at least 1000 metres.

Core drilling of 56 mm boreholes with reverse circulation of the drilling water has been tested successfully down to 300 metres depth. The reverse circulation drilling method reduces local chemical contamination of the groundwater by the drilling fluid.

6.10 CHEMISTRY

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

The geochemical investigations have been concentrated to the Äspö HRL site. Groundwater is continuously sampled from several points during the ongoing tunnel excavation. The isotopic signature of deep groundwaters below 400 to 600 m indicate that these waters have not been involved in the surface water circulation since the latest glaciation.

A large scale redox experiment has been initiated in a fracture zone at about 500 m from the Äspö tunnel entrance. The goal is to define whether or not the increased water circulation caused by the tunnel construction could result in oxidizing pathways from a repository at several hundred meters depth up to the surface.

The radionuclide chemistry work has included studies of solubility and sorption, of organic complexes, colloids and microbes and of sorption and diffusion. An evaluation has been made of the importance of radionuclide transport in the form of colloidal particles, as humic complexes or with microbes. One conclusion was that the organic complexes will cause a minor decrease in the sorption coefficient. Due to the low concentrations of colloidal particles transport by particulates will be insignificant for safety even with the very pessimistic assumption of no retention at all. Several experiments and field studies (at Finnsjön) demonstrates that technetium will be reduced to IV-valence state in the geochemical environment existing in the deep bedrock. This means that its migration from the repository will be extremely slow and it would not reach the biosphere even if it would be leached from the fuel.

Modelling of the Finnsjön tracer experiments continues within the INTRAVAL project. Tracer experiments have been made at Stripa as part of the SCV-programme which was finished in June 1991.

A long pumping test using radioactive tracers was made at Äspö in the autumn of 1990. The results of the tracer break through curves are consistent with the pattern of fracture zones given by the conceptual model developed from other preinvestigations in the area. The flow paths did, however, not agree completely with those inferred from the numerical model. The predicted residence times were underestimated compared to the experimental results. This can be interpreted as due to uncertainty in the flow porosity used for the predictions.

6.11 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. All experiments at Stripa were completed according to plans by June 30, 1991. The mine was then abandoned by the owner.

Evaluation of results and reporting has continued and will be completed during the first half of 1992. A final Stripa symposium is planned for October 1992 in Stockholm.

6.12 THE ÄSPÖ HARD ROCK LABORATORY

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 the excavation of the access tunnel started on October 1, 1990. The main contractor for the construction work is Siab, Swedens third largest construction company. SKB has established a site office responsible for the scientific documentation of the tunnel, for performing special investigations and for monitoring of logging equipment in boreholes etc. An extensive effort has been made to plan in detail the integration documentation, investigations and construction. So far this effort has been successful. The first 800 m of the access ramp was considered as a "learning" stretch in order to work out this integration in detail.

The results from the pre-investigation phase has been summarized in four Technical Reports. The predictions made as part of the pre-investigation work forms the basis for the minimum documentation to be performed in the ramp and in the monitoring programme.

During 1991 a new communication system for monitoring and collecting data from boreholes was installed. The data are transmitted by radio to a computer at the site office.

A Blasting Damage Experiment was carried out in the ramp as a part of the disturbed zone studies. It was aimed at studying the distribution and character of the blasting damage around the tunnel contour. Three different blasting schemes were used. Several methods of investigations were used to detect the damage; The damage zone was 0.3 – 0.6 m in the tunnel walls and 1.0 m – 1.7 m in the floor depending on blasting scheme. Drilling precision was not unexpectedly found to be a major factor controlling the development of blast induced fractures in the contour.

In order to prepare for the passage of a major fracture zone (NE-1) at about 1250 m special studies have been carried through. Several tasks have been performed when passing the fracture zones EW-7 and NE-3. Efforts have been taken to ensure that a practical and acceptable grouting programme will be used in the tunnel when grouting is needed. The difficulty is to avoid affecting potential future experimental areas when cement grout is injected.

The planning of the surface buildings on Äspö – often referred to as the Äspö Research Village – proceeds. A turn-key contract for ventilation of the underground research caverns was awarded to Svenska Fläkt AB. A turn-key contract for installation of the hoist system including the shaft installations for the hoist was also awarded to ABB Drives AB.

Three agreements with foreign organizations have now been signed for participation or cooperation in the Äspö HRL. These organizations are Atomic Energy of Canada Limited, Power Reactor and Nuclear Fuel Development (PNC), Japan and Central Research Institute of Electric Power Industry (CRIEPI), Japan. PNC and CRIEPI have attached personnel to the site in order to follow the work.

In order to celebrate the start of the Äspö Project an international seminar and a special ceremony took place May 13-14. Proceedings from the event have been published.

6.13 NATURAL ANALOGUE STUDIES

The studies of natural analogues is an important tool to enhance the confidence in our models with regard to long-term processes. SKB has during 1991 been engaged in three such studies i.e. the Poços de Caldas project, the Cigar Lake project and the studies at Oklo recently initiated by CEA and CEC.

The Poços de Caldas project was formally finished in 1990. Some reporting work has, however, also continued through 1991. Besides that additional modelling work has proceeded and given new insights in particular concerning redox fronts and also behaviour thorium and rare earths.

The Cigar Lake uranium ore body is situated in northern Saskatchewan, Canada at a depth of 430 m. The ore is embedded in illitic clay and the overlaying rock is sandstone. Under the ore is the crystalline basement rock. The ore is of the order 1300 million years and is very rich in uranium. SKB participates since 1989 with AECL in the investigation of this analogue. The investigation programme covers rock mineralogy and geochemistry, ore and nuclear reaction products, hydrogeology, hydrogeochemistry, colloids, organic geochemistry and microbiology, radiolysis and finally modelling. The modelling efforts have been intensified during 1991. The present agreement between SKB and AECL expires in 1992 but discussions on some continuation are in progress.

The studies at Oklo have now the opportunity to investigate also underground reaction zones in addition to the zones in open pits discovered in the 1970s. Some interest has also been directed to a newly discovered zone at Bagombe which is not disturbed by the mining and thus would be of special interest for investigation of the natural hydrogeologic situation.

6.14 BIOSPHERE

The aim of the biosphere program is to improve confidence in long term modelling of the transfer of radionuclides from deep groundwater to man. The program includes studies of distribution in soils and sediments , site specific recipient studies, participation in three international model validation exercises and also uses the Chernobyl fallout to get a better understanding of redistribution processes.

One of the two studies of distribution in soils and sediments have been completed in 1991 and have investigated the difference between inflow areas and normal sediments in lakes. The other study concerns the K_d concept in soils and sediments and tries to take thermodynamic data into account.

The evolution of the recipient areas and sediments around Äspö are studied in another study since 1989. The water flow through the sediments have been shown to be very slow and horizontal.

BIOMOVS II started up in 1991 as a follow up of the BIOMOVS study. The initiative was taken by the National Institute for Radiation Protection, SSI. Among the expected results of this exercise is international consensus on a reference biosphere modelling concept. Other validation exercises VAMP and PSAC1b are concentrating on parameter values and on probabilistic approach.

Chernobyl fallout has been used as tracers in an attempt to get a better understanding of redistribution processes. The Gideå area was well investigated before the accident and was used for sampling. This study will be reported on in 1992 and 1993.

6.15 INTERNATIONAL COOPERATION

SKB recognizes the need for extensive international cooperation and information exchange. Both written and informal agreements with organisations in other countries dealing with nuclear waste have been established.

During 1991 the most active cooperative work has been performed together with TVO in Finland, CEA in France and AECL in Canada. Also the work in different working groups and projects put together by international organisations like CEC EURATOM, OECD/NEA and IAEA has a high priority in the SKB programme.

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 3 000 to 5 000 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 at 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 electricity production and the future costs for the back-end operations related to this electricity production. The results of the 1991 calculations were presented in PLAN 91 /7-1/. The total future electricity production (from 1991) was estimated to be about 1 340 TWh, if all twelve reactors are operated to year 2010. Up to the end of 1990 about 660 TWh have been produced making a total of about 2 000 TWh in the Swedish programme. For this production a fuel volume of about 7 900 tonnes of U is required.

The total future back-end costs were estimated to be about GSEK 47.4 (price level of January 1991). Up to and including 1991 already SEK 8.0 billion have been spent. The total cost for the back-end of the nuclear fuel cycle is thus about SEK 55 billion. The breakdown of the costs are roughly (old reprocessing costs excluded):

Transportation of waste	4%
Interim storage of spent fuel	19%
Encapsulation and final disposal of spent fuel and long-lived waste	41%
Final disposal of operational and nuclear power plant decommissioning waste	5%
Decommissioning and dismantling of nuclear power plants and	21%
Miscellaneous including R&D, pilot facilities	10%

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 1992 shall be SEK 0.019 per kWh on an average. This is the same fee as for the last eight 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 1991 about GSEK 9.7, an increase by GSEK 2.0 since 1990.

7.4 DECOMMISSIONING OF NUCLEAR POWER PLANTS

During 1991 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

Initiated by the interest shown by foreign organizations to share the know-how and experience gained in SKB's nuclear waste management program, a small group was set up within SKB in 1984 for the management of consulting services. Such services are normally carried out by project teams tailored to cover the competence needed in each specific case, see Figure 8-1. Project team members are selected among experts in SKB's own staff or from other organizations involved in SKB's Swedish programme – "Associated Groups".

From the start in 1984 about 60 assignments have been accomplished for some 20 clients in Europe, Canada, USA, the Far East and Australia. The tasks have referred to desk studies of general programmes, performance assessments, barrier functions, specific facilities (for interim storage of spent fuel, transportation and disposal) as well as to field work (borehole measurements of hydrological, geophysical, geochemical and rock stress parameters).

Consulting services performed during 1991 are summarized below.

Australia

A preliminary feasibility study of a possible system for disposal of HLW in Australia was reported to the SYNROC STUDY GROUP in 1990. During 1991 this study has been supplemented by a tentative plan for further investigations.

Finland

As a continuation of earlier services to TVO radar measurements have been performed in a number of boreholes in Finland. SKB has also prepared compilations of groundwater flow scenarios and of properties of gabbro formations for TVO.

Hungary

An interim storage facility for spent nuclear fuel is planned at the Hungarian power plant PAKS. SKB has been contracted for assistance in the evaluation of tenders. Representatives of SKB have attended a number of meetings in Hungary.

Japan

In 1990 SKB was contracted by the Power Reactor and Nuclear Fuel Development Corporation, PNC, for hydrogeological measurement and groundwater sampling in a 1000 m deep borehole in Japan. The work was performed in early 1991, using one of SKB's umbilical hose equipments.

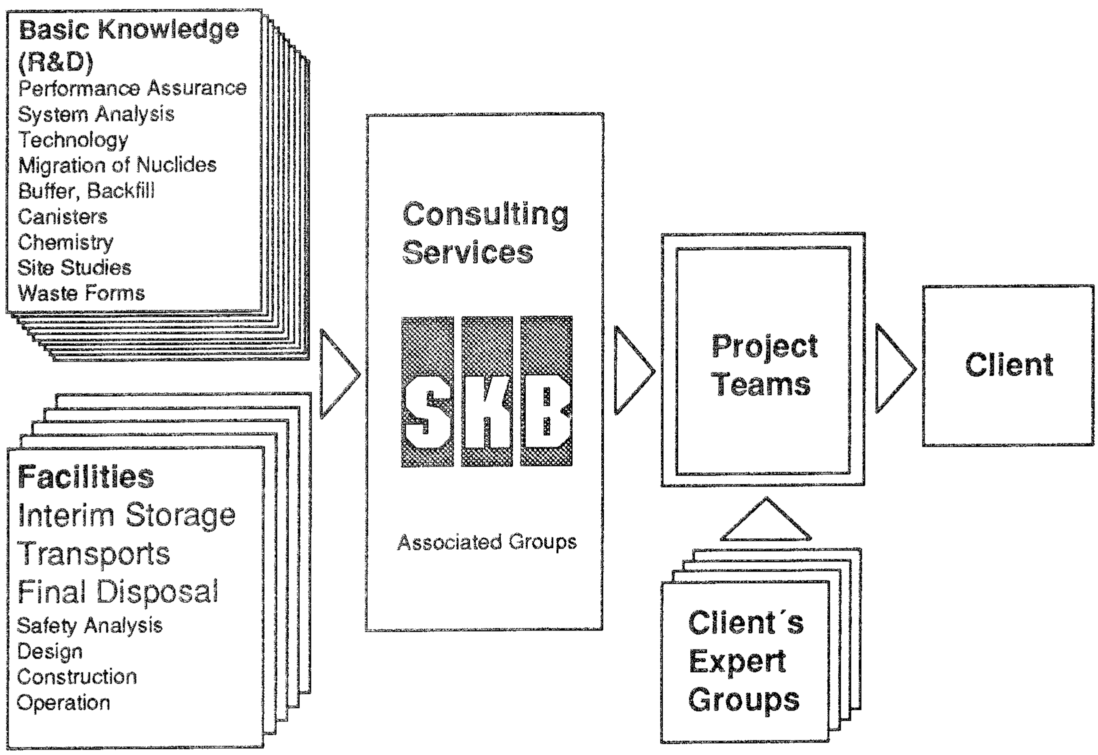

Figure 8-1. The SKB Consulting Services.

A report on the development of the Swedish nuclear waste management program with regard to organization, distribution of responsibilities, legislation and public interaction has been prepared for the Japanese consulting company IEA.

A contract for transfer of know-how and experience connected to the function of barriers in an underground repository for operational wastes has been signed with SHIMIZU CORPORATION.

Spain

In early 1990 SKB was contacted by its corresponding organisation in Spain, ENRESA, and invited to present a proposal for consulting services aiming at the conceptual design of HLW/spent fuel repository in Spanish granite. Based on a proposal from SKB of July 1990 a contract was signed on October 1, 1990.

For the project SKB organized a multidisciplinary team with representatives from the own staff and from Associated Groups (ABB-ATOM, Clay Technology, Conterra, Kemakta, Safetech Engineering and VBB-VIAK). The proejct team also included four engineers from ENRESA's Spanish consultant INITEC, who worked in SKB's office during the period October 1990 to June 1991. The intention was, that these engineers should be trained and get insight in actual matters for taking the primary responsibility for finalizing the project work in Spain.

The first phase of the project, finalized in February 1991, included compilation of information needed for the selection of a reference repository concept. In the second phase different combinations of alternatives for repository lay-out and design, canister design and emplacement mode etc were evaluated with regard to technical feasibility, safety and costs. The work during this phase was reported by the end of 1991 together with recommendations to ENRESA.

In the third phase of the project the reference repository concept chosen by ENRESA (with possible back-up alternatives) will be further developed in more detail. This work will be performed during the first half of 1992 in Spain by INITEC as responsible party and with SKB available for advice. More independent contributions from SKB regarding safety assessment and planning of R&D activities are foreseen.

South Korea

Instruments for radar measurements in boreholes have been delivered to Korea Institute for Energy and Resources, KIER.

Taiwan

In March 1991 a general cooperation agreement was signed by Radwaste Administration (RWA) and SKB, laying down procedures and conditions to be applied for consulting services from SKB. RWA is the regulatory and supervisory agency for nuclear waste issues in Taiwan and is part of the Atomic Energy Council (AEC).

In August 1991 RWA declared an interest to have a discussion with SKB in Taiwan about matters of mutual interest with a focus on Swedish experience from final disposal of operational wastes. A representative of SKB visited Taiwan one week in early October and presented the Swedish waste management program. Where relevant, possible applications of Swedish experience in the Taiwanese program were discussed. The discussions have been documented in a report to RWA.

Czechoslovakia

The Czech Geological Survey has commissioned SKB as advisor in the planning of geological investigations for a repository for radioactive wastes.

9 PUBLIC AFFAIRS AND MEDIA RELATIONS

9.1 GENERAL

Public information is an integrated and important part of the Swedish radioactive waste management programme. The need for support by the general public calls for extensive activities by SKB, both locally and on the national level. The goal of the communication programmes is to present a clear and unbiased view of the main issues today and the principal plans for tomorrow. All work is based on the firm belief that the Swedish public is entitled to open and comprehensible information on the different aspects of the handling and disposal of radioactive waste.

During the last year Sweden has seen the domestic energy debate changing towards new perspectives with a slightly increased acceptance of nuclear power. However, the earlier parliament decision to abolish nuclear energy in the year 2010 is still valid.

Two 1991 opinion polls made by an independent research institute show an unchanged majority of 85% of the Swedish people accepting the disposal of spent nuclear fuel within Sweden. A small majority of 54-56% also accept a final repository in their own neighbourhood.

9.2 SKB INFORMATION ACTIVITIES

As before, two mobile SKB exhibitions toured Sweden during part of 1991 – one on wheels between April and November and one aboard the SKB transport ship M/S Sigyn during the summer. Almost 120,000 visitors were received at 75 different locations around Sweden. Local politicians, members of different associations, high school students, and local media representatives were invited individually to special receptions at each new place.

This very important activity within the field of public information and media relations was supplemented by a series of six advertisments in selected newspapers and magazines. These ads featured facts about radioactive waste management, such as the total waste volume, the

Figure 9-1. *The SKB transport ship M/S Sigyn is used each summer as a floating exhibition hall visiting harbour cities all around the Swedish coast. The aft sign says: "Welcome Aboard. This is how SKB is taking care of the Swedish radioactive waste."* (Photo by Bengt O. Nordin.)

Figure 9-2. By means of computers mounted in mock-up runic stones young and old visitors to the SKB mobile exhibitions can find out more about the radioactive waste management system. (Photo by Bengt O. Nordin.)

total cost of the Swedish waste management system as well as the political consensus behind the system.

Parts of the SKB printed material was updated during 1991. The most basic presentation of the SKB activities – in the form of a pocket-size folder – was once again brought up to date. An English version of "Activities 1990" was produced.

A new permanent exhibition was added to the access tunnel of the Äspö Hard Rock Laboratory in time for the formal inauguration.

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.

On invitation by local community councils around the country, the SKB management has participated in a number of public meetings at or near research sites.

A new SKB publication was launched during 1991 under the name of "Lagerbladet". Its four issues a year has a circulation of 25 000 free copies. The readers are mainly decision-makers, local politicians and people who are interested in SKB activities. The in-house magazine "SKB-nytt" (SKB News) appeared seven times during 1991. The distribution includes a wide selection of scientists, researchers and consultants working for SKB.

9.3 PRINTED MATERIAL

The SKB printed material is continuously updated and most of it is available in the English language. Single copies of the following titles can be ordered without cost from SKB, Public Affairs & Media Relations:

- How Sweden takes care of its Radioactive Waste (annually updated pocket-size folder, order no. Ha12 145 010 E).
- Activities 1990 (annually updated report on 32 pages, order no. Ha15 124 005 E).
- Transportation of Radioactive Waste (order no. Ha23 147 005 E).
- SFR, Swedish Final Repository for Radioactive Waste (order no. C003 E 818 025).
- CLAB, Central Interim Storage Facility for Spent Nuclear Fuel (order no. Ha22 145 005 E).
- Final Disposal of Spent Nuclear Fuel (order no. Ha27 204 005 E).

Figure 9-3. This is the natural analogue corner of the exhibition. The Kronan canon, salvaged after 300 years in the Baltic Sea, provides an interesting example of copper corrosion. The wall screens feature the Cigar Lake uranium deposit in Canada and the Oklo "reactors" in Africa. (Photo by Bengt O. Nordin.)

- The Äspö Hard Rock Laboratory (folder, order no. Ha26 E 112 003).
- Stripa – A Deep Underground Facility.
- Nuclear Waste Management in Sweden (folder co-produced with OECD/NEA, order no. X99 E 842 020, also available in French as no. F99 842 010 and in German as no. D99 939 010).

9.4 VIDEO CASSETTES AND FILMS

Some of the current SKB video cassettes and films are available with English sound track and in the PAL, SECAM and NTSC formats:

- SFR – a final repository for Radioactive Waste (order no. C 1001 835), also available with a German sound track.
- CLAB in action (order no. C 1002 602), also available with a French sound track.
- The Stripa Project (order no. C 1005 950).

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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
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CHAPTER 7

7-1 PLAN 91
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SKB ANNUAL REPORT 1991

Part II

Research and Development during 1991

CONTENTS PART II

Page

10. REPOSITORY DESIGN STUDIES

10.1 GENERAL

During 1991 the design studies on repository concepts, canister alternatives and encapsulation processes were coordinated in "Project on Alternative System Studies (PASS)". The studies concern the Swedish reference repository concept, KBS-3 /10-1/, and two alternative designs, Very Long Holes (VLH) /10-2/ and Very Deep Holes (VDH) /10-3/. The main differences between the designs are shown in Figure 10-1. For each repository concept different canister designs are considered.

The objective of PASS is to rank these repository concepts as well as the canister alternatives for each concept. This work was already in 1990 split up in three separate parts:

- Technology for construction and operation;
- Long Term Safety considering the time after repository closure;
- Costs for encapsulation and final disposal.

In 1991 conceptual designs were made for different canister alternatives. Major parts of conceptual engineering of equipment for VLH canister and bentonite emplacement were as well carried through.

The comparison of differences between the repository concepts started with the goal of presenting a ranking in mid 1992. The milestone to be met during 1991 was to define the methodology to be used in this process. The methodology is described below.

The project work is conducted in cooperation with TVO based on exchange of information of results, and, in certain defined cases, jointly financed studies.

10.2 CANISTER DESIGNS

The KBS-3 reference canister features an outer 100 mm thick corrosion resistant copper shell and a lead filled interior (cast lead). In the SKB 91 project a copper thickness of only 60 mm was shown to be sufficient. The

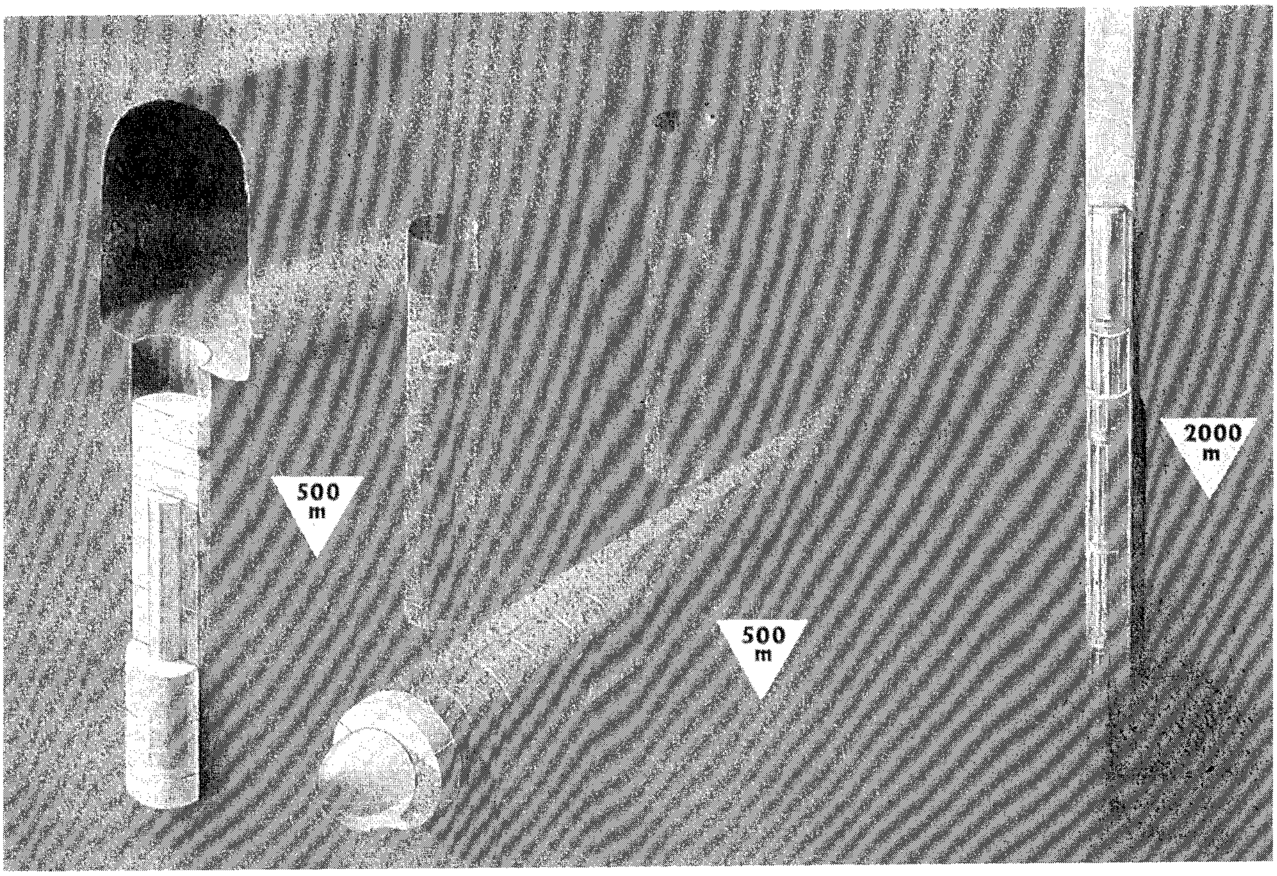


Figure 10-1. Left; KBS-3 – The Swedish reference concept for final spent fuel disposal with deposition holes containing one canister each. Middle; VLH – An alternative concept with bigger canisters in a long deposition drift made by full face boring machine (TBM). Right; VDH – An alternative concept with smaller canisters deployed in vertical deep boreholes. In all concepts the canisters are surrounded by a buffer of bentonite clay.

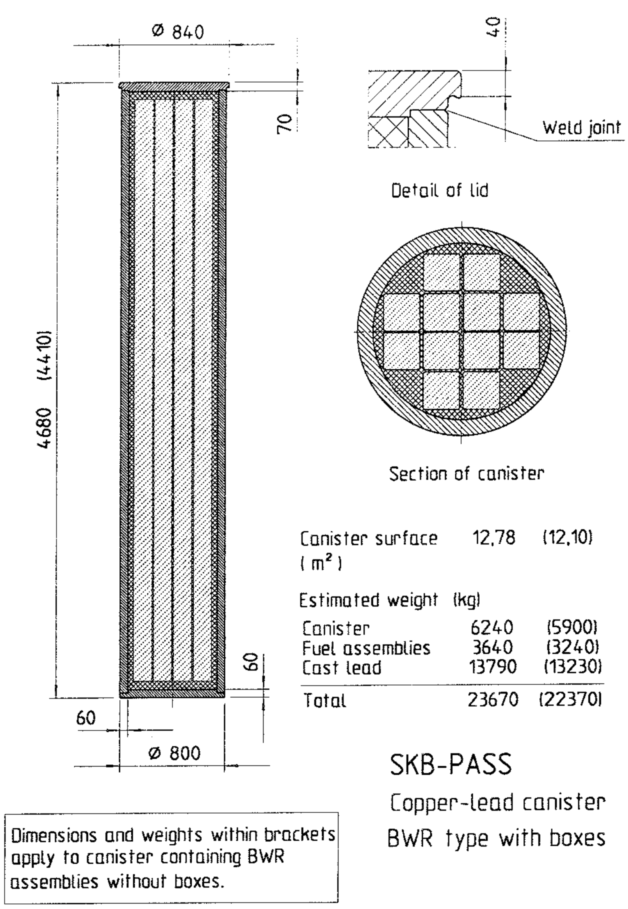


Figure 10-2. *KBS-3 copper/lead canister with room for 12 BWR assemblies. The lid is designed with a special grip for hooking lifting devices. The length of the canister varies if assemblies are deposited with or without boxes.*

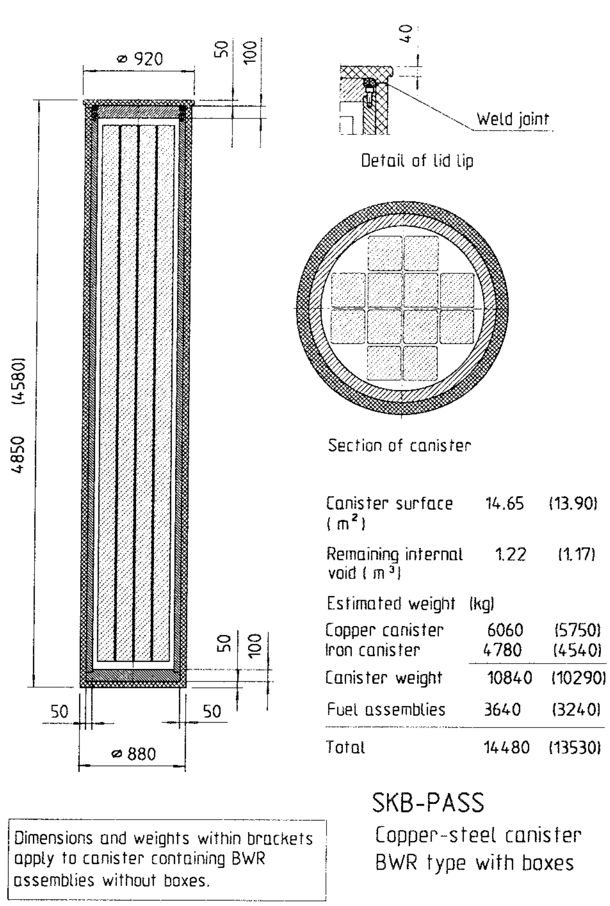


Figure 10-3. *KBS-3 composite canister with room for 12 BWR assemblies. Measures are shown for assemblies with or without boxes.*

outer diameter is the same. The extra space inside the copper structure provides room for more spent fuel, up to 12 BWR assemblies. The improved design is shown in Figure 10-2.

In 1990 a composite canister based on TVO's design /10-4/ was studied. The design consists of an inner steel canister for carrying external loads, and an outer copper shell for corrosion protection. With the same inner diameter as the KBS-3 reference canister and a copper thickness of 50 mm the outer diameter becomes 880 mm compared to 800 mm for the KBS-3 canister, see Figure 10-3.

Designs were also made for the hot isostatic pressure (HIP) canister alternative, a steel canister alternative (without copper protection), and a new alternative: a steel structure filled with cast lead. The interesting feature of the latter alternative is that the focus in long term isolation is on the lead filling.

The VLH concept has less candidate canister designs. The main alternatives feature a steel structure covered by copper for corrosion protection. The ends may be either hemi-spherical or flat, see Figures 10-4 and 10-5. The option is a steel canister. The designs of this are similar to the steel structure of the composite designs.

For the VDH concept a low cost canister has been designed, see Figure 10-6. A maximum outer canister diameter of 500 mm in order to fit into the casing of the borehole allows for placing 4 BWRs in each canister. In case of rod consolidation a compaction factor of two may be obtained resulting in a load of spent fuel from 8 BWRs per canister. The temperature in the bentonite, however, reaches 120°C in the bottom of the hole (4 km depth) with 4 BWRs and more than 150°C with fuel from 8 BWRs, if ambient bedrock temperature data from the Gravberget hole, central Sweden, are assumed /10-3/.

10.3 REPOSITORY DESIGNS

10.3.1 General

The design of KBS-3 is based on the disposal of the canisters in vertical position in holes bored in the floor of disposal drifts. One canister is placed in each hole /10-1/. The general dimensions are shown in Figure 10-7.

The VLH concept features disposal of the canisters in horizontal position in long drifts. The drifts have a diameter of 2.4 m for the 1.6 m diameter canisters. The

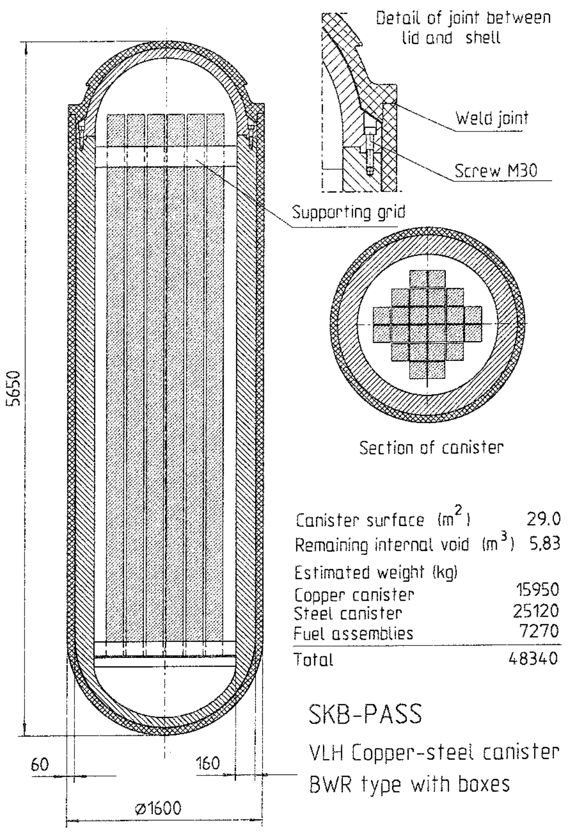


Figure 10-4. VLH composite canister with hemi-spherical ends. The temperature criterion in the bentonite (100°C) limits the load to 24 BWR assemblies at an outer canister diameter of 1.6 m. The canister length is the same if assemblies are deposited with or without boxes.

canisters are placed in a row. Three parallel drifts are assumed, which will have to be about 4.5 km long in order to host the Swedish amount of spent fuel /10-2/.

In the VDH concept the canisters are placed vertically inside a casing installed in about 4 km deep holes bored with a diameter of 0.8 m. The canisters are placed in a column from the bottom of the hole up to 2 km depth /10-3/.

10.3.2 KBS-3 Improvement

One major improvement achieved in the design of the KBS-3 repository is a decreased height of the deposition drifts. Earlier the height was dictated by the wish to keep the canister in a vertical position above the deposition hole before starting to lowering it. During the year an improved deployment method has been outlined. It features a deployment vehicle which moves the canister in a cradle when lowering it down into the deposition hole, see Figure 10-8. This device requires only a drift height of about 3.5 m for 4.5 m long canisters. A machine for

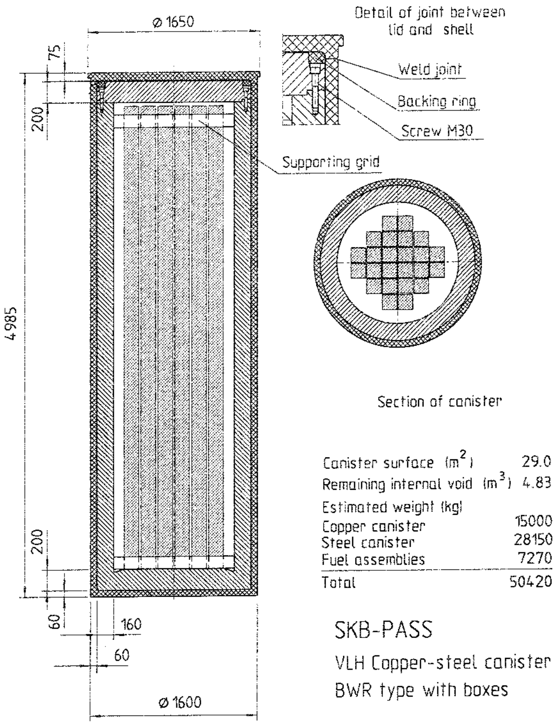


Figure 10-5. VLH composite canister with flat ends.

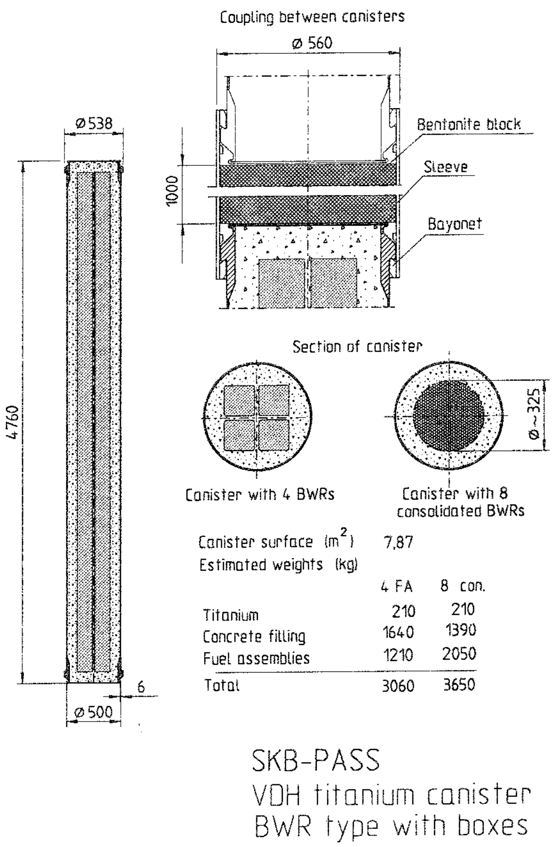


Figure 10-6. VDH titanium canister filled with concrete. The internal area provides space for either 4 intact BWR assemblies with boxes or 8 consolidated BWRs.

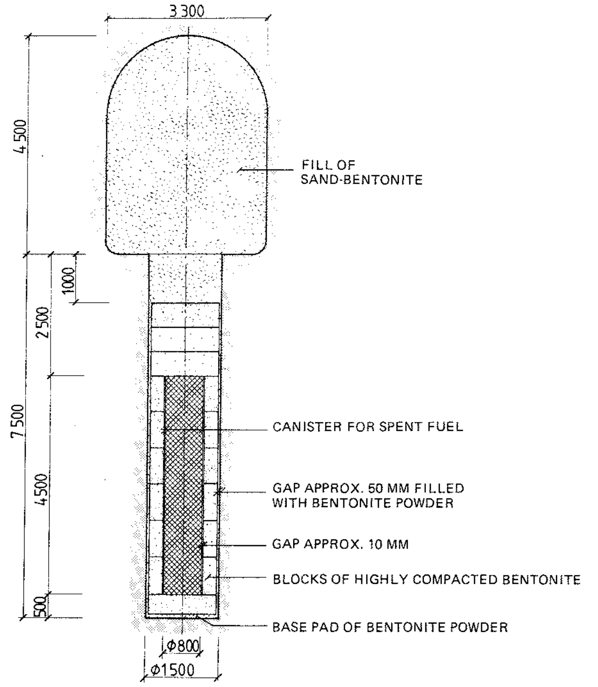


Figure 10-7. *Dimensions of deposition drift when canister is to be held in vertical position before being lowered down into the disposal hole.*

boring the deposition holes in a 3.5 m high drift has been identified as well.

10.3.3 Engineering of VLH Emplacement Machines

Conceptual engineering has been carried through regarding the equipment for emplacement of canisters and bentonite. The solution proposed is based on trackless vehicles. One unit carries and deploys the canister. Two separate units carry and emplace the bentonite surrounding the canister; one handles the end blocks covering the hemi-spherical ends as well as the bottom blocks on which the canister is placed, and the second unit handles the blocks to be put in place after deployment of the canister. Each of the bentonite units are equipped with a bentonite block manipulator. Figure 10-9 shows the phases for installing the bentonite blocks and emplacing of the canister, and Figure 10-10 the canister emplacement vehicle.

10.4 COMPARISON OF REPOSITORY CONCEPTS

10.4.1 Ranking Methodology

The comparison and ranking is initially made separately for: Technology, Long Term Safety and Costs. Thereafter a merged ranking is produced. A schematic flowsheet of the ranking process is shown in Figure 10-11.

The canister alternatives are to be considered in that way that the alternatives for each repository concept are initially ranked and one alternative is selected for each of the concepts in the comparison. With this approach it is natural, in the course of the comparison, to reconsider if the selected canister alternative has an impact on the ranking of the repository concepts as well as if other basic parameters have a guiding affect on the result. In such cases the comparison can be made once more with another set of assumptions. This is in practice a problem only for the KBS-3 concept, for which canister alternatives are defined with major principle differences in design and long-term performance.

10.4.2 Technology

The analysis so far has indicated a large difference between VHD on one hand and KBS-3/VLH on the other. The major negative comments regarding the VDH concern:

- Host rock characterization;
- Surface environmental impact during construction, i.e. boring;
- Deployment of canister and emplacement of the bentonite buffer;
- Possibilities to achieve and validate emplacement quality.

The long term safety potential of the VDH concept is based on a low hydraulic conductivity in the rock at 2-4 km depth. This was found to be the case in the deep boring at Gravberget, central Sweden, which penetrated the bedrock down to 6.6 km depth (in 1986-89) /10-3/. In addition the ground water is highly saline at depth, and has an increasing grade toward depth, which provides a potential for preventing thermally induced buoyancy from the disposed canisters.

More basic information regarding the properties of crystalline rock at depth has been analyzed during 1991. The structure and properties of the rock in three deep borings

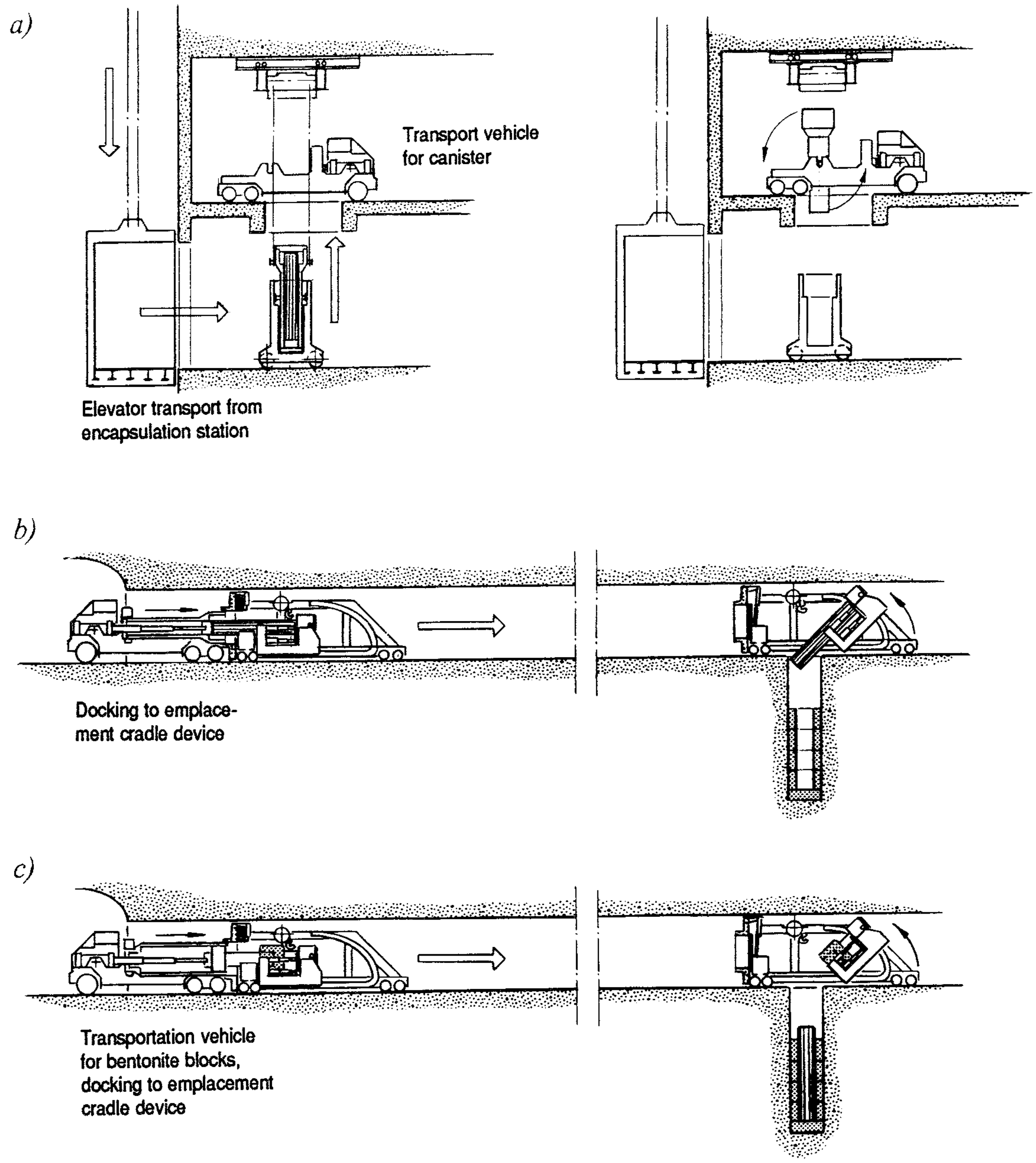


Figure 10-8. *Cradle device for 3.5 m heigh drifts; a) transport of canister, b) emplacement of canister, c) emplacement of bentonite blocks.*

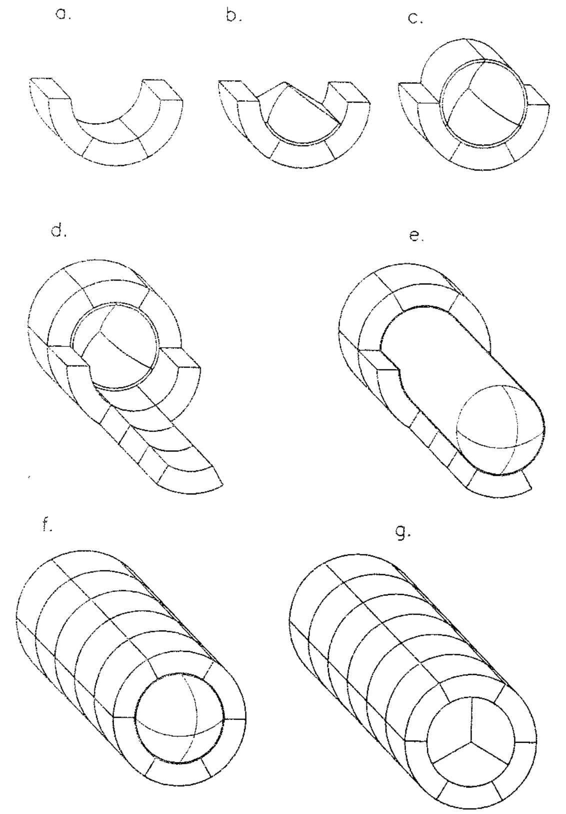


***Figure 10-9.** Phases of installing the bentonite blocks and emplacing the canister. The cycle starts with installing the back bottom block and two side-blocks (a). The concave back for the canister is built (b) and (c) and the full area of the drift is filled (d). The bottom bed is laid (d) and the canister is emplaced on top of this (e). Finally the blocks surrounding the canister are installed (f) and the hemi-spherical front covered (g) resulting in a flat wall against which the next cycle is starting.*

in Russia and Ukraine have been compiled, and the way of modelling the salt gradient has been studied.

The information from Russia (Kola deep hole, 12 260 m deep, Tyrauz hole, Caucasus, 4 001 m deep) and Ukraine (Krivoy Rog hole, 4 549 m deep) has been provided by NEDRA, the organization conducting the deep borings in the Commonwealth of Independent States. The study (report to be issued) specifically focused on the horizon between 2 and 5 km depth. The result among other things indicates a separation into three levels with respect to ground water movements and ground water salinity. The upper 1-2 km is defined as having Free Circulation and a salinity of up to 60 g/l. The second zone is defined as having Hindered Circulation implying some connections with the upper zone. The zone extends to 4-5 km depth, where the salinity reaches about 200 g/l. Below that the hydraulic regime is defined as having Deep Water and a salinity of up to about 350 g/l. This information confirms the general features of the bedrock at depth that was studied in the Gravberget bore hole.

The importance of the salinity was indicated already in 1989 /10-3/. A more thorough approach to model the thermally induced buoyancy in a rock with a salinity gradient toward depth started in 1991. The first phase of the work resulted in a formula for describing the impact of a salt gradient versus depth on the thermally induced upward movement of ground water in a vertical fracture plane at some distance from the deposition hole /10-5/. Numerical exercises for a thermal point source in a VDH borehole indicate only limited vertical upward movements at a salt concentration difference of 2% over a height of 1 000 m (the concentration difference observed in the Gravberget hole). A second phase, scheduled for 1992, will aim at modelling a line source as well as the cylindrical symmetry of the region closest to the hole.

10.4.3 Conclusions Regarding Ranking so Far

The VDH concept will get a lower ranking than both the KBS-3 and VLH concepts for Technology as well as for Costs /10-6/. The ongoing comparison of Long Term Safety has indicated that the VDH concept has a high potential for safe isolation of the spent fuel. The study in parallel with PASS - safety analysis SKB 91, see Chapter 11, has in addition documented the high long term safety standard of the KBS-3 concept. Consequently a higher ranking in Long Term Safety of the VDH concept than the KBS-3 would have a lower weight in the merged ranking than the ranking regarding Technology and Costs. It is therefore not necessary to wait for the result from the work on Long Term Safety to conclude that the VDH concept may not get a higher final ranking than the KBS-3 concept. It is also the belief that the VDH will get a lower ranking than the VLH, as this concept, as well, is judged to feature a high safety potential. This, however, has not been documented; a task for 1992.

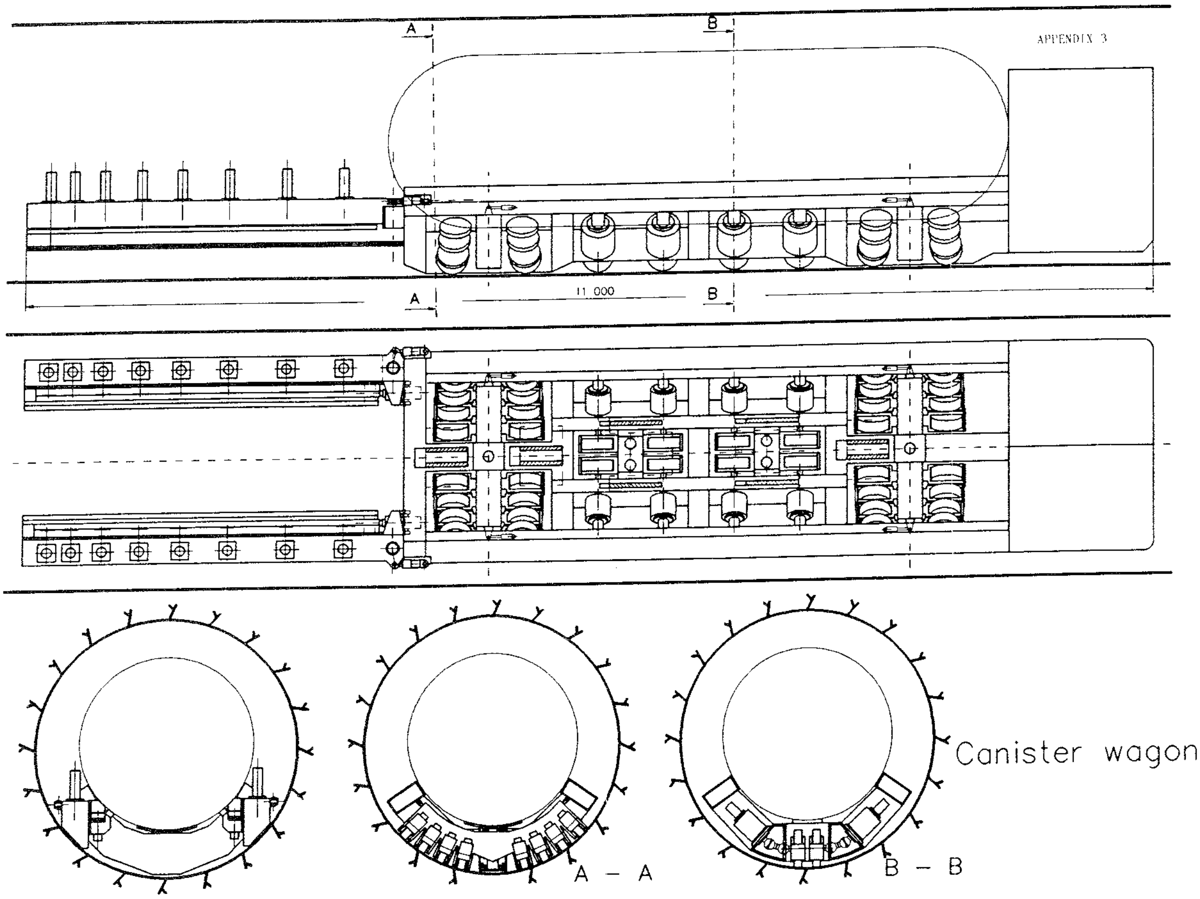


Figure 10-10. *Wagon for canister emplacement. The wagon transports the canister up to the front with the canister in the position shown in 10-10a. The two forks straddle the bentonite bottom and the canister is moved over to the forks. The jacks of the forks are lowered (10-10b) thereby depositing the canister on the bentonite bed. 10-10c shows the bogie construction and 10-10d the driving arrangement (hydraulic motors).*

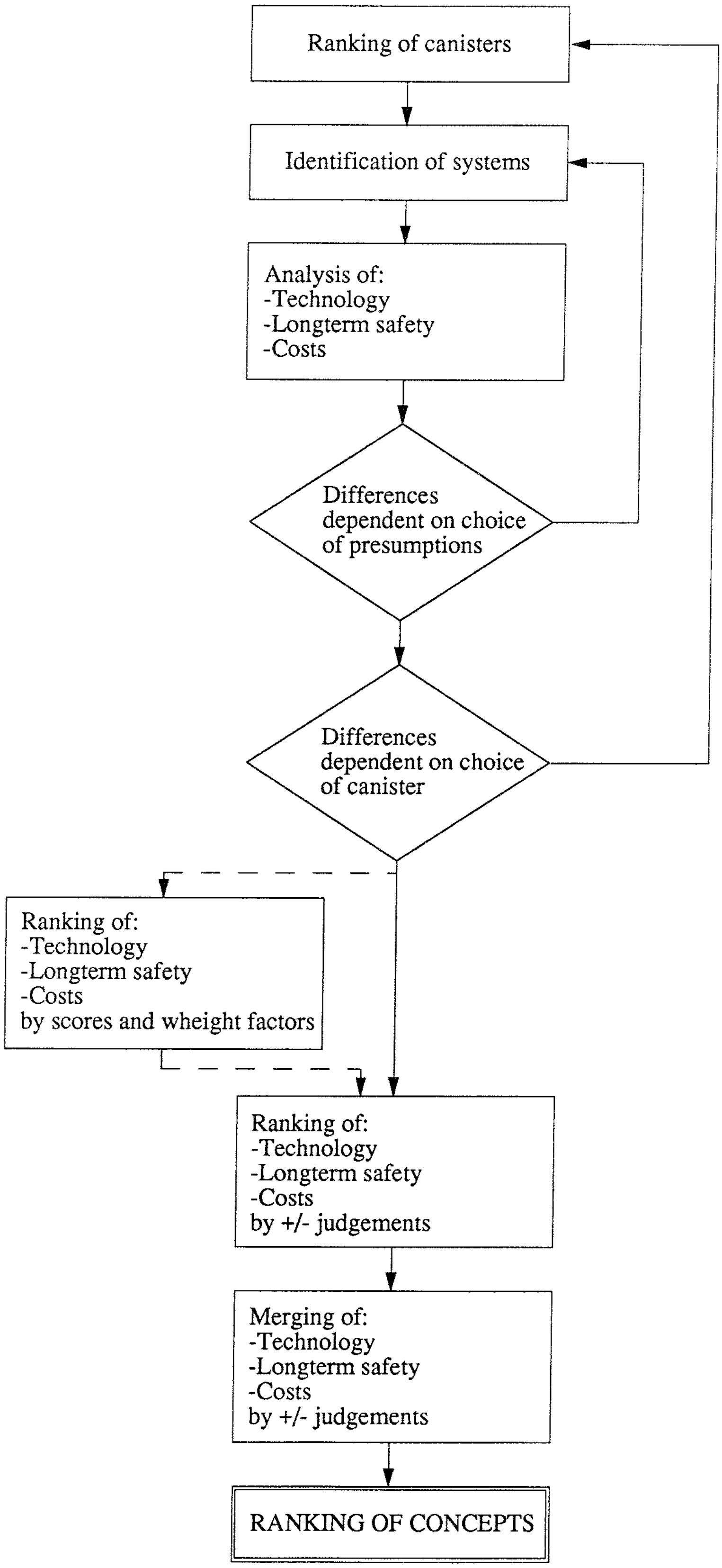


Figure 10-11. *Flowsheet of PASS' ranking methodology. It is believed that the differences can be expressed by +/- scoring in the final end. As a basis for the final verdict it is considered necessary to initially use a scoring with figures in order to identify important differences.*

11. SAFETY ANALYSIS

11.1 GENERAL

In accordance to the R&D-Programme 89 a new integrated safety assessment, SKB 91, has been made with the objective to clearify the role of the site geology for the safety of the repository.

During 1990 and 1991 the modelling approach and data were defined and most of the calculations were made. Although the report was not finalized until spring 1992, it is still reported in this annual report in order not to delay the information about it. During the summer the SKB 91 report will be translated into english and published in the SKB Technical Report series for 1992.

The summary of this report, including the background for the assessment, the objectives, the modelling approach, the results of the calculations and the conclusions that have been drawn, are presented in extenso in section 11.4.

A project-specific Quality Assurance plan was produced for SKB 91. The intention was to test the applicability and usefulness of QA for large scale performance assessments. The results will be reviewed in 1992 in an attempt to evaluate the experience gained.

During the last year some activities not directly related to SKB 91 have also been pursued. This work has mainly focused on scenarios and the development of alternative ways to model groundwater and radionuclide transport, and is reported below in sections 11.2 and 11.3.

11.2 SCENARIOS

Beside the evaluation of the importance for safety of a number of site specific features and a presentation of a glaciation scenario for Scandinavia made in SKB 91, the work on scenarios has addressed human intrusion and preservation of information.

The work on human intrusion has been initiated within the OECD/NEA cooperation. The area is strongly affected by non-technical considerations. The objective is to achieve an international exchange in this area and to see if a consensus on the approach for acceptance criteria can be found.

The work on information preservation is done within an Nordic cooperation effort /11-1/. The objective is to evaluate the need for preserving information regarding waste repositories, and to establish a common Nordic view on the regulations in this area. The study, which involves an inventory of available information, media types and volumes as well as current archive regulations, historic development of archives etc, will be reported during 1993.

11.3 TRANSPORT MODELLING

A Compartment model for the near-field

A model that is able to calculate the instationary release of radionuclides from the near-field of a repository has been developed /11-2/ and is presently being tested. The model is based on dividing the complex geometry of the engineered barriers of the repository nearfield into a number of compartments. Mass transport between compartments is defined by transfer factors and by the concentrations in each compartment. Only transport by diffusion is considered in the clay and in the rock matrix. Transport by flow is accounted for in the fractures in the rock. The interior of the canister is modelled as one well mixed compartment.

The model describes the release of dissolving radionuclides out through a small hole in a canister wall and further out into the bentonite. The radionuclides follow different pathways to reach the various zones of flowing water in the rock.

The number of compartments can be kept low by using a technique based on semianalytical solutions at the mouth of the fractures in the rock and at the entrance of the hole through the canister wall. This ensures that these very important "pinch" points are handled correctly. Because of the coarse compartmentalization the code is very flexible and can be adapted to different geometries. Different locations of fractures, damaged zones etc. can be modelled with only minor changes in the specifications of the compartments. New pathways can also be added with little effort.

Sample calculations for a KBS-3 type geometry using Pu-239 with a solubility limit of $2.0 \cdot 10^{-8}$ mol/l and initial inventory of 28.1 moles have been performed, see Figure 11-1.

The advantage of the model is that is capable to show differences in instationary release of radionuclides from different repository layouts.

Coupled geochemical/transport model

The development of a computer code for coupled geochemistry/transport calculations has continued. The numerical solver of the code has been improved and the code has been tested on the redox front movement of the Poços de Caldas natural analogue.

Channel network model

The development of a channel network model for radionuclide migration has continued. The concept is based on

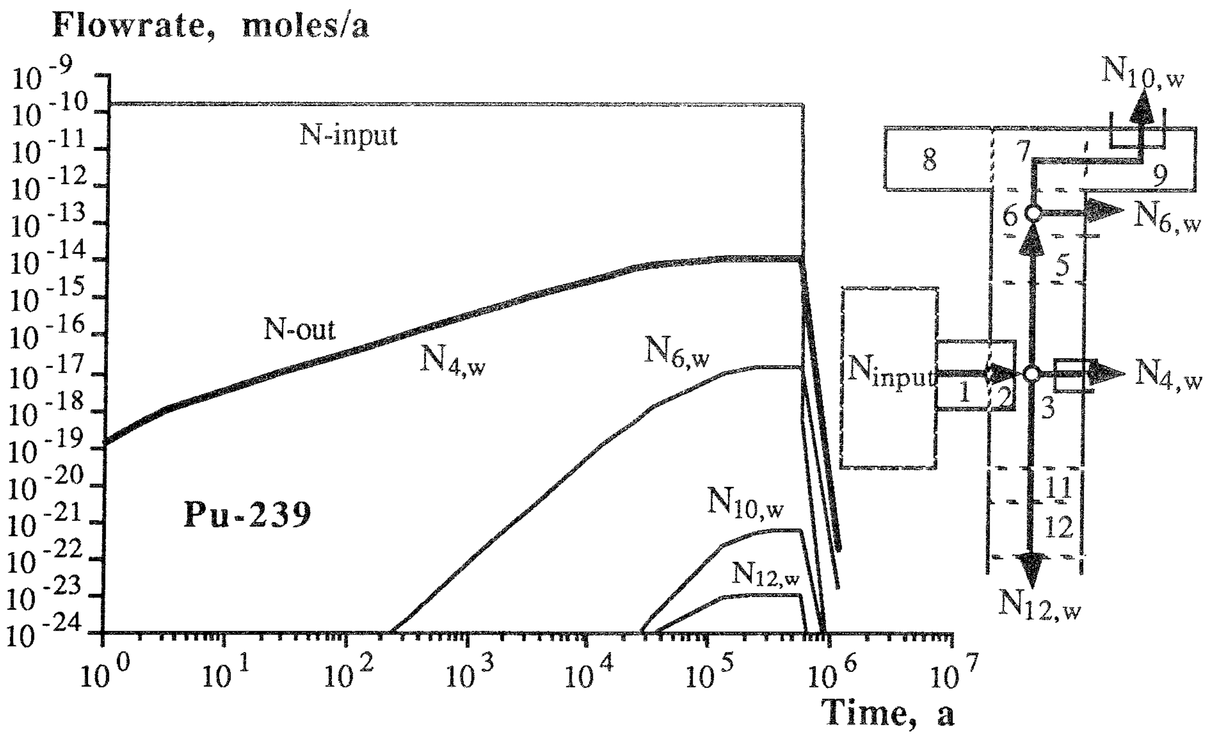


Figure 11-1. Flowrates of Pu-239 through different pathways versus time. The notations on the lines $N_{i,w}$ *refers to the release of nuclide from the compartment into the water.*

the assumption that the water flows in a network of channels in the fractured rock /11-3/. All the individual channels may have different conductivities, volumes and widths. The flowrate distribution in the network is readily calculated by methods similar to those used in calculating currents in electrical networks. Solute residence times are calculated using particle tracking for the mobile fluid, and matrix diffusion of the solute is calculated by use of the analytical solution for the inverse of the residence time in a single channel where matrix diffusion (and sorption) is active.

Earlier data from boreholes, the Stripa 3-D experiment, SFR and the Kymmen tunnel were used to calibrate the model to "real rock" and to obtain channel lengths and to simulate flowrate and tracer distributions.

Recently also data from the Stripa SCV-Experiment have become available. The model was used to simulate the flowrate and tracer distribution in a small fracture zone. Also the channel lengths, flow porosities and flow wetted surfaces were estimated using the model. The channel lengths were found to be typically 1 – 1.5 m. The standard deviation (log normal) was 2.4 – 3.2. This is the same range as obtained for other rocks. The flow wetted surface was estimated to be less than 1 m^2/m^3 and the flow porosity about 10^{-4}. Both these values are half an order of magnitude less than those evaluated from tracer experiments.

Modelling of ground water flow

An ongoing research project at the department of Land and Water Resources at the Royal Institute of Technology, Stockholm, is investigating methods for the upscaling of measured data into effective values for model parameters when predicting ground water flow in fractured rock.

A computer code for sensitivity analysis of ground water flow, GWHRT-S, has been applied on the hydrology of the Finnsjön area /11-4/. The code is a tool for estimating how variations of input parameters or boundary conditions affect the output data. The sensitivity of the piezometric head as well as the Darcy flux was calculated using an adjoint technique. Both parameters were evaluated pointwise and integrated over the assumed repository area and the discharge area.

11.4 Project SKB 91

The safety of a deep repository for spent nuclear fuel has been assessed in the SKB 91 project. The spent fuel is assumed to be encapsulated in a copper canister and deposited at a depth of 600 m in the bedrock. The primary purpose has been to shed light on the importance of the geological features of the site for the safety of a final repository.

The assessment shows that the encapsulated fuel will, in all likelihood, be kept isolated from the groundwater for millions of years. This is considerably longer than the more than 100 000 years that are required in order for the toxicity of the waste to have declined to a level equivalent to that of rich uranium ores.

However, in order to be able to study the role of the rock as a barrier to the dispersal of radioactive materials, calculations have been carried out under the assumption that waste canisters leak. The results show that the safety of a carefully designed repository is only affected to a small extent by the ability of the rock to retain the escaping radionuclides. The primary role of the rock is to provide stable mechanical and chemical conditions in the repository over a long period of time so that the function of the engineered barriers is not jeopardized.

11.4.1 Background

One of SKB's responsibilities is to come up with recommendations as to how and where the final disposal of Sweden's radioactive waste should be arranged. After review and approval by the regulatory authorities, SKB shall also design and build the necessary facilities and carry out final disposal of the waste.

Between 1977 and 1983, in keeping with the requirements in the Stipulations Act, subsequently superseded by the Act on Nuclear Activities, SKB published a series of reports examining the feasibility of final disposal of spent nuclear fuel in Swedish bedrock. After extensive circulation of the reports for review by Swedish and foreign experts, the Government found in 1984 that a method has been presented that could be accepted with regard to safety and radiation protection.

During the 1980s, SKB has continued its investigations of study sites in Sweden and examined alternative methods for final disposal. The body of knowledge has been expanded in terms of both an understanding of the processes that are important for long-term safety and data and models for being able to quantify them.

The experience gained from these studies has lent further support to the view that it is possible to isolate the fuel from the groundwater over a long period of time by encapsulating it in a copper canister. In a suitable environment, this isolation can be maintained for such a long period of time that the toxicity of the waste will decline to a level equivalent to that of uranium ores. The granitic bedrock in Sweden at a depth of a few hundred metres or more exhibits suitable chemical conditions for long-lasting canisters. The results of the studies have also strengthened the belief that the bedrock in Sweden offers many sites where the rock also has a high capacity to retain radionuclides should they escape from the repository's engineered barriers.

A fundamental principle of all planning for a final repository in Sweden is that its safety shall be based on the multi-barrier principle, i.e. that the safety of the repository shall not be dependent on a single safety barrier. Accordingly, even if the copper canister is capable of isolating the waste from the groundwater for a very long time, it is also important to define the safety-related requirements on the bedrock under the assumption that radionuclides nevertheless escape from the repository.

11.4.2 Purpose and Delimitations

According to existing plans, system selection and siting for a final repository will begin during the 1990s. The present safety assessment (SKB 91) examines how the long-term safety in a final repository is affected by the geological characteristics of the repository site, i.e. how the rock barrier performs under the assumption that radionuclides leak out of the repository. The report is intended to form part of the background material that is required for the siting of a final repository for spent nuclear fuel.

The following questions are explored:

- What importance do the site-specific characteristics of the bedrock and the hydrological regime around the repository have for overall safety?
- What relative importance do different site-specific characteristics have for safety?
- How can the placement and design of the repository be adapted to conditions on the site in order to take advantage of the safety barriers offered by the bedrock?

The assessment deals with the safety of the repository during the post-closure phase. The possibility of achieving adequate safety during the operating phase – i.e. during treatment, transport and deposition of the waste – is in all essential respects independent of the geological conditions on the repository site.

SKB's continued work during the '90s will include selection of the schematic design, siting of the final repository and adaptation of the design and the barrier system to the chosen site. During this phase, SKB 91 will serve as a basis for systematic analyses where parameters that affect safety are varied. A secondary goal is therefore to test, in connection with SKB 91, a system of efficient procedures for carrying out safety assessments.

The report covers only final disposal of spent nuclear fuel, since this waste category contains the largest quantities of radiotoxic materials and thereby imposes the strictest demands on the protective function of the repository. Certain types of long-lived decommissioning waste, internal reactor parts and operational waste may be disposed of in the repository for spent fuel, but the different repository sections do not have to be situated in such a manner that they affect each other.

11.4.3 Main Features of the Repository

Principles

The following principles have served as a basis for the design:

- Final disposal is done in crystalline Swedish bedrock at a depth that protects the repository against disturbances from the surface (i.e. 300 – 700 m) in one or more blocks of rock surrounded by structurally weak zones;
- The waste is encapsulated in canisters that are handled as separate units. Their fuel content, size and geometric placement pattern in the repository is chosen so that the temperature on the surface of the canister is limited to well under 100°C;
- The waste is surrounded by several different barriers to isolate the waste from surrounding groundwater and prevent or delay the dispersal of radionuclides from the deposited waste;
- The repository is arranged so that it is not dependent for its safe function on long-term surveillance and inspection. However, the placement of the repository in the crystalline rock will make it possible to access the waste as long as the existence and location of the repository are known.

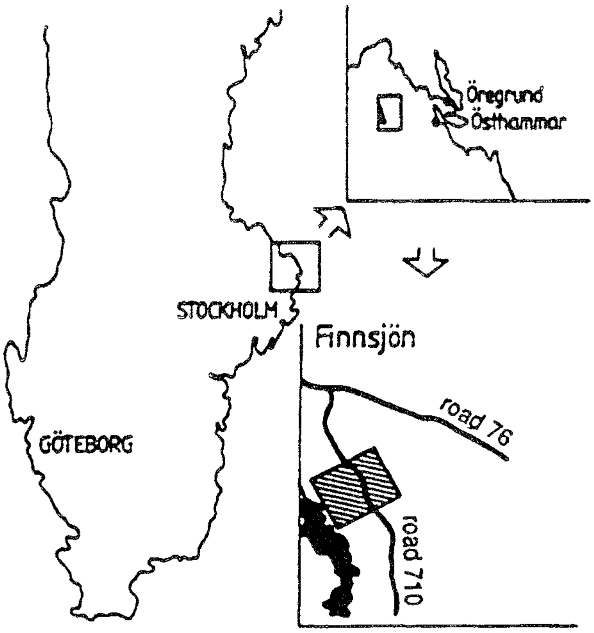


Figure 11-2. The Finnsjön area in northern Uppland.

Repository site

The topography, geology and other site-specific characteristics of the repository site have been chosen in agreement with the conditions in the Finnsjön area in northern Uppland, see Figure 11-2. The area has been chosen as an example, since an extensive body of data is available from the area. Finnsjön was judged in KBS-3 to be a possible site for locating a final repository, though less favourable than some of the other study sites. The present-day understanding of the geology of the site is strengthened by data from the Forsmark area and the repository for low- and intermediate-level waste, SFR, as well as data from Dannemora Mine.

Deposition is arranged largely as described in the KBS-3 report, see Figure 11-3. The spent fuel is placed in copper canisters, which are then filled with lead. The canisters are deposited one by one in holes drilled in the floor of a system of drifts in the rock. The space between canister and rock is filled with bentonite clay. The system of storage drifts is assumed to be regular with a distance of 25 m between the drifts. The distance between the deposition holes is 6 m. The quantity of fuel is equivalent to 7 800 tonnes of uranium, i.e. the quantity obtained from the Swedish nuclear power programme through the year 2010.

At closure of the repository, all cavities are backfilled. Drifts and shafts are provided with sealing plugs to block potential transport pathways for the groundwater.

11.4.4 The Assessment

General

The time spans that have to be taken into account in the assessment of the safety of a final repository are long and the processes that can be of importance for safety are many and often slow. Safety assessments can therefore not be based solely on the results of experiments. The analyses must be based on models for known and possible interactions between the components in the repository. The external environment in which the repository has been placed and the environment that may exist in the future must also be taken into consideration.

Since long-term safety can be affected by changes in the repository's future environment, the analysis of future scenarios occupies a central place in the safety assessment. By a "scenario" is meant a description of a conceivable future situation or sequence of events that can be of importance for the safety of the repository. International efforts have been made to formalize the assessment and to establish appropriate procedures. One important question is how to show that no important phenomena have been overlooked.

In the safety assessment, an analysis is made of how the transport of radionuclides from the repository to the biosphere can take place. The factors and processes that can affect the transport are identified and evaluated. In order to avoid underestimating environmental impact, many

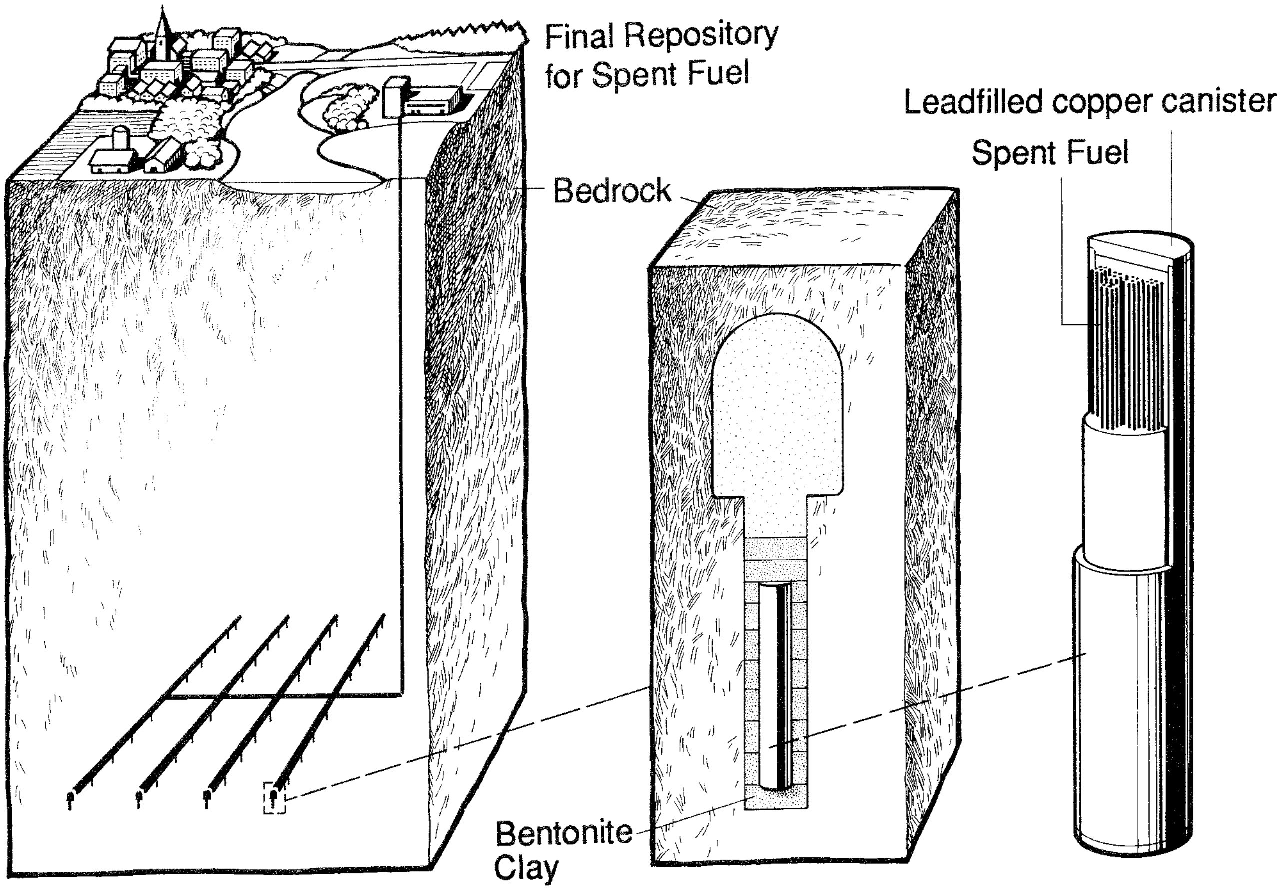


Figure 11-3. Schematic design of a final repository for spent nuclear fuel in crystalline basement.

data have been chosen pessimistically (in an unfavourable way). The calculation results should therefore not be viewed as a prediction of expected releases, but rather as upper limits.

Reference scenario and variations

The reference scenario describes the repository to be assessed and defines the external environmental conditions that constitute the basis for the safety assessment.

Since the aim in siting a repository is to avoid areas with unusual minerals or ores, with regional zones of movement and with extreme topographical gradients, it can be foreseen that all potential repository sites will resemble each other in these respects. The biosphere description in the assessment has been simplified, since site-specific differences in the biosphere between the studied sites in Sweden are considerably less than the changes that can occur over time. Intrusion scenarios have not been discussed, since the probability or consequences of someone intentionally or unintentionally getting into the repository cannot be expected to differ considerably for the different candidate sites.

The analyses are carried out under the assumption that deposition takes place at an even pace, after which the excavated space will begin to be backfilled. Finally, it is assumed that the repository will be sealed some time in the 2050s.

The most likely situation is that all canisters fulfil the integrity requirements that have been established for encapsulation, i.e. that the groundwater will not come into contact with the fuel for a very long time. To evaluate the performance of the rock as a barrier to dispersal of radionuclides, however, certain releases must be assumed. The reference case has therefore not been based on the most likely state of the repository, but has been defined so that each canister that is deposited has a probability of 0.1% of having an initial manufacturing defect. For the entire repository, this means that 5-6 canisters will have defects. The defect is defined as a hole penetrating the canister's welded joint.

Climate changes will probably occur during the time the repository is supposed to function. A temperature increase is likely in the shorter perspective, but in the longer perspective, on the 10 000-year scale, new ice ages similar to the most recent one are expected.

A glaciation changes many of the premises for a safety assessment. The most important change from the safety viewpoint is, however, that the strong link between radioactive materials in the biosphere and doses to humans is broken when the intensive cultivation of soil for food production ceases. Therefore, a future ice age is not included in the reference scenario, even though many regard one as likely.

However, to shed light on how a future glaciation could develop and in what way it could affect a deep repository, the main report also describes a glaciation scenario.

Besides the reference case, the importance of certain variations in the properties of the site is also assessed in SKB 91. The purpose is to quantify the safety-related importance of various geological conditions. The variables have been selected because they are assumed to have a safety-related importance, contain large uncertainties, or constitute parameters that can be varied relatively freely in designing the repository. The calculations are carried out with the chain of models from the reference case or with models that are more directly associated with varied parameters.

The parameters that have been subjected to variations are listed below.

- The groundwater flow;
- The groundwater travel time from the canister to the surface;
- Dispersion conditions in the model block;
- The area of the rock surfaces in contact with the mobile groundwater;
- The chemical conditions in the immediate vicinity of the canister;
- The influence of salinity on groundwater circulation;
- The depth of the repository;
- The presence or absence of flat-lying fracture zones;
- The respect distance between the periphery of the repository and surrounding fracture zones;
- The conductivity contrast between fracture zones and rock mass;
- The size of the regional gradient;
- The perturbed zone in the rock caused by the excavation work, and its orientation;
- The various receiving bodies for the deep groundwater's outflow in the biosphere.

In addition, certain conditions have been discussed in a qualitative fashion, for example the importance of groundwater composition and temperature for the safety of the repository.

Models and data

A number of pessimistic simplifications were made in KBS-3 where positive factors were disregarded if they could not be quantified. For example, it was assumed that the effectiveness of the canister in inhibiting the release of radioactive materials is completely lost when it is penetrated by the first hole, and that the radionuclides reach the biosphere at the same instant they reach a major fracture zone. Such simplifications have been avoided wherever possible in SKB 91, but remain in certain cases where the process is so complicated that a detailed analysis does not appear meaningful today. The purpose has been to present a realistic and not overly pessimistic picture of the performance of the repository so that the effect of assumed variations in the characteristics of the site are not hidden behind exaggerated safety margins. Figure 11-4 shows a schematic diagram of the assessment procedure and the flow of information between the different sub-assessments.

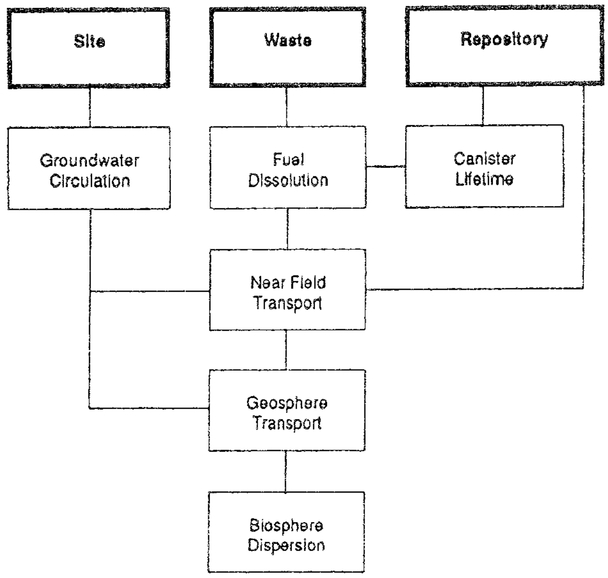


***Figure 11-4**. Schematic diagram of safety assessment in SKB 91 and its information flows.*

The repository's far field has been analyzed with the aid of a stochastic hydrology model, i.e. a model that takes into account the fact that the characteristics of the rock can vary from point to point in an irregular fashion. Since the assessment is being performed for a site where the data base was originally gathered for other purposes than the siting of a final repository, the statistical material on the properties of the rock may be deficient in some respects. Such a situation with limited data availability closely resembles the one that exists at an early stage of a site investigation. Here again the initial assessments must be made on the basis of a few boreholes and the results must be viewed as possible outcomes. With a larger quantity of data available, the uncertainty is expected to decrease. The assessment can indicate the difference between favourable and unfavourable assumptions concerning groundwater conditions on the site, and also indicate places where a better database is essential or unimportant, as the case may be.

In contrast to the assessment of the hydraulic conditions in the far field, fuel dissolution and the radionuclide transport in the near field have been evaluated deterministically, partly so that uncertainties in the description of the near field will not conceal the effects of variations in the far field on the model results, and partly because the parameters in the near field can be quality-controlled to a higher degree than those in the far field.

The general premises and calculation sequence used in SKB 91 are presented below.

- The quantity of spent nuclear fuel is based on SKB's Plan reports and the assumption that the Swedish nuclear reactors will be operated up to the year 2010;
- The radionuclide inventory and residual heat in the fuel at different times are calculated on the basis of previous operating data and a forecast for the time up to shutdown;
- Temperature is calculated for a repository design similar to that in the KBS-3 report;
- The groundwater movements in the area are calculated regionally and locally. The modelling is based on topography, lineament interpretation and measurements of hydraulic conductivity;
- Canister performance is based on
    - thermodynamic stability in pure water, groundwater flux in the repository area, measured levels of corrosive substances in the groundwater and diffusive mass transport between groundwater and canister,
    - build-up of gas pressure from the radioactive decay process,
    - a probability of 1/1 000 that an individual canister is deposited with an initial defect;
- Dissolution of the fuel is calculated based on
    - the assumption that it will take at least 1 000 years before water comes into contact with the fuel,
    - a model where the transformation of the fuel matrix is controlled by oxidant production via α-radiolysis;
- Nuclide transport in the near field is calculated using
    - a transient model for calculating the transient breakthrough of radionuclides to the far field,
    - a stationary model for diffusion through a canister hole via the buffer material up to the mobile groundwater in a fracture or in a disturbed zone around the drift;
- Nuclide transport in the far field is calculated on the basis of flow paths from different parts of the repository, generated by the groundwater model, and one-dimensional modelling of matrix diffusion and sorption;
- Dispersal of radioactive materials in the biosphere is calculated for a standard biosphere taking into account different pathways to man via well, cattle, grain cultivation and fishing;
- The dose conversion factors are based on the ICRP's recommendations.

The importance of changes in certain premises has been evaluated by means of variation analyses with relevant models or with the entire model chain.

11.4.5 Conclusions

General

The SKB 91 safety assessment differs in certain respects from previous analyses. Greater knowledge has made it possible to take into account factors that were previously dealt with in a simplified fashion. One example is the limitation of the leakage from a damaged canister due to the transport resistance offered by the hole in the canister wall, another is the transport of radionuclides in fracture zones. The increased computing power of modern computers and new assessment models have also made it possible to take into account the variability in the hydraulic conductivity of the rock, as well as the actual geometry of the repository.

Aside from the fact that initially defective canisters are assumed to have been deposited, in order for there to be any releases at all to be calculated, the new models make the assessments more realistic than before. At the same time, the results are also affected more strongly by the features of the repository site, i.e. the results are more site-specific than before. This is necessary in order for it to be possible to examine the impact the rock barrier has on safety, but also means that a transfer of the results of this study to other sites must be done with caution.

Repository safety

Probable conditions

The engineered barriers in the repository have been designed so that they provide a long-term isolation of the radioactive materials from the surrounding groundwater. The fuel is encapsulated and deposited in a carefully controlled manner so that in all likelihood the repository will not contain any defective canisters.

The canister and buffer materials have been chosen so that the barriers are not sensitive to reasonable changes in groundwater chemistry or temperatures. The chemical environment in deep granitic bedrock is such that the copper walls of the canisters will not be penetrated by corrosive substances until possibly after several tens of millions of years.

The lead-filled canisters will act as solid bodies in the rock and will withstand the prevailing pressures, including those that can arise in the event of a future glaciation. Possible rock movements caused by changes in rock stress after a glaciation will be released in the regional fracture zones that surround the repository and are structurally weak parts of the bedrock. Rock movements of such magnitude that the canister would be sheared off will only occur in fracture zones with a length of 10 km or more. Such structures can be identified during the construction of a repository and no canisters will be deposited there.

One possible reason for the canisters losing their integrity is that an inner helium pressure is built up in the canister by α-decay in the fuel. This pressure will not reach the level of the yield limit of the copper canister until some 10 million years or so after encapsulation.

Thus, the copper canister will isolate the spent fuel for a very long time, considerably longer than the 100 000 years-plus that are required for the toxicity of the radioactive materials to decline to a level equivalent to that of rich uranium ores.

Reference scenario

To substantiate the safety assessment, the repository's impact on the environment has also been studied for less probable cases. One assumption is thereby that leaky canisters have been deposited owing to the fact that defects during manufacture have not been detected in the quality control. A reference scenario has been defined where 0.1% of the deposited canisters have initial defects. Fuel dissolution, transport of radionuclides from the barriers in the near field, through the bedrock and the biosphere, and dose to man are calculated for this scenario.

The release of radionuclides from a damaged canister is limited strongly by the slow dissolution of the fuel and by the maximum possible size of an initial defect. The calculations show that if the radionuclides escaping from a damaged canister travel directly up to the biosphere without being affected at all by their transport through the bedrock on top of the repository, the dose would be no more than 0.001 mSv/y for all nuclides except cesium-135, see Figure 11-5.

Part of the inventory of isotope cesium-135 is assumed to have been released from the fuel matrix and thus be available for outward transport as soon as the groundwater comes into contact with the fuel. With the above assumption that this amount of cesium from a damaged canister would reach the biosphere directly, it can give rise to a dose of about 0.03 mSv. In reality it takes about 10 years before the maximum release rate from the near field is reached, which reduces the annual dose from cesium to a few percent of the values given in Figure 11-5.

In other words, the barriers in the near field limit the releases to levels that lie below the suggested dose limit of 0.1 mSv/y.

Thus, the principal safety-related requirement on the rock around the repository is that it shall preserve a chemically and mechanically stable environment around the repository, so that the performance of the engineered barriers is ensured.

In order to determine the safety-related importance of the rock barrier at Finnsjön, a geohydrological modelling of the area has been performed. Water flow and travel times up to the biosphere in different parts of the repository have been calculated.

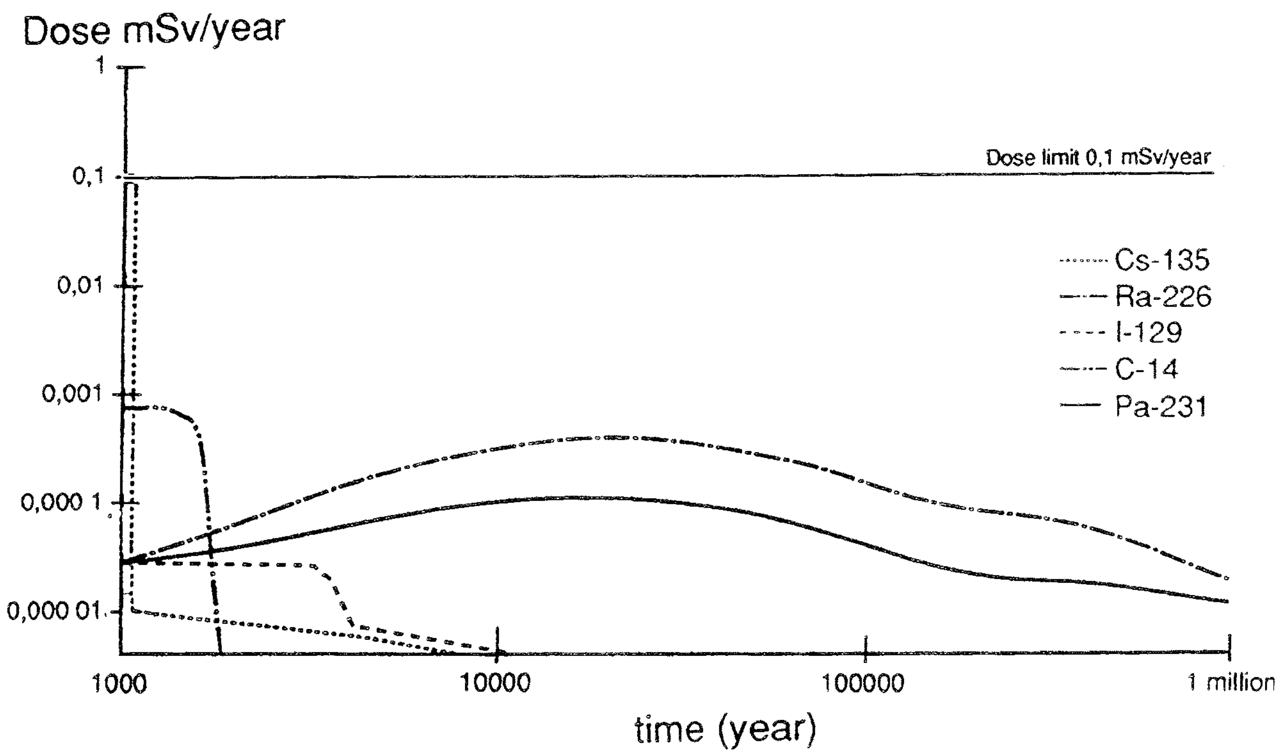


Figure 11-5. *Dose rate to individual under the assumption that the release from an initially defective canister takes place directly to the biosphere.*

Sampling in the Finnsjön area has shown that water at repository depth has a higher salinity than shallower water. This stratification of the groundwater's density reduces the groundwater flux. Studies indicate a groundwater travel time between repository depth and ground surface that is between 10 and 100 times longer at existing salinities, compared with a pure fresh water case. The calculations in SKB 91 are based on the less favourable fresh water case, since the prevailing situation may change during the span of time that must be considered, and since the excavation work may disturb the balance. A release to salt water normally gives a considerably lower dose than one to potable water.

The analysis of the radionuclide release rates in the event of an initial canister defect shows that the release from the near field is only slightly affected by the water flow around the deposition hole.

The groundwater fluxes in the model block have been calculated with both stochastic and deterministic hydrology models. The flow patterns that are generated are in good agreement with each other. The results show that the flow is mainly determined by topographical conditions and a flat fracture zone above the repository. Other fracture zones only affect the flow pattern to a small extent. The principal discharge of groundwater from the repository area takes place to Lake Skälsjön, or to the surface water that runs down towards Lake Skålsjön along the Imundbo zone, see the fold-out map at the back of the report.

The travel times for water up to the ground surface have been calculated for flow paths that start in different parts of the repository. For nearly half of the flow paths, the transit time is so long that water from repository depth does not reach the ground surface until after 10 000 years, see Figure 11-6. For the flow paths that reach the ground surface before 10 000 years, the median value of the groundwater travel time in the reference case has been calculated to be 110 years.

The calculations show that the size of the release of nuclides to the biosphere is affected to some extent by the groundwater travel time. If the nuclides released from the near field reach the biosphere via a flow path with a groundwater travel time of less than 10 years, the calculations give a dose approximately 10 times higher than if the

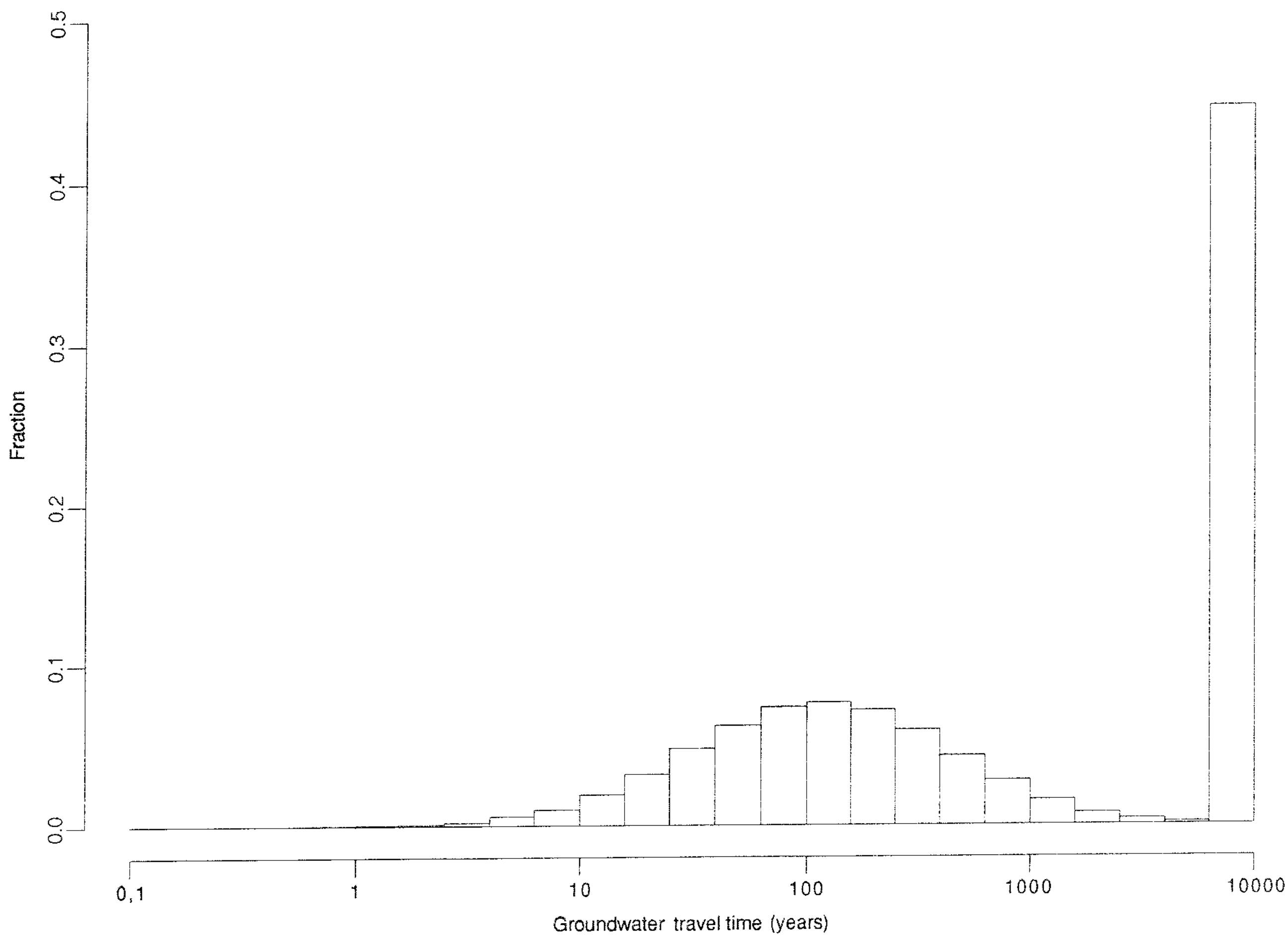


Figure 11-6. *Histogram of groundwater travel time for water from different parts of the repository to the ground surface for the reference case.*

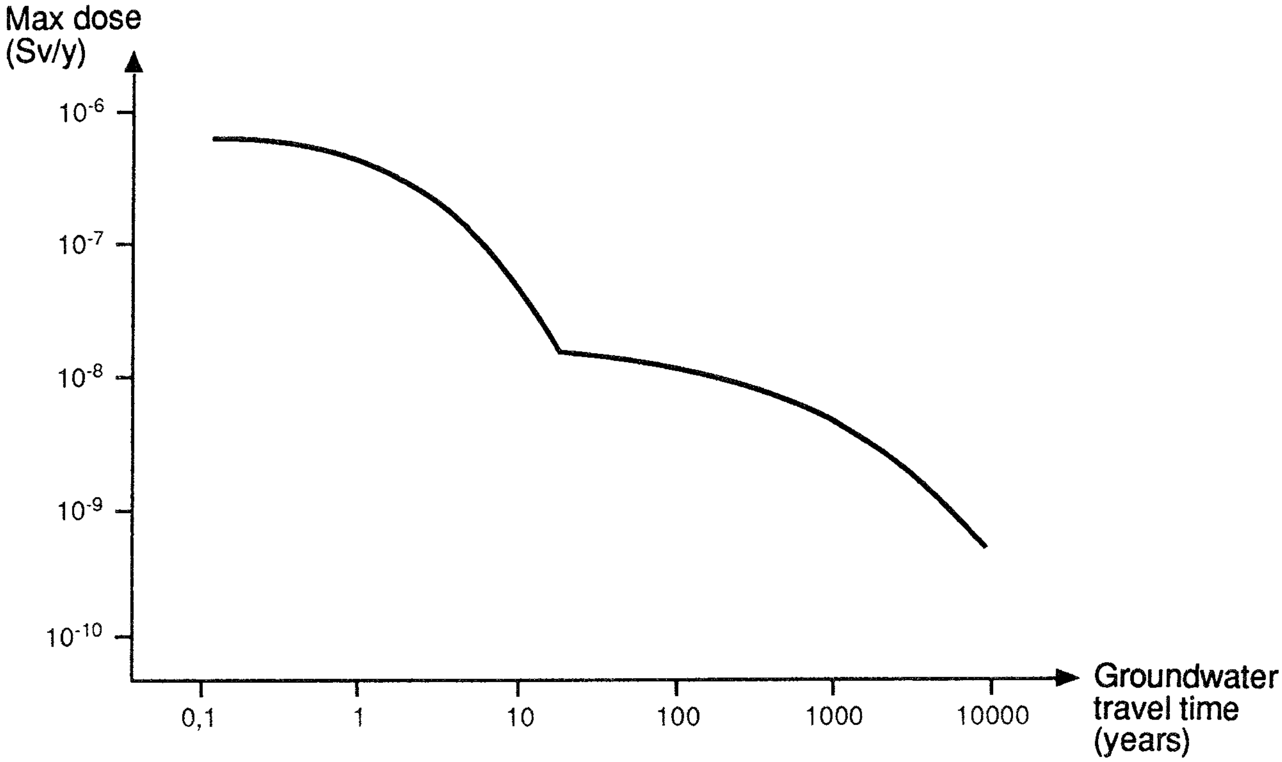


Figure 11-7. *Maximum annual dose commitment for release from an initially defective canister at different travel times for groundwater from canister to biosphere.*

release had taken place via a flow path with a travel time of 100 years. At a groundwater travel time of 10 000 years the dose is about 10 times lower, see Figure 11-7.

The entire chain of calculations from release from the fuel to dose in the biosphere has been carried out for the reference case. The results show that the repository's impact on the environment is several powers of ten less than the dose limit suggested by the authorities. Compared to this margin, the effect on the results of the random variability in the hydraulic conditions is limited, see Figure 11-8.

The importance of the way in which radioactive materials enter the biosphere has been studied with a biosphere model. Compared to a leakage to potable water on land, the same release to the Baltic Sea gives doses that are about 100 times lower. If a well should be so extremely positioned that it manages to collect all the radionuclides that leak out from a repository, an individual who fills his entire water need with water from this well alone would receive a dose up to 100 times higher.

In summary, the assessments show that the barriers in the near field isolate the radioactive materials in the spent fuel very effectively. Radioactive fission products and all actinides with high initial inventory and with the potential to give high individual doses are retained in the near field. Thus, cesium-137 and strontium-90 decay before the water comes into contact with the fuel in a defective canister. The solubility limits and sorption in the bentonite clay prevent other materials with high initial activity – such as the actinides plutonium, neptunium and americium and the long-lived fission products zirconium-93, palladium-107 and tin-126 – from escaping into the rock even if the canister has an initial defect.

In practice, only the highly soluble and long-lived nuclides carbon-14, iodine-129 and cesium-135, plus the long-lived uranium daughters radium-226 and protactinium-231, can escape from the near field. This limits the release (even with a damaged canister) to such a low level that the safety-related importance of the rock as a barrier to radionuclide transport is very limited. The principal safety-related requirement on the rock is therefore that it should provide a mechanically stable environment where canisters can be emplaced without landing in the middle of potential zones of movement, and that it should provide a chemically stable reducing environment for the near field.

The rock as a barrier – variation calculations

The safety requirements on a repository are intended to ensure that the safety of the final disposal system is based on several passive barriers. Thus, even if it is not necessary from a dose point of view to find the geologically absolutely most favourable site for a repository in Sweden, it is reasonable to attempt to utilize optimally the potential of the rock on the chosen site to act as a barrier against radionuclide migration.

The chemical environment in the Swedish bedrock, and the stability that rock blocks being considered for the repository can be credited with, differ very little from

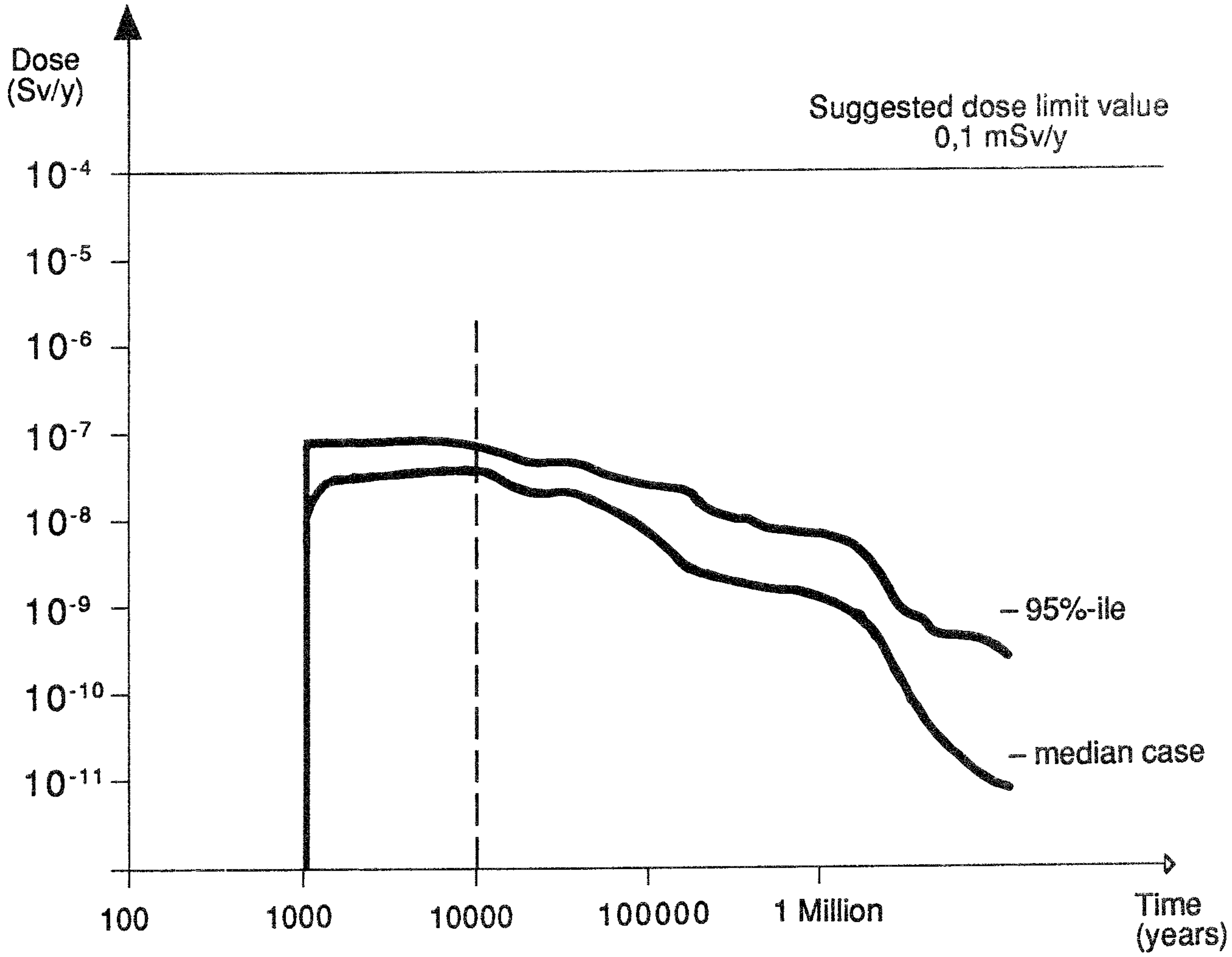


***Figure 11-8**. The reference case – Dose commitment for individuals at different times after closure of the repository. The curves show a typical case and an unfavourable case.*

place to place. The factor that most readily summarizes the barrier potential of a given rock volume is the distribution of groundwater travel times from the repository to the biosphere.

To shed light on how this property, i.e. the distribution of travel times shorter than 10 000 years, is affected by different site-specific characteristics and parameters, some fifteen or so variations of the geohydrologic features of the site have been carried out in the reference case.

The variations cover

- properties of the rock mass in the repository area;
- properties of steeply dipping fracture zones;
- properties of near-horizontal fracture zones;
- the size of regional and local hydraulic gradients.

Other variations have been performed to demonstrate the importance of contact area between flowing groundwater and rock, dispersion and matrix diffusion, or the importance of salinity stratification in the groundwater.

A general observation is that streamline patterns and commonly occurring groundwater travel times in a bedrock such as in the Finnsjön area are relatively little affected by the locations of the steeply dipping fracture zones and their distance from the repository. In order for a clear effect to be apparent, the ratio between the hydraulic conductivity of the fracture zones and that of the rock must be increased from just over a factor of 10 to more than 100. Figure 11-9 shows how the distribution of travel times changes.

On the other hand, a clearer effect of changed conditions is obtained for fracture zones with a nearly horizontal orientation. If the flat-lying zone lying above the repository is replaced with "normal" rock, the flow pattern is changed and the flow paths become flatter. The effect is even clearer if a similar flat zone is assumed to lie below the repository. Figure 11-10 shows how the changes affect the groundwater travel times from the repository up to the ground surface.

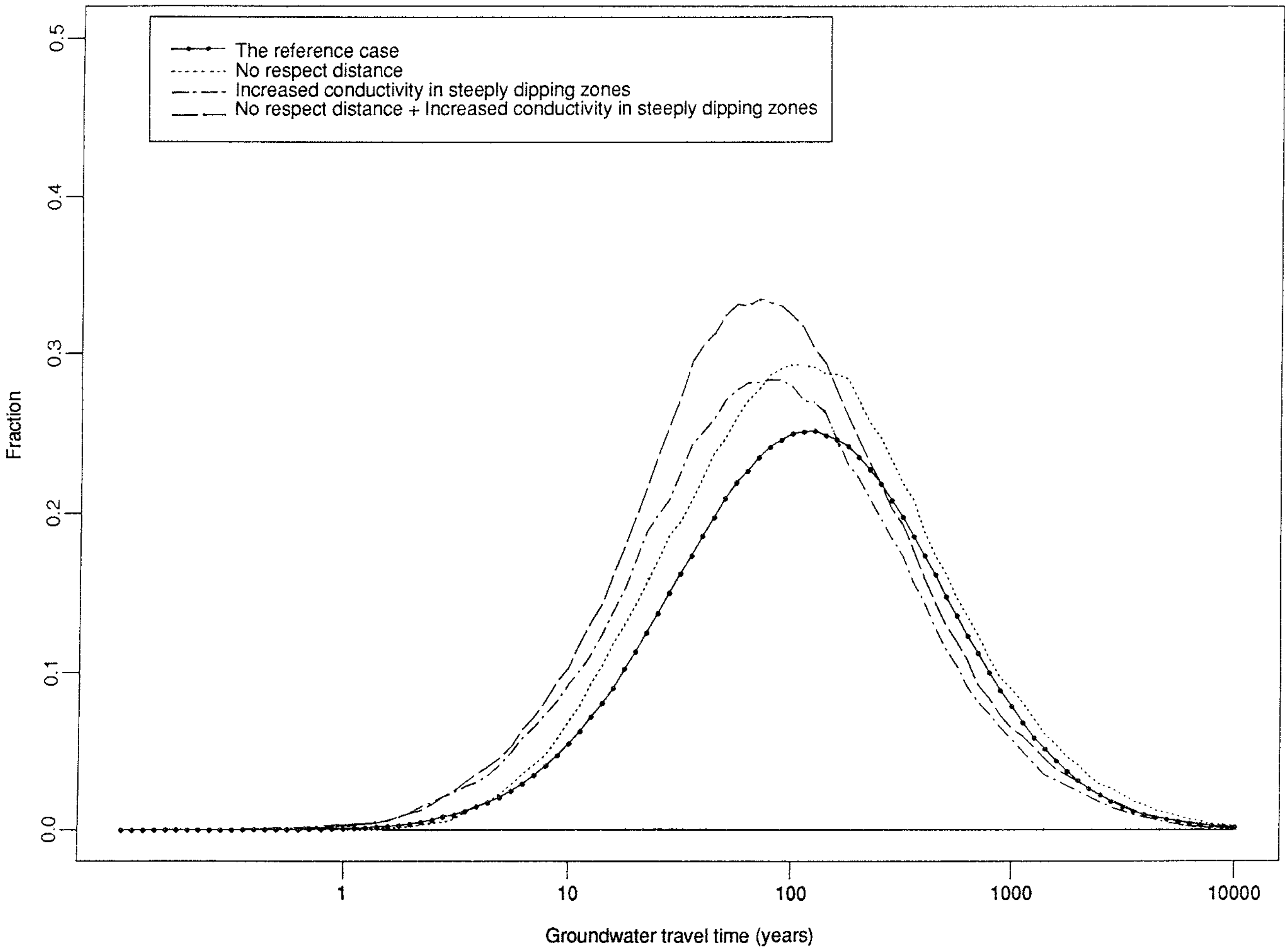


Figure 11-9. Dependence of groundwater travel times on the distance between repository and fracture zones and on the ratio between the hydraulic conductivity in fracture zones and rock.

In summary, the variations show that the flow pattern and groundwater travel time for water from the repository to the biosphere are changed to a relatively small extent by most of the variations of the hydrogeological characteristics on the site that have been performed. Significant changes are mainly caused by flat-lying, highly conductive zones, which can create both more and less favourable conditions than in the reference case by isolating the repository from groundwatergradients at the ground surface or by routing the water that passes the repository quickly up into a nearby discharge area. However, even in these cases, the effect of the repository's engineered barriers means that the dose is not affected by more than an order of magnitude or so, i.e. less than the margin to the recommended dose limit values.

If a high salinity in the groundwater around the repository persists for a long time, a lower groundwater flux will be obtained at the same time as wells with deep groundwater will become saline.

The effect of many of the variations discussed above is naturally dependent on the local conditions that have been chosen for the reference case. Even if there is a great similarity between future candidate sites, conclusions drawn from the results for one site may only be applied to other sites with caution.

Repository configuration – adaptation to local conditions

The excavation of deposition drifts can create a zone with higher hydraulic conductivity parallel to the drift. If the direction of the drift is perpendicular to the hydraulic gradient, no appreciable effects will be obtained. Even when the drifts are oriented maximally unfavourably with respect to the fractures and the hydraulic gradient, the effects are small. Only when the above conditions are combined with large differences in hydraulic conductivity between the rock and nearby fracture zones will an increase in the short travel time fraction be noticeable, see Figure 11-11.

The migration of radionuclides is controlled by the flow paths through the repository. Unsuitable flow paths can be

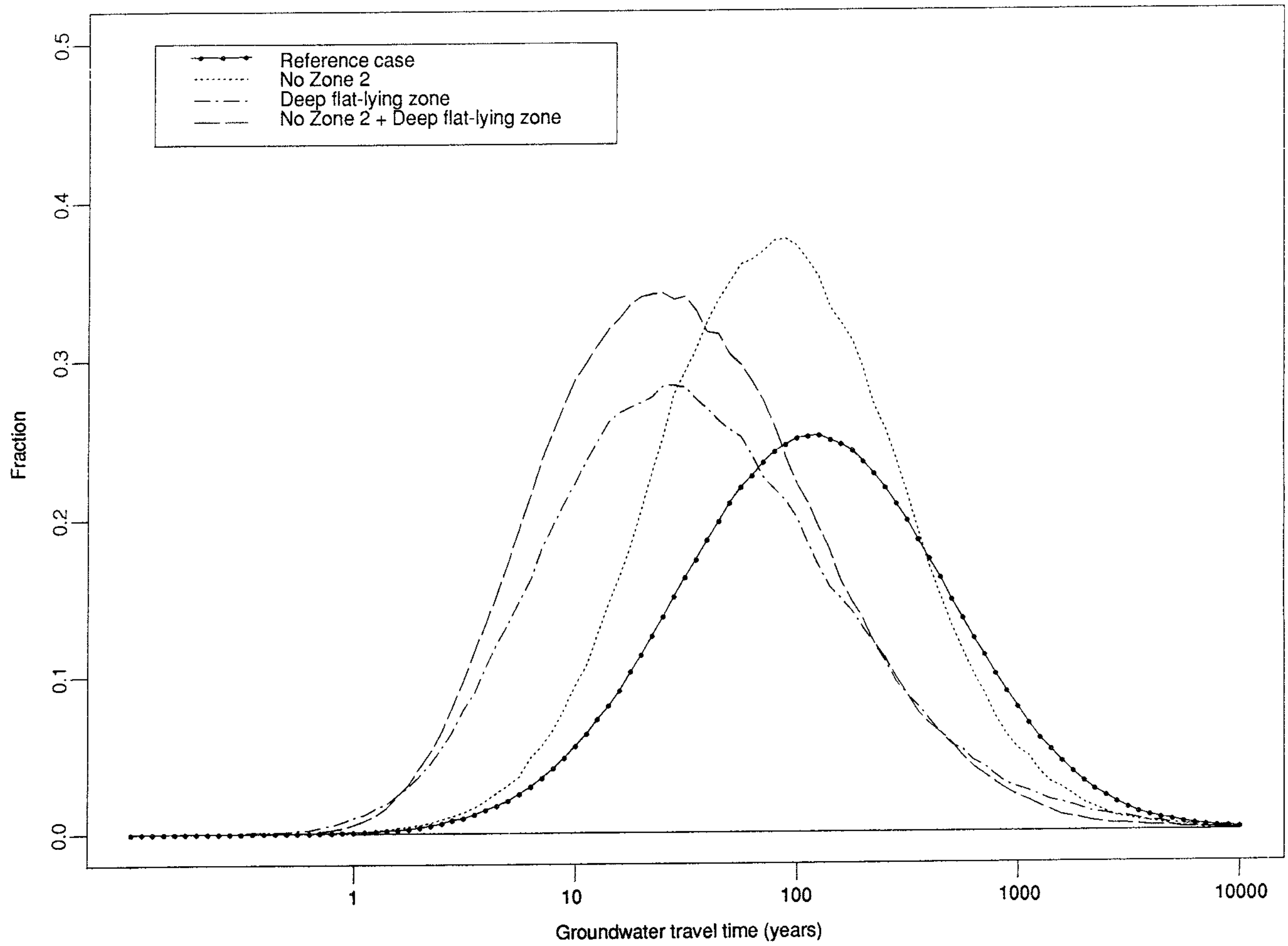


Figure 11-10. *Dependence of groundwater travel times on flatlying zones with high conductivity.*

avoided by adapting the position of the repository horizontally and in depth to the flow pattern.

Provided that the rock block is sufficiently large, or that several adjacent blocks can be used for deposition, the repository layout utilized provides a good opportunity to adapt the positions of drifts and deposition holes to progressively obtained information on the local properties of the repository rock. The analyses show that the hydraulic conditions in the evaluated repository block are such that the shortest travel times are always associated with a specific corner in the repository. For the Finnsjön area, the value of not depositing in this corner is greater than trying to avoid deposition positions that by chance have been located in unfavourable conditions.

The variations covering zones above and below the repository show that a respect distance between major flat-lying fracture zones and the nearest canister positions of around 100 m is well warranted. A change in the depth of the repository by 100 m up or down affects the travel times by a factor of two.

In summary, it can be concluded that some opportunity exists to exploit the potential of the local bedrock to act as a safety barrier by adapting the geometric configuration of the repository. However, the differences do not normally appear to be of such a magnitude that they would be decisive in determining whether a site is acceptable or not. One main reason for this is that the repository is extensive in space. Even if a certain placement of the repository were to bring a number of canister positions into a less favourable location, the safety of all the canisters in the repository would be affected only marginally.

Qualitative evaluations such as the above are deemed to be valid for all sites studied in Sweden. A quantification of the value of adapting the repository to local conditions is highly site-specific, however. Moreover, only part of the site-related information at Finnsjön has been obtained for the purpose of being used in a safety assessment.

Similar judgements of the importance of various parameters must nevertheless always be made when adapting a repository to a given site. There are great similarities as far as the limitations of the body of data are concerned between the premises for SKB 91 and the conditions that will prevail at an early stage of a site evaluation. The essential difference is that the geological investigations can be continuously focused on parameters and structures which are found to be important in the general analyses. In-depth analyses based on a larger body of data, interspersed with verifying investigations and a progressive refinement of the body of data, will permit a gradually improved understanding to be obtained of the safety-related performance of the site and a local adaptation of the repository design.

The assessment methodology that has been used for SKB 91 has therefore been built up so that it permits running assessments in parallel with ongoing site characterization and repository design. Models can be replaced to match the desired level of detail, and databases and most parameters can be changed in a simple manner, without requiring modifications in models and computer programs.

11.4.6 Summarizing Conclusions

The SKB 91 safety assessment shows that a repository constructed deep down in Swedish crystalline basement with engineered barriers possessing long-term stability fulfils the safety requirements suggested by the authorities with ample margin. The safety of such a repository is only slightly dependent on the ability of the surrounding rock to retard and sorb leaking radioactive materials. The primary function of the rock is to provide stable mechanical and chemical conditions over a long period of time so that the long-term performance of the engineered barriers is not jeopardized.

SKB 91 has shown that the safety-related requirements on a site where a final repository is to be built are such that they are probably met by most sites SKB has investigated in Sweden. The assessments also show that there are a number of factors that can strongly determine how the bedrock performs as an extra safety barrier. Examples are the presence and location of flat-lying structures and their hydraulic conductivity.

SKB 91 constitutes an example of how performance and safety assessments can be used to shed light on the importance of different geological structures in a potential repository area and to clarify factors that are essential from a safety point of view. The methodology can, in the continued siting work, be utilized to adapt the repository in such a way that the ability of the rock to contribute to the safety of the repository is effectively utilized. However, this requires access to site-specific data and an opportunity to augment these data continuously as the safety assessments progress.

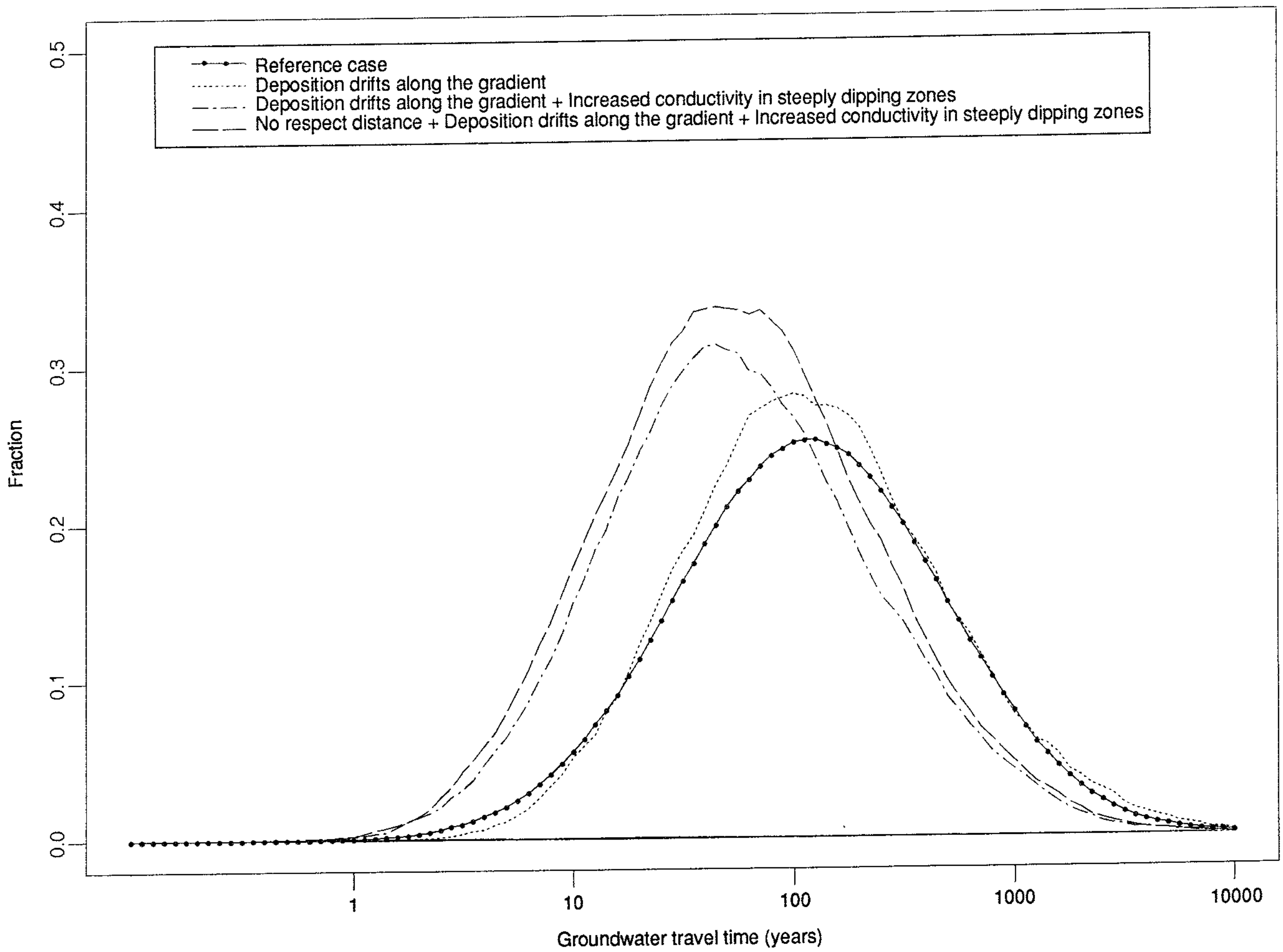


***Figure 11-11**. Dependence of groundwater travel times on increased conductivity around the repository drifts.*

12. SITING OF A FINAL REPOSITORY FOR SPENT FUEL

12.1 GENERAL

The siting of a deep geological repository for spent nuclear fuel and other long-lived waste is one of the main remaining tasks within the Swedish Nuclear Waste Management programme. Siting of this repository will be done in stages and the work will go on during the 1990-ies and a few years into the next century before a license to construct the repository can be expected. This siting process can build on more than 15 years of research, development and field studies and it will be supported by the results and experiences continuously obtained within the ongoing programmes for research, system studies, safety assessments and Äspö HRL. The main stages of the siting process are illustrated in Figure 12-1.

12.2 ORGANIZATION

Since autumn 1991 the SKB activities directly related to siting of a deep repository are coordinated within a project that is organized as shown by Figure 12-2. Later, when candidate sites have been established, there will be local site offices to coordinate site investigations as well as information to and interaction with the local communities.

12.3 OVERVIEW STUDIES. ASSESSMENT OF SITING FACTORS

The first stage of the siting process is a systematic assessment of all important aspects concerning the future proposal of suitable candidate sites for further investigation. This stage, which was started after summer 1991, encompasses:

- Studies of technical, geoscientific and safety related aspects of importance for the siting of a deep repository.
- Studies of legal, social, infrastructural and sociopolitical aspects of importance for the siting of a deep repository.
- Planning for the stage 2 activities e.g. preparation of a programme for geoscientific pre-investigations, studies of the potential impact on the environment, local infrastructure and economy.
- Planning of information activities and of measures to ensure local community and public involvement.

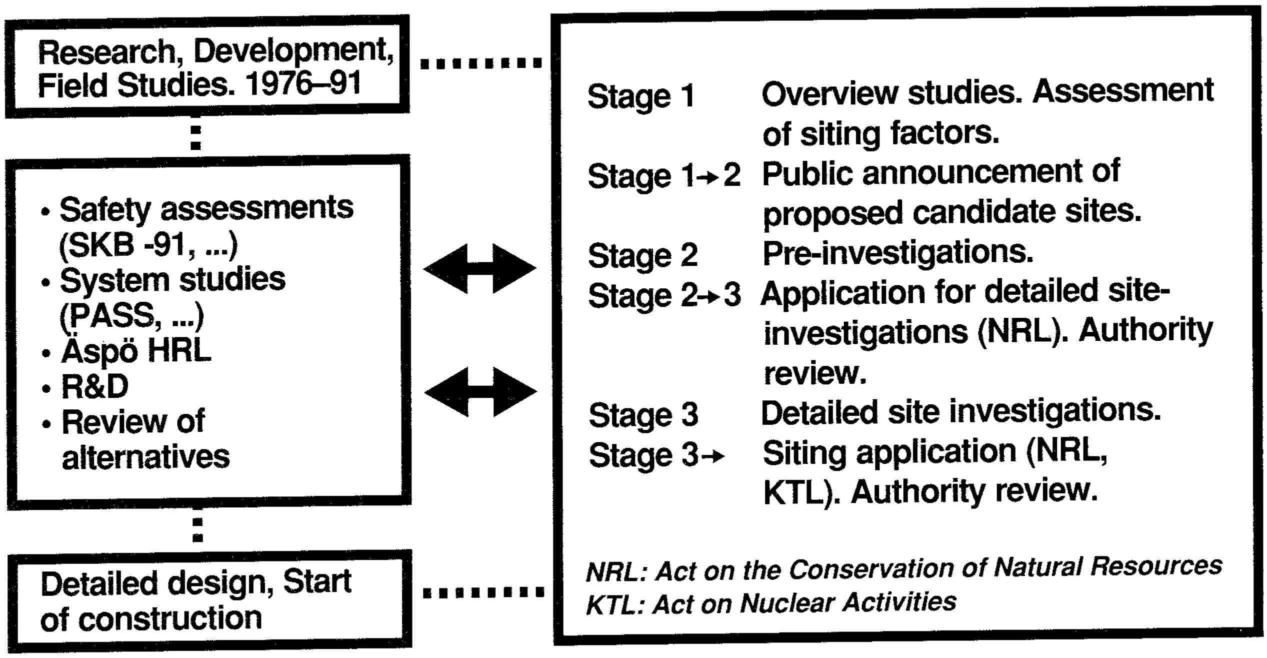


Figure 12-1. *The main stages of the siting process.*

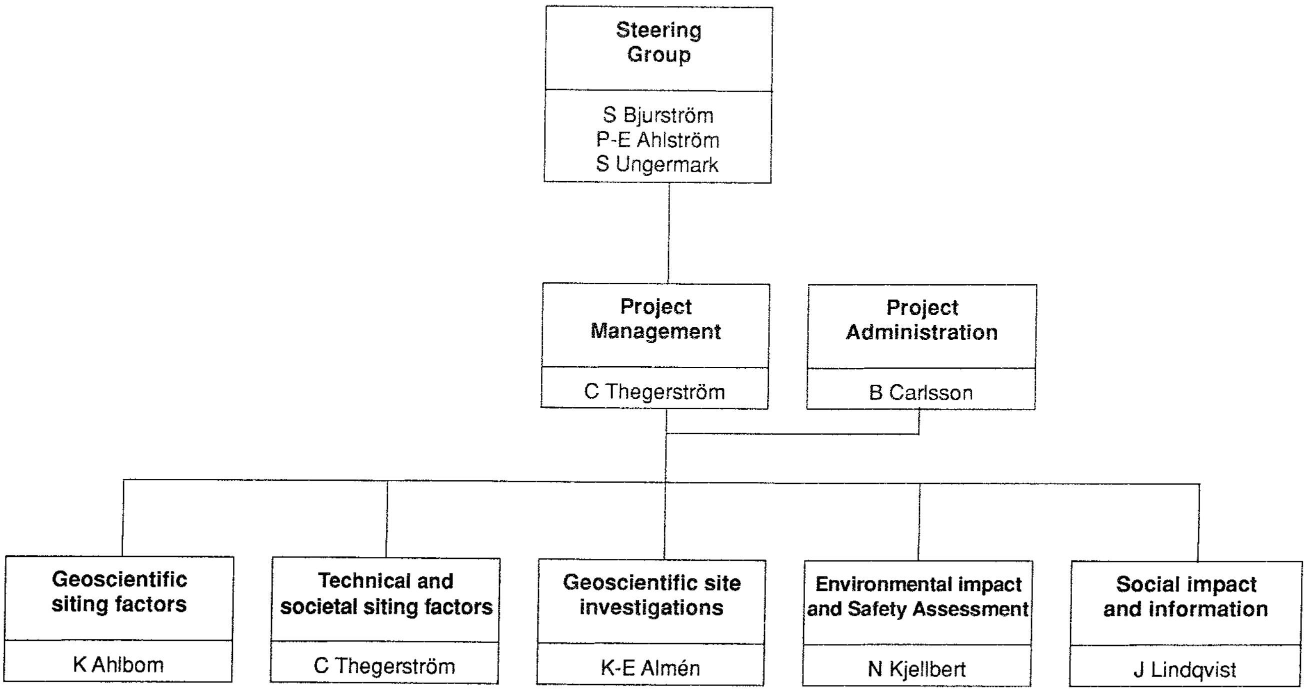


Figure 12-2. *SKB Siting Project organization.*

During the autumn 1991 plans have been prepared for the work to be done in stage 1 as indicated above. Concept specific siting factors are evaluated within PASS, see Chapter 10. An evaluation of the safety factors affecting siting is made within SKB 91, see section 11.4 Regional geoscientific factors are discussed below in section 12.5. Studies have been initiated concerning e.g. legal requirements in different stages of the siting process and foreign and other experiences of siting radioactive waste repositories or other potentially controversial facilities. The work to identify, compile and analyze information about important siting factors has also started.

12.4 TIMETABLE AND GENERAL STRATEGY

Present planning is to complete stage 1 (overview studies and assessment of siting factors) by mid 1993. It is estimated that pre-investigations (stage 2) and detailed site investigations (stage 3) will require in total about 10 years which would mean that a siting application could be sent to the authorities for review a few years after the turn of the century. The overall strategy and timetable for siting of a deep geological repository in Sweden is presently being discussed from different aspects within SKB and in the next R&D-plan (September 1992) the siting strategy and timetable will be described in more detail.

12.5 REPOSITORY SITING – GEOLOGICAL OVERVIEW

12.5.1 Compilation of Data from Former Investigated Study Sites

In preparation for the siting process an effort is made 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 activities. The Gideå and Fjällveden sites are now reported /12-1/, /12-2/ and Sternö, Kamlunge, Klipperås, Finnsjön will be published during 1992.

12.5.2 Gabbro as a Host Rock for a Repository

Studies regarding the suitability of gabbro as a host rock for a repository have been a part of the Swedish programme since 1979. The studies have included a nationwide inventory to identify all larger gabbro bodies and, in more detail, the drilling and testing of a 700 m deep borehole in the Taavinunnanen gabbro. In 1986 SKB concluded that due to difficulties in selecting a suitable gabbro body, when both geologic and non-geologic factors are considered, no further studies of gabbro were necessary. This conclusion was not shared by SKN and explains why SKB in 1991 decided to initiate three additional studies to evaluate if there is any reason for changing its conclusion regarding gabbro. These studies concern the geochemical and geohydrological characteristics of gabbro, as well as its mechanical properties and also incorporates experience from underground constructions /12-3, 4, 5/. A separate study has been made in cooperation with TVO which included an evaluation of earlier gabbro inventories in Sweden and the main results from the investigations at Taavinunnanen /12-6/. The results from these studies will be compiled in a Technical Report during 1992.

From a repository safety performance assessment point of view, gabbro and ultramafic rock types, may offer some advantages over granites/gneiss regarding the potential degree of radionuclide retardation and absorption through the rock mass via hydraulic fracture zones. These properties of gabbro have, however, not been tested or confirmed by laboratory nor field tests.

In comparison to granites and gneiss, a reduced hydraulic conductivity, is another potential advantage of gabbro. This may be attributed to the self-sealing capacity of fractures in basic rock types due to the swelling of clay minerals. To some extent this is probably the case for homogeneous gabbros. However, the large size of a repository implies that heterogeneities in the far-field, such as layering within the gabbro, fracture zones, dykes etc., will be significant, and therefore the overall performance will probably not be significantly different from a repository in other rock types. This is indicated by the Taavinunnanen studies and also by the well archives.

The main disadvantage with gabbro as a repository host rock, when both geologic and non-geologic factors are considered, is the limited number, if any, of suitable large gabbro massifs. Another disadvantage, more difficult to assess, is the economic ore potential of gabbro which might lead to accidental intrusion by future prospecting activities.

12.5.3 A Review of the Seismotectonics of Sweden

Seismotectonics involves the integration of all those factors that constrain deformation in the crust such as: stress-state, temperature, structure, permeability, strain (as determined geodetically, from tide gauges, seismically, and from Holocene changes in land-level and neotectonics). Many of these data-sources have inherent problems of measurement and the construction of a seismotectonic model demands a critical review of the data to allow these undercertainties to be quantified. As in many continental intraplate regions the relative scarcity of data (in particular the low-level of seismicity) encourages extrapolation, often far beyond what the available evidence safely permits. SKB has initialized a project which aims to construct a data set, with its uncertainties quantified, for seismotectonic modelling in Sweden. The analysis of relevant data sets have been ongoing during 1991 and the evaluation will be presented during 1992.

12.5.4 Implication of Fractal Dimension on Hydrogeology and Rock Mechanics

A fractal or a fractal set is a set made of subsets in some way similar to the whole. In brittle tectonics it is often obvious that different sets of fractures, zones or lineaments have similar strikes and that these trends occur in different interpretation scales. This may be an effect of the physical processes of fracture genesis or it may indicate a wider scope of the applicability of fractal dimension as an index for comparison of the bulk mechanical and hydraulic properties of rock.

An extensive literature review with complementary scoping modelling has been carried out /12-7/ in order to analyze the implication of fractal dimension as an index in the siting process. Although no application was identified which directly has used fractals as a geohydrologic index it is found that within the oil industry fractal dimension is commonly used to select locations for production and exploration wells. Different references in literature demonstrate that consistent and meaningful fractal dimensions can be derived from lineaments, fracture maps, etc. and that the fractal dimension can be used to compare different geologic geometries. However, further studies will be required if one wants to determine which values of the fractal dimension are to be preferred in the context of geological environment evaluation.

12.5.5 Development of a Hydrogeological Classification System

During the last decade some standardized systems for classification of groundwater vulnerability have been used in Sweden in order to minimize the contamination risks to shallow aquifers used for water supply. These types of classification systems may be further developed for the purpose of comparing nuclear waste disposal sites from the hydrogeological point of view.

On behalf of SKB the Department of Geology at Chalmers University of Technology, Gothenburg, has further developed the ideas of an hydrogeological decision-analysis framework /12-8/. The general purpose should be a classification system that takes into account the uncertainties of the hydrogeologic environment and allows for decision analysis of site selection. The critical parameters need to be established through consensus within an expert group.

12.5.6 Geophysical Surveys for Offshore Site Investigation

The Swedish spent fuel disposal programme includes the possibility of a repository in the bedrock beneath the sea. For the present this disposal concept has low priority but in order to follow the development of offshore techniques it has been decided to compile the knowledge on the application of high resolution geophysical surveys /12-9/ in Swedish sea environment.

13 SPENT FUEL

The cooperation with other groups in the world performing similar studies has continued during 1991, through the spent fuel workshop which was held in Spain and arranged by MBT, Barcelona, and ENRESA. Direct co operative work has also been performed together with Atomic Energy of Canada Ltd.

A more detailed account of the findings up to data within the SKB programme for spent fuel studies are given in /13-1/.

13.1 FUEL CHARACTERIZATION STUDIES

The current and generally-accepted model for spent fuel corrosion consists of three chronologically-overlapping mechanisms: a) the rapid dissolution of species released to fuel/cladding surfaces during irradiation, b) grain boundary attack, and c) matrix dissolution. Only the first process is thought to be independent of the redox conditions at the fuel/water interface.

The model is being applied both to LWR fuel (with burnups about 40 MWd/kg U and with linear power rating (LPR) values of the order of 30 kW/m at the beginning of irradiation but in general decreasing during the following cycles) and to CANDU fuel (with burnups of about 10 MWd/kg U but with LPR values up to 50 kW/m.) As would be expected from the difference in irradiation conditions, the higher power ratings in operating CANDU fuel enhance the release of mobile species such as cesium and iodine from the fuel, and higher values for the first mechanism (Instant Release Fraction) are observed in corrosion tests on CANDU fuel than for LWR fuel.

The current evidence for grain boundary attack is mainly indirect, being based on the persistently higher release rates for cesium compared with strontium in fuel corrosion tests, although there is some experimental evidence that even strontium release rates are largely controlled by strontium segregation or enhancement at the grain boundaries. Direct experimental evidence by the examination of corroded fuel and identification of corrosion sites, however, is presently limited to observations of grain pull-out during ceramographic preparation of corroded fuel specimens.

In the case of matrix corrosion, it is evident from corrosion tests that even under oxic conditions the measured corrosion rates are low, so that if the process is controlled only by the exposed fuel surface, direct evidence of corrosion by means of examination of corroded spent fuel may be extremely difficult. However, in addition to migration and relocation of fission products,which are the processes underlying corrosion mechanism a) and b), there are other structural changes imposed on the fuel during irradiation which may steer corrosion towards preferred sites. In the case of LWR fuels,the outer rim of the fuel pellet (a few hundred micron in width) may present such a preferred site, since at a burnup threshold of 40-45 MWd/kg U, porosity increases sharply while grain size decreases, apparently by grain division. Since in the fuel rim there is also a build-up of both fission products and actinides due to neutron spectrum effects,this zone is of interest both because of an enhanced specific surface, and a favoured environment for localized oxidative dissolution due to alpha radiolysis.

SEM examinations of fragments of the reference Oskarshamn BWR fuel exposed to corrosion for over 4 years showed clear signs of corrosion at the fuel rim /13-8/. During 1991, the programme on fuel characterization has been directed towards the systematic examination of fuel samples from the Ringhals 1 BWR rod which is the source material for the ongoing Series 11 corrosion tests, see section 13.2 below. The characterization programme includes measurement of the radial variation of grain size, porosity, concentration of selected fission products (Nd, Cs, Mo, Sr and Xe) and alpha activity. SEM photomicrographs (magnification x5000) have been taken at regular intervals along the radius of both the polished fuel and the fracture surface for later comparison with selected specimens from the corrosion tests. Two fuel specimens from the rod have been dissolved and are being used for correcting the measurements. At the end of the year most of the experimental part of the programme was complete. ORIGEN-2 and possibly MICBURN calculations will shortly be performed in an attempt to refine the current SKB model for the correlation of corrosion rate with alpha dose if subsequent examination of corroded specimens from Series 11 should confirm if the fuel is preferentially corroded at the fuel rim.

13.2 SPENT FUEL CORROSION STUDIES

The fuel corrosion programme is now into its tenth year and specimens from the first BWR series have reached a cumulative contact time of over 3500 days. A second series using a PWR fuel rod was started in 1986 and in 1990 a series of experiments on a BWR stringer rod was started (Series 11). In this series the burnup varied along the fuel rod from 21 MWd/kg U to 49 MWd/kg U. For the first two series, fuels with an average burnup of about 42 MWd/kg U were used.

13.2.1 Fission Products

These three series show consistent patterns for the behaviour under oxic conditions of cesium, strontium and technetium, which are elements representing three different classes of fission products. Cesium is known to migrate to grain boundaries, fuel surfaces and clad in operating reactor fuel. Strontium is generally considered as being present in solid solution in the fuel and the release of strontium may be used as an indicator of the UO_2 matrix alteration. Technetium is known to segregate in the fuel in the form of metallic inclusions together with other 4d-elements.

Figure 13-1 shows the cesium behaviour. After an initial rapid release of material segregated to the fuel clad gap, the release rates decrease rapidly with contact time but, with the data so far available, appear to level off with time.

The corresponding data for Sr-90 release are presented in Figure 13-2. Here it can be seen that during the first few weeks of water contact, the Sr-90 release rate is more or less constant, before showing the same decrease with time as the values for Cs-137, but with appreciably less scatter. The Sr-90 values are also always lower than the corresponding values for Cs-137.

However, for the strontium release small but persistent differences have been observed between samples of the same burnup taken from different locations along the fuel column. It is important for the modelling of spent fuel

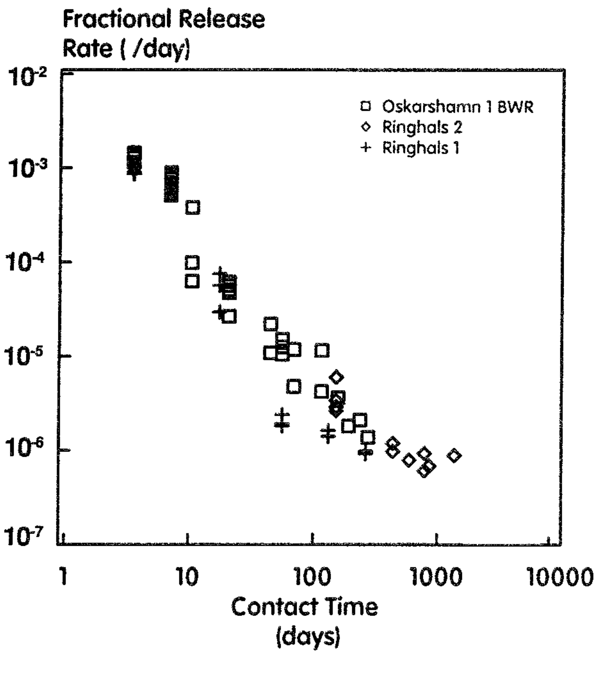


Figure 13-1. Fractional release rates for Cs-137 under oxic conditions.

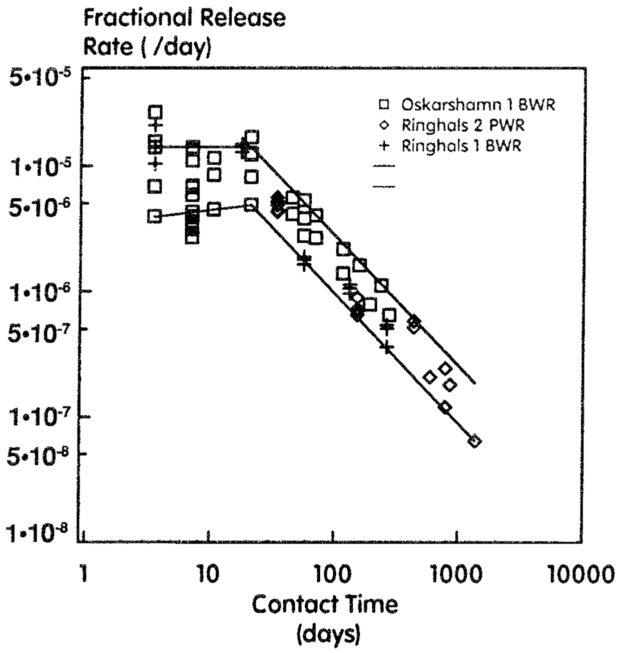


Figure 13-2. Fractional release rates for Sr-90 under oxic conditions.

dissolution to establish if these observed effects are representative of a preferential corrosion attack at zones in the fuel enriched in Sr-90 or whether the release rates in the latter stage in Figure 13-2 represent matrix dissolution. If the second alternative is valid, a reasonable hypothesis could be that the difference between the release behaviour of Cs-137 and Sr-90 shown in Figures 13-1 and 13-2, reflects only the migrational behaviour of cesium during irradiation: the Instant Release Fraction, representing cesium released from the fuel grains to fuel/clad surfaces, while the difference in the later stages of corrosion represent attack on grain boundaries enriched in migrated cesium.

The available data on Tc-99 release under oxic conditions are presented in Figure 13-3. Here the measured release rates for the two reference Ringhals rods show broad agreement, although with more scatter than was observed for Cs-137 and Sr-90. As can be seen in Figure 13-3, the release of Tc-99 is maintained at a rate of between 10^{-5} and 10^{-6} /day, such that after a few years it exceeds those for Cs-137 and Sr-90. Compared with these two nuclides, the presence of Tc-99 at the fuel grain boundaries has been well documented. Metallic inclusions in sizes ranging from in the micrometers down to tens of nanometres of the 4d-metals Mo, Tc, Ru, Rh and Pd have been observed. The larger of these inclusions are located at or close to the grain boundaries. The access of water through fuel cracks and networks of gas bubble sites to these technetium sources is thus relatively easy, and the release of Tc-99 is probably controlled only by the oxidation of the inclusions.

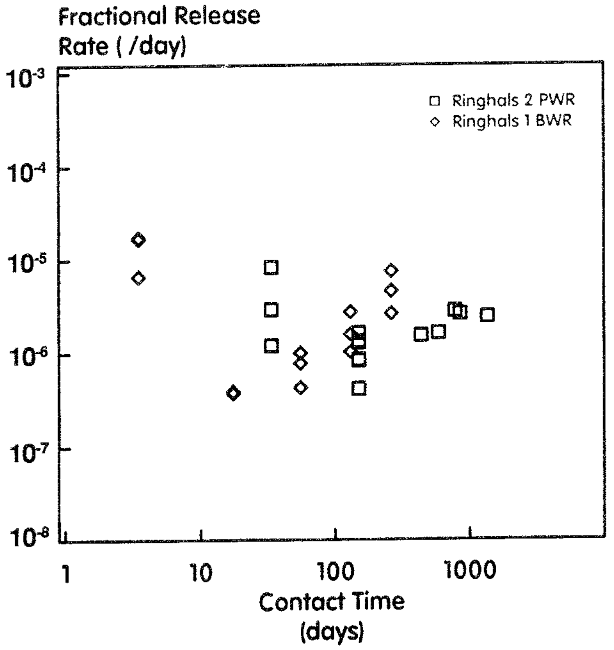


Figure 13-3. Fractional release rates for Tc-99 under oxic conditions.

Under reducing or anoxic conditions, the average Tc-99 concentration is found to be $6 \cdot 10^{-9}$ mol/dm^3. This is in good agreement with the predicted technetium solubility of $3 \cdot 10^{-8}$ mol/l, controlled by TcO_2.

13.2.2 Actinides

Throughout the experimental programme, it has been observed that the concentrations of uranium and plutonium attain a constant value independent of contact time. For uranium this value is rapidly reached, while for plutonium the solution concentrations are initially higher and the Pu/U ratio in solution is comparable to the Pu/U ratio in the fuel itself. However, after prolonged contacts with water the plutonium concentrations drop and after ca 200 days reach a constant level. This behaviour is indicative of solubility control. However, when the measured solution concentrations of uranium are compared with the solubilities of U(VI) hydrates, they are found to be at least one order of magnitude lower than predicted /13-2/. The lower uranium concentrations would require either the precipitation of more stable uranyl silicates or a lower redox potential than expected in an aerated system. In none of experiments performed in groundwater within the SKB programme has a secondary phase been identified. In experiments performed in deionized water has the formation of dehydrated schoepite been observed, but there are indications that this precipitate was actually formed after the spent fuel specimens were removed from the solution and exposed to air. There are, however, some observations of uranyl silicates which has been formed at elevated temperatures in spent fuel leach tests /13-3/.

An alternative hypothesis for the explanation of the observed actinide concentrations in the fuel corrosion experiments could be that the redox conditions are not controlled by the air/water system, but by the UO_2 fuel corrosion. It is not unexpected that the water/air system is at disequilibrium. If it is assumed that the redox potential of the U_3O_7/U_3O_8 transition controls the solubility of the radionuclides, a very good agreement between calculated and observed concentrations is obtained. For uranium, this is illustrated in Figure 13-4.

Also for plutonium there is reasonable agreements between the calculated and experimental results (See Tables 13-1). The plutonium solubilities are not redox sensitive within the range of redox potentials relevant for the experiments. Thus, the Pu data neither supports nor contradicts the presented hypothesis. However, it should be pointed out that the data base, used for the EQ3/6 calculations, fails to account for the difference in over one order of magnitude in Pu concentrations in groundwater and deionized water.

The neptunium data presented has been taken from the US Yucca Mountain Project /13-3/. The reported average Np concentration is -8.3 (log mol/l). This is to be compared to a calculated solubility of -8.5 (log mol/l) using EQ3/6 at a redox potential given by the U_3O_7/U_3O_8 transition.

There are very few Np results reported in the literature and no data have so far been obtained within the SKB

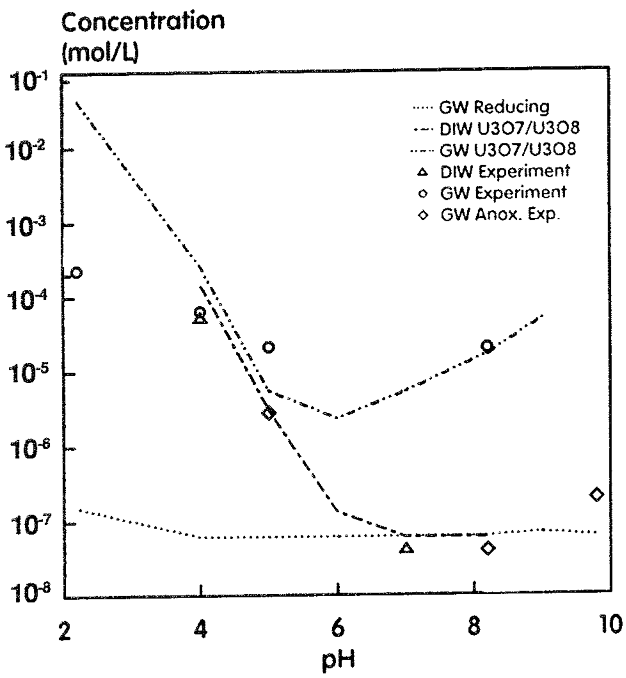


Figure 13-4. Comparison between calculated uranium solubilities and measured average concentrations as a function of pH.

programme. The data indicates that if there is a solubility control for the Np release, the redox conditions must be such that the solid phase is a Np(IV) phase. At higher redox potentials, Np(V) phases are stable and EQ3/6 predicts Np concentrations in the millimolar range.

Table 13-1. Average plutonium concentrations (log/l) measured in fuel corrosion experiments in deionized water and in groundwater and calculated solubilities.

	DI Water	Groundwater
Experiment	-7.9	-9.1
EQ3/6	-8.3	-8.3

An extended analysis programme, including neptunium analyses, is currently being planned as well as specific experiments designed to verify to proposed hypothesis. These studies will commence during 1992.

13.2.3 SIMFUEL

The study of the dissolution behaviour of an unirradiated chemical analogue to spent nuclear fuel (SIMFUEL) is still in progress and a status report has been issued /13-7/.

The results obtained have shown the usefulness as well as the limitations of SIMFUEL in the study of the kinetics and mechanism of dissolution of the minor components of spent nuclear fuel. Molybdenum, barium and strontium have shown a trend to congruent dissolution with the SIMFUEL matrix after a higher initial fractional release.

13.3 MODELLING

Work aiming at an electrochemically-based model for the dissolution of UO_2 has since long been in progress at AECL Research, Whiteshell Laboratories. Jointly, AECL and SKB have during 1991 had a status report compiled /13-6/. Dissolution rates under oxidizing conditions are predicted by extrapolating steady-state electrochemical currents for the anodic dissolution of UO_2 to the corrosion potentials measured in solutions containing various oxidants, including the products of the gamma and alpha radiolysis of water. A threshold rate has been established, below which the oxidative dissolution of UO_2 becomes negligible in comparison with the rate of chemical dissolution.

For dissolution due to alpha radiolysis, oxidative rates are uncertain, but could be above this threshold for a period of 500 to 30 000 years for light water reactor fuel. The uncertainty in this range reflects the relatively poor quality and limited number of corrosion potential measurements in the presence of alpha radiation. Work to collect the data necessary for the refinement of the model are in progress within a joint AECL-SKB project.

13.4 NATURAL ANALOGUES

The studies of alteration products of natural uraninite (UO_{2+x}) in contact with oxidizing groundwater has continued during 1991 and further work is currently being planned for 1992 and 1993. 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.

During 1991 work has been concentrated on the formation and subsequent dehydration of schoepite, $UO_3 \cdot 2H_2O$. Schoepite and other uranyl oxide hydrates has been found to form early in the oxidative alteration of uraninite /13-4/. Recent studies have shown that loss of structural water from the schoepite leads directly to the formation of dehydrated schoepite, $UO_3 \cdot 0.8H_2O$. The dehydration causes the expansion of schoepite parallel to cleavage planes, expanded grain boundaries, and extensive fracturing. Although these effects allow increased access of groundwater, schoepite does not re-precipitate where in contact with dehydrated schoepite. Instead, uranyl silicates and uranyl carbonates precipitate within these gaps and subsequently replace both schoepite and dehydrated schoepite. Thus, early formation of schoepite is kinetically favoured, but schoepite is not a long-term solubility limiting phase for uranium under oxidizing conditions /13-5/.

14 CANISTERS

During 1991, the studies have been focused on long-lived canisters with copper as the outer corrosion barrier. In addition to studies of the chemical and mechanical stability of copper, some efforts have been directed towards corrosion studies of carbon under aerobic and anaerobic conditions.

The reference group for mechanical integrity of canisters, which was formed in 1990 has continued its work during 1991 as well as the theoretical and experimental work initiated by the reference group. A final report containing results and recommendations is foreseen for 1992.

14.1 COPPER CANISTERS

14.1.1 Creep Studies

Creep tests have been carried out on oxygen free copper, oxygen free copper containing small amounts of phosphorous (50 ppm) and oxygen free copper containing 0.15% silver at temperatures between 180 and 450°C. In the previous creep studies, the creep properties of copper were investigated at repository relevant temperatures as well as slightly elevated temperatures (75°C to 145°C).

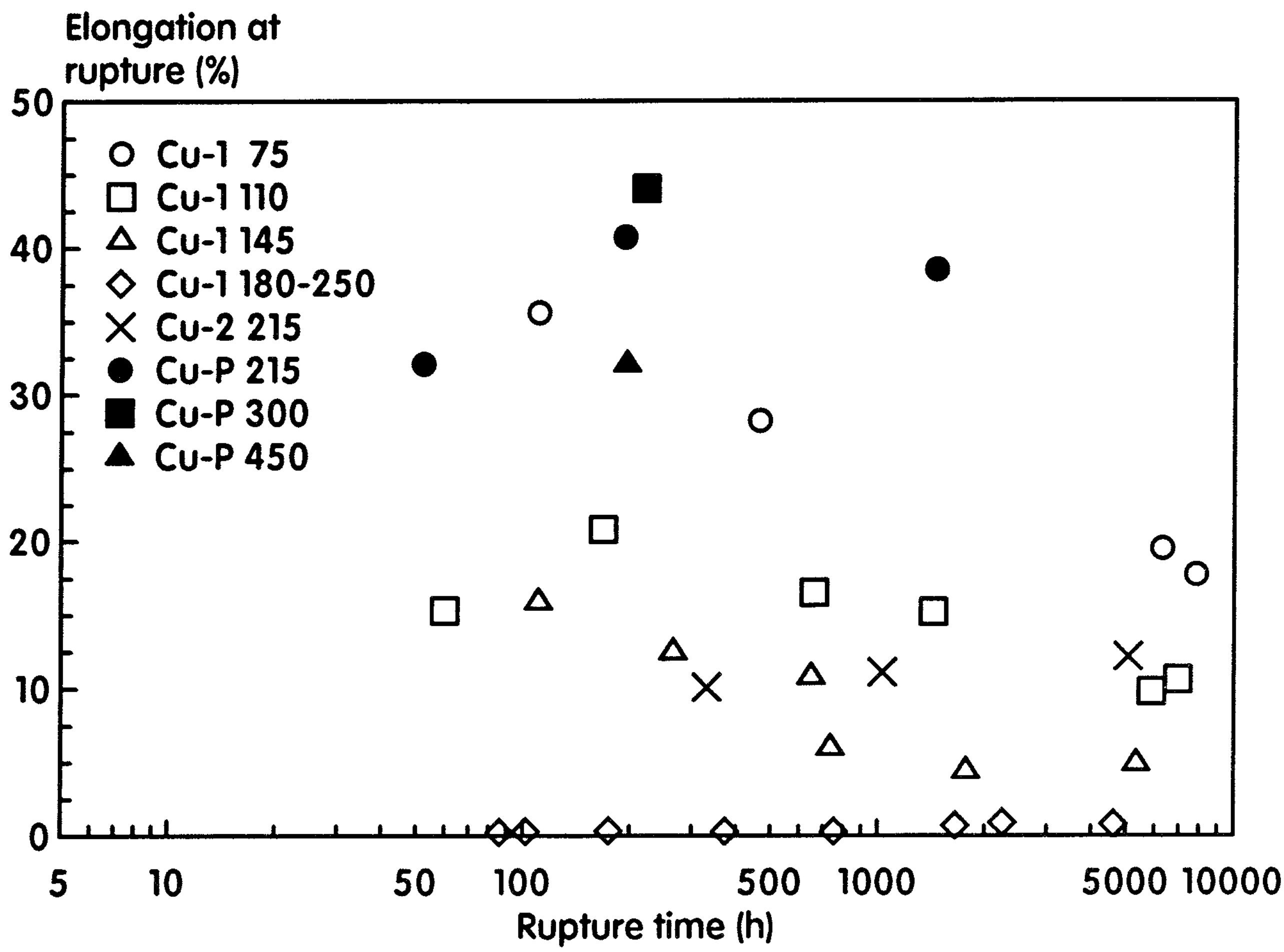


Figure 14-1. Elongation at rupture as a function of rupture time for two types of pure oxygen free copper (Cu-1 and Cu-2) and an oxygen free copper micro-alloyed with phosphorous (50 ppm).

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. The results of these tests showed that high elongation to fracture (30-40%) could be achieved at high stresses and low temperatures ($\leq 100^{o}C$). However, at temperatures above $145^{o}C$ and stresses below 100 MPa the elongation was less than 10% /14-1, 14-2/.

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 and at more realistic stresses.

The results of the creep tests, which were started in 1989, are summarized in Figure 14-1. As can be seen, creep rupture occurs at extremely low strains, less than 1%, for oxygen free copper (Cu-1) with an average grain size of 60 μm and a sulphur content of 10 ppm. A second batch of oxygen free copper Cu-2), with a somewhat smaller grain size (45 μm) and a lower sulphur content (6 ppm) was found to be more ductile. These difference in ductility have been attributed to a combination of sulphur content and grain size /14-3/.

Limited tests on phosphorous containing oxygen free copper and on Cu-0.15Ag indicated that these two alloys do not suffer from the same ductility problems as pure oxygen free copper and failure strains in the region of 30 to 50% were obtained though sulphur was detected at the cavity surfaces. The improvement in ductility could be due to a change in sulphur distribution or co-segregation of P and Ag and competition with S for grain boundary sites.

Creep rate measurements under realistic conditions has shown that creep strains in the range of 1% will be reached already after a few hundred years at a stress level of 50 MPa /14-7/. Thus, a very low creep ductility would considerably shorten the service life of the canister.

In view of the difficulty in controlling the sulphur content and maintaining a small grain size (<60 μm) over all areas of the nuclear waste canisters further work will be conducted on copper, micro-alloyed with e.g. phosphorous or magnesium.

14.1.2 Corrosion Studies

A simple reaction between copper and sulphate is thermodynamically impossible, but copper could react to form copper sulphide if an additional electron donor such as Fe(II) is available. It is a part of the general knowledge of chemistry that purely chemical reduction of sulphate to sulphide does not take place in dilute solutions at temperatures below $100^{o}C$. This fact is, however, poorly documented and it has been necessary to substantiate it by drawing on numerous individual findings from different areas of pure and applied chemistry /14-4/. In that study it was found that corrosion of copper by sulphate under final storage conditions and in the absence of sulphate reducing bacteria can be ruled out with a probability verging on certainty.

14.2 CARBON STEEL CANISTERS

The experimental work on localized corrosion of carbon steel was finalized already in 1990. The final analysis of the data, however, was completed and reported in 1991 /14-5/.

The statistical analysis of the pit growth kinetics showed that the best fit was achieved by assuming an unlimited distribution function rather that a limited distribution function. It was shown that the rate of pit propagation was slower than that suggested by earlier work and that the maximum pitting period is only a very small fraction of the canister service life.

14.3 COMPOSITE CANISTERS

Following the performance assessment of the advanced cold process canister, which was performed in 1990, an evaluation of production methods and costs was initiated /14-6/.

The study showed that several manufacturing routes are possible and in keeping with the current quality requirements for the canisters. The preferred method was hot rolling, bending and electron beam welding the seam on the cylindrical part of the canister. This route seems to best assure the small grain size which is preferable for the inspection of the final electron beam welded seam of the lid. This method also turned out to be the most economical one. Other methods considered involved hot extrusion of the cylindrical part of the canister.

15. BUFFER AND BACKFILL

15.1 CLAY ALTERATION

Two major studies concerning the influence of repository environment on canister-embedding smectitic clay were conducted in 1991:

1. Completion of the SKB/CEA joint experiment at Stripa with French Fo-Ca clay surrounding a central steel tube with a surface temperature of up to about 170°C.
2. Initiation of laboratory tests with water uptake under thermal gradients simulating canisters located in rock with salt groundwater.

The experiments at Stripa, which comprised two tests at the 360 m level, had blocks placed in 3 m deep boreholes with 0.2 m diameter, see Figure 15-1. One of the tests was terminated after about 6 months, while the other had a duration of slightly less than 4 years. A major observation was that water uptake in the clay took place according to the simple diffusion model that was worked out about 10 years ago. The temperature was around 170°C at the surface of the central steel heater, while it was about 90°C at the borehole periphery at midheight heater, 7 cm from the heater surface, see Figure 15-2.

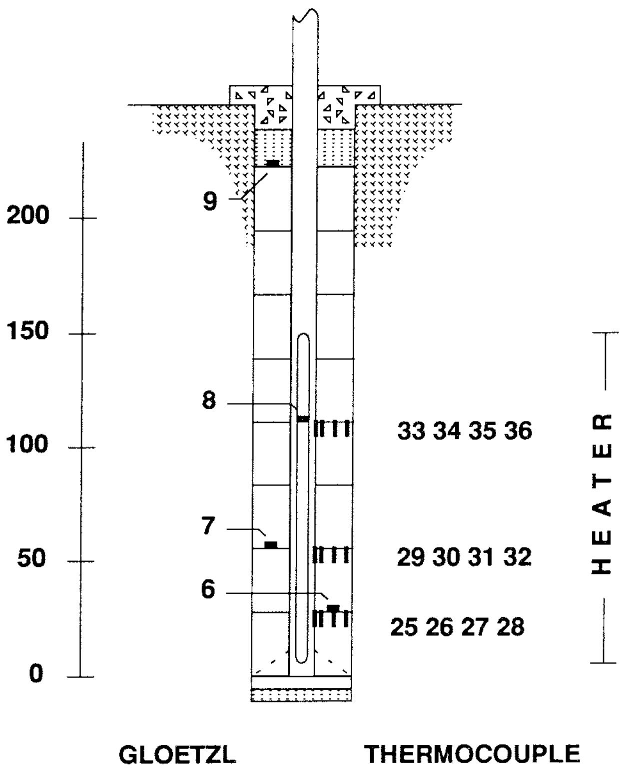


Figure 15-1. Test arrangement of the CEA/SKB heater test in Stripa. The left axis shows the distance from the bottom in cm. Numbers 6-9 represent the location of Gloetzl pressure cells. Numbers 25-36 denotes locations of thermocouples.

Another important finding was that the water uptake led to a high degree of saturation of the major part of the clay column after 6 months, whereafter drying of the innermost part started. This phenomenon, which was associated with the formation of a claystone annulus close to the steel heater, was interpreted as being caused by evaporation of interlamellar hydration water associated with heat-induced collapse and cementation, or by hydrogen gas production by shallow corrosion of the steel casing of the heater, see Figure 15-3. The latter explanation is favoured by the recorded corrosion depth, which corresponds to the same gas content as the one evaluated from the known water content and porosity of the clay.

The clay columns underwent very small mineralogical changes, except for the 1 cm thick claystone annulus that was formed in the 4 year experiment, where kaolinite, quartz and feldspars as well as pyrite and calcite were partly dissolved. Sulphates were precipitated in the hottest zone. Also amorphous silica emanating from the dissolved minerals was precipitated there during the cooling phase. This caused strong cementation and claystone formation, with complete loss of swelling capacity and a dramatic increase in hydraulic conductivity. Rather significant cementation took place also in the outermost, coldest part of the clay due to migration of aluminum from the hot zone.

The other types of experiments, i.e. laboratory testing of water uptake under a counteracting thermal gradient and with water of salinity corresponding to that of the oceans, led to accumulation of salt at the "wetting front", see Figure 15-4. This process is expected on theoretical grounds, applying the "evaporation/condensation" moisture cycling that is assumed to take place at the wetting of canister-embedding clay in rock with saline groundwater. The process was identified in the Buffer Mass Test experiments at Stripa but the salt accumulation in these tests was insignificant due to the very low salinity of the Stripa groundwater. If disposal takes place in a salt ground water regime the problem is assumed to be largely eliminated by using clay blocks with an initially high degree of water saturation.

Figure 15-2. Heater and surrounding Fo-Ca clay after central part of the heater has been sampled. In order to extract the clay body the overcoring technique was used. The pipes of the slot holes, made in the rock, make the recovered piece look like a Greek or Roman temple column.

Figure 15-3. *Part of clay closest to the heater from the 4 year test. The darker color of the clay in contact with the heater indicates the transformation into claystone. The thickness of this layer is 1 cm.*

15.2 PHYSICAL PROPERTIES OF MONTMORILLONITE-RICH CLAY SATURATED WITH SALT POREWATER

The fact that the salinity of groundwater increases with depth and may approach that of the oceans at one or a few kilometres depth requires that the physical properties of smectite buffers and backfills are known. Such a study was conducted in 1991 on montmorillonite-rich smectite clay. The following major conclusions were drawn.

- The swelling pressure of Na and Ca montmorillonite is practically unchanged by increasing the salinity from virtually zero to 3.5% NaCl and $CaCl_2$ respectively, in the temperature interval 20 - 130°C at a density of around 2.0 g/cm^3. At lower densities the swelling pressure decreases with increasing salt content for Na montmorillonite and with increasing temperature for Ca montmorillonite.
- The hydraulic conductivity is practically the same for previously heated samples of Na and Ca montmorillonites at a density of around 2.0 g/cm^3 and with salt content between zero and 3.5% in the pore water. At the density 1.8 g/cm^3 the hydraulic conductivity is up to five times higher for solutions with 3.5% salt compared to distilled water.

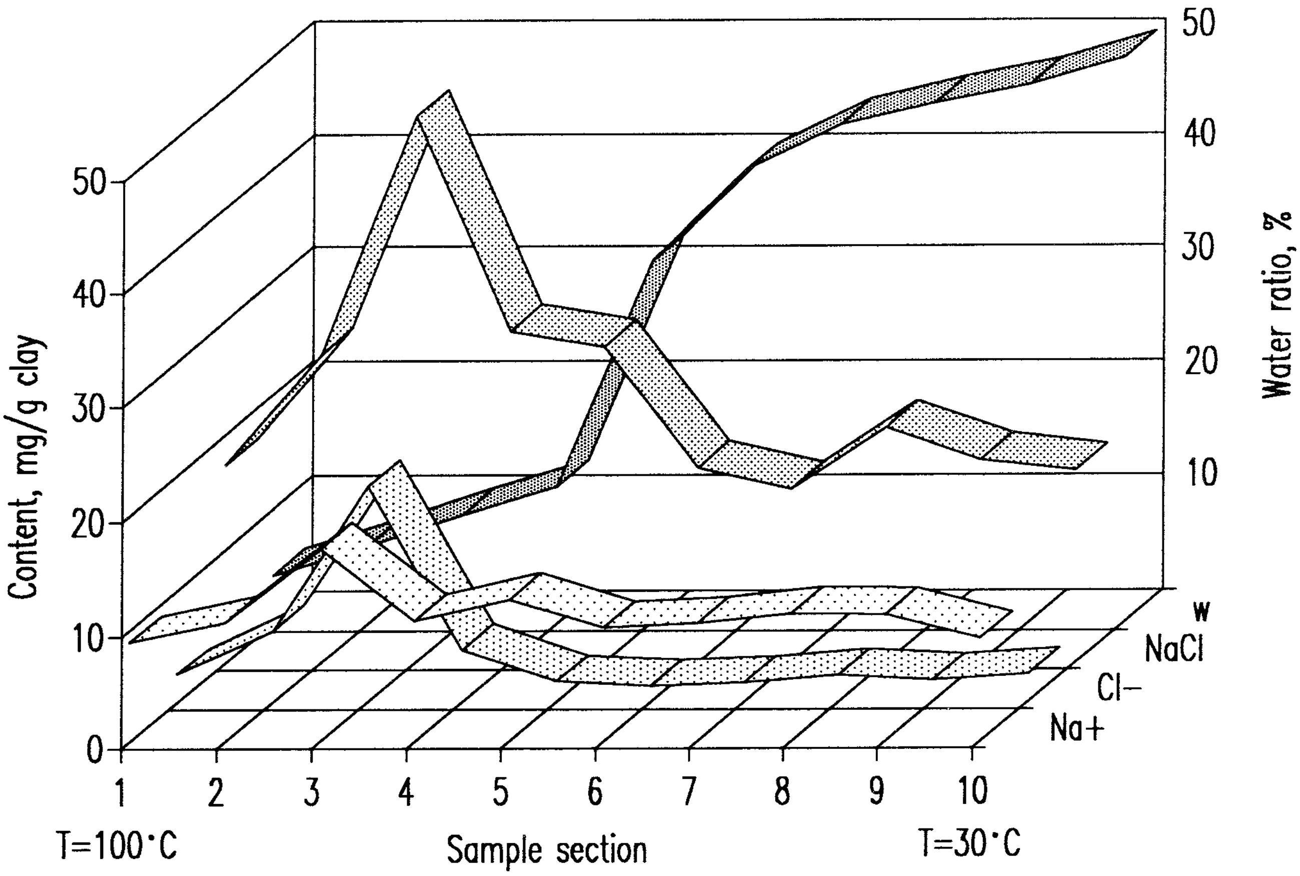


Figure 15-4. Salt accumulation as recorded in uni-axial saturation of dense Na bentonite with 3.5 % NaCl solution. The Na and Cl contents were determined by chemical analyses, and the NaCl content by electrical conductivity measurement. The clay water ratio curve (darkest line) shows high saturation at the water supply side ($T = 30^oC$) and a marked drop in section 4 – 5, and low values close to the hot end ($T = 100^oC$). Notice the salt accumulation peak at the wetting front.

15.3 CLAY CHARACTERIZATION

Characterization of commercial bentonite materials has continued using the standard procedure that has been developed for SKB clay materials. In 1991 beidellite- and saponite-rich smectites have been investigated. Both appear to give at least as high swelling pressures and low conductivities as montmorillonitic smectites. Beidellite, however, is not recommended for use as long-term seal because it is spontaneously and quickly converted to hydrous mica (illite) at any temperature, if potassium is present. The study indicates how to identify beidellite for avoiding buffers and backfills containing significant amounts of such material.

15.4 CLAY RHEOLOGY

Systematic laboratory work using triaxial testing under drained and undrained conditions has continued for development of complete material models, that can be used for predicting all thermally and stress-induced processes in Na or Ca clay buffers at any density and temperature within planned intervals. They include the expansion of the clay under wetting, settlement and upheaval of canisters, tectonically induced shear of the rock/clay/canister system, and extrusion of clay from the deposition holes into fractures etc.

ABAQUS is the tool used for development of models and for calculation of all the stress/strain/time processes at different temperatures in the operative lifetime of the buffers. The modelling is verified by field and laboratory work, of which the large-scale canister settlement test at Stripa is a major experiment that is presently being evaluated.

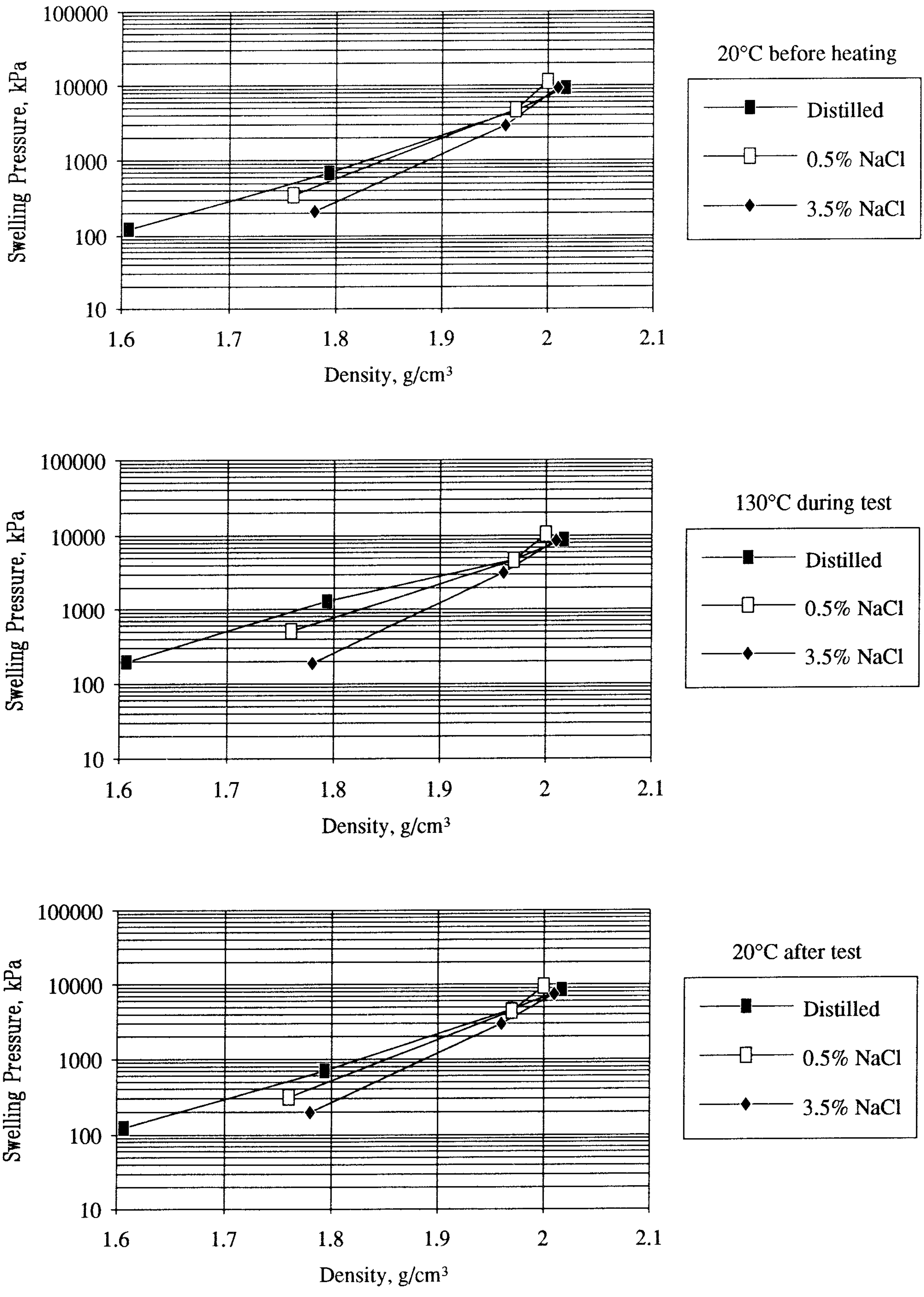


Figure 15-5. *Swelling pressure of Na montmorillonite clay before (upper), during (middle) and after (bottom) heating.*

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, i.e. groundwater flow modelling and transport modelling, water chemistry as well as geochemistry. Interdisciplinary approaches are used in several SKB activities as:

- the Äspö Hard Rock Laboratory (HRL),
- the Comparison of Alternative Repository Designs (PASS),
- the Safety Assessment Programme, e.g. SKB 91,
- the Siting of Final Repository.

During 1991 the geoscience programme has involved the following tasks:

- Groundwater Movements in the Rock.
- Bedrock Stability.
- Post-Glacial Studies in the Lansjärv Area in Northern Sweden.
- Repository Siting – Geological Overviews.
- Development of Instruments and Methods.

16.2 GROUNDWATER MOVEMENTS IN THE ROCK

An understanding of groundwater movements is essential for a 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 is of importance for assessment of radionuclide transport of non-sorbing and sorbing species is the transport time of ground water from repository depth to the biosphere. The flow-rate of water in the bedrock is dependent on porosity, conductivity, connectivity and the driving forces. The importance of small density contrast for the overall groundwater flow distribution has been recognized.

The conceptualization of how groundwater flows 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.

16.2.1 Two Phase Flow in the Skin Zone of a Rock Drift

From several investigations dealing with the behaviour of the flow gradients surrounding a bedrock tunnel, it seems that the hydraulic conductivities are decreased nearby the walls. The results were, at first consideration, surprising as due to the excavation damages one would expect increasing permeabilities. However, the phenomenon nowadays is well-known and attempts have been made to find the explanation according to mechanical stress field alteration as well as to precipitations within the fractures. Furthermore there may at least be a third explanation of the conductivity lowering phenomena, e.g. the phase limit between air, or other gases, and water in the fractures just outside the tunnel walls. The phase limit is created by capillary effects and it has been decided to further investigate these nonlinear processes in order to quantitatively and qualitatively better predict tunnel water inflow /16-1/.

16.2.2 Red-coloration of Wall Rock Adjacent to Fractures and Fracture Zones – Indirect Sign of Flow Path?

Groundwater modelling by means of discrete fracture networks are increasingly common. Accordingly better conceptual models are needed for describing the "true" water ways in the bedrock. Thus one looks for different indirect signs of water-bearing fractures in order to create a more reliable model in the context of water-bearing fracture connectivity.

Red staining or colouring are common in the surroundings of fractures in crystalline rocks. The reason for the colour alteration is usually explained as a result of hydrothermal conditions.

However, the explanation may be revised as recent ideas say that identical phenomena may occur at low pressures and temperatures. In such a case the red colour alteration could be of interest for a better description of present possible waterways. Thus the scientific conditions for this type of indirect hydraulic signs have been investigated /16-2/.

16.2.3 Stochastic Continuum – Sensitivity Studies on a Synthetic Data Set

The transport of ground water in fractured rock is to a large extent controlled by the spatial variability in the fluid advection which are due to heterogeneities in the hydraulic properties of the studied rock formation. This variability is largely unknown, and thus geohydraulic modelling is associated with undercainty.

This uncertainty can be accounted for by using stochastic simulation, and can possibly be reduced further by incorporating all available information, quantitative and qualitative.

To study the effects of incorporating qualitative (soft data) information, the Non-parametric and Parametric stochastic continuum approaches were applied to a large realistic synthetic hydraulic conductivity field (hard data) generated in two dimensions /16-31/. From this reference domain, a number of data points were selected, in a designed or random fashion, to form a sample data set. The points were classified as either hard or soft information. These data correspond to our measured hydraulic conductivity and supporting geological/geophysical information from the field.

Based on established experimental variograms and the conditioning data, 100 realizations each of the studied domain were generated through a conditioned parametric method as well as a conditioned non-parametric method (with and without soft information). The flow field was calculated for each realization using a linear hydraulic gradient. A number of particles were released at the upstream end of the domain and particle breakthrough and distribution along the discharge boundary was evaluated.

The specific conclusions of the study are that conditioning on soft data reduces the uncertainty of solute arrival time and conditioning on soft data indicates an improvement in characterizing channelling effects, although the latter statement requires further study.

16.2.4 Development of Coupled Modelling – the DECOVALEX Project

The bedrock response to disposal of spent nuclear fuel is a complex phenomenon related to the interaction between thermal, hydrological, mechanical and chemical processes. A multi-disciplinary interactive and co-operative research effort in the field of thermo-hydro-mechanical (THM) processes has recently been initialized by the Swedish Nuclear Power Inspectorate (SKI). SKB is a funding party among nine other international organizations. The overall goal for the so called DECOVALEX-project is to increase the understanding of various THM-processes of importance for radionuclide release and transport from a repository to the biosphere. Furthermore the objective is to elaborate how the THM-processes could be described by mathematical models /16-4/.

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 displacements in a repository as consequences of earth-quakes, glaciation and land uplifts,
- process, evaluate and increase knowledge concerning the geodynamic processes in the Baltic Shield.

16.3.1 Stressfield Variation in the Baltic Shield

The brittle tectonic history of the Baltic shield is essential for conceptualization of the structure of the crystalline bedrock. The paleo-stressfield may be evaluated by means of dyke swarms, coated fractures, mineral infillings, etc. and then related to certain time periods. Furthermore, different kinds of isotope data may indicate the vertical load in terms of sedimentary overlaying strata. Our country has also been subject to successive glaciation loadings. Hypothetically, the Baltic shield has been influenced by forces in all directions and there is probably no evidence for new fracturing, only reactivation, during the present tectonic regime. However, this statement has to be further supported. An initial investigation phase on this subject has just commenced and will be reported in 1992.

16.3.2 The Protogine Zone

It is assumed that the bedrock of south-eastern Sweden belongs to the most stable areas of the country. This south-eastern megablock is delimited to the west by the Protogine zone consisting of a system of deformation zones where there is a variety of evidences for movements during the last 1000 million years. Geological maps of Sweden describe the Protogine zone as an approximately N-S tending zone of strong schistosity and a boundary between two bedrock provinces of different age, see Figure 16-1. However, from a tectonic point of view the lithological definition of the zone seems to be simplified. On behalf of SKB the geology and mobility during the last 1500 million years has been analyzed /16-5/.

The Protogine zone is a complex geological and geophysical feature with a long tectonic history. NNW, N-S and NNE tending deformation zones occur as well as magmatic intrusions, metamorphic breaks, hydrothermal mineralization and geophysical anomalies. E-W tension is

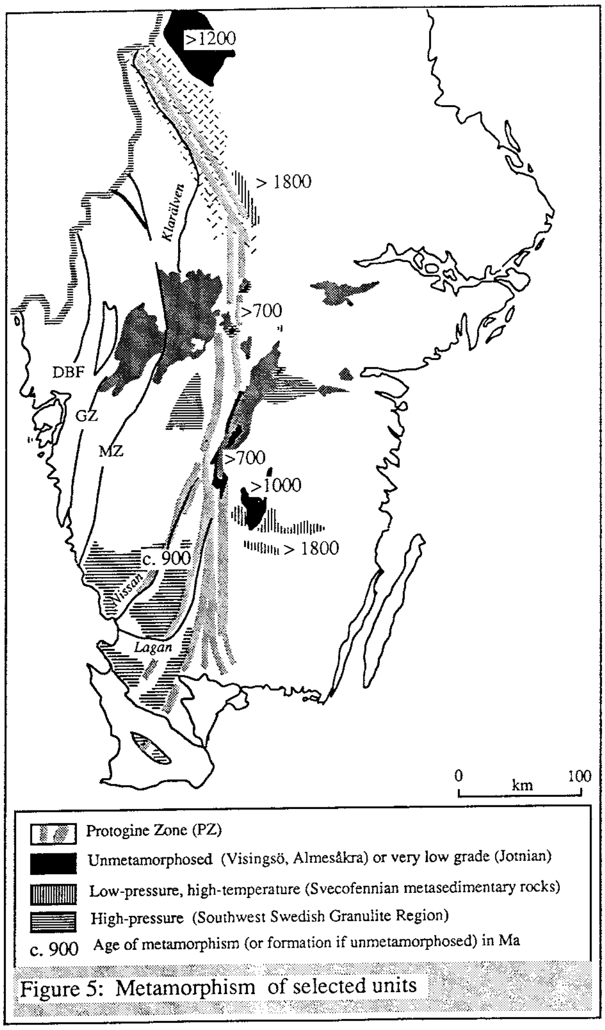


Figure 16-1. *Metamorphism of selected units which surround the Protogine Zone (from /16-5/).*

indicated by three generations (1500, 1200 and 900 million years ago) of mafic dyke swarms. Syenitic and granitic rocks intruded at the 1200 million years event. The conspicuous foliation was probably formed during the uplift of the south-western gneiss complex approximately 915 million years ago. The continued deformation has been more shallow and thus under brittle conditions. The zone has most probably been affected by the Caledonian, Hercynian and Alpine orogenies. Local faulting, i.e. reactivation, may has occurred during the late deglaciations.

16.3.3 Bedrock Stability in South-eastern Sweden – Evidence from Fracturing in the Ordovician Limestone of Northern Öland

A detailed study of fracturing in the Ordovician limestones exposed along the west coast of the island of Öland has been carried out /16-6/. Because the age of deformation is clearly post-Ordovician the objectives of the study has been to analyze the magnitude and significance of fracturing in the underlying Precambrian crystalline basement on the adjacent mainland.

Northernmost Öland shows a somewhat altered fracture pattern compared to the rest of the investigated area. However, south of the Byxelkrok bay the fracture pattern shows rather constant characteristics dominated by a NW tending set which often is coated by calcite. A second dominant fracture set has a more variable NNE-ENE trend. 90% of the fractures show no lateral displacement whatsoever. Less than 10% of the fractures in both sets show fossil displacement all shorter than a maximum movement of 5 cm.

Geophysical seismic recordings are available from former offshore oil and gas prospecting activities. In order to broaden the tectonic knowledge within south-eastern Sweden these recordings from the Hanö bay, nearby the county of Blekinge, are now being reinterpreted.

16.3.4 Isostatic Uplift Using the Lake Tilting Method

The glacio-isostatic uplift is of interest not only because of future bedrock movements but also from the hydrogeological boundary condition point of view. During 1991 glacio-isostatic uplift studies were commenced.

A nonuniform rebound results in differential upheaval for different parts of an area. If a lake outlet is situated in an area with the greatest rate of uplift, then the lake will be continuously transgressed. Previous lake levels can be estimated by dating transgressed peat at different depths in such a lake and in turn the uplift may be determined empirically /16-7/.

Reconnaissance activities have so far been done and some possible lakes for investigations have been chosen in different parts of Sweden. The study will be reported in late 1992 by the Swedish Geological Survey (SGU).

16.3.5 Shore Line Displacements in the South-western Part of the County of Värmland

In the beginning of this century the Swedish geologist Lennart von Post made detailed investigations of the Vänern lake basin. He also levelled previous shore lines within the basin. The land uplift was evaluated and isolines of the rebound was presented in maps. The unevenness in some isolines was explained as a result of neotectonic movements according to the deglaciation.

A reinterpretation is now ongoing by means of modern methodology and measuring techniques. Several lakes situated below the marine limit (MG) are used for the study. The isolation level of the lakes will be evaluated by diatomic analysis, and mineral magnetic susceptibility. C-14 dating will also be made.

The localities of the lakes are chosen in a manner which will make it possible to produce revised shore line displacement curves. Neo-tectonic movements or not will be interpreted from the new displacement curves.

This project is carried out at the Department of Quaternary Research, University of Stockholm and sponsored by

SKB and by the Swedish Nuclear Power Inspectorate in collaboration.

16.3.6 Modelling of Future Glaciations

In 1990 SKB and TVO of Finland elaborated an assumed future ice age scenario in order to describe related phenomena for safety assessment studies. Based on the scenario and related assumptions some scoping calculations on the consequences of permafrost on groundwater flow were carried out /16-8/ /16-9/. SKB has continued the modelling activities on glacial events. The Department of Geology and Geophysics, University of Edinburgh, will produce a time-dependent model of future glaciations in Sweden. The intention is to predict glacial loadings and meltwater discharges into the subsurface over the next 100 000 years. A prediction of time dependent permafrost depth, during the same time period, will also be involved in the study. The model will be calibrated to a best estimate of the Weichselian climate changes and to a till thickness distribution along an approximate ice flowline.

16.3.7 Rock Mass Response to Glaciation, a Sensitivity Study

During 1990 the response of the rock mass in the Finnsjön area was examined according to the process of glaciation, deglaciation, isostatic movement and ice lake water pressure using the distinct element computer code UDEC, Itasca. A supplementary study has now investigated the sensitivity of the Finnsjön rock response to variations in the in-situ stress, state of stress and the strength properties of the rock fractures /16-10/. In total 18 model simulations has been done. The sensitivity study was made to explore the importance of the uncertainty in the extrapolation of stresses to 2000 m depth was uncertain and that the fracture strength parameters were estimated and not based on actual lab or field data.

Three phases of ice loading has been simulated. For each loading, two simulations were conducted: one with and one without an ice lake (and the accompanying increased pore water pressure). The various loading phases included: consolidation of the in-situ stresses, 3 km of ice loading, 1 km of ice loading, ice retreat forming a thinning of the ice sheet from 0 to 1 km over the area of interest and finally no surface loading.

The results from the stress measurements were statistically analyzed to provide three possible linear depth variations for input to the UDEC code.

For each stress state variation, the minimum fracture strength was chosen to not fail during consolidation of in-situ stress. The maximum fracture strength was chosen such that the entire model was in an elastic condition during the largest loading phase.

Among the results, the following can be mentioned:

- The increased pore pressure reduced the shear deformation in a slightly dipping fault zone (the so called zone 2) independently of stress state or zone strength which made the major stress anomalies in the model diminish.
- The smallest stress state gave the most dramatic reaction to increased pore pressure. Most of the steeply dipping single zones fail through the whole model and maximum shear displacement is one order of magnitude larger than in general, i.e. 0.5 m instead of 0.05 m. The stresses are reoriented and locally, high stress concentrations are in connection with failed zones.
- The least reaction from the overload and the pore pressure can be seen in the analysis with the largest in-situ stress.
- Except from the case with the smallest stress, negligible effects on the stress distribution can be seen between the different strength cases.

16.3.8 Direct Fault Dating

During the past few years new dating techniques and new methods of investigating geological structures have implied a possibility of direct dating of faults. SKB has initialized a project on this subject. During 1991 the sampling activities were undertaken within a comparative study on different dating techniques. Specimens from a fault in the access ramp to the Äspö Hard Rock Laboratory are to be analyzed. Petrographic, Palaeomagnetic, Electron Spin Resistance (ESR) and Isotope techniques will be employed in attempts to assess the age of the most recent movements on the fault. The study will be reported during 1992.

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

In 1989 the results from an interdisciplinary study of the supposed postglacial faults in the Lansjärv area were presented /16-11/. In the summer 1990 complementary investigations were concentrated to one of the faults at the Molberget, where a approx. 4 metre high vertical bedrock scarp had been localized. In order to get a more detailed knowledge of the fault at this locality three trenches were excavated across the scarp down to the bedrock. The exact locations of the trenches were based on seismic refraction measurements. After mapping of the bedrock in the trenches three cored boreholes were drilled through the fault scarps. Samples from the bedrock and the drillcores were collected for a mineralogical study with the primary purpose to provide information on the tectonic history of the fault zone.

In June 1991 a group of international and Swedish experts was invited by SKB to participate in discussions and a field excursion to the Lansjärv area. According to the summarizing comments from the experts the postglacial faults are mainly reactivated older fracture zones, but the occurrence of new fracturing to some extent cannot be excluded.

The causes of the postglacial movements are probably a combination of rapid changes in vertical load, with possible large earthquakes associated with deglaciation and horizontal crustal shortening related to continental plate boundary forces. Today, there is no clear evidence that any of the postglacial faults are still active but displacement measurements, using a Sliding Micrometer, have been carried out during 1991 in three boreholes of Molberget. The proceedings from the afore-mentioned excursion as well as the displacement measurements will be published during 1992.

16.5 DEVELOPMENT OF INSTRUMENTS AND METHODS

Reflection seismics

During initial stages of a site characterization program most of the information is collected from surface mapping and geophysical measurements and a limited number of boreholes. Vertical and subvertical structures can normally be identified while horizontal and subhorizontal structures by experience are more difficult to detect, in special in crystalline rock. The reflection seismic method, which by tradition is commonly used and well proven in sedimentary rock for detecting horizontal and slightly dipping structures, is less useful in crystalline rock formations. A number of measurements for rock characterization in Sweden, with use of explosives as a source, have been more or less impossible to evaluate with diverging results from different data processing concepts.

Large scale seismic profiles with deep penetrations are often carried out with heavy mobile vibrators as a source. In order to study whether the vibroseismic method can be applied for site characterizations in crystalline rock, a small portable vibrator source was used in a seismic reflection survey at Äspö. The measurements were conducted in 1991, processing and evaluation is ongoing and the results will be reported in 1992.

Tunnel radar and tunnel seismics

In the Äspö tunnel, a method testing program was carried out aiming at examining the usefulness of tunnel radar and tunnel seismics for characterizing the rock around the tunnel and ahead of the tunnel front. The measurement configuration was similar to Vertical Seismics Profiling (VSP) and Vertical Radar Profiling (VRP) respectively, however, carried out in a tunnel instead of in a borehole. Also reflection measurements were carried out, predominantly for surveying the volume around the tunnel. For radar measurements, the recently developed tunnel radar antennas were used /16-11/. Seismic measurements were carried out with use of explosives and hammer as source. Results from the method tests showed that for the Äspö rock mass good agreement was found between strongest radar and seismic reflectors and "significant" features in the tunnel /16-12/. Due to the low resistivity of the Äspö rock formation, mainly depending on the saline pore water, the range of the radar measurements was only approximately 20 m, while the range of the seismics was approximately 130 m.

Point dilution probe

Dilution measurements in boreholes have for some years been used by SKB for determination of groundwater flow. A tracer is introduced to a borehole section and the dilution of the tracer, caused by groundwater flow across the section, is recorded. One version of the method was used in the Äspö project where the dilution measuring technique was inbuilt in the multipacker system for groundwater monitoring /16-13/. Another version is the point dilution technique where all components for tracer injection and dilution recording are assembled in a probe with a straddle packer. Measurements can then be performed with greater precision than with the first described version. A prototype of the point dilution probe for use in shallow and larger diameter holes was developed for some eight years. During 1991, a new point dilution probe for 56 mm boreholes and depth capacity of 1 000 – 1 500 m is under development, see Figure 16-2.

Reverse circulation core drilling

A full scale field test of core drilling with reverse circulation of the drilling water has been conducted. Cooling of the drill-bit is maintained by means of pumping formation water from fractures penetrating the borehole up through the drill-string. As no water will be pressed out through the drill-bit no contamination of the groundwater chemistry or introduction of drill-cuttings into the fractures will occur.

Air-lift pumping of the drill-string was made by using double pipes down to 100 m. Therefore reverse circulation drilling could not start above that depth. During the field test the design of drill-pipes, core barrels, drillbits etc. was gradually modified in order to increase the rate of pumping the mixture of water and drill cuttings. Especially during rotation the transport of drill cuttings was a problem which had to be solved.

Approximately 200 m of core drilling with reverse circulation was carried out down to 300 m depth. The field test showed that the technique is possible to use. However, the drilling technique is more time-consuming than conventional drilling and will therefore only be attractive for special purposes, as when no contamination of the borehole is accepted.

A probable, secondary effect of reverse circulation drilling technique may be that the core entrance into the core barrel will be somewhat helped by the reversed water flow, which may result in easier drilling in "bad rock", i.e. longer runs between uptakes.

Äspö Hydro Monitoring System

Groundwater monitoring is an essential part of the Äspö Project, during pre-investigation as well as during construction phase. A monitoring program was set-up during the pre-investigations as a part of the characterization work. The system has been in operation during the construction of the tunnel to observe groundwater responses for the purpose of validating predictions, see section 19.3.

The borehole installations, i.e. packer system, transducers, dataloggers, etc., are in principle the same as during the pre-investigation phase /16-13/. The major improvement of the monitoring system is the establishment of a central data acquisition system, to which most of the boreholes have been hooked up. Moreover, additional monitoring points will successively be connected to the system as the tunnel construction will progress, i.e. inflow measurements to the tunnel, consumption water to the tunnel and drainage water out from the tunnel, moisture transport in the ventilation air, etc. The frame of the data acquisition system is a computer network with a central host station at the site office which communicates with a number of measuring stations, which in turn communicates with data loggers distributed at the surface and in the tunnel, see Figure 16-3.

By means of this on-line monitoring system, information from the measuring points are accessible from the site office at any time. Moreover, the SKB computer network makes operation of the Hydro Monitoring System possible from the SKB head office and appointed SKB contractors in Sweden. The system enables flexible measuring frequencies, advanced data processing and presentation, calibration facilities with indication of quality level of the presented data and data storage redundancy at several levels of the system.

As during the pre-investigation phase, the borehole installations besides monitoring of piezometric levels also enables groundwater sampling, groundwater flow measurements across borehole sections and fluid conductivity observations.

Videoimagescope for borehole inspections

A videoimagescope has been purchased for inspection of short boreholes drilled from the tunnel of the Äspö Project. The instrument gives high resolution, colour images of the walls of up to 22 m long boreholes. The method has been used to detect blasting-induced cracks. In special, it is proven as effective to locate grouting materials in fractures, in order to study the penetration of pre-grouting in the tunnel. Also water inflows into boreholes (channelling etc.) can be effectively characterized with the method, provided that the borehole is not filled with water, see Figure 16-4.

Pre-investigation methodology report

A summarizing report field investigation methodology and instruments used during the pre-investigation phase of the Äspö HRL was released in the end of 1991 /16-23/. The report covers surface as well as borehole investigation techniques.

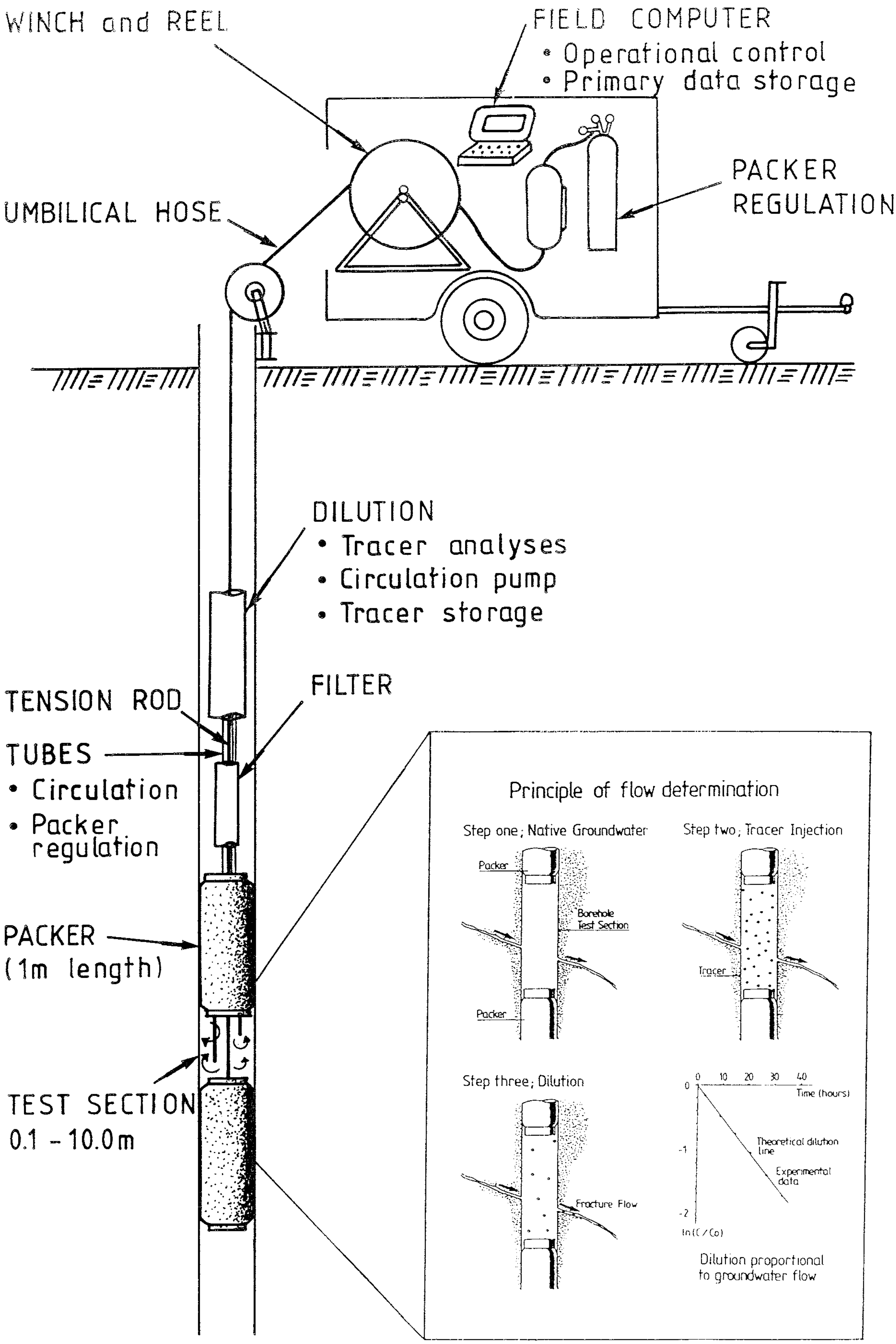


Figure 16-2. *Illustration of groundwater flow determination with the point dilution probe.*

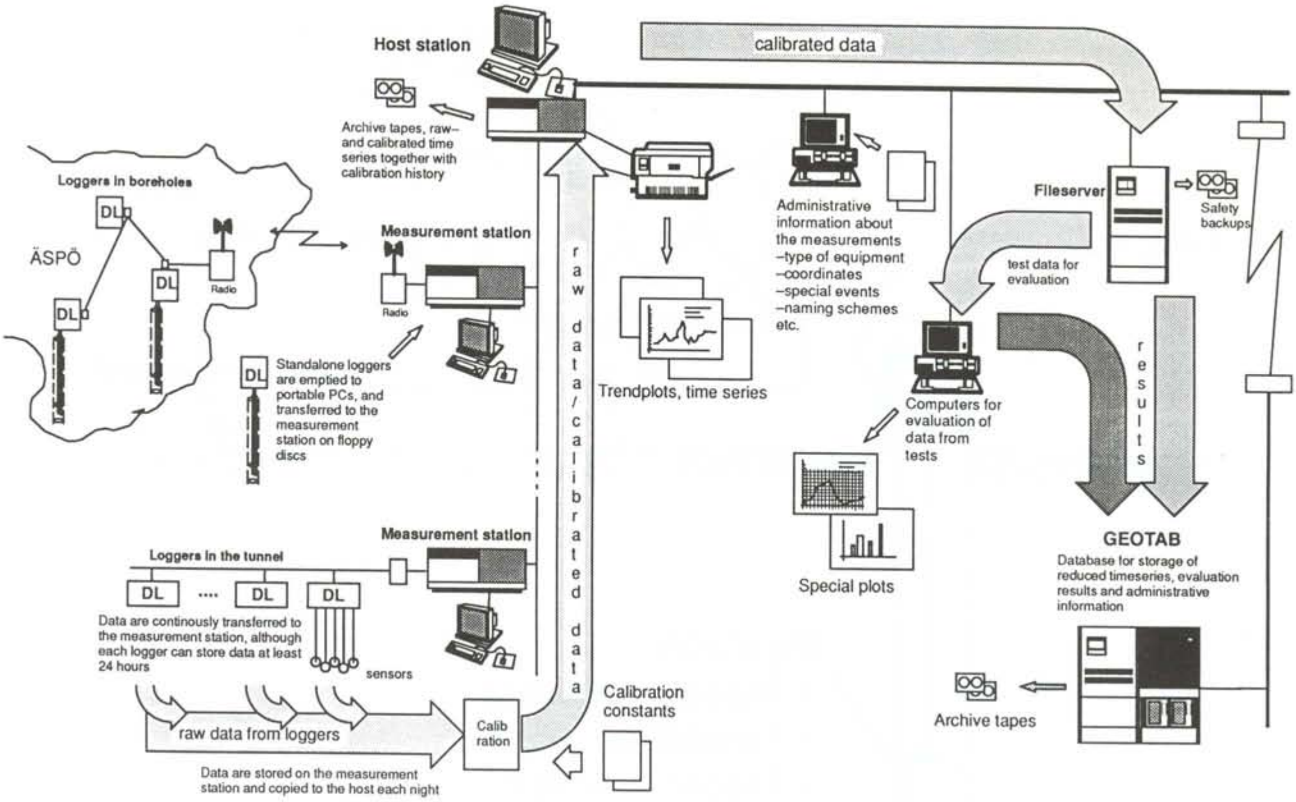
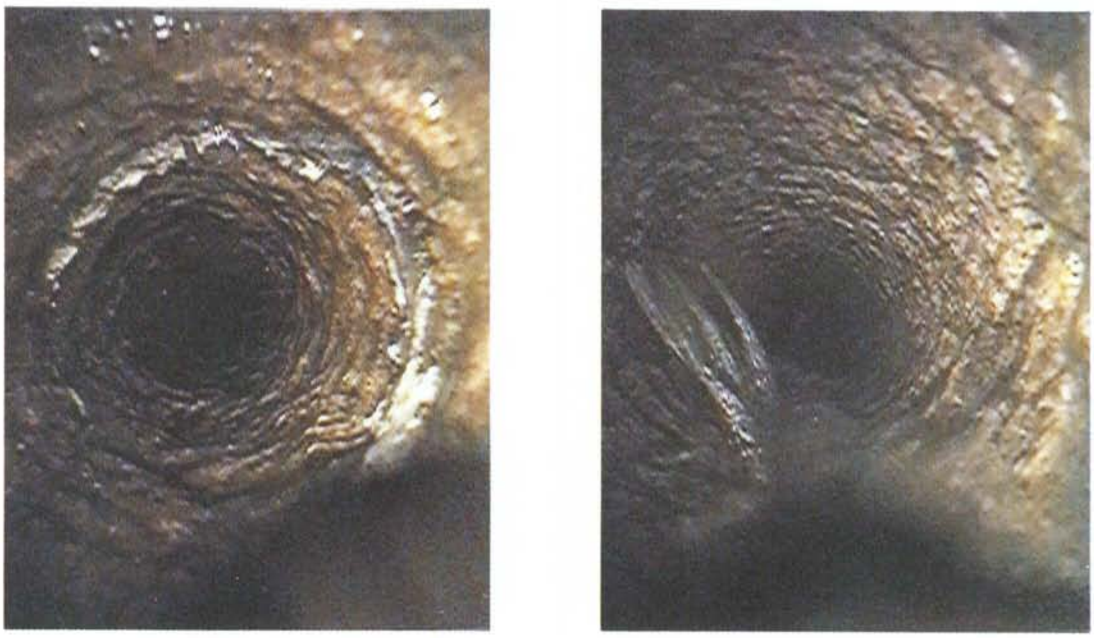


Figure 16-3. The Äspö Hydro Monitoring System (HMS).



a b

Figure 16-4. *Hardcopies from videoimagescope survey in boreholes, showing;*
a) grouting materials in a fracture at 7.2 m depth in a borehole,
b) point leakage of water (channelling) from a fracture into a borehole, at 15.2 m depth.

17. CHEMISTRY

17.1 GEOCHEMISTRY

17.1.1 General

The geochemical investigations have been concentrated to the Äspö HRL site. The groundwater sampling has been made in the entrance tunnel mainly from probing holes. The results of the analyses show that saline water dominates as soon as the tunnel has reached beyond a depth of about 20 metres. At tunnel sections overlain by the sea the salinity is higher than at the sections where the tunnel goes under land /17-1/.

17.1.2 Groundwater Chemistry

The pre-investigation phase at Äspö was ended in 1991 by finishing the conceptual modelling, the numerical groundwater flow calculations and the predictions set up for the construction phase /17-2, 17-3/.

For evaluation of the chemical situation of the groundwater the salinity of the water has been the most useful parameter. The salinity of the groundwater at Äspö increases linearly by depth giving the water a chloride concentration of approximately 6 000 mg/l at a depth of 500 m. This linear behaviour is, however, not strict. There are borehole sections where the salinity is either higher or lower than the value of the linear relationship. These borehole sections are located in water conducting fracture zones and the higher or lower salinity is thought to be due to discharge or recharge of groundwater.

The isotopic signature (oxygen-18) suggests that the water below a depth of 400 to 600 metres is very stagnant and that it has not been involved in the surface water circulation since the latest glaciation. In the upper part of the rock mass meteoric water, glacial melt water and sea water have been mixed. Presently there is a wash-out of the saline water by the precipitating rainwater, a process which started when Äspö rose above the sea level some 3 000 years ago.

17.1.3 Large Scale Redox Experiment

At the 500 m section the Äspö tunnel penetrates a fracture zone which was indicated as a depression in the ground surface. This zone was selected for studying how oxidizing surface water is reaching the tunnel due to the increased flow caused by the drainage of the tunnel.

The goal of the large scale redox experiment is to define whether or not the increased water circulation caused by the tunnel construction might result in oxidizing pathways from a repository at several hundred metres depth up to surface.

Such pathways could contribute to a fast transport of radionuclides from a leaking waste canister.

The kinetics for the reactions between the oxidizing groundwater and the reducing (fracture) minerals in the rock is largely unknown. Therefore it is necessary to find out both how long time it takes for the oxidizing water to enter the tunnel and how much have the minerals reacted with the oxygen in the water. At the tunnel section 513 m a short side tunnel was blasted and three core holes were drilled into the fracture zone, see Figure 17-1. Groundwater samples were collected and the Eh of the water was monitored in order to see the break through of the oxidizing front.

Before the tunnel reached the fracture zone, one borehole was drilled through it. This was sampled immedi-

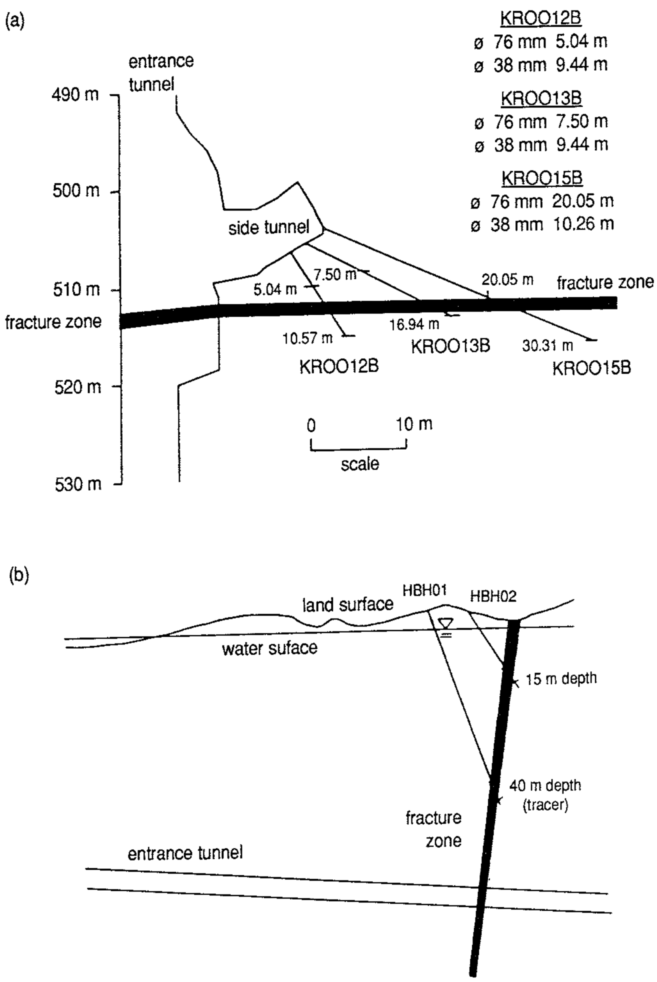


__Figure 17-1.__ (a) Plan view of fracture zone under study. The dimensions of the boreholes are given in the upper right corner of the figure. (b) Section view of fracture zone and entrance tunnel (not to scale).

ately indicating that the water was stagnant with a salinity of 5 000 mg/l, which is almost twice as high as in the surrounding Baltic Sea. The iron concentration of the water was fairly high, 0.54 mg/l. Two weeks after the tunnel had reached the fracture zone the salinity and the iron content of the inflowing water had decreased to 950 and 0.02 mg/l respectively.

The breakthrough of the surface water and the oxygen was calculated based on the estimated water inflow to the tunnel but before the freshwater reached the tunnel /17-4/. Depending on the concept for the flow and for the reactive components the expected breakthrough for the surface water can vary from six hours up to 18 days, whereas the breakthrough of the oxygen can with the same concepts vary from 36 hours to five years.

The drillcores have been carefully mapped. Especially the redox buffering minerals have been quantified both in the fracture coatings and in the bulk rock. The same boreholes will be overcored after oxygen break through and the mapping repeated.

Water samples are regularly collected and analyzed for main constituents and redox sensitive elements. Isotopic analyses are also made in order to facilitate the interpretation of the complex flow situation. The results are gathered and will be presented in a common report. A scientific coordinator has been appointed to the project.

The results of the analyses show that the water contains large portions of recently precipitated surface water. Tritium and organic carbon concentrations are high. There are also proportions of deep water as the chloride concentration remains at levels of 1 000 to 3 000 mg/l.

17.1.4 Redox Capacity

In cooperation with the Finnish power company TVO the available redox capacity in crystalline rock has been investigated. The experimental work was made at the Technical Research Center of Finland (VTT) /17-5/. Fracture coatings, ruptured drillcores and polished rock pieces were used. In order to accelerate the reactions between the oxygen and the reducing minerals a pressure of 100 bar pure oxygen was used. Thus the duration of the tests of two month correspond to a reaction time of almost 100 years in nature.

The results show that the reaction has gone deep into the rock matrix. For the natural fractures the reaction depth was up to 25 mm and about 1 mm in the ruptured rock samples. The polished samples could not be evaluated since the polishing procedure in itself seemed to oxidize the surface minerals in an unpredictable way.

From the decrease in Fe(II)/Fe(tot) ratio the amount of oxidized iron was calculated for that particular sample. The resulting amount, varied from 18 to 620 mol/m^3. This is a measure of the available redox capacity.

17.1.5 Fracture Minerals

The distribution of uranium and rare-earth elements (REE) between fracture minerals and groundwater has been investigated on drillcores and groundwater samples from Äspö /17-6/. The same kind of investigations were earlier made on samples from Klipperås /17-7/. In Table 17-1 the distribution factors are listed together with laboratory values selected to describe sorption within the SKB-91 safety assessment /17-8/.

The laboratory data which are used in SKB 91, are considered to be conservative. It is, however, obvious from the data in the table that some are in good agreement with those obtained in-situ from Äspö. The large difference between the Äspö and Klipperås data are likely due to the difference in salinity. In Klipperås all groundwater is fresh, in Äspö it is saline.

17.1.6 Acidification of the Soil Caused by Acid Rain

The effect of acid rain on the bedrock has been investigated /17-9/. The acidification results from the combustion of fossile fuels. With the present use these resources will be depleted within 300 years. The effects of the acidification will, however, remain for a longer time period. In case the exhaustion control is moderate or strong, the effect of the acidification will disappear within the next 500 years. In case no emission control is made the vegetation disappears and the erosion of the soil and rock will reach a depth of about 150 m within the next 60 000 years, i.e. until next major ice period.

17.2 RADIONUCLIDE CHEMISTRY

17.2.1 Solubility and Speciation

The laboratory measurements of technetium dioxide solubility in neutral and alkaline carbonate solutions have been evaluated and were presented at the Migration 91 conference in Jerez de la Frontera, Spain /17-10/. The measured equilibrium constants are presented in Table 17-2. In normal carbonate containing groundwaters and under reducing conditions the solubility is dependent on pH. At lower values than pH 7.5 the solubility is less than 10^{-8} M and $TcO(OH)_2$ is the dominating species in solution. Above pH 8 the solubility increases and $Tc(OH)_3CO_3^-$ dominates.

The solvent extraction technique has been used to determine the constants for hydrolysis of thorium /17-11/. The measured hydrolysis constants are presented in Table 17-3. Comparisons have been made with earlier published results. It was concluded that constants for tri- and tetra-

Table 17-1. The distribution factor (K_d) for uranium and rare-earth elements calculated from concentrations in groundwater and fracture minerals compared to values used for the SKB 91 safety analyses. The distribution factor is m^3/kg. Values in parentesis are estimates.

Element	Distribution factors (K_d) Äspö	Klipperås	SKB 91
Sr	0.002 – 0.17	1 – 4	0.003
Rb	0.4 – 10	22 – 160	(0.003)
Ba	1 – 3	5 – 30	(0.003)
Cs	0.02 – 22	19 – 6030	0.03
Eu	48 – 1504	900 – 1400	0.2
U	0.05 – 240	10 – 97	2
Ce	47 – 3400	2900 – 6800	0.2
Sc	125 – 1902	2000 – 7600	0.2

Table 17-2. Equilibrium constants for technetium(IV) in carbonate containing solution /17-10/.

Equilibrium reaction	Equilibrium constants log K
$TcO_2 . nH_2O = TcO(OH)_2 (aq)$	-8.17 ± 0.05
$TcO_2 . nH_2O + H_2O = TcO(OH)^{3-} + H^+$	-19.06 ± 0.24
$TcO_2 . nH_2O + CO_2 (g) = Tc(OH)_2CO_3 (aq)$	-7.08 ± 0.08
$TcO_2 . nH_2O + CO_2 (g) + H_2O = Tc(OH)_3CO_3^- + H^+$	-15.34 ± 0.07

Table 17-3.

Species formed	Stepwise stability constants New values[a]	Literature[b]
$Th(OH)^{3+}$	$1.3 . 10^9$	$5.0 . 10^9$
$Th(OH)_2^{2+}$	$7.2 . 10^9$	$2.5 . 10^{10}$
$Th(OH)_3+$	$1.4 . 10^7$	$2.0 . 10^8$
$Th(OH)_4$	$8.6 . 10^6$	$4.0 . 10^9$

[a]Reference /17-11/.
[b]Baes and Mesmer "The hydrolysis of cations", Wiley & Sons, 1976.

hydroxide complexes have been overestimated in earlier studies, see Table 17-3.

Studies of thorium complexes with carbonate ions using potentiometric titration have been published /17-12/. The kinetics of thorium dioxide dissolution in water with varying pH and carbonate content have been investigated. The experiments have been performed in a continuous-plug-flow reactor. There was a strong dependence on pH especially in the alkaline region rather than on carbonate concentration as one would expect.

A selection of thermodynamic constants for plutonium have been made for the EQ3/6 geochemical code /17-13/. The constants have been tested by calculating solubilities of plutonium and compare with results from measurements reported in the literature. The EQ3/6 code have been used for calculation of solubilities and speciation of radionuclides for the SKB 91 safety assessment.

SKB is continuously supporting participation of Swedish experts in the international OECD/NEA project TDB to compile and evaluate databases of thermodynamic constant for relevant radionuclides. SKB is also participating in the CHEMVAL project which is organized by CEC and actively engaged in the validation of geochemical codes.

17.2.2 Organic Complexes, Colloids and Microbes

Dissolved organic compounds in groundwater from the Äspö Hard Rock Laboratory and the analogues study sites Oklo and Cigar Lake are being investigated. The relative content and chemical character of the humic and fulvic acids in the samples are normal and does not vary very much between the sites despite the sometimes exotic locations.

As much as 90% of the organic content in groundwater is composed of other than humic substances. These compounds are also hydrophilic but have a low complex forming capability.

Studies of complex binding of europium by aquatic fulvic acids have been published /17-14/. The ion-exchange and ultrafiltration techniques have been successfully applied and will therefore be used for the study of other complexes between metal ions and humic substances.

The effects of pH, ionic strength and fulvic acids on the size distribution and surface charge of colloidal quartz and iron(III)oxide have been investigated using photon correlation spectroscopy /17-15/. The technique was useful for particles in the range 5 nm to 1 µm. Quantitative measurements were possible down to 0.3 mg/l and detection capability was at least 0.1 mg/l. It was found that quartz colloides are stable also in the presence of fulvic acids. Iron(III)oxide colloids with fulvic acids are stable at high pH but flocculates at low pH (see Figure 17-2).

Column experiments with goethite colloides have been performed at Oak Ridge National Laboratory by Birgit Sätmark, jointly supported by Chalmers University, department of nuclear chemistry and SKB. Different goethite concentrations, pH values and the dependence on flow were tested. There was a marked flow dependence at goethite concentrations of 5 mg/l indicating kinetic effects. The sorption of technetium, cesium, strontium and promethium on colloids from silica, bentonite and grinded granite have been measured as a function of pH and particle diameter /17-16/.

Analyses of microbes in deep groundwater have continued. It has been demonstrated with experiments in Stripa and Laxemar that bacteria in flowing groundwater have the ability to adhere to surfaces and grow there, see Figure 17-3 /17-17/. Therefor it should be expected that microbes at depth are occurring at the surfaces of water conducting rock fractures. This was studied by a recent investigation in the Äspö Hard Rock Laboratory where natural rock fractures were sampled fresh after tunnel blasting. A surface cover of bacteria was indicated /17-18/.

The reversible sorption of radionuclides on bacteria has been demonstrated /17-18/. The potential of bacteria to cause geochemical reactions has also been shown by experiments. Two such reactions are CO_2 assimilation and sulphate reduction /17-17/. Other indications of sulphate reduction have been found earlier in Stripa /17-19/ and recently in Äspö.

An evaluation have been made on the importance of radionuclide transport in the form of colloidal particles or as humic complexes. The possibility that radionuclides migrate with microbes was also investigated. It was

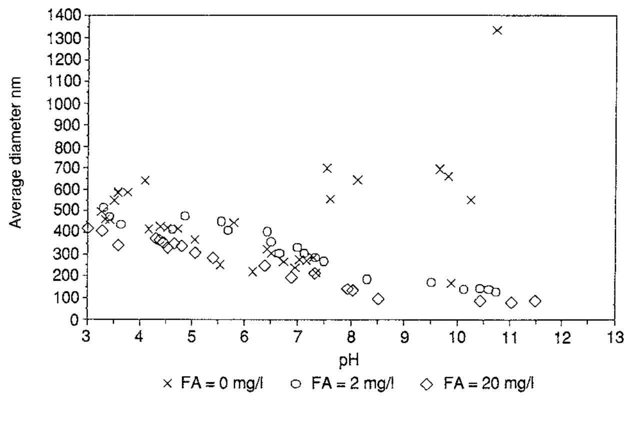


Figure 17-2. Stability of ferric oxide colloides as a function of pH and concentration of fulvic acids, FA. The organic acids are stabilising the colloids in the high pH region.

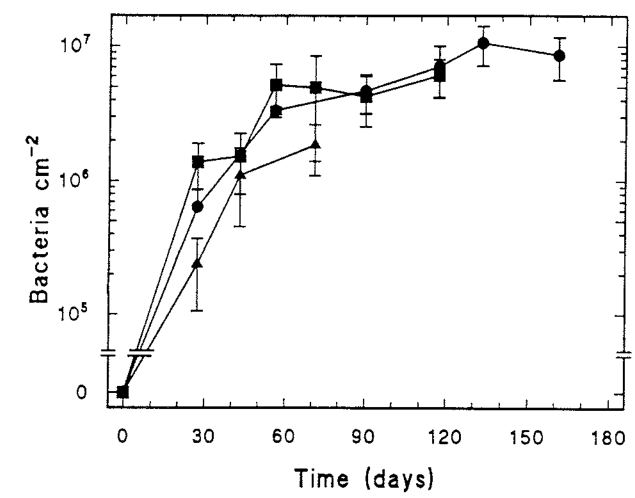


Figure 17-3. The total number of attached bacteria on surfaces exposed to flowing groundwater from sampling sections at different depths in the Stripa borehole V2 for different times. Symbols: circle, 812-820 m 10°C; square, 970-1240 m, 10°C; triangle, 970-1240 m, 20°C. Bars indicate standard deviation.

necessary to do this prior to the SKB 91 performance assessment of spent fuel disposal. The evaluation was based on results of groundwater analyses of colloids, microbes and humic materials. Also used were the interpreted experiments of radionuclide uptake on these aggregates.

One conclusion was that the organic complexes will cause a minor decrease in the value of the sorption coefficients K_d. The magnitude of the decrease depends on the valency of the radionuclide ions and the concentration of the humic substance.

Another conclusion is that mobile particles in the form of inorganic colloids and microbes can indeed sorb and transport radionuclides. If the sorption on the particles is reversible there is only minor consequences for the retention.

The irreversible uptake of radionuclides on mobile particles is a quite different situation. In the worst case with no retention of the particle the nuclide will travel with the flow of water. However, calculations were made which showed that even in such an extreme case with no retention at all the consequences for the safety were insignificant due to the low concentrations of colloidal particles. The evaluation is summarized in an SKB report /17-20/.

Sorption and diffusion

Data on diffusion of radionuclides in bentonite backfill and granitic rock have been compiled and summarized for the use in the SKB 91 performance assessment /17-21/.

Sorption coefficients for radionuclides on rock minerals have also been summarized /17-22/. A selection of K_d-

values for the most important nuclides at different pH values and ionic strengths was made for SKB 91. The correction of K_d-values for complex formation is further discussed in SKB TR 91-50 /17-20/.

Experiments have been performed with technetium, simulated groundwater and granite in closed, oxygen free systems /17-23/. This is part of a series of experiments which clearly demonstrates that pertechnetate is reduced in contact with iron(II) containing rock minerals /17-24/. This has also been observed by others, e.g. by Vandergraaf et al. /17-25/. Field studies of technetium migration in-situ confirms the laboratory results /17-24/. Consequently only K_d-values corresponding to equilibrium with natural reducing conditions have been suggested for use in the SKB 91 performance assessment. This is an improvement as compared to KBS-3 where a case of no reduction was also considered.

Basic experiments have been performed to test the applicability of the surface complexation model for radionuclide sorption on minerals. This is done in order to improve our understanding of the processes involved in sorption.

A series of such experiments have started with the adsorption of carbonate on goethite as a function of pH and ionic strength /17-26/. The results indicated that carbonate is adsorbed on goethite as an inner sphere complex. Besides revealing the fundamental processes involved in sorption the experiment also demonstrated the ability of hydrous iron oxides to retain C-14 released as carbon dioxide or carbonate from radioactive waste. The experiments were carried out in cooperation with Chalmers University of Technology, Dept. of Nuclear Chemistry and Los Alamos National Laboratory, USA.

17.3 VALIDATION OF TRANSPORT MODELS

17.3.1 Laboratory Experiments

The laboratory experiments with overcored natural rock fractures have continued through 1991. Migration of radionuclides and flow properties in the fractures are being studied. The drill cores used originate from the Stripa mine.

17.3.2 Tracer Tests at Finnsjön and Stripa

Within the international INTRAVAL project the modelling of the Finnsjön test case continues. Material on both the tracer tests and the hydraulic injection tests have been compiled and presented at the workshops.

In-situ reduction of a redox sensitive radionuclide was tested in Finnsjön. Technetium was used as a tracer in the dipole test and injected in the form of highly mobile pertechnetate. The technetium was retained as expected in the fracture zone due to its reduction to Tc(IV) proving the effectiveness of the in-situ reduction reaction /17-24/.

Tracer experiments have been performed in the Stripa mine. Two parallel holes were drilled in a fracture plan at about 2 m distance /17-27/. Conservative tracers were injected in five locations in one hole and recovered in many isolated locations in the other hole. The result confirm the assumption of flow restricted to connected channels in the fracture plane. Intersecting fractures diverted a large amount of the tracers to distant points in the tunnel.

17.3.3 Tracer Tests at Äspö

Dilution measurements

The deep boreholes on Äspö are equipped with a permanent packer arrangements in which two of the packed off intervals can be used for circulation of water to the surface. In the circulating volume a dye tracer is added which can be easily analyzed. Within this loop a dilution of the color is due to groundwater flow through the packed off section. Thus by analyzing the tracer concentration at regular time intervals the groundwater flow can be calculated down to the limit of molecular diffusion, which is less than 0.1 ml/min.

The dilution measurements have been made in all the core drilled boreholes on southern Äspö, i.e. KAS02, KAS04 – KAS14. On the northern part of Äspö KAS03 has been tested. These test have been made both under the long term pumping tests LPT-1 and LPT-2 and also under undisturbed conditions /17-28/. The results are listed in Table 17-4.

The results in the table can be compare to the results in terms of groundwater flows calculated on the basis of the hydraulic head and conductivity.

LPT-2 tracer test

The last activity of the pre-investigations at Äspö was a long term pumping test combined with a tracer test. For the performance of the test the same permanently packed off sections as the ones used for the dilution measurements were used. Figure 17-4 is a schematic illustration of the outline of the experiment.

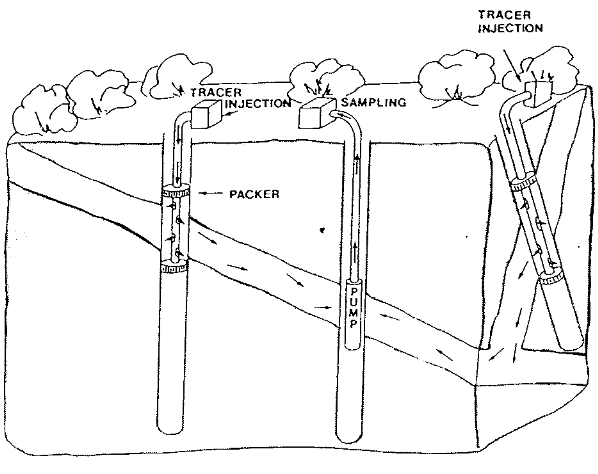


Figure 17-4. Schematic outline of the LPT-2 tracer test.

Table 17-4. Groundwater flow in packed off borehole sections under natural and disturbed conditions.

Borehole	Code	Section (m)	LPT-1	Flow (ml/min) NG1	NG2	LPT-2	T^1 (m^2/s)
KAS02-4	B4	309-345	1.1	–	(89)	14, 2	2.0E-5
KAS02-2	B2	800-854	(127)	–	(127)	4	4.0E-5
KAS03-5	C5	107-252	–	–	6.9	–	3.0E-6
KAS03-2	C2	533-626	–	–	164	–	4.0E-6
KAS04-2	D2	332-392	28	–	12	–	4.0E-5
KAS05-3	E3	320-380	6.5	–	0.4	12, 10, 9	2.4E-6
KAS05-1	E1	440-549	40	1.8	1.3	11	7.8E-6
KAS06-5	F5	191-249	197	25	27	ph	1.7E-4
KAS06-1	F1	431-500	79	52	25	ph	3.1E-5
KAS07-4	J4	191-290	ph	–	1.0	33,20,17,18,18	4.9E-6
KAS07-1	J1	501-604	ph	–	5.3	–	>1.3E-5
KAS08-3	M3	140-200	4.3	–	4.0	16,5,21	3.9E-5
KAS08-1	M1	503-601	20	5.5	7.6	54,51,50,48, 46,47,45,44	3.2E-4
KAS09-4	AD	116-150			11	–	6.4E-4
KAS11-5	CE	47-64			0.3	–	3.3E-5
KAS11-2	CB	153-183			33	–	2.5E-4
KAS12-3	DC	235-278			0	–	2.3E-6
KAS12-2	DB	279-330			12	111,99,94,122, 116,115,100,97	2.7E-5
KAS13-4	ED	151-190			1.1	–	3.7E-6
KAS13-3	EC	191-220			4.7	3.3	2.7E-5
KAS14-4	FD	131-138			3.1	–	2.2E-4
KAS14-2	FB	147-175			18	11	1.0E-4

– = No measurement
ph = pumphole
1 = KAS02-08, transient 3 m packer test, evaluated with Jacobs method (SKB database GEOTAB), KAS09-14, spinner measurements (Rhén et al., 1991b).

For the experiment three short lived radioactive tracers were used together with one colored dye. The tracers are listed in Table 17-5.

Uranine and perrhenate was added in a second borehole section after break through from the first section.

Table 17-5. Tracers used for the LPT-2 tracer test.

Tracer	Half-life	Chemical form	Added in borehole; section
In-114	49.5 d	EDTA-complex	KAS02; 4
I-131	8.0 d	Iodide ion	KAS07; 4
Re-186	3.8 d	Perrenate ion	KAS08; 1
			KAS08; 3
Uranine	Stable	Fluorecent dye	KAS05; 3
			KAS12; 2

The results of the tracer break through curves are consistent with the framework of fracture zones presented in the conceptual model of Äspö /17-2/. However, the predicted flow paths did not agree completely with those predicted by the numerical model /17-29/.

Out of six injection points the predicted residence time was overestimated for four points by a factor of two or three. From one injection point the predicted residence time was underestimated and from the sixth no evaluation was possible. The discrepancy shows how sensitive the residence times are to flow porosity. In the predictive modelling a flow porosity of 10^{-3} was applied to all zones, whereas the results of the tracer test gives a flow porosity varying between 2 x 10^{-4} to 5 x 10^{-2}.

18. THE INTERNATIONAL STRIPA PROJECT

18.1 SITE CHARACTERIZATION AND VALIDATION

The main objective of the SCV Project is to determine how well the techniques and approaches used in site characterization can be used to predict groundwater flow and radionuclide transport in a fractured medium. The central aims of the project are:

- to develop and apply an advanced site characterization methodology which integrates different tools and methods,
- to predict distribution of groundwater flow and solute transport pathways in a specific volume of the fractured Stripa granite,
- to develop and apply a methodology to validate that the models (both conceptual and numerical) are appropriate to the processes under examination in a fractured rock mass.

The concept underlying the SCV Project is that model-based predictions should be checked against experimental results on an iterative basis. Hence, the SCV Project includes 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	|
III	Detailed characterization and preliminary validation	88–89	validation/ data gathering	↓ ↑
IV	Detailed predictions	89-90	prediction	second
V	Detailed evaluation	90–91	validation	↓

The basic experiment within the SCV Project is to predict the distribution of water flow and tracer transport through a volume of rock, before and after excavation of a sub-horizontal drift, and to compare these predictions to the actual field measurements.

Stage I comprised the drilling and investigation of 5 boreholes for preliminary characterization. Three 200 m long semi-horizontal boreholes were drilled 60 m apart towards north (N2-N4). Two 150 m long boreholes were drilled towards west 70 m apart (Wl and W2). The volume of rock investigated was situated in a granitic pluton around 380 m below ground to the north of the mined-out region in the Stripa Mine, see Figure 18-1.

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 six 100 m long parallel boreholes (the D boreholes) that outline a cylinder (diameter 2.4 m) centrally located within the SCV site. Four different types of numerical groundwater flow models were used for the inflow predictions.

In **Stage III** five boreholes (the C-boreholes) were drilled from essentially the same point at the 360 m level towards the central portion of the site and investigations made in them to provide data for detailed predictions of inflow to the Validation Drift (to be excavated in Stage V, Figure 18-1) and for a check on the first conceptual model. An access drift was excavated from the 410 m level to the 385 m level. The six 100 m long D-boreholes were drilled from the end of the Access drift, the inflow measured, and compared to predictions. This constituted the first attempt of validating the models.

In **Stage IV** the conceptual model was updated based on the additional data available from Stage III. This model was used as input to the upgraded numerical models which were used to make predictions on fracture occurrences, distribution of groundwater inflows, and tracer transport to the Validation Drift.

At the beginning of **Stage V** the Validation Drift was excavated in place of the first 50 m of the cylinder outlined by the D-boreholes. This was followed by fracture mapping, measurements of groundwater inflow, and tracer transport to the drift.

The experimental activities within the SCV Project were completed in June 1991 when the Stripa mine was closed. In addition to the experimental work much effort has been devoted during 1991 to analysis and reporting of obtained results. The activities and results of the SCV Project will be summarized in a final report which will be published in 1992.

18.2 FRACTURE NETWORK MODELLING

1991 saw the culmination of the modelling work. The data from stage three investigations and stage four interpretations of the SCV programme was available and the four modelling teams were able to demonstrate the progress made over the course of the project by predictive modelling for a series of large scale experiments.

The first of these was the Validation Drift inflow experiment. The predictions for this exercise were presented in February 1991 to the fracture flow modelling task force, along with the experimental results. The final interpretation of the results from this exercise have been prepared by the task force at the other two meetings in June and

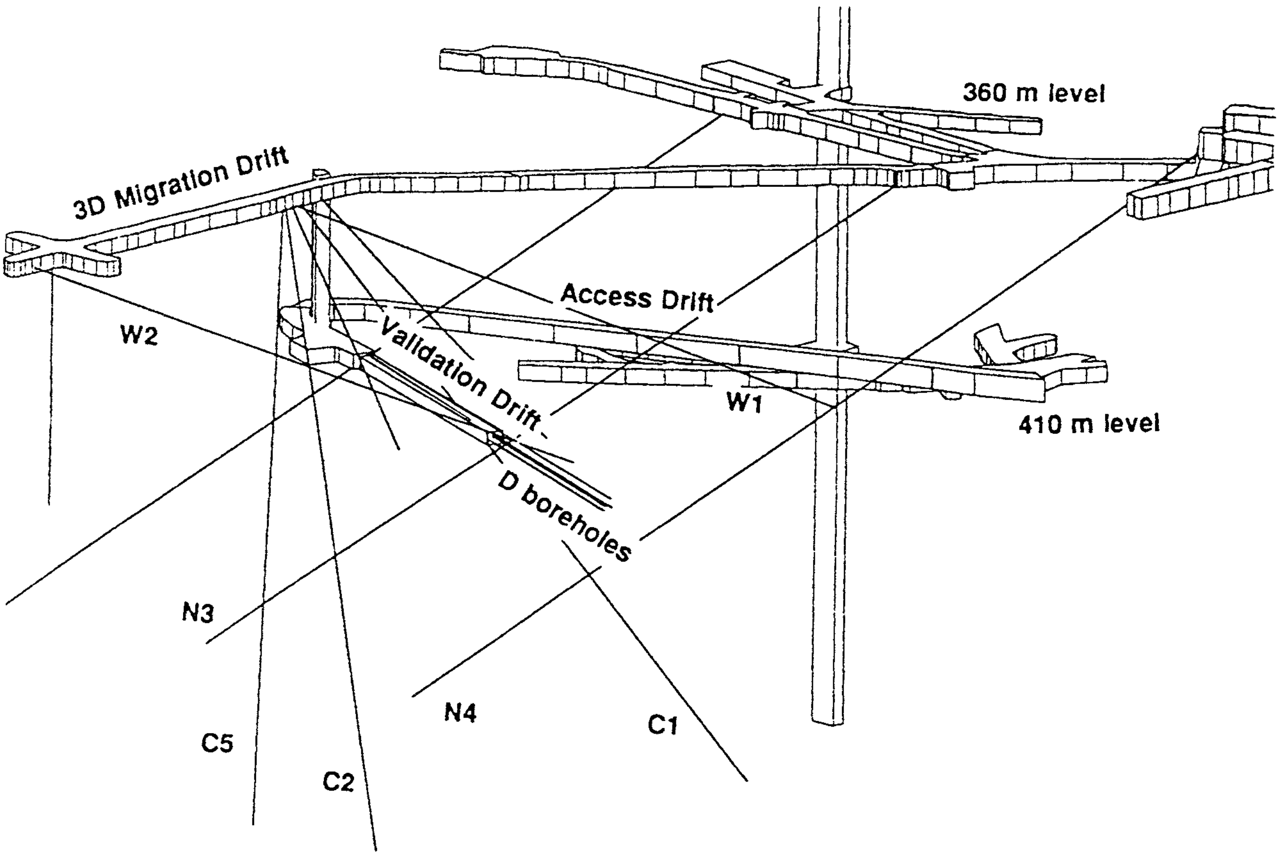


Figure 18-1. *The SCV site is located north of existing mine workings. The site was investigated from boreholes drilled from the 360 m level. The Validation Drift and the D boreholes at the 385 m level were used to check the predictions.*

December 1991. Briefly, the various flow modelling approaches all performed well, and made good predictions of the inflow, but failed to explain the disturbed zone around the drift excavation. Whilst experience enabled the modellers to predict that there should be a reduction of flow into the drift as compared with D boreholes, attempts to explain this in terms of physical models were not successful. In general, predictions of inflow to the Simulated Drift Experiment (SDE) were better, and the best representation of the disturbed zone was a simple reduction of transmissivity for conduits near the tunnel. The inflow experiment together with the SDE has provided for the first time a precise quantification of the importance of the disturbed zone, and highlighted conceptual uncertainty concerning the mechanisms involved.

During the second half of the year, the effort was concentrated on the development of approaches for predicting transport experiments. Given the uncertainty in the flow properties of the disturbed zone and the transport properties of the site, the programme was arranged in a series of three modelling exercises. First, a strong injection of a highly concentrated saline solution with recovery in the D-holes. The results of this experiment were available to the modellers in 1990, and the modellers used this experiment to calibrate transport models. Second, a repeat of this experiment with recovery in the Validation Drift provided a 'training exercise' for predictive modelling. Finally, a series of tracer transport experiments, with low injections of a series of metal-complex and dye tracers in boreholes around the Validation Drift, with recovery in the drift. These tracers were injected into the natural flow field of the drift inflow. Two cross-hole tracer tests were also carried out at the end of the project. In general the models made good predictions of these experiments, particularly when the flow fields were accurately represented. The models illustrated the importance of the fracture network geometry as a (predictable) source of tracer dispersion.

The Stripa project modelling teams at AEA D&R and Fracflow developed and demonstrated an integrated approach to modelling in fractured rock, using discrete modelling codes on the small scale, below representative volumes, and using continuum approximations in conventional porous medium modelling on the scale of the mine or the SCV site as a whole. This approach could be used as an integrated part of a site investigation programme. In contrast, the two collaborative modelling teams from LBL and Golder Associates demonstrated quite distinct approaches, illustrating the use of discrete models on the large scales. These approaches were based on equivalent discontinuum and fracture network methods respectively. Their conclusions are sometimes quite different.

As this is the final annual report, the following sections describe the modelling approach, results and conclusions of each team in turn. The experimental results and code predictions did not identify one single approach as 'correct', rather we conclude that each of these approaches has value and helps in our understanding of flow and transport through fractured rock. The approach chosen at any given site will also depend on the data available at that site and the purpose of the modelling.

In conclusion, the modellers have successfully developed the techniques required for modelling flow and transport at fractured sites. They have applied these techniques to make genuine, 'blind' predictions of field experiments (as opposed to the more usual modelling exercises for which the answers are known in advance). Finally, this structure programme of experimental site characterisation and modelling prediction, with close interaction between modellers and experimental groups, has made a significant step forward in our understanding of flow and transport through fractured rock.

18.3 ROCK SEALING TEST

The study aimed at investigating whether relatively fine-fractured rock can be sealed by use of clay or cement grouts and what the longevity will be in repositories for highly radioactive waste, where heat is produced.

Three large-scale experiments and comprehensive laboratory work and flow modelling were conducted in the 5 year Stripa Rock Sealing project. "Dynamic" injection was applied for sealing fine-fractured rock using clay or cement.

The investigation of the extension and properties of disturbed zones around blasted tunnels and of the possibility to seal them by "hedgehog" grouting (Test 2), was completed in 1991, and so was Test 4, which was an investigation of whether a fine-fractured, natural water-bearing discontinuity can be sealed by cement grouting.

The comprehensive study of the longevity of clay and cement grouts has been completed.

19. ÄSPÖ HARD ROCK LABORATORY

19.1 GENERAL

The scientific investigations within SKB's research programme are 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. Up to January 1, 1992 1103 m of the access ramp has been excavated.

Overview map

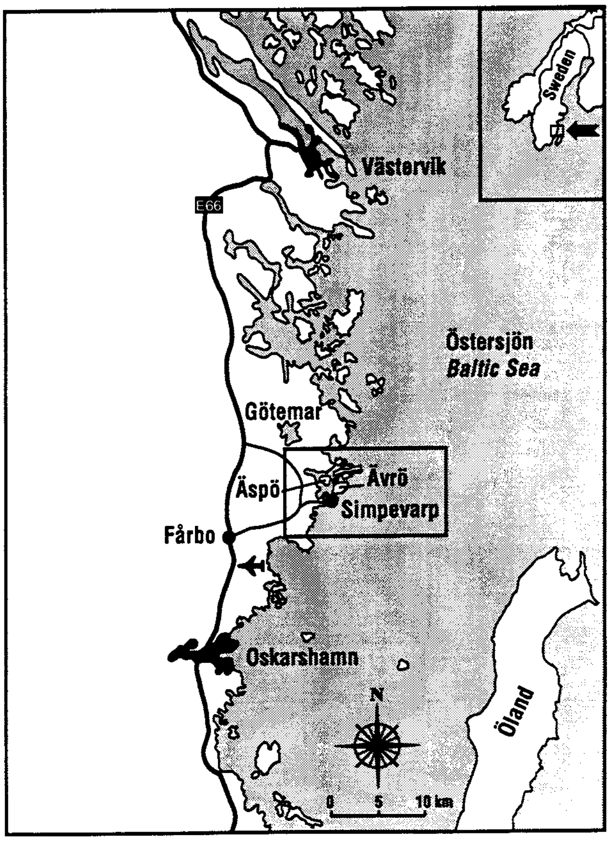


Figure 19-1. Äspö island with environs.

The work with the Äspö Hard Rock Laboratory, HRL, has been divided into three phases: the pre-investigation, the construction and the operating phase.

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 construction of the laboratory. The investigations have been summarized in four Technical Reports during 1991 /19-2--5/. 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, /19-6/. The operating phase is very much aimed at research and developments of models for transport of groundwater flow and transport of solutes, tests of methods for construction and handling and pilot-tests of important parts of a repository system.

The project has so far received considerable international interest. Up to January 1, 1992 three international organizations participate at the Äspö HRL. Atomic Energy of Canada Limited, Power Reactor and Nuclear Fuel Development, Japan and Central Research Institute of Electric Power Industry, Japan are the present participating organizations. Negotiations are still going on with organizations in France, England, USA and Finland.

A separate Annual Report 1991 has been prepared for the Äspö Hard Rock Laboratory /19-7/ and the reader is referred to this publication for a more detailed account of the achievements for 1991.

An outline of the project (goals, scope, schedules, organization, previous work) can be find in R&D Programme 1989 /19-6/, in previous Annual Report or elsewhere /19-8/.

19.2 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,

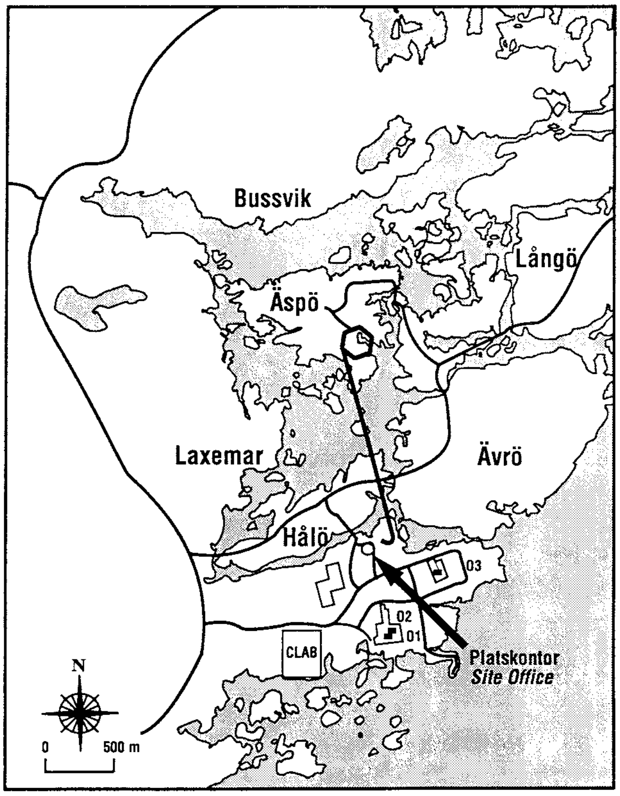


Figure 19-2. Location of the Äspö Hard Rock Laboratory.

SKB made a decision to locate the laboratory on the southern part of the island of Äspö, see Figure 19-2.

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 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 19-3. The entrance is located on the Simpevarp peninsula.

19.3 OVERVIEW OF WORK 1986 – 1990

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 /19-9/ and from the site description stage in /19-10/.

The aim of the prediction stage was to perform a more detailed characterization of the target area, south part of Äspö in order to finalize the predictive models of the bedrock. A number of new boreholes were drilled and investigated. Hydraulic interference testing was performed for 3-D characterization of the major hydraulic conductors. A large scale pumping test and a tracer test using radioactive tracers ended the pre-construction data acquisition. In all 14 cored holes were drilled at Äspö, ranging from 99 to 1002 m. The number of percussion holes drilled at Äspö are 20, ranging from 93 to 200 m. These boreholes are monitored with respect to groundwater pressure head in 142 borehole sections. In order to detect changes in the salinity/fresh water interface of the formation several holes measure the electric conductivity of the groundwater. Most of the sections are connected on-line to a central computer at the site office. An overview of all investigations during the pre-investigation phase is published in /19-2/. The technology used to collect the data is described in /19-3/. As a basis for the predictive models conceptual models were derived /19-4/. The models are prepared in several geometrical scales and to relevant key questions /19-11/ The predictions have been published in a separate report /19-5/ and these predictions are a basis for comparison with outcome during the on-going construction phase.

Two examples of predictions are showed in Figure 19-4 and Figure 19-5. The first figure show the prediction in site scale in the position of geological zones close to the ramp. The next figure show a prediction of the pressure and salinity fields in a horizontal section along the tunnel. These calculations has been performed using the PHOENICS code and a body-fitted coordinate grid giving a resolution of 2 m close to the tunnel.

Along with the site characterization, activities were carried out to prepare for the construction phase. Permits were obtained accordingly to Act on Conservation of Natural Resources by the Swedish government in April 1990, accordingly to the Planning and Building Act in September 1990 and the Act on Water 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, 1990 was the day for the first excavation of the access ramp.

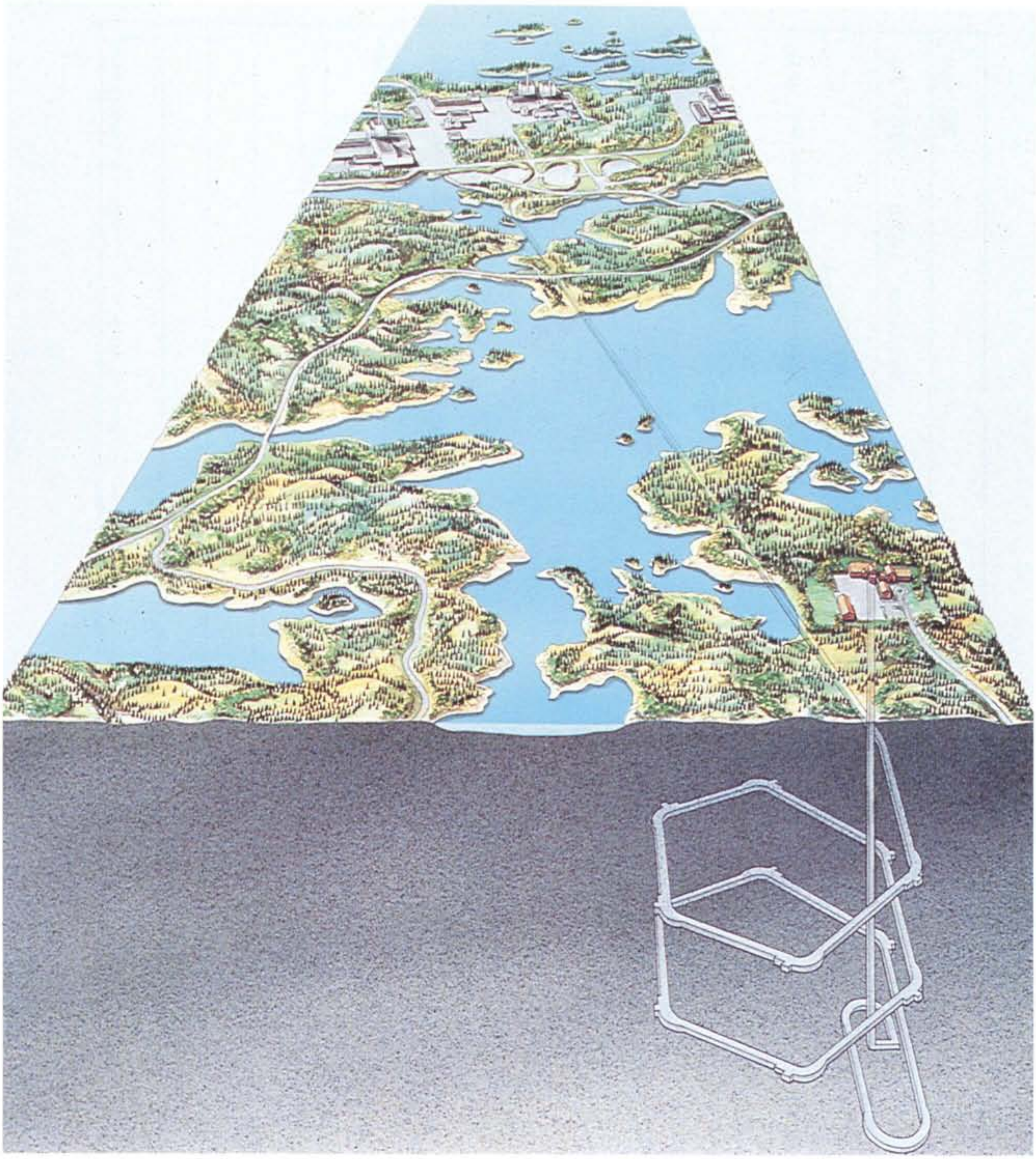


Figure 19-3. *Design of the laboratory.*

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.

In October 1, 1990 the construction of the tunnel started. A new organization was set up at the site. An overview of the organization, including the site office (c. 10 people) is shown in Figure 19-6.

Drilling and blasting is the technique used for excavation. The contractor, Siab, has a crew of 30 people at the site. The construction excavations are done in two shift. Drilling is performed by a computerized drilling rigg with three 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

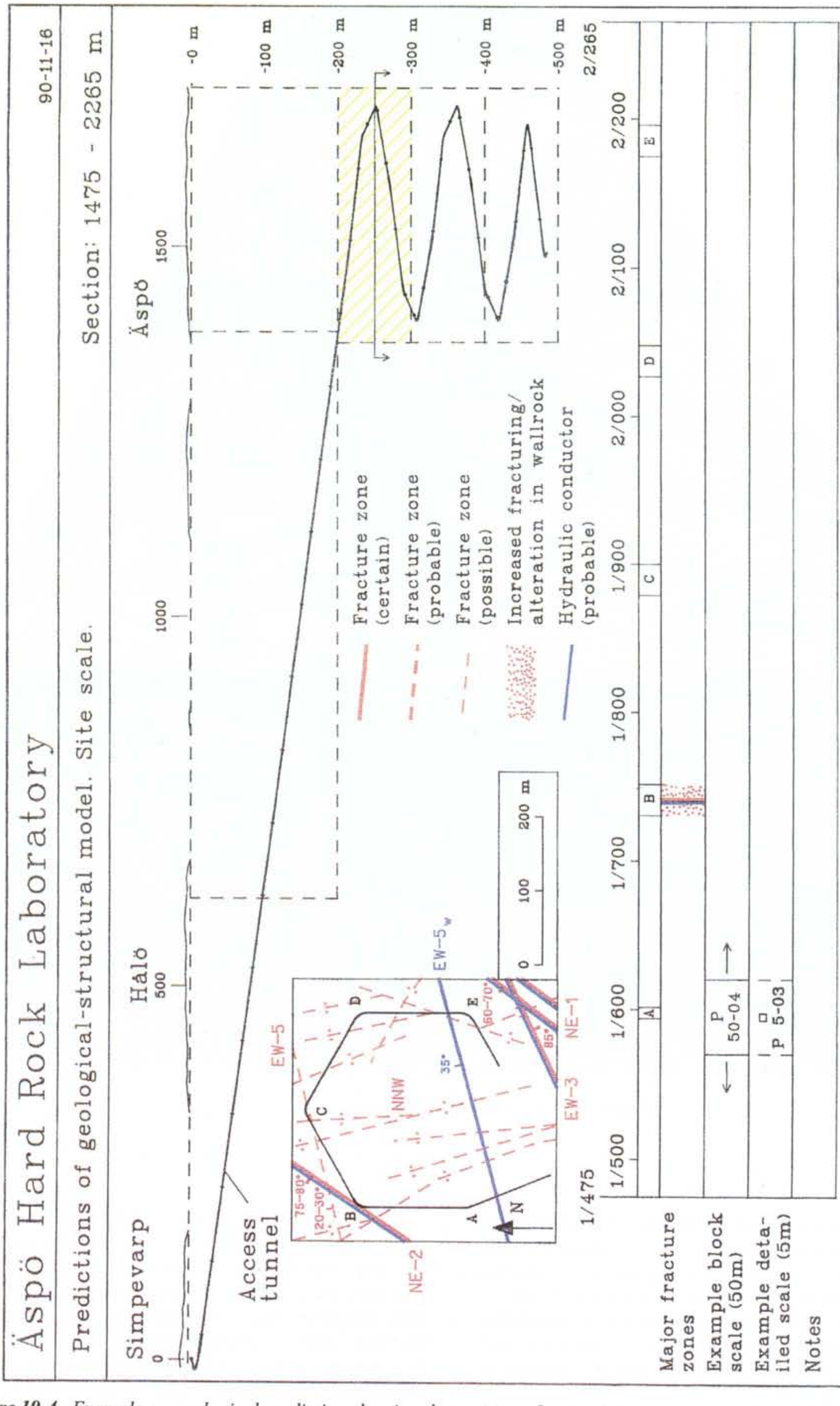


Figure 19-4. Example on geological prediction showing the position of major fracture zones section 1475 – 2265 m.

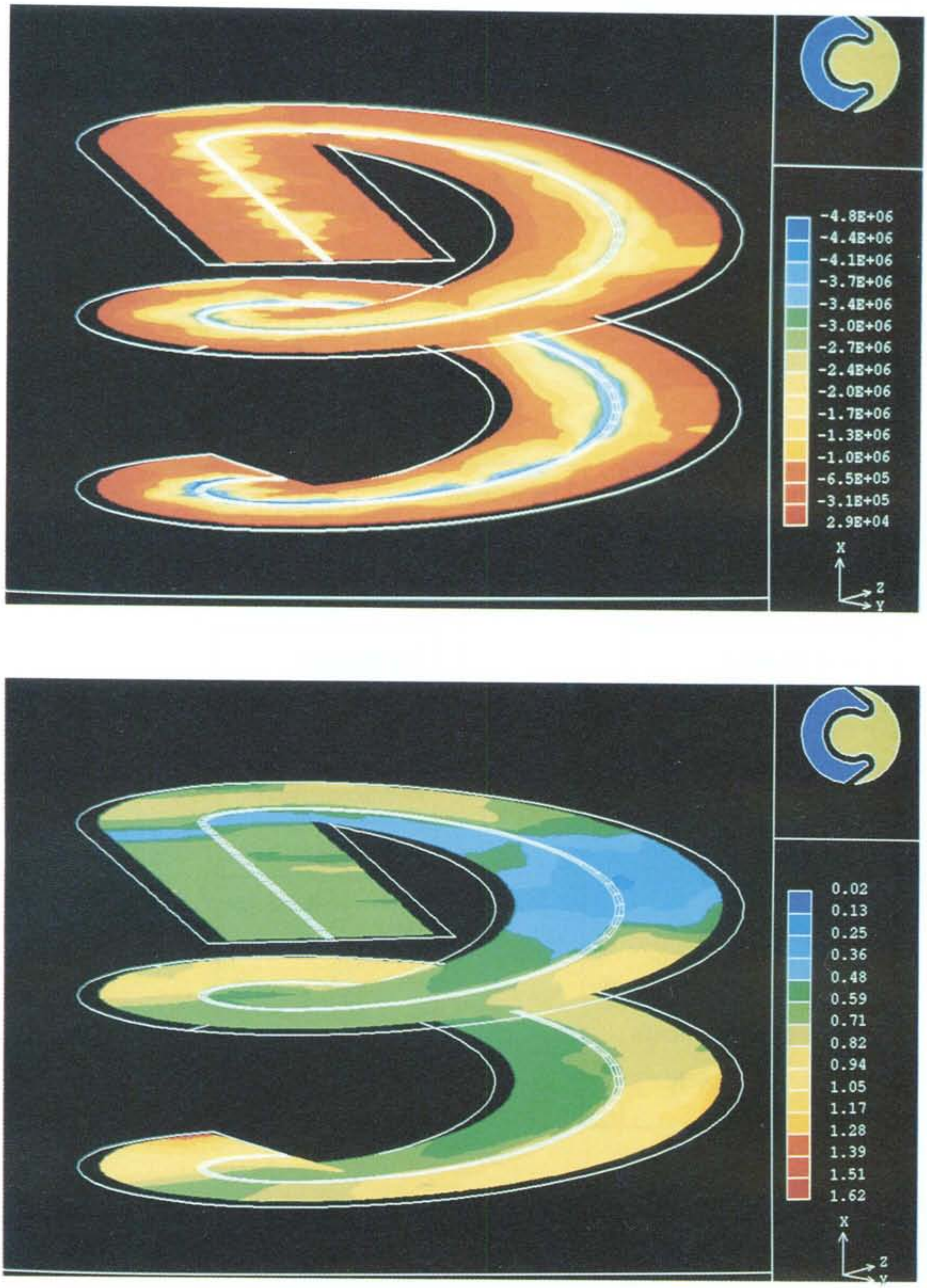


Figure 19-5. *Pressure and salinity fields in a horizontal section along the tunnel .*

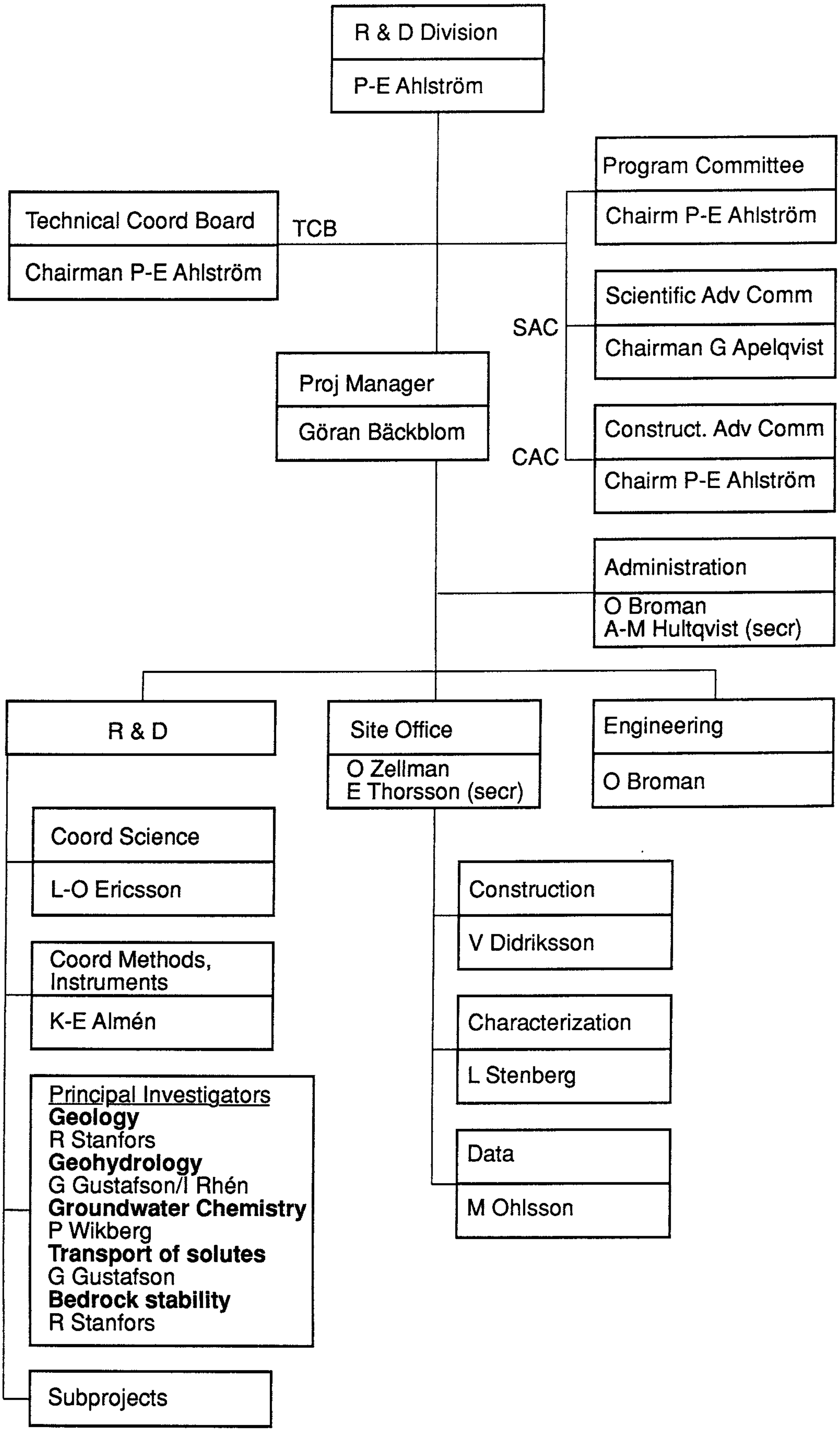


Figure 19-6. *Overview of the organization.*

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.

19.4 HIGH-LIGHTS DURING 1991

The pre-investigation phase has been summarized in four Technical Reports /19-2--5/. The predictions forms the basis for the minimum documentation to be performed in the ramp and in the monitoring programme.

The first 800 m of the ramp was used as a training stretch in order to set the details for the construction/testing integration. In order to obtain overviews of the collected data in the tunnel sheets are now prepared for every 150 m section. An example is given in Figure 19-7.

During 1991 a new communication system for monitoring of boreholes was installed. The measurements are transmitted by radio to a computer at the site office, see Figure 16-3.

A Blasting Damage Experiment was carried out in the ramp as a part of The Disturbed Zone Project. It was aimed at studying the distribution and character of the blasting damage around the tunnel contour. Three different blasting schemes were used. Several methods of investigations were used to detect the damage; The damage zone was 0.3 – 0.6 m in the tunnel walls and 1.0 m – 1.7 m in the floor depending on blasting scheme. Drilling precision seems to be the major factor controlling the development of blast induced fractures in the contour.

In order to prepare for the passage of a major fracture (NE-1) a Passage of Fracture Zone project has been carried through. Several tasks have been performed when passing the fracture zones EW-7 and NE-3. Efforts have been taken to finalize a practical grouting programme to be used in the access ramp. The revised grouting programme design is based on the following guide-lines a) ensure the stability of the tunnel b) limit the total inflow to the facility c) perform groutings so that the penetration from the tunnel perimeter is limited (10 – 15 m) d) avoid re-groutings.

The plans for Äspö Research Village proceeded. A turn-key contract for ventilation of the planned underground research caverns was awarded to Svenska Fläkt AB. A turn-key contract was as well awarded to ABB Drives AB. They will install the hoist system including the shaft installations for the hoist.

Three international agreements organizations participate now at the Äspö HRL. Atomic Energy of Canada Limited, Power Reactor and Nuclear Fuel Development (PNC), Japan and Central Research Institute of Electric Power Industry (CRIEPI), Japan are the present participating organizations. PNC and CRIEPI has attached personnel to the site in order to follow the work.

In order to celebrate the start of the Äspö Project special events took place May 13-14. The First Äspö International Seminar took place the first day. Close to 100 participants listened to invited speakers from Sweden, USA, Switzerland and France on the subjects, the Underground, the Waste and the Safety. The second day was devoted to the Äspö Project Start ceremony visited by close to 200 persons. Speeches was delivered by several invited speakers from Sweden, Canada, USA and Japan. The agreement with PNC was signed. The speeches delivered May 13 – 14 has been put together in a special proceeding.

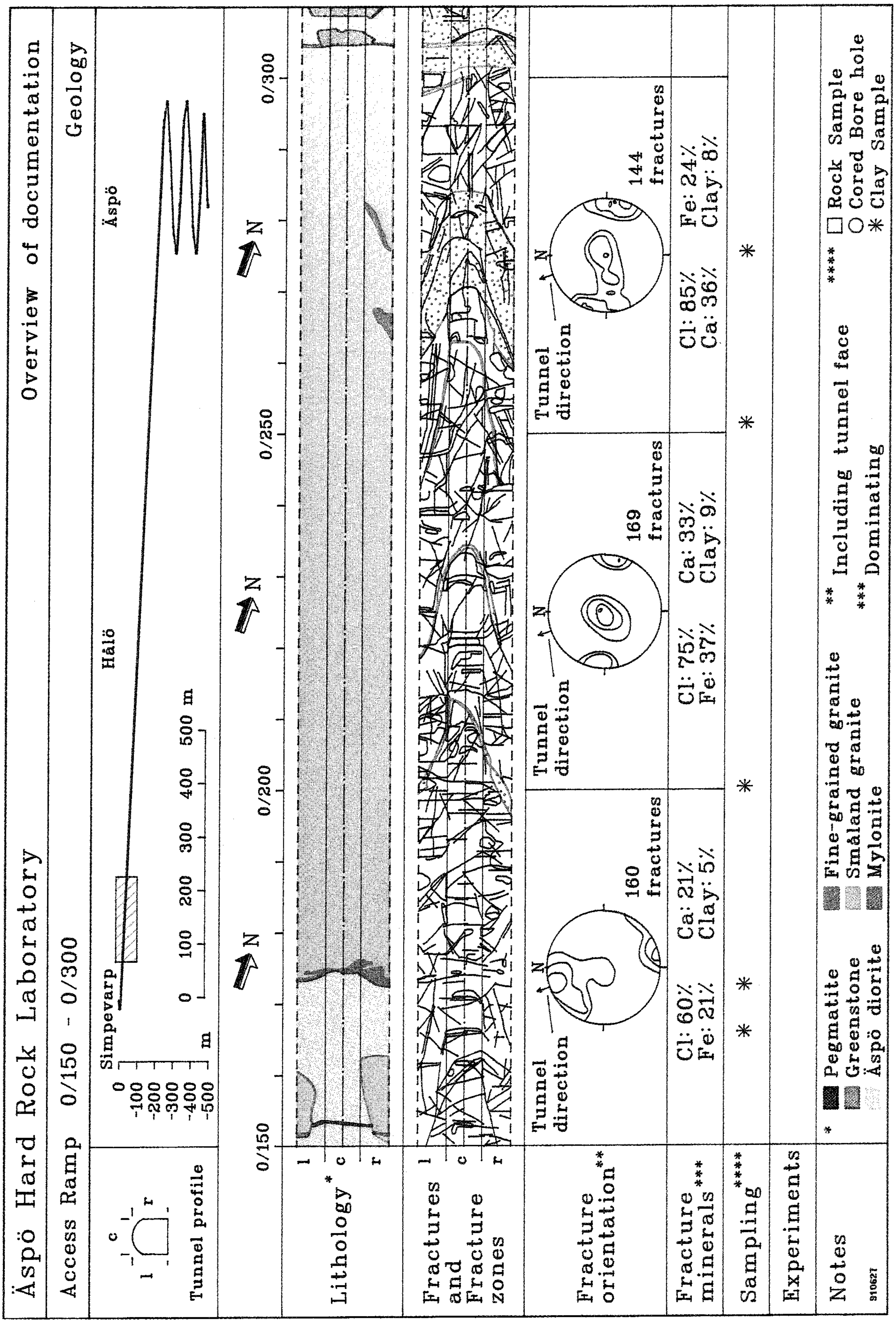


Figure 19-7. Examples of overview presentation of geological data collected in the ramp.

20. NATURAL ANALOGUE STUDIES

20.1 THE POÇOS DE CALDAS PROJECT

The project was finished in March 1990. During the rest of 1990 and during 1991 the project reports have been prepared and most of them printed. The content of these reports were summarized in the last SKB Annual Report for 1990. Articles covering the reported material are being submitted to the Journal of Geochemical Exploration. Some evaluations, improvements of earlier interpretations and refined modelling of the Poços de Caldas data have been obtained in the aftermath of the project. Further evaluations of the implications of the Poços de Caldas results for performance assessment extends into 1992.

The redox conditions have been interpreted and shown to be another example of the general system valid for study sites in Sweden as well as other deep groundwater environments /20-1/.

Further modelling work have been presented concerning the propagation of the redox front /20-2/. New calculations were made with the coupled chemical equilibria-transport code CHEQMATE describing the redox front development and the movement of uranium across the front. Earlier difficulties encountered in the correct prediction of pH were overcome by using better thermodynamic data in the HATCHES database /20-3/.

A new code for calculations of coupled transport and reaction has been developed and tested on the moving redox front in Poços de Caldas. The code was tested against other geochemical codes such as EQ3/6 and the coupled code CHEQMATE. The quasi-stationary state approximation proposed by Lichtner is used /20-4/. The calculation code is fast and can handle sharp reactions fronts such as redox fronts /20-5/.

The behaviour of thorium and light rare-earth elements in the Morro do Ferro formation in Poços de Caldas have been further evaluated. Thorium has been fixed by the formation of thorite. The trivalent cerium has been oxidised to less soluble cerium(IV) forming the mineral cerianite. In contrast the trivalent light rare-earth elements have migrated further down and formed secondary minerals such as neodynium lanthanite. In addition to the formation of mineral phases there has also been retention due to adsorption on poorly crystallised iron and manganese oxyhydroxides /20-6/. This, in a qualitative sense, is quite compatible with the prediction of relative retention of trivalent and tetravalent radionuclides in rock groundwater environment obtained from laboratory studies.

20.2 THE CIGAR LAKE PROJECT

The Cigar Lake uranium ore body is situated at a depth of about 430 m. The ore is embedded in illitic clay. Overlaying host rock is sandstone. Under the ore is the crystalline basement rock. The ore contains uranium in the form of uraninite (uranium dioxide) and is very concentrated. The age of the ore is 1.3 billion years.

Numerous prospection holes have been drilled. A test excavation shaft made by the Cigar Lake Mining Company, CLMC, gives access to the ore body.

Since April 1989 AECL and SKB have, with the permission of CLMC, been engaged in a joint project to investigate Cigar Lake as a natural analogue to a spent fuel repository. In September 30, USDOE signed an agreement on cooperation in waste management research with AECL which has added USDOE as a third partner to the project.

The second project year was concluded in April 1991 with a workshop in Saskatoon. A field trip to Cigar Lake was arranged for the participants. Data and modelling efforts were presented and reviewed at the meeting. A second Annual Report, covering the period from April 1990 to April 1991 have been produced /20-7/.

The investigation program is divided into the following tasks:

- Rock mineralogy and geochemistry.
- Ore and nuclear reaction products.
- Hydrogeology.
- Hydrogeochemistry.
- Colloids.
- Organic geochemistry and microbiology.
- Radiolysis.
- Modelling.

The activities within the modelling task have been intensified during 1991. Working group meetings in the field of performance assessment oriented modelling have been held. Preliminary results on testing of the following models were presented and discussed;

- Models for solubility and speciation of trace elements, radionuclides and nuclear reaction products.
- Spent fuel dissolution models.
- Mass transport models.
- Models for influence of colloids, organics and microbes on geochemistry and radionuclide migration.

Figure 20-1. Drill cores through the clay halo and the uranium ore.

At this stage in the project it is interesting to note that radionuclides such as H-3, C-14, Cl-36, Tc-99, I-129 and Pu-239 are being produced in measurable amounts in the ore body.

There is a redox front at the uranium ore, see Figure 20-1. Radiolysis of groundwater is a plausible cause for the extensive oxidation observed. Further indications of current water radiolysis have been noted.

So far only minor effects of oxidation have been observed on the uraninite. Preliminary near field transport modelling have been performed.

The redox geochemistry of the Cigar Lake groundwaters have been evaluated. A control by the iron redox system is indicated. The total concentration of uranium in the water in the ore is ranging from 0.3 to 30 µg/l in good agreement with thermodynamic calculations and not much different from what can be found in any deep groundwater.

20.3 MISCELLANEOUS

SKB is engaged in the CEC sponsored project in Oklo. The project is managed by CEA in France.

Zones where nuclear criticality occurred about two billion years ago have been found in the uranium ore at the Oklo mine and in the adjacent Okelobondo. Oklo is an open pit mine and Okelobondo is the site for an underground mining operation. During prospection a new natural reactor was discovered many kilometres away in a place named Bagombe. This later reactor zone is close to the ground surface (10 – 30 m) and undisturbed by mining operation.

A reconnaissance study of Bagombe was performed in 1991. SKB has also participated in water sampling, mineral analyses and hydrology testing.

21. THE BIOSPHERE

The biosphere studies shall describe the transfer of radionuclides from the deep groundwater to biota and the subsequent dose to man from these nuclides. 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 short term problems like atmospheric fallout and by internationally comparing the results from different groups. This has been the basis for the Chernobyl studies and the participation in BIOMOVS.

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 yearly dose to man. 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 1 000 years. More dramatical changes in nature, as lakes drying up, 1 000 to 10 000 years, iceages and changes in sea level in 10 000 to 100 000 years while geological changes operates in timescales of several million years. This timescale covers six orders of magnitude.

The assumption that all processes are in a semi steady state, would simplify the treatment of biosphere. It is possible though, that some reservoir could accumulate radionuclides (not necessary 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 shorter time. One example of this is the ageing lake, where the sediment of a lake evolves into farmland. Other examples like accumulation in peat /21-1/ exist but no systematic study has been accomplished. The ageing lake example /21-2/ /21-3/ shows that these processes can occur but the effect in the assessment is limited.

21.1 VALIDATION OF MODELS: BIOMOVS

BIOMOVS (BIOspheric MOdel Validation Study) is an international cooperative study initiated in 1985 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 first study was run for five years and ended in 1990. BIOMOVS I forcefully demonstrated the short-comings of our present capabilities for biosphere modelling /21-4/. Older models involving well studied pathways and relatively shortlived radionuclides (e.g. Cs-137 and I-131) need improving, 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 modellers by 3, 4 and even 5 orders of magnitude, with estimates of uncertainties about these parameters by the individual modellers 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.

In 1991 the second phase BIOMOVS II was started at a workshop in Vienna in October and is jointly managed by five organisations:

- The Atomic Energy Control Board of Canada;
- The Atomic Energy of Canada Limited AECL Research;
- Centro de Investigaciones Energeticas Medioambientales y Technologicas, Spain;
- Empresa Nacional de Residuos Radioactivos SA, Spain;
- Swedish Radiation Protection Institute.

As all important exposure pathways, scenarios and reasons for differences in predictions, could not be addressed in BIOMOVS I some of the goals and justifications remain valid for BOIMOVS II. The primary objectives of BIOMOVS II are 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 workshop in October focused on identifying the issues to be tackled at a working group level. The background for this were the four broad themes proposed from BIOMOVS I. The following four themes were defined for BIOMOVS II:

1 Scenario development and Model Intercomparison – Uranium Mill Tailings (model intercomparison) Atmospheric and aquatic release of U,Th Ra and daughters and of the stable elements Cu,As,Ni and V;

- Special Radionuclides (model intercomparison)
  Accidental release of tritium,
  Carbon-14. Not settled but four possible scenarios .
- Complementary studies;
  Transfer of contaminants on solid material,
  Exposure pathway analysis.

2 Uncertainties and Validation;
- Guidelines for Uncertainty Analysis,
- Quantification of Uncertainties,
- Use of Natural Analogue Data,
- Effects of Model Complexity on Uncertainty.

3 Reference Biosphere Scenario for Long Time Assessment ;

4 Additional themes;
- Use of post-Chernobyl Data for Model Testing,
- Environmental risk analysis.

SKB will actively take part in the work with emphasis on the third theme "Reference Biosphere Scenario for Long Time Assessment" as we believe it is of great value to get an international consensus how to deal with the conceptual uncertainties arising with time.

21.2 VALIDATION OF MODELS: VAMP

SKB is participating in an IAEA/CEC program "Validation of Models on the transfer of Radionuclides in Terrestrial, Urban and Aquatic Environment and Acquisition of Data for that Purpose" (VAMP). In this programme modelling of Cs-137 in lakes and uncertainty analysis is intercompared between several working groups from several countries. The lake model and the codes BIOPATH and PRISM are the tools SKB tries to validate in this study. The definition of the scenario was completed in 1991 and most of the modelling is also ready. To the original scenario rivers has been added as an extra receptor. The project will be reported in 1992.

21.3 VALIDATION OF MODELS: PSAC 1b

This international OECD/NEA exercise "Probabilistic Systems Assessment Code(PSAC) User Group of the OECD Nuclear Energy Agency" PSACOIN level lb deals with the verification of codes used in biospheric modelling / and uncertainty analyses. Most of the work was finalised during 1991 and a report will be published in May 1992.

Site specific studies of recipients at Äspö

This project is divided into the following three phases:

Phase I	Prestudy to find out what data is 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 1 000 to 10 000 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 during 1991 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 and in some cases neutron activation analysis was used. Measurements with gammameter have been made along two well determined profiles, complementing previous measurements. The sediment cores need long time for evaluation but they can be stored for future more extensive analysis. The work has been reported in a progress report within the Äspö laboratory series /21-5/.

Phase III has been started up in 1991 and will continue during 1992.

The flow patterns in surrounding bogs have been recorded for use in coastal zone model. Judging from the primary evaluation of the sediment cores a dynamic model describing postglacial development of the area is worthwhile to attempt.

21.4 SKB-91 SAFETY ASSESSMENT

The special safety study SKB-91 does in general not deal with the uncertainties in the biosphere but will use a set of dose conversion factors, relating release rate from the far field, directly to dose to individuals in a critical group. These dosefactors apply to a relatively conservative situation that gives high doses but still has a high probability of occurring subsequently within the studied timescale. Three cases have been studied, one central case with radionuclides reaching biosphere via a lake and partly via a well, one with all radionuclides reaching the well and one case where the sea is the recipient.

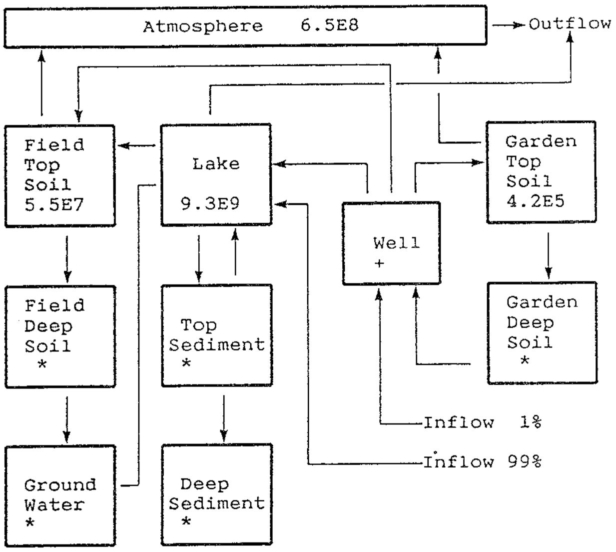


Figure 21-1. *Structure of the compartment model of the studied biosphere with masses indicated.*

This standard biosphere constituted of a well and lake with adjacent farming-land /21-6,7,8,9/. It was assumed that a fraction of 1% of the activity reached a well directly while the remaining part was directly diluted into lake water. Ten exposure pathways originating from activity in well and lake water were considered. The ecosystem was assumed to be similar to present conditions in Sweden. So was also the case concerning diet and living habits. No delay or reduction of activity by accumulation in the interphase geosphere and biosphere was considered. A seven compartment model of the studied biosphere was designed, see Figure 21-1 where flows of activity are described by arrows. The BIOPATH-code was used for solving the differential equations and calculating the doses. Adults and five year old children were considered, respectively.

The uncertainty in the results due to the uncertainty in input parameter values were examined with the PRISM-system. The major contribution to the uncertainty in the results was the dilution volume for the nuclides in the groundwater. This dilution was 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. This represents staying on the fields and the garden plots.

Results, as arithmetic mean values of the total dose are presented in Figure 21-2. All these results do not consider any contributions from daughter nuclides from disintegrations in the biosphere. These contributions were only notable for Zr-93 and Th-229. Including them the conversion factors would increase with 7 and 36 percent, respectively.

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

21.5 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. The outflow is often to 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 is reported in /21-10/. We can conclude, however, that there are no significant processes that will require a different modelling at least not with the fairly coarse methods we currently use. The enrichment of uranium is correlated to the levels of organic matter. The immobility of Ti Zr and Hf in aquatic solutions have been confirmed in this study.

21.6 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 need for techniques to model this important part of the biosphere models in a better way /21-11,12,13/. Thus, a project was initiated in 1989 to better understand the long-term modelling of the accumulation of nuclides in sediments and soils. This can be achieved by:

- extend the understanding of sorption phenomena relevant to both the biosphere and the geosphere;

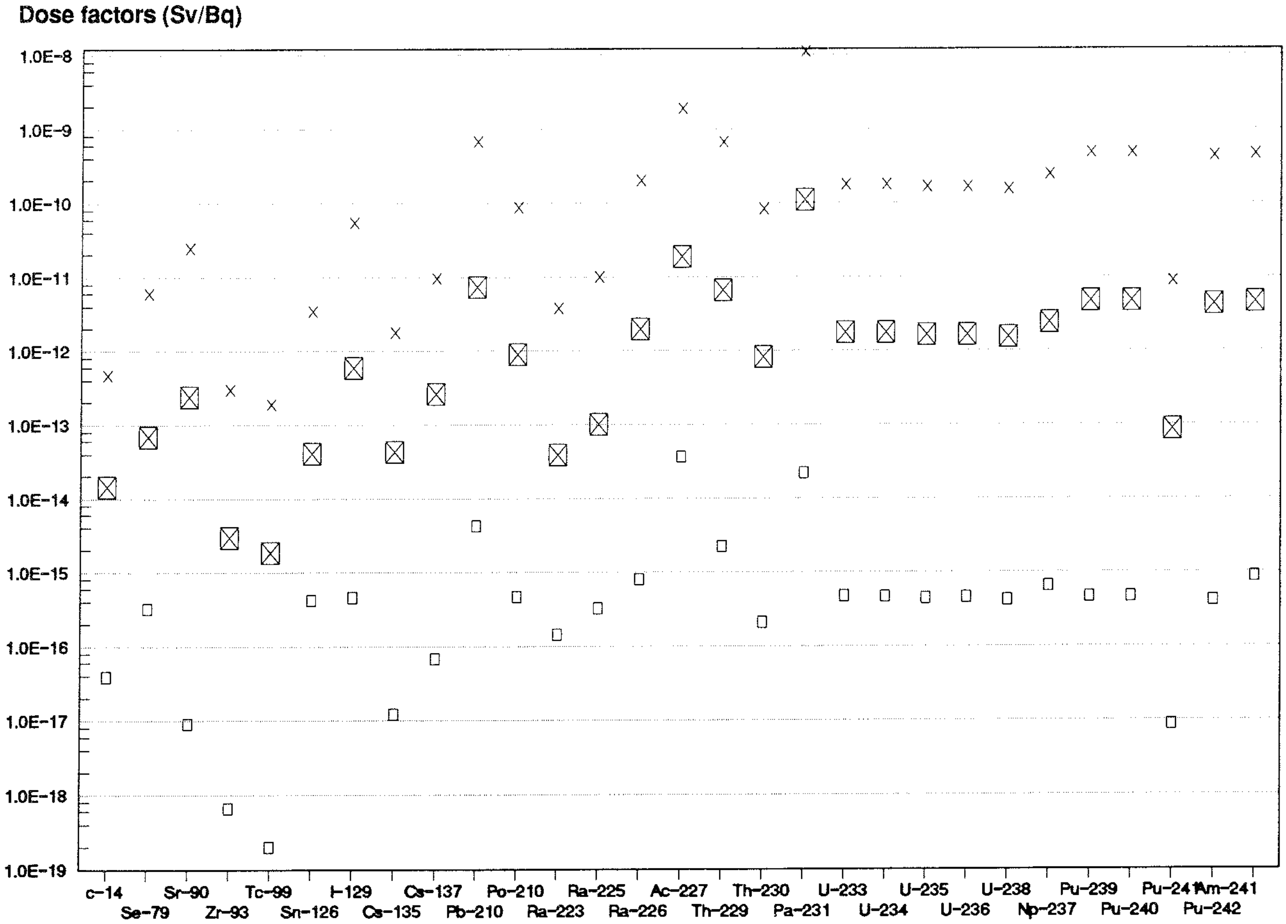


Figure 21-2. *Dose factors expressed as arithmetic mean values of the total dose for three studied cases:*

1) Squares relate to a case with total release into the Baltic Sea.
2) Crosses relate to the case where all nuclides are released to a well.
3) Crossed squares relates to a case where 1% of the nuclides are released to a well.

– 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 literature.

The study has been delayed but is expected to be reported in 1992. Some main difficulties are:

– Organic substances wont fit into thermodynamics;
– Redoxfronts in organic matter;
– Biological processes as bioturbation.

For iodine these difficulties has had great impact and this nuclide had to be dropped from the study.

21.7 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 /21-14,15,16,17,18,19,20,21/. Model evaluations are currently performed using both compartment models /21-17/ and continuous flow models /21-20/. An other main issue is the chemical properties of the observed radionuclides, currently studied by migration in soil /21-21/. Measurements of radionuclides originating from the Chernobyl accident in samples of deep and superficial ground water, soil profiles and well sediment from the Gideå and Finnsjön areas has been performed. The studied radionuclides 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 /21-20/ 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 respectively 516 days. This transport speed, discussed in /21-22, 23,24/, is surprising as some previous experiments /21-25/ have shown that i.e. Cs is strongly sorbed. Other experiments have shown a minor amount migrating almost without any retention /21-26/. A possible explanation can be the speciation or the existence of organic complex or colloids or particles. The speciation analysis have shown that Cs is not transported in the cationic Cs^+ form, as it is found in the anion exchanger or charcoal in the deep groundwater. In the surface waters, on the other hand, it is transported as a cation /21-27/.

The migration of radionuclides in the soil profiles shows that the transport in till is relatively slow compared to sand and peat (the profiles were sampled each year since 1986). Other conclusions from this study is that:

- Co-60 moves relatively 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-110 m 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.

The data from the area has been compiled into models using both compartment and finite element methods. To get a better understanding of the total flows, a soil map has been prepared for the area /21-28/. The modelling results serves as a quality control on the measurements and indicates among other things that only about 5% of the initially deposited Cs-137 has left the area after 5 years /21-29/.

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 SKB's 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,
- The former 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 group for the Hard Rock Laboratory.

TVO and SKB jointly reported 1991 existing knowledge on the importance of ice ages and related phenomena for the assessment of the repository's safety, see section 16.3.6.

Regarding waste canisters SKB and TVO have made evaluations of production methods and costs of an Advanced Cold Process Canister with an inner steel canister and an outer corrosion shield of copper, see section 14.3. During 1991 a scale 1:4 canister was manufactured.

An agreement on joint work and information exchange on alternative designs for waste repositories (The PASS-project) was signed in February 1991.

During 1991 a joint SKB/TVO investigation on the available redox capacity in crystalline rock has been carried out, see section 17.1.4.

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 relationships 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 4-year test conducted at Stripa with highly compacted French smectite clay in a simulated deposition environment at approx. 170°C has been completed, see section 15.1. The results were 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 Natural Analogues

SKB is engaged in the CEC sponsored natural analogue project in Oklo which CEA is managing, see section 20.3.

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.

During 1991 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 20.2.

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 first phase of 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/. A new phase of the CHEMVAL project called CHEMVAL2 started up during 1991 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, see section 17.2.1.

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 1991 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 technetium.

The TDB Project is a very important effort to develop a welldocumented, 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 were published 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. SKB is supplying data for this study as indicated in section 17.3.2

22.7 COOPERATION WITHIN IAEA

Cooperation has during 1991 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.

22.6.3 VAMP

SKB is participating in an IAEA/CEC program on "Validation of Models on the Transfer of Radionuclides in Terrestial, Urban and Aquatic Environment and Acquisition of Data for that Purpose" (VAMP), see section 21.2.

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 90,
- in the series of SKB Technical Reports,
- in contributions to scientific journals, symposia and conferences in different subject areas, see Appendix 2,
- in SKB 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 1991 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 1991, 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, 5/. 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 43 sites and data from 489 boreholes in many of these. Data are structured in 15 subject areas, 99 different measuring methods and 515 tables containing 4932 columns. Total data volume is only about 210 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 SKB's 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 /23-6/. An "Users Guide" /23-7/ is also available. 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 GEO-

TAB can be correctly formatted for direct use by a large number of programs and automatically transferred to the PC.

23.4 SKB BIBLIOGRAPHICAL DATABASE

SKB has built up a database containing bibliographical data and abstracts on all reports currently available in the SKB library. The database, called BIBAS, contained by the end of 1991 about 12 000 references. The software used to manage the database is AskSam which has a powerful free-text search capability.

23.5 COMPUTER SYSTEM AT SKB

23.5.1 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 are connected to local area network (LAN) of the physical type "ethernet". Three segments are connected via two pairs of ethernet bridges, operating over 64kbps lines, making the three segments appear as one LAN.

Two standard protocols are used in the network – TCP/IP and DECNET. TCP/IP is used by all 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 also used 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 2 SUN386i and 3 SUN Sparc workstations with 10 Gbyte on 10 disks, 3 2.3 Gb Exabyte and 4 QIC tape stations are used. 2 CD-Rom stations are also available. 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.

23.5.2 Minisupercomputer

The CONVEX C210 was during 1991 upgraded to a 2-processor vector computer. It has been very easy to operate, running 24 hours a day with no major problems and with the expected vector capacity of about 24 Mflops (floating point operations per second). 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 128 Mbyte main memory, 6 Gbyte on 6 disks, a 6250 bpi tape drive, 2 ethernet transceivers and 16 asyncronous ports.

23.5.3 Minicomputer

The VAX 11/750 is now conceptually more than 13 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.

23.5.4 Workstations and Measuring System

Currently the 5 SUN workstations are mainly used as PC network servers but they are of course also used as personal workstations.

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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Appendices

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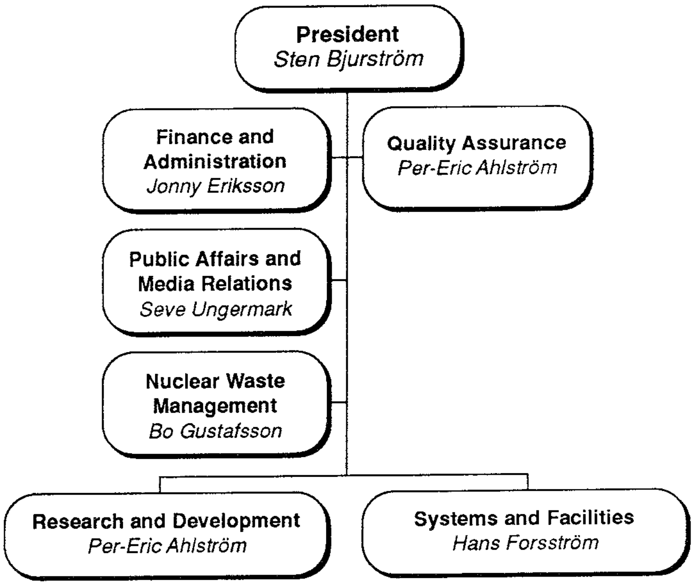

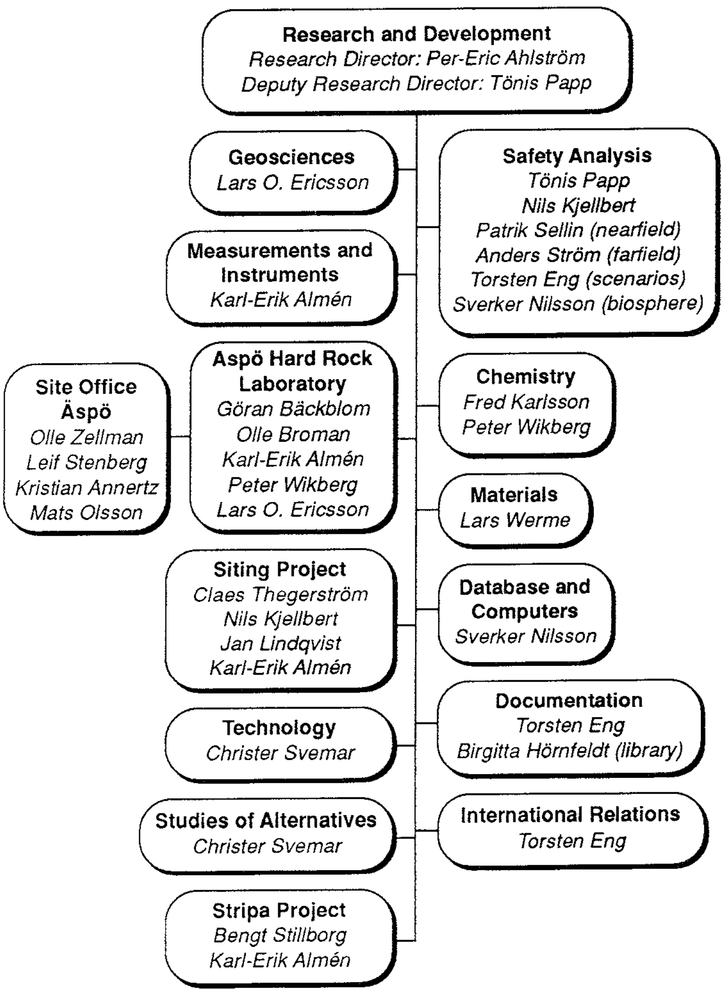

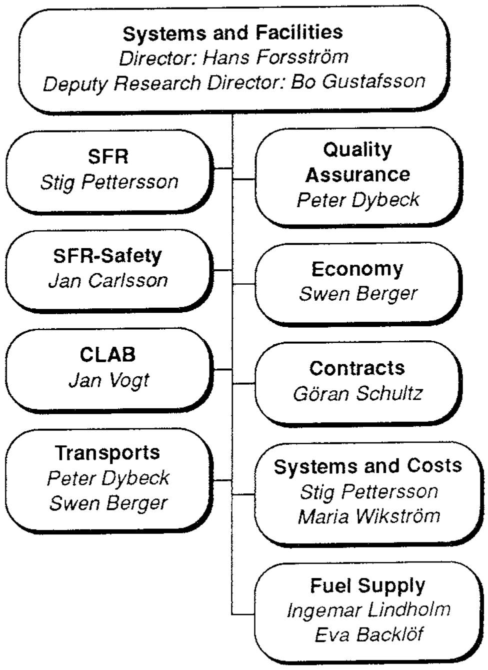

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Bengtsson, Akke; Widén, Hans
Kemakta Konsult AB
May 1991

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Casas, I 1); Sandino, A 2); Caceci, M S 1); Bruno, J 1); Ollila, K 3)
MBT Technologia Ambiental, CENT, Cerdanyola, Spain 1); KTH, Dpt. of Inorganic Chemistry, Stockholm, Sweden 2); VTT, Tech. Res. Center of Finland, Espoo, Finland 3)
September 1991

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Sandstedt, Håkan 1); Wichmann, Curt 1); Pusch, Roland 2); Börgesson, Lennart 2); Lönnerberg, Bengt 3)
Tyréns 1); Clay Technology AB 2); ABB Atom 3)
August 1991

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Ageskog, Lars; Sjödin, Kjell
VBB VIAK
September 1991

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Auerkari, Pertti; Leinonen, Heikki; Sandlin, Stefan
VTT, Metals Laboratory, Finland
September 1991

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Rajainmäki, Hannu; Nieminen, Mikko; Laakso, Lenni
Outokumpu Poricopper Oy, Finland
June 1991

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Grauer, Rolf
Paul Scherrer Institute, Switzerland
July 1991

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Sundblad, Björn; Puigdomenech, Ignasi; Mathiasson, Lena
December 1990

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Bergström, Ulla; Nordlinder, Sture
Studsvik AB
May 1991

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Sensitivity analysis of the groundwater flow at the Finnsjön study site
Bao, Yung-Bing; Thunvik, Roger
Dept. Land and Water Resources, Royal Institute of Technology, Stockholm, Sweden
September 1991

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Falk, Lars
ABEM, Uppsala, Sweden
July 1991

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Moreno, Luis; Neretnieks, Ivars
Department of Chemical Engineering, Royal Institute of Technology, Stockholm, Sweden
September 1991

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The implications of soil acidification on a future HLNW repository. Part I: The effects of increased weathering, erosion and deforestation
Nebot, Josefa; Bruno, Jordi
MBT Tecnología Ambiental, Cerdanyola, Spain
July 1991

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Some mechanisms which may reduce radiolysis
Neretnieks, Ivars; Faghihi, Mostapha
Department of Chemical Engineering, Royal Institute of Technology, Stockholm, Sweden
August 1991

TR 91-47
On the interaction of granite with Tc(IV) and Tc(VII) in aqueous solution
Eriksen, Trygve E; Cui, Daquing
Royal Institute of Technology, Department of Nuclear Chemistry, Stockholm, Sweden
October 1991

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A compartment model for solute transport in the near field of a repository for radioactive waste (Calculations for Pu-239)
Romero, Leonardo; Moreno, Luis; Neretnieks, Ivars
Department of Chemical Engineering, Royal Institute of Technology, Stockholm, Sweden
October 1991

TR 91-49
Description of transport pathways in a KBS-3 type repository
Pusch, Roland 1); Neretnieks, Ivars 2); Sellin, Patrik 3)
Clay Technology AB, Lund 1); The Royal Institute of Technology, Department of Chemical Engineering, Stockholm 2); Swedish Nuclear Fuel and Waste Management co (SKB), Stockholm 3)
December 1991

TR 91-50
Concentrations of particulate matter and humic substances in deep groundwaters and estimated effects on the adsorption and transport of radionuclides
Allard, Bert 1); Karlsson, Fred 2); Neretnieks, Ivars 3)
Department of Water and Environmental Studies, University of Linköping, Sweden 1); Swedish Nuclear Fuel and Waste Management Co, SKB, Stockholm, Sweden 2); Department of Chemical Engineering, Royal Institute of Technology, Stockholm, Sweden 3)
November 1991

TR 91-51
Gideå study site. Scope of activities and main results
Ahlbom, Kaj 1); Andersson, Jan-Erik 2);
Nordqvist, Rune 2); Ljunggren, Christer 2);
Tirén, Sven 2); Voss, Clifford 3)
Conterra AB 1); Geosigma AB 2); U.S. Geological Survey 3)
October 1991

TR 91-52
Fjällveden study site. Scope of activities and main results
Ahlbom, Kaj 1); Andersson, Jan-Erik 2);
Nordqvist, Rune 2); Ljunggren, Christer 2);
Tirén, Sven 2); Voss, Clifford 3)
Conterra AB 1); Geosigma AB 2); U.S. Geological Survey 3)
October 1991

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Impact of a repository on permafrost development during glaciation advance
Vallander, Per; Eurenius, Jan
VBB VIAK
December 1991

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Hydraulic evaluation of the groundwater conditions at Finnsjön. The effects on dilution in a domestic well
Axelsson, C-L 1); Byström, J 1); Eriksson, Å 1); Holmén, J 1); Haitjema, H M 2)
Golder Geosystem AB, Uppsala, Sweden, 1); School of Public and Environmental Affairs, Indiana University, Bloomington, Indiana, USA 2)
September 1991

TR 91-55
Redox capacity of crystalline rocks. Laboratory studies under 100 bar oxygen gas pressure
Pirhonen, Veijo; Pitkänen, Petteri
Technical Research Center of Finland
December 1991

TR 91-56

Microbes in crystalline bedrock. Assimilation of CO_2 and introduced organic compounds by bacterial populations in groundwater from deep crystalline bedrock at Laxemar and Stripa

Pedersen, Karsten; Ekendahl, Susanne; Arlinger, Johanna

Department of General and Marine Microbiology, University of Göteborg, Sweden

December 1991

TR 91-57

The groundwater circulation in the Finnsjö area – the impact of density gradients.
Part A: Saline groundwater at the Finnsjö site and its surroundings.
Part B: A numerical study of the combined effects of salinity gradients, temperature gradients and fracture zones.
Part C: A three-dimensional numerical model of groundwater flow and salinity distribution in the Finnsjö area

Ahlbom, Kaj (Part A) 1); Svensson, Urban (Part B and C) 2)

CONTERRA AB 1); CFE AB 2)

November 1991

TR 91-58

Exploratory calculations concerning the influence of glaciation and permafrost on the groundwater flow system, and an initial study of permafrost influences at the Finnsjön site – an SKB 91 study

Lindbom, Björn; Boghammar, Anders

Kemakta Konsult AB, Stockholm

December 1991

TR 91-59

Proceedings from the Technical Workshop on Near-Field Performance Assessment for High-Level Waste held in Madrid October 15-17, 1990

Sellin, Patrik (ed.) 1); Apted, Mick (ed.) 2); Gago, José (ed.) 3)

SKB, Stockholm, Sweden 1); Intera, Denver, USA 2); ENRESA, Madrid, Spain 3)

December 1991

TR 91-60

Spent fuel corrosion and dissolution

Forsyth, R S 1); Werme, Lars 2)

Studsvik AB, Nyköping, Sweden 1); Swedish Nuclear Fuel and Waste Management Co., Stockholm, Sweden 2)

December 1991

TR 91-61

Heat propagation from a radioactive waste repository. SKB 91 reference canister

Thunvik, Roger; Braester, Carol

Royal Institute of Technology, Stockholm, Sweden

March 1991

TR 91-62

The kinetics of pitting corrosion of carbon steel applied to evaluating containers for nuclear waste disposal. Final report 1991

Marsh, G P 1); Taylor, K J 2); Harker, A H 3)

Strategic Studies Department, AEA Environment and Energy, AEA Technology, Harwell Laboratory 1); Applied Electrochemistry Department, AEA Industrial Technology, AEA Technology, Harwell Laboratory 2); Theoretical Studies Department, AEA Industrial Technology, AEA Technology, Harwell Laboratory 3)

July 1991

TR 91-63

An electrochemistry-based model for the dissolution of UO_2

Shoesmith, D W; Sunder, S

AECL Research, Whiteshell Laboratories, Pinawa, Manitoba, Canada

December 1991

AUTHORS OF SKB TECHNICAL REPORTS 1991

AUTHOR	TECHNICAL REPORT NO
Ageskog, Lars VBB VIAK	*36*
Ahlbom, Kaj Conterra AB	*08, 32, 51, 52, 57*
Allard, Bert Dep. of Water and Environmental studies, Univ. of Linköping	*50*
Almén, Karl-Erik SKB	*21*
Andersson, Jan-Erik Geosigma AB	*24, 51, 52*
Andersson, Peter Swedish Geological, Uppsala	*05*
Apted, Mick Intera, Denver, USA	*59*
Arlinger, Johanna Dep. of General and Marine Microbiology, Univ. of Gothenburg	*56*
Auerkari, Pertti VTT, Metals Laboratory, Finland	*37*
Axelsson, C-L Golder Geosystem AB, Uppsala	*13, 54*
Bao, Yung-Bing Dep. Land and Water Res, Royal Inst. of Technology, Stockholm	*42*
Bengtsson, Akke KEMAKTA Konsult AB	*11, 26, 31, 33*
Bergström, Ulla Studsvik Nuclear	*41*
Bjelkås, Jan KEMAKTA Konsult AB	*12*
Boghammar, Anders KEMAKTA Konsult AB	*12, 26, 58*
Braester, Carol Royal Institute of Technology, Stockholm	*61*
Brandberg, Fredrik KEMAKTA Konsult AB	*16*
Bruno, Jordi MBT Tecnologia Ambiental, CENT, Cerdanyola, Spain	*04, 34, 45*
Byström, J. Golder Geosystem AB, Uppsala	*54*
Börgesson, Lennart Clay Technology, Lund	*35*
Caceci, M S MBT Tecnologia Ambiental, CENT, Cerdanyola, Spain	*34*
Casas, I MBT Tecnologia Ambiental, CENT, Cerdanyola, Spain	*34*
Cui, Daquing Dep. of Nuclear Chem., Royal Inst. of Technology, Stockholm	*47*
Ekendahl, Susanne Dep. of General and Marine Microbiology, Univ. of Gothenburg	*56*
Ekstav, Anders Golder Geosystem AB	*10*
Ericsson, Lars O. SKB	*32*
Eriksen, Trygve E. Dep. of Nuclear Chem., Royal Inst. of Technology, Stockholm	*47*
Eriksson, Ebbe SGAB, Luleå	*06*
Eriksson, Å Golder Geosystem AB, Uppsala	*54*
Erlström, M SedRock Consulting	*20*
Eurenius, Jan VBB VIAK	*53*

AUTHOR **TECHNICAL REPORT NO**

CONTRACTORS SKB R&D 1991

ABB Atom AB, Västerås
ABEM AB, Malå
AECL, Whiteshell Research, Ottawa, Canada
Anders Rasmuson KemTek, Mölndal
Axel Johnsson Instrument AB, Solna
Befo, Tomas Franzén, Stockholm
BERGAB - Berggeologiska Undersökningar, Gothenburg
CFE AB, Urban Svensson, Norrköping
Chalmers University of Technology, Dep. of Geology, Gothenburg
Chalmers University of Technology, Dep. of Nuclear Chemistry, Gothenburg
Chemflow AB, Stockholm
Chemima AB, Täby
Clay Technology, Lund
Conterra AB, Uppsala
EB, Olle Broman, Stockholm
Ergodata, Gothenburg
ES-konsult, Stockholm
Geokema AB, Lidingö
Geokonsult Stille AB, Upplands-Väsby
Geosigma AB
Geopoint AB, Spånga
Gesellschaft für Strahlen- und Umweltforsch., Munich, Germany
Golder Associates, Seattle, Washington, USA
Golder Geosystem AB, Uppsala
Gustafson Computing, Stavanger, Norway
Harwell Laboratory/AEA, Oxfordshire, UK
Interra Sciences, Leicestershire, UK
IPA-KONSULT AB, Oskarshamn
Itasca Geomekanik AB, Falun
JAA AB, Luleå
JP-Engineering OY, Raisio, Finland
Kemakta Konsult AB, Stockholm
Linköping University, Dep. of Water and Environmental Studies
Linköping University, Dep. of Chemistry
Luleå University of Technology, Division of Rock Mechanics
Lunds Tekniska Högskola, Avd för byggnadsteknik, Lund
MBT Tecnologia Ambiental, Cerdanyola, Spain
Measurement Systems Scandinavia AB (MSS), Åkersberga
NCC, Malmö
NEDRA, Jaroslavl, Russia
OKG AB, Oskarshamn
Rock Store Design, Rox AB, Nacka
R Stanfors Consulting AB, Lund
Roger Thunvik, Stockholm
Royal Institute of Technology, Dep. of Chemical Engineering, Stockholm
Royal Institute of Technology, Dep. of Inorganic Chemistry, Stockholm
Royal Institute of Technology, Dep. of Land and Water Res., Stockholm
Royal Institute of Technology, Dep. of Nuclear Chemistry, Stockholm
Saanio & Riekkola Oy, Helsinki, Finland
Scottish Universities Research & Reactor Centre, Glasgow, UK
SGAB Borr, Malå
Siab AB
Starprog AB, Stockholm
Studsvik Nuclear, Nyköping
SvedeFo, Finn Ouchterlony
Sveriges Geologiska Undersökning, Uppsala
Sydkraft Konsult AB, Malmö
Technical Research Centre of Finland, Helsinki, Finland
Terralogica AB
The Welding Institute, Cambridge, UK
Tyréns, Sundbyberg
Université Louis Pasteur de Strasbourg, France
University of Gothenburg, Dep. of Gen. & Marine Microbiology
University of New Mexico, Dep. of Geology, Albuquerque, USA
Uppsala University, Institute of Geology, Uppsala
Vattenfall HydroPower AB, Ludvika
VBB VIAK AB, Gothenburg
VBB VIAK AB, Stockholm
Vattenfall Energisystem AB, Vällingby
Vattenfall Ennginering AB
Vibrometic Oy, Helsingfors, Finland
Åbo University, Alf Björklund, Finland

SKB ANNUAL REPORT 1991

Part IV

Summaries of Technical Reports Issued During 1991

SKB Technical Report No 91-01

Description of geological data in SKB's database GEOTAB. Version 2

Sehlstedt, Stefan; Stark, Tomas

SGAB, Luleå

January 1991

ABSTRACT

Introduction: Since 1977 the Swedish Nuclear Fuel and Waste Management Co, SKB, has been performing a research and development programme for final disposal of spent nuclear fuel. The purpose of the programme is to aquire knowledge and data of radioactive waste. Measurements for the characterisation of geological, geophysical, hydrogeological and hydrochemical conditions are performed in specific site investigations as well as for geoscientific projects.

Large data volumes have been produced since the start of the programme, both raw data and results. During the years these data were stored in various formats by the different institutions and companies that performed the investigations. It was therefore decided that all data from the research and development programme should be gathered in a database. The database, called GEOTAB, is a relational database. It is based on a concept from Mimer Information Systems, and have been further developed by Ergodata. The hardware is a VAX 750 computer located at KRAB (Kraftverksbolagens Redovisningsavdelning AB) in Stockholm.

The database comprises six main groups of data volumes. These are:

- Background information
- Geological data
- Geophysical data
- Hydrogeological and meteorological data
- Hydrochemical data
- Tracer tests

In the database, background information from the investigations and results are stored on-line on the VAX 750, while raw data are either stored on-line or on magnetic tapes.

This report deals with geological data and describes the dataflow from the measurements at the sites to the result tables in the database. All of the geological investigations were carried out by the Swedish Geological Survey, before 820701, and by Swedish Geological Co, SGAB, after that date.

The geological investigations have been divided into three categories, and each category is stored separately in the database. They are:

- Surface Fractures
- Core Mapping
- Chemical Analyses

At SGU/SGAB the geological data were stored on-line on a PRIME 750 mini computer, on microcomputer floppy disks or in filed paper protocols. During 1987 the data files were transferred from SGAB to datafiles on the VAX computer. The data from the protocols were punched to data files either on the PRIME (before the transfer) or on the VAX. The flyleafs (tables containing background data) were also punched, transferred and loaded into the database.

In the following chapters the data flow of each of the three geological information categories are described separately.

SKB Technical Report No 91-02

Description of geophysical data in the SKB database GEOTAB. Version 2

Sehlstedt, Stefan

SGAB, Luleå

January 1991

ABSTRACT

For the storage of different types of data collected by SKB a database called GEOTAB has been created. The following data is stored in the database:

- Background data
- Geological data
- Geophysical data
- Hydrogeological and meterological data
- Hydrochemical data
- Tracer tests

This report describes the data flow for different types of geophysical measurements. The descriptions start with measurements and end with the storage of data in GEOTAB. Each process and the resulting data volume is presented separately. The geophysical measurements have been divided into the following subjects.

- Geophysical ground surface measurements
- Geophysical borehole logging
- Petrophysical measurements

Each group of measurements is described in an individual chapter. In each chapter several measuring techniques are described and each method has a data table and a flyleaf table in GEOTAB.

SKB Technical Report No 91-03

1. **The application of PIE techniques to the study of the corrosion of spent oxide fuel in deep-rock ground waters.**
2. **Spent fuel degradation.**

Forsyth, R S

Studsvik Nuclear

January 1991

ABSTRACT

The direct disposal of spent fuel is an increasingly favoured alternative to fuel reprocessing and subsequent vitrification of the highly active waste solutions for the closure of the nuclear fuel cycle. The direct disposal route is based on a multi-barrier concept, one barrier being the corrosion resistance of the fuel itself. Corrosion of spent fuel in groundwaters is being studied in several countries, and the results currently available suggest three, partly overlapping, processes, of which two in particular are dependent on structural changes and migration effects produced in the fuel during reactor irradiation. Thus, in order to be able to define and quantify these processes for the purpose of safety analysis, it is necessary that, in addition to extensive leachant analysis after corrosion tests, PIE techniques are applied to the detailed study of spent fuel both before and after water contact. This paper presents results and observations from the Swedish programme which illustrate the problems involved.

SKB Technical Report No 91-04

Plutonium solubilities

Puigdomènech, I 1); Bruno, J 2)

Environmental Services, Studsvik Nuclear, Nyköping, Sweden 1); MBT Tecnologia Ambiental, CENT, Cerdanyola, Spain 2)

February 1991

ABSTRACT

Thermochemical data has been selected for plutonium oxide, hydroxide, carbonate and phosphate equilibria. Equilibrium constants have been evaluated in the temperature range 0 to 300°C at a pressure of 1 bar for $T \leq 100°C$ and at the steam saturated pressure at higher temperatures.

Measured solubilities of plutonium that are reported in the literature for laboratory experiments have been collected. Solubility data on oxides, hydroxides, carbonates and phosphates have been selected. No solubility data were found at temperatures higher than 60°C.

The literature solubility data have been compared with plutonium solubilities calculated with the EQ3/6 geochemical modelling programs, using the selected thermodynamic data for plutonium.

SKB Technical Report 91-05

Description of tracer data in SKB's database GEOTAB. Version 1

Andersson, Peter 1); Gerlach, Margareta 2)

Swedish Geological, Uppsala 1); Swedish Geological, Luleå 2)

April 1991

ABSTRACT

During the research and development program performed by SKB for the final disposal of spent nuclear fuel, a large quantity of geoscientific data is collected. Most of this data is stored in a database called GEOTAB. Here, the data is organized into eight groups (subjects) as follows:

- Background
- Geology
- Geophysical borehole logging
- Ground surface geophysical methods
- Geohydrological and meteorological measurements
- Chemical methods
- Tracer methods
- Petrophysical measurements

The present report describes data within the Tracer methods group (tracer subject).

The results of the tracer investigations have been divided into five subgroups (methods) and each method is presented separately in the database. In addition there is a method with check tables for tracer and injection types.

DILUTION	Dilution Test
DIPOLE	Dipole Test
FLUSH	Flushing Water Test
RADCON	Radially Converging Test
RADDIV	Radially Diverging Test
TRCHECK	Check tables

A method consists of one or several data tables. In each chapter a method and its data tables are described.

SKB Technical Report No 91-06

Description of background data in the SKB database GEOTAB. Version 2

Eriksson, Ebbe; Sehlstedt, Stefan

SGAB, Luleå

March 1991

ABSTRACT

During the research and development program performed by SKB for the final disposal of spent nuclear fuel, a large quantity of geoscientific data was collected. Most of this data was stored in a catabase called GEOTAB. The data is organized into eight groups (subjects) as follows:

- Background information
- Geological data
- Borehole geophysical measurements
- Ground surface geophysical measurements
- Hydrogeological and meteorological data
- Hydrochemical data
- Petrophysical measurements
- Tracer tests

Except for the case of borehole geophysical data, ground surface geophysical data and petrophysical data, described in the same report, the data in each group is described in a separate SKB report.

The present report describes data within the Background data group. This data provides information on the location of areas studied, borehole positions and also some drilling information.

Data is normally collected on forms or as notes and this is then stored into the database.

The background data group (subject), called BACKGROUND, is divided into several subgroups (methods).

- BGAREA area background data
- BGDRILL drilling information
- BGDRILLP drill penetration data
- BGHOLE borehole information
- BGTABLES number of rows in a table
- BGTOLR data table tolerance

A method consists of one or several data tables. In each chapter a method and its data tables are described.

SKB Technical Report 91-07

Description of hydrogeological data in SKB's database GEOTAB. Version 2

Gerlach, Margareta (ed.)

Mark Radon Miljö MRM Konsult AB, Luleå

December 1991-12

ABSTRACT

During the research and development program performed by SKB for the final disposal of spent nuclear fuel, a large quantity of geoscientific data was collected. Most of this data was stored in a database called GEOTAB. The data is organized into eight groups (subjects) as follows:

- Background information
- Geological data
- Borehole geophysical measurements
- Ground surface geophysical measurements
- Hydrogeological and meteorological data
- Hydrochemical data
- Petrophysical measurements
- Tracer tests

Except for the case of borehole geophysical data, ground surface geophysical data and petrophysical data, described in the same report, the data in each group is

The present report describes data within the hydrogeological data group.

The hydrogeological data group (subject), called HYDRO, is divided into several subgroups (methods).

BHEQUIPE	: Equipments in Boreholes
CONDINT	: Electrical Conductivity in Pumped Water
FLOWMETE	: Flowmeter Tests
GRWB	: Groundwater Level Registrations in Boreholes
HUFZ	: Hydraulic Unit Fracture Zones
HURM	: Hydraulic Unit Rock Mass
HYCHEM	: Hydraulic Test during Chemical Sampling
INTER	: Interference Tests
METEOR	: Meteorological and Hydrological Measurements
PIEZO	: Piezometric Measurements at Depths in Boreholes
RECTES	: Recovery Tests
ROCKRM	: Hydraulic Unit Rock Types in the Rock Mass

SFHEAD	: Single Hole Falling Head Test
SHBUP	: Single Hole Build Up Test
SHSINJ	: Single Hole Steady State Tests
SHTINJ	: Single Hole Transient Injection Tests
SHTOLD	: Single Hole Transient Injection Tests – Old Data

A method consists of one or several data tables. In each chapter a method and its data tables are described.

SKB Technical Report No 91-08

Overview of geologic and geohydrologic conditions at the Finnsjön site and its surroundings

Ahlbom, Kaj 1); Tirén, Sven 2)

Conterra AB 1); Sveriges Geologiska AB 2)

January 1991

ABSTRACT

The geologic and tectonic conditions of the Finnsjön site and its surroundings have been studied on several scales ranging from regional to site scale. The Finnsjön study site is situated within a 50 km^2 shear lens. This lens is a part of a regional, c. 20-30 km wide, WNW trending shear belt that was developed 1600 – 1800 million years ago. The final repository for reactor waste (SFR) at Forsmark is also situated within this shear belt.

The Finnsjön Rock Block, bounded by regional and semi-regional fracture zones, constitute the main part of the Finnsjön site. The size of the block is about 6 km^2. A northeasterly trending fracture zone, Zone 1, divides this block into two lower order blocks, the northern and the southern block.

In general, interpreted fracture zones, as well as the rock mass in general, are far better known in the northern Finnsjön block compared to the southern block. This is due to extensive and detailed investigations of a gently dipping fracture zone, Zone 2, in the northern block.

A tectonic model including 14 fracture zones is suggested for the Finnsjön site and its surroundings. These zones have mainly been interpreted from lineament maps and to some extent from borehole measurements. The lack of borehole data implies that many of interpreted fracture zones, especially in the southern block and outside the Finnsjön site, should be regarded as tentative.

The good general knowledge of the geologic and geohydrologic conditions in the northern Finnsjön block, and possible stagnant groundwater conditions below Zone 2, makes the northern block the most suitable location for the generic repository at the Finnsjön site.

SKB Technical Report No 91-09

Long term sampling and measuring program. Joint report for 1987, 1988 and 1989. Within the project: Fallout studies in the Gideå and Finnsjö areas after the Chernobyl accident in 1986

Ittner, Thomas

SGAB, Uppsala

December 1990

ABSTRACT

A redistribution and migration study of the Chernobyl fallout begun in 1986. It was realized in an early stage that the fallout from Chernobyl could be used as a large scale tracer study. After one early sampling and measurement it was concluded that at least five of the radioactive nuclides could be used in a long term perspective. The sorption and migration of these elements in geohydrological systems have been investigated during a period of three and a half years and a model of the redistribution is now prepared.

The basis for successful modelling of the redistribution of fallout products within a small catchment area is dependent on accurate input. A repeated sampling of geological materials (and the following determination of the radionuclide concentration), and "direct" measurement of gamma radiation in feld, will then be needed.

This report is a summary of the work that has been performed during 1987, 1988 and 1989 within sampling and measurement of radionuclide content in geological materials and surface vegetation. Migration studies and modelling work are other parts of the project that are not presented here.

The collecting of field data is mainly done in an small catchment area (0.74 km^2) c. 30 km N-E of the city of Örnsköldsvik, county of Västernorrland. A minor field study is also done in an area east of Lake Finnsjön, situated c. 50 km north of the city of Uppsala.

The conclusions that can be drawn from the Gideå study site surface measurements are that the gamma radiation in general is decreasing with varying magnitude. But the picture is not all unambiguous. In the subsurface layers of studied soil profiles, an increase can be observed in the upper part of the enriched layer. The outflow of radionuclides with ground water seems to be fairly constant after the peak flow in 1986. Some indications of larger transport and outflow of radionuclides in connection with heavy rain or spring flood is also present.

Results from the Finnsjö area are not yet be complete. Many of the samples are still waiting for their gamma spectra to be analyzed and evaluated.

SKB Technical Report No 91-10

Sealing of rock joints by induced calcite precipitation. A case study from Bergeforsen hydro power plant

Hakami, Eva 1); Ekstav, Anders 2); Qvarfort, Ulf 2)

Vattenfall HydroPower AB 1); Golder Geosystem AB 2)

January 1991

ABSTRACT

The possibilities of sealing rock fractures by injecting water saturated with calcite solution, and hereby inducing a calcite precipitation inside the fracture, is investigated. The way of reaction and the amount of calcite precipitation will depend on the saturation of calcium carbonate in the water, the temperature, the pH and the CO_2-pressure.

There is experience of lime-saturated water injection in the rock foundation below the dam at Bergeforsens power plant (1955-1968). It was observed that the consumption of injected lime water decreased with time.

A possible reason to the decrese in lime water consumption is that calcite has precipitated such that the permeability of the rock in general is lowered. Another explanation to this could be that calcite precipitation is concentrated to the fractures surrounding the injection holes, thus preventing the lime water from penetrating further into the rock.

It is recommended that further studies of the fracture fillings in drill cores from Bergeforsen is performed. The aim of such a study should be to determine the extent of induced calcite precipitation and to investigate its chemical and physical properties.

SKB Technical Report No 91-11

Impact from the disturbed zone on nuclide migration – a radioactive waste repository study

Bengtsson, Akke 1); Grundfelt, Bertil 1); Markström, Anders 1); Rasmuson, Anders 2)

KEMAKTA Konsult AB 1); Chalmers Institute of Technology 2)

January 1991

ABSTRACT

During excavation of tunnels in crystalline rock a permeable zone is developed around the tunnel wall periphery – a disturbed zone. In the present report both numerical and analytical calculations have been performed to evaluate the importance of the disturbed zone for radionuclide migration from a final storage of radioactive waste.

The magnitude of the groundwater flow rate within the disturbed zone depends on the orientation of the repository tunnels relative the regional flow direction. The largest flow rate increase is obtained when the regional flow direction is parallel to the tunnel principal axis. In this case the magnitude of the flow rate increase is approximately proportional to the permeability contrast between the disturbed zone and the undisturbed rock. For flow transverse the tunnel axis the flow rate increase is limited to maximum twice the flow in the undisturbed rock.

In the numerical groundwater flow calculations, particles have been released hom the positions of the canisters below the tunnel floor. The results show that at least some of the pathways from the canisters reach to the disturbed zone when the tunnel axis is oriented parallel to the regional flow.

The radionuclide migration calculations show that the nuclide transport velocity within the disturbed zone might be faster than the transport velocity in the undisturbed rock.

Finally, it is concluded that there is a need for a more accurate study of the modelling strategy for the near-feld in order to account for the release of radionuclides to the disturbed zone.

SKB Technical Report No 91-12

Numerical groundwater flow calculations at the Finnsjön site

Lindbom, Björn; Boghammar, Anders; Lindberg, Hans; Bjelkås, Jan

Kemakta Consultants Co., Stockholm

February 1991

ABSTRACT

The Swedish Nuclear Fuel and Waste Management Company (SKB) has initiated a research project called SKB 91, which is related to performance assessment of repositories for high level waste from nuclear power plants. Specifically the Finnsjön site is of concern. As part of this research project, the present report describes groundwater flow calculations at the Finnsjön site, located in northern Uppland, approximately 150 km north of Stockholm. The calculations have been performed with the finite element method applying the porous media approach. The project comprises three steps, the first of which is concerned with the presence of salt below a hydraulically significant structure. This step was modelled in two dimensions in a semi-generic fashion, while the two following steps comprised three-dimensional modelling of the site at a semi-regional and a local scale.

The semi-regional model covered approximately 43 km^2 while the area of the local model was roughly 6.6 km^2. The semi-regional model included well expressed regional fracture zones that were explicitly modelled in a deterministic manner. Apart from a few of these regional fracture zones present on the semi-regional scale, the local model also consisted of some minor, less expressed local fracture zones. These were implicitly modelled in a manner so that their hydraulic properties were averaged over the elements that were crossed by these zones. In order not to have the fracture properties averaged over too large distances, the mesh on the local scale was extremely fine discretised.

The modelling was performed with the finite element code NAMMU, used together with the program package HYPAC. The latter was used for pre- and postprocessing purposes. The modelling was performed with 8-noded brick elements for the three-dimensional calculations, and the two-dimensional model involved the use of 8-noded rectangular elements. NAMMU and HYPAC are both implemented on a Convex computer, model C-210.

The present report is a revised version of a report previously published as a working report. The difference between the present report and the previous one, is that the present report describes the conclusions more site-specifically, the presentation of a number of the cases tackled has been pruned down, some editorial effort has been put into having the volume of the report reduced, and finally the Summary has been edited and cut down.

The project has been carried out under contract from SKB. The background data has been supplied by the Swedish Geological Company (SGAB).

SKB Technical Report No 91-13

Discrete fracture modelling of the Finnsjön rock mass. Phase 1: Feasibility study

Geier, J E; Axelsson, C-L

Golder Geosystem AB, Uppsala

March 1991

ABSTRACT

The geometry and properties of discrete fractures are expected to control local heterogeneity in flow and solute transport within crystalline rock in the Finnsjön area. Safety assessment of a generic repository located in this rock must take this local heterogeneity into account. The present report describes the first phase of a discrete-fracture modelling study, the goal of which is to develop stochastic-continuum and channel-network descriptions of the Finnsjön rock based upon observed fracture geometric and hydrologic properties. In the first phase of this study, the FracMan discrete fracture modelling package was used to analyse discrete fracture geometrical and hydrological data. Constant-pressure packer tests were analysed using fractional dimensional methods to estimate effective transmissivities and flow dimension for the packer test intervals. Discrete fracture data on orientation, size, shape, and location were combined with hydrologic data to develop a preliminary conceptual model for the conductive fractures at the site. The variability of fracture properties was expressed in the model by probability distributions. The preliminary conceptual model was used to simulate three-dimensional populations of conductive fractures in 25 m and 50 m cubes of rock. Transient packer tests were simulated in these fracture populations, and the simulated results were used to validate the preliminary conceptual model. The calibrated model was used to estimate the components of effective conductivity tensors for the rock by simulating steady-state groundwater flow through the cubes in three orthogonal directions. Monte Carlo stochastic simulations were performed for alternative realizations of the conceptual model. The number of simulations was insufficient to give a quantatative prediction of the effective conductivity heterogeneity and anisotropy on the scales of the cubes. However, the results give preliminary, rough estimates of these properties, and provide a demonstration of how the discrete-fracture network concept can be applied to derive data that is necessary for stochastic continuum and channel network modelling.

SKB Technical Report No 91-14

Channel widths

Palmqvist, Kai; Lindström, Marianne

BERGAB-Berggeologiska Undersökningar AB

February 1991

ABSTRACT

At the request of SKB, BERGAB-Berggeologiska Undersökningar AB have carried out a study of documented water leakage in two TBM tunnels.

The hydrogeological mapping of the tunnels include a classification of leakage according to flowrate and width. This report is based upon the hydrogeological mapping and gives a further analysis of the documented data. The objective is to study the distribution of flowrates and leak widths in channels. Further the object has been to examine if the flowrates are dependent of the widths.

SKB Technical Report 91-15

Uranite alteration in an oxidizing environment and its relevance to the disposal of spent nuclear fuel

Finch, Robert; Ewing, Rodney

Department of Geology, University of New Mexico, USA

December 1990

ABSTRACT

Uraninite is a natural analogue for spent nuclear fuel because of similarities in structure (both are fluorite structure types) and chemistry (both are nominally UO_2). Effective assessment of the long-term behavior of spent fuel in a geologic repository requires a knowledge of the corrosion products produced in that environment. UO_2 retains the fluorite structure when oxidized to $UO_{2.25}(U_4O_9)$. Further oxidation in laboratory experiments indicates formation of $UO_{2.33}(U_3O_7)$, $UO_{2.67}$ (U_3O_8) and amorphous UO_3; analogous anhydrous oxides have not been confirmed in nature. Hydrous uranyl oxides schoepite ($UO_3 \cdot 2H_2O$), dehydrated schoepite ($UO_3 \cdot 0.8 - 1.0\,H_2O$), becquerelite ($CaU_6O_{19} \cdot 10H_2O$); and hydrous uranyl silicates, including uranophane $Ca(UO_2)_2$ (SiO_3 OH) $5H_2O$), boltwoodite ($K(H_3O)$ (UO_2) $SiO_4 \cdot n\,H_2O$, sklodowskite ($Mg(UO_2)_2(SiO_3OH) \cdot 5H_2O$), and perhaps haiweeite ($3CaO \cdot 4UO_3 \cdot 10SiO_2 \cdot 24H_2O$), have also been identified in corrosion studies on UO_2 or spent fuel; these phases are all known in nature. The uranyl oxide hydrates possess layer-type structures similar to orthorhombic U_3O_8 with large, low-valence cations (e.g. Ca^{2+}, Ba^{2+}, Pb^{2+}) and water molecules occupying exchangeable interlayer sites. This is important to the alteration and paragenesis of these phases and for the potential role of the uranyl oxide hydrates as "scavengers" for radionuclides and fission products. No uranyl phosphates or other complex uranyl phases have been identified in laboratory experiments, although such phases are common in the nature. More than 160 naturally-occurring uranyl phases are known, but fewer than 20 uranyl phases have been identified to date in laboratory corrosion studies.

Several important natural analogue sites are reviewed, illustrating a wide variety of environments from oxidizing to reducing, including, among others: Cigar Lake, Canada, a uraninite-bearing ore body at depth within a strictly reducing environment; the ore body has "seen" extensive groundwater interaction with virtually no significant oxidation or mobilization of U apparent. Koongara, Australia is a highly altered uraninite-bearing ore body partially exposed to meteoric water; alteration at depth has resulted from interaction with groundwater having a somewhat reduced Eh compared to the surface. Uraninite, Pb-uranyl oxide hydrates and uranyl silicates control U solubility at depth; uranyl phosphates and U adsorption onto clays and FeMn-oxides control U solubility near the surface. Poços de Caldas, Brazil displays a redox front moving through uraninite-bearing rocks near the surface and shows local remobilization of U. Oklo, Gabon, a uraninite- and coffinite-bearing ore body, locally affected by intense hydrothermal alteration during fission reactions, demonstrates restricted radionuclide and fission product transport within a reducing environment. A current study being conducted by the authors at Shinkolobwe, Zaire, a uraninite-bearing ore body exposed to highly oxidizing conditions at the surface, provides over 50 species of uranyl phases for detailed study, and illustrates a complex uranyl phase paragenesis over several million years, from earliest-formed uranyl oxide hydrates and uranyl silicates to later-formed uranyl phosphates.

SKB Technical Report 91-16

Porosity, sorption and diffusivity data compiled for the SKB 91 study

Brandberg, Fredrik; Skagius, Kristina

Kemakta Consultants Co, Stockholm

April 1991

ABSTRACT

The SKB 91 study is an integrated safety analysis of the KBS-3 concept of a repository located in the Finnsjön area. For this study, values of important transport parameters in the bentonite backfill and in the rock are proposed. K_d-values, diffusivities and diffusion porosity for different elements in compacted MX-80 bentonite are based on experimental data found in the literature. With regard to sorption, both a best estimate and a conservative value is given. Because sorption on bentonite is very much dependent on the conditions prevailing and experimental data are limited and not necessary representative for the conditions expected in the repository, the proposed best estimate values may include large uncertainties.

Data proposed for rock are matrix diffusivities, matrix porosity and diffusivity in mobile bulk water. These values are based on experimental results on Finnsjö rock.

SKB Technical Report 91-17

Seismically deformed sediments in the Lansjärv area, Northern Sweden

Lagerbäck, Robert

May 1991

ABSTRACT

Many fault scarps, interpreted as post- or late-glacial in age, occur in northern Sweden and adjacent parts of Finland and Norway. The dimensions of the fault scarps, extending up to about 150 km and with vertical displacements between 5 and 30 m, suggest that the faulting may have been associated with violent seismic activity. This assumption is supported by numerous landslides occuring in the vicinity of the fault scarps. The conception of strong seismic activity connected with the faulting is also strongly supported by the fact that different types of sediment deformation, interpreted as being seismically induced, were found in the Lansjärv area in northern Sweden when actively sought after. The types of deformation observed occur mainly in layered sandy and silty sediments but are also recorded in glacial till. Deformation is thought to be due to vibration, liquefaction and compaction of unconsolidated and saturated deposits. Extensive deformation proved to be very common in sediments deposited, or already in existence, during the deglaciation phase or shortly after whilst almost no deformation was found in younger deposits. This agrees fully with the concept of a short-lived early post-glacial co-seismic faulting. The report presents an exposition of the different types of sediment deformation found in the Lansjärv area and aims to serve as reference material when studying possible seismites in other areas.

SKB Technical Report 91-18

Numerical inversion of Laplace transforms using integration and convergence acceleration

Gustafson, Sven-Åke

Rogaland University, Stavanger, Norway

May 1991

ABSTRACT

This report describes a computational scheme for the numerical inversion of Laplace transforms in the case when all singularities occur on the real line. The determination of the value of the inverse function at a given point *t* proceeds in four major steps:

* Using the Bromwich inversion formula the inverse is represented as an integral over an infinite interval.
* By means of the trapezoidal rule this integral is written as an infinite sum
* The sum is converted to a power series.
* This power series is evaluated using convergence acceleration.

In order to carry out the last step in an efficient way an aggregation of terms is employed to ensure stability and rapid convergence. The truncation error decreases exponentially with the number of terms used and this fact may be exploited in error estimation and the selection of corresponding parameters in the computer programs. If certain general conditions are satisfied, then only a finite number of parameters is required to specify a function with a preselected accuracy. Thus the values of the inverse transform are calculated on a finite grid, and the transform is determined at all other points with interpolation. It is described how to construct the grid to guarantee that the resulting error does not surpass a bound, defined by the user. An inversion routine based on the ideas put forth in this report has been developed for use with the PROPER code package.

SKB Technical Report 91-19

NEAR21 - A near field radionuclide migration code for use with the PROPER package

Norman, Sven 1); Kjellbert, Nils 2)

Starprog AB 1); SKB AB 2)

April 1991

ABSTRACT

The near field radionuclide migration computer code NEAR21 has been developed as a submodel of the probabilistic package PROPER, and can be considered a PROPER version of the near field models used in the KBS-3 study.

NEAR21 computes the migration rates of radionuclide chains from the near field of one KBS-3 canister. Diffusive transport, canister corrosion, fuel matrix dissolution, solubility limitations under oxidizing and reducing conditions, washout of instantly released portions of the inventories and chain decay are all taken into account.

SKB Technical Report 91-20

Äspö Hard Rock Laboratory. Overview of the investigations 1986-1990

Stanfors, R; Erlström, M; Markström, I

June 1991

ABSTRACT

In order to prepare for the siting and licensing of a spent fuel repository SKB has decided to construct a new underground research laboratory.

The pre-investigations for the Äspö Hard Rock Laboratory started in late 1986.

This report gives a comprehensive compilation of the different investigations performed during the pre-investigation phase (1986-1990). The information is mainly compiled in CAD-generated maps and illustrations in which the reader can gather information concerning the scope of work as well as references to more detailed reports for further study.

SKB Technical Report 91-21

Äspö Hard Rock Laboratory. Field investigation methodology and instruments used in the pre-investigation phase, 1986-1990

Karl-Erik Almén, Olle Zellman

December 1991

ABSTRACT

The Äspö Hard Rock Laboratory project started in 1986. The pre-investigation phase, 1986-1990, involved extensive field measurements from the surface as well as from boreholes, aimed at characterizing the rock formation with regard to geology, geohydrology, hydrochemistry and rock mechanics.

The field investigation methodology used in the project was based on experience from and developments during the previous SKB Study Site investigation programme. However, in some respects the techniques were changed or modified. Major changes have been possible due to a new drilling technique, telescope-type drilling.

This report describes the logistics of the investigation programme, characterized to a large extent by multi-purpose planning and performance of the activities in order to optimize the use of available resources: time, personnel and equipment.

Preliminary hydraulic testing and groundwater sampling were conducted during the drilling of each borehole. When the drilling was completed an extensive set of singlehole investigations were carried out: geophysical logging, borehole radar, hydraulic tests of different kinds, water sampling and rock stress measurements.

Multipackers were installed in the boreholes as soon as possible after the borehole investigations. The system enables monitoring of groundwater pressure, water sampling and groundwater flow measurements to be performed by means of dilution tests and tracer injection. Boreholes with such equipment were used as obseNation holes during interference pumping tests and long term hydraulic and tracer tests. The monitoring programme will continue during the subsequent phases of construction and operation of the Äspö Hard Rock Laboratory.

SKB Technical Report 91-22

Äspö Hard Rock Laboratory. Evaluation and conceptual modelling based on the pre-investigations 1986-1990

Wikberg, P (ed); Gustafson, G; Rhén, I; Stanfors, R

June 1991

ABSTRACT

In order to prepare for the siting and licensing of a spent fuel repository SKB has decided to construct a new underground research laboratory.

The pre-investigations for the Äspö Hard Rock Laboratory started late in 1986. Intermediate reports on the investigations were published in 1988 and 1989.

The investigations have been grouped to several geometric scales under the disciplines of geology, geohydrology and groundwater chemistry, transport of solutes and mechanical stability.

Geological mapping and geophysical measurements have been made both on a regional and on a site scale. On the site scale additional surface measurements, drilling of 35 percussion boreholes and 19 cored boreholes was made. The results of the geological investigations show that the Äspö bedrock is a complex mixture between Småland granite, Äspö diorite and fine grained granite. The island is divided into a southern and a northern block by a shear zone, with a strike to the NE.

Hydraulic and chemical data was collected from existing well records within the Kalmar County. Hydraulic conductivity measurements and interference pumping tests were made in the core drilled holes and to some extent in the percussion holes. The hydraulic conductors are basically the fracture zones, but one of the most important is a NNW striking system of single fractures which is difflcult to distinguish geologically.

The chemical conditions of the groundwater and the fracture minerals from waterbearing sections of the core drilled holes have been examined. Water samples were collected from percussion boreholes. The groundwater can be divided into three cathegories. Fresh water down to approximately 50 m depth. Mixed fresh and seawater 50-100 m, present and/or relict seawater 100-500 m and old (relict) seawater below a depth of 500 m.

An important task in the evaluations is to set up "conceptual models". These models are the basis for calculations of the ambient groundwater situation and the way in which the hydrological regime will change during the excavation of the laboratory.

In order to allow for different levels of detail the conceptual models are established on different scales. The geometrical scales chosen are 500 m, 50 m and 5 m. For every scale a lithological-structural model is presented. This basic model is supplemented with hydraulic properties and data on groundwater chemistry. Depending on the scale, deterministic or stochastic methods have been used to facilitate interpretation.

SKB Technical Report 91-23

Äspö Hard Rock Laboratory. Predictions prior to excavation and the process of their validation

Gustafsson, Gunnar; Liedholm, Magnus; Rhén, Ingvar; Stanfors, Roy; Wikberg, Peter

June 1991

ABSTRACT

In order to prepare for the siting and licensing of a spent fuel repository SKB decided to construct a new underground research laboratory.

The pre-investigations for the Äspö Hard Rock Laboratory started in late 1986. Intermediate reports on the investigations were published in 1988 and 1989. This report presents those predictions made prior to excavation of the laboratory. These predictions are based on data collected during the pre-investigations conducted between 1986 and 1990.

Comparisons between the predictions and observations will be made during excavation in order to verify the reliability of the pre-investigations.

The predictions concern five key questions: geological structures, groundwater flow, groundwater chemistry, transport of solutes and mechanical stability. These predictions are made in three scales: site scale (100-1000 m), block scale (10-100 m) and detailed scale (0-10 m).

SKB Technical Report 91-24

Hydrogeological conditions in the Finnsjön area. Compilation of data and conceptual model

Andersson, Jan-Erik; Nordqvist, Rune; Nyberg, Göran; Smellie, John; Tirén, Sven

February 1991

ABSTRACT

Introduction: The objective of this report is to give a detailed description of the hydrogeological conditions of the Finnsjön area. The intention is that the report should provide sufficient input data needed for a variety of model campaigns planned for the safety assessment (SKB-91) of a generic repository located at the Finnsjön site. Thus, in the report all available data of potential use for different kinds of groundwater flow and transport models and hydrochemical models are included together with an assessment of the quality of the data and a brief description of the actual sampling and analysis methods used. In addition, all previously modelling efforts within the Finnsjön area are briefly summarized. The report mainly constitutes an updating and extension of the previous report by Carlsson and Gidlund (1983) concerning the hydrogeological conditions in the Finnsjön area.

The present report is an updated version of the report by Andersson et al. (1989b) with the same title and issued as SKB Progress Report 89-24. The updated parts mainly concern Section 4.2 (Hydraulic units) in which slight modifications of the hydraulically conductive fracture zone intervals in some of the boreholes have been made according to the updated geological interpretation by Ahlbom and Tirén (1991) and consequences hereof on the conceptual model in Sections 9.1-4. Furthermore, additional fracture mapping data for fracture network modelling have been described in Section 7.6 and listed in Appendix 9:2.

In the present report the same definitions of regional, semi-regional and local areas are used as in the geological overview report by Ahlbom and Tirén (1989, 1991). In addition, a semi- regional and local area for the hydrogeological modelling is proposed. A subdivision of hydraulic conductivity data in hydraulic units according to the geological interpretation has been made together with an identification of possible model boundaries, e.g major fracture zones.

As a background to the following chapters a location map of the Finnsjön area showing borehole locations and some of the fracture zones is presented in Figure 1.1 (see document). The regional and semi-regional areas, defined by Ahlbom and Tirén (1989, 1991) are shown in Figures 1.2 and 1.3, respectively. The semi-regional area includes the Finnsjön Rock Block in its central part.

Chapter 2 summarizes the hydrology and water balance of northern Uppland and the Finnsjön area. Chapter 3

describes the groundwater head conditions, Chapter 4 presents all available hydraulic parameters calculated from single-hole tests and interference tests and a subdivision of data in hydraulic units together with a geostatistical analysis of hydraulic conductivity data. Chapter 5 presents the results of tracer tests, dilution tests and an estimation of the natural groundwater flow within Zone 2 and the conductive fracture frequency in selected boreholes. Chapter 6 summarizes the hydrochemical data of groundwater from the Finnsjön area. Chapter 7 provides statistical data of lineaments and fractures on different scales. Chapter 8 summarizes the previous modelling of the Finnsjön area. In Chapter 9 conceptual models of the hydrogeological conditions on semi-regional and local scales are presented. Finally, a data summary including the accessibility of the data is presented in Chapter 10.

SKB Technical Report 91-25

The role of the disturbed rock zone in radioactive waste repository safety and performance assessment. A topical discussion and international overview

Winberg, Anders

Conterra AB

June 1991

ABSTRACT

A discussion was presented of the role and relative importance of the disturbed rock zone (DRZ) around the underground openings of a repository for nuclear waste in crystalline rock. The term disturbed rock zone was defined and possible criteria to be used to distinguish it from undisturbed rock was suggested.

The processes decisive for the hydraulic characteristics of the DRZ were discussed. With regard to the integral hydraulic characteristics of the DRZ, the effects of the excavation methodology, stress redistribution, thermal changes, chemical changes and backfill were discussed.

A review of in-situ observations of the DRZ was provided. Model analysis where the DRZ has been explicitly or implicitly represented, either from a phenomenological and performance assessment aspect were reviewed.

The implications of the disturbed rock zone for the safe performance of a nuclear waste repository were discussed. Conceptual models for the geometry the DRZ and hydraulic conductivity distribution in the DRZ were suggested.

SKB Technical Report 91-26

Testing of parameter averaging techniques for far-field migration calculations using FARF31 with varying velocity

Bengtsson, Akke 1); Boghammar, Anders 1); Grundfelt, Bertil 1); Rasmuson, Anders 2)

Kemakta Consultants Co 1); Chalmers Institute of Technology 2)

June 1991

ABSTRACT

This report was prepared for SKB as a part of the SKB 91 performance assessment study. The object of the study was to test different averaging techniques for averaging velocity profiles. The average velocities obtained with the different techniques were used to set appropriate values on the Peclet number, Pe, and the groundwater travel time, t_w, and used as input to the FARF31 code. The output from the FARF31 calculations were compared against numerical simulations made with TRUCHN. Three different averaging techniques were tested: volume averaging, flow averaging and a technique based on the principle of additive variances. Four different nuclides were studied, ^{238}U, ^{237}Np, ^{135}Cs and ^{129}I. Five velocity profiles were tested, four generic profiles and one particle track from the groundwater flow calculations made for the Finnsjö site.

SKB Technical Report 91-27

Verification of HYDRASTAR – A code for stochastic continuum simulation of groundwater flow

Norman, Sven

Starprog AB

July 1991

ABSTRACT

Introduction: Generally speaking a person with a desire to model the hydraulic performance of a subsurface repository will face a very complex problem. To start with a certain amount of knowledge about the rock is given. This knowledge has a lot of different forms, for instance

- location of inferred fracture zones,
- fracture statistics from surface outcrops, tunnels and core mappings,
- single hole packer tests, transient and stationary,

- interference tests, cross-hole tests,
- tracer tests,
- general geological information.

From this information it is possible to form different models of the rock as a medium for water and radionuclide transport. Such a model will always be uncertain for several reasons

a. the translation of knowledge into a model and model parameters such as conductivity values or distributions for fracture densities does always involve some assumptions difficult to assess,
b. the hydrological properties of the rock is very heterogeneous whereas the measurement locations are sparsely located.

HYDRASTAR is a code developed at Starprog AB at the request of SKB AB designed to deal with a restricted form of the formidable problem above. The restriction is mainly that the knowledge used is almost only the stationary single-hole packer test measurements. Referring to the point a. above the basic assumptions employed are

- The rock is assumed to behave like a stochastic continuum in the following sense: for some range of scales s, $L_1 \leq s \leq L_2$ the rock obeys the isotropic form of Darcy's law and the introduced conductivity field is regarded as a stochastic function.
- The stationary single-hole packer tests can be used to calculate the value of the conductivity at a position given as the midpoint of the packer interval.

In this connection it should be stated that this approach has been inspired by [Neuman, 1988].

With these assumptions the problem to take the uncertainty in unsampled regions into account, point b. above can be posed in a stringent fashion for the conductivities. This requres that one first infers a model for the stochastical function equal the conductivity field and then uses this to simulate the conductivity field in the unsampled regions conditioned on the performed measurements. This conditional simulation is then repeated and the related fields such as heads, velocities and so forth are calculated. From these repeated simulations it is possible to collect statistics and thus obtain a grip on the resulting spatial variability and the uncertainty in the hydraulic situation around a repository.

The comprehensive detailed description of HYDRASTAR is deferred to a later report. The scope of this report is to compare results generated using HYDRASTAR with:

A. Input semivariogram functions and analytical perturbation solution to the hydrology equation.
B. Finite element solutions to the hydrology equation with a deterministic conductivity field. The computational example and the finite element solutions are taken from the international verification project for groundwater computer codes [Hydrocoin, 1988].

This leads to the division of the report in four main parts:

- In order to discuss the sometimes rather technical aspects of the comparisons, in particular with regard to the random function generator we start with a thorough description of those parts of HYDRASTAR being tested by A and B above. These are the generator of the unconditional conductivity simulations in chapter 2, the hydrology equation solver in chapter 3 and the estimation of output statistics in chapter 4.
- Derivation of the analytical perturbation solution in chapter 5.
- Description of the results generated in part A in chapter 6.
- Description of the results generated in part B in section 7.

SKB Technical Report 91-28

Radionuclide content in surface and groundwater transformed into breakthrough curves. A Chernobyl fallout study in an forested area in Northern Sweden

Ittner, Thomas; Gustafsson, Erik; Nordqvist, Rune

SGAB, Uppsala

June 1991

ABSTRACT

Large areas of Sweden was covered by the radioactive fallout from Chernobyl in 1986. This event started a study of migration and sorption behavior of the radionuclides in a small forested catchment area in northern Sweden. Within this study, over a period of three years, radionuclide breakthrough were modelled from data obtained from groundwater sampling in an artesian borehole with packed-off sections. Also the creek that drains the studied catchment area and a shallow well were sampled to study the radionuclide concentration. The content of the radionuclides in the water samples leads to the conclusion that Chernobyl radionuclides have penetrated down to large depths (>100m) and that a large outflow of radionuclides from the studied catchment area took place within two months after fallout.

A computer based non-linear regression method makes it possible to determine transport parameters out of the obtained radionuclide breakthroughs in the borehole. The artesian borehole (length: 705m) is divided into three packed-off sections, 28-96 m, 97-106 m and 107- m. The breakthrough curves for section 97-106m shows that Ruthenium-106 is deviating from Cobalt-60 and Cesium-137 in terms of velocity. The Ruthenium peak concentration arrives 263 days after deposition. For Cesium and Cobalt the arrival is 516 and 599 days respectively. In terms of

dispersivity Cobalt is the deviating nuclide due to its broad peak. The drawn-out peak can probably be ascribed to the different chemical behavior of Cobalt compared to the other analyzed radionuclides. The transport of the radionuclides from ground surface to the artesian borehole is performed in fissured crystalline rock. The distance has been approximated to about 300 m. Radionuclide concentration in surface water as stagnant well water and creek water are also discussed.

SKB Technical Report 91-29

Soil map, area and volume calculations in Orrmyrberget catchment basin at Gideå, Northern Sweden

Ittner, Thomas; Tammela, P-T; Gustafsson, Erik

SGAB, Uppsala

June 1991

ABSTRACT
Fallout studies in the Gideå study site after the Chernobyl fallout in 1986, has come to the point that a more exact surface mapping of the studied catchment basin is needed. This surface mapping is mainly made for area calculations of different soil types within the study site. The mapping focus on the surface, as the study concerns fallout redistribution and it is extended to also include materials down to a depth of 0.5 meter. Volume calculations are made for the various soil materials within the top 0.5 m. These volume and area calculations will then be used in the modelling of the migration and redistribution of the fallout radionuclides within the studied catchment basin.

SKB Technical Report 91-30

A resistance network model for radionuclide transport into the near field surrounding a repository for nuclear waste (SKB, Near Field Model 91)

Nilsson, Lennart; Moreno, Luis; Neretnieks, Ivars; Romero, Leonardo

Department of Chemical Engineering, Royal Institute of Technology, Stockholm

June 1991

ABSTRACT
A model has been developed, describing the steady state transport of dissolving species of radionuclides from a single canister in a repository for spent nuclear fuel out into the passing water in fractures in the surrounding rock matrix. The transport of nuclides is described by a network of transport resistances, coupled together in the same way as an electrical circuit network. With the model a number of calculations are done for various sets of fracture geometry data. The calculations indicate that the resistance network model gives results comparable to those of a complex 3-dimensional numerical model.

SKB Technical Report 91-31

Near field studies within the SKB 91 Project

Widén, Hans; Bengtsson, Akke; Grundfelt, Bertil

Kemakta Consultants AB, Stockholm

June 1991

ABSTRACT
A number of near field studies was performed during the early part of the SKB 91 project. This report summaries this work and includes:

- Simulation of the steady state release from the near field with different time for canister penetration.
- Simulation of tbe release from a repository with 5300 canisters with different penetration times for different parts of tbe canisters due to manufacturing error, glaciations, inner over pressure and corrosion.
- Calculation with a numerical model of the transient release of the instantaneously dissolvable species and the effect of different boundary conditions both at the canister/bentonite and the bentonite/rock interface.
- Description of the implementation of a resistance network model for the calculation of the steady state transport resistances in the different pathways from the canisters
- Comparison of two analytical models for the calculation of the release of the instantaneously dissolvable species.

SKB Technical Report 91-32

SKB/TVO Ice age scenario

Ahlbom, Kaj 1); Äikäs, Timo 2); Ericsson, Lars O 3)

Conterra AB 1); Teollisuuden Voima Oy (TVO) 2); Svensk Kärnbränslehantering AB (SKB) 3)

June 1991

ABSTRACT

Foreword: Ice ages have repeatedly occurred throughout geological history, and it is likely that they will also occur in the time-span considered for the disposal of spent nuclear fuel. Based on the present status of knowledge, this report discusses when future ice ages will occur and the possible changes in the geosphere that might be of importance for repository performance. The report is intended to be used as a basis when developing scenarios for safety analysis of a final repository for spent nuclear fuel. The principal processes predicted to occur during future glaciations, and which are likely to be of importance for a repository, were initially formulated at working meetings and finally discussed at a seminar held in Helsinki, June 13, 1990. The state-of-the-art was compiled in two reports by Eronen & Olander (1990) and Björck & Svensson (1990). This report constitutes a synthesis of the results from the above-mentioned meetings and reports, together with other relevant data. During the spring of 1991, a draft version of this report was reviewed by Prof. G.S.Boulton and many of the improvements suggested by him have been implemented.

SKB Technical Report 91-33

Transient nuclide release through the bentonite barrier – SKB 91

Bengtsson, Akke; Widén, Hans

Kemakta Konsult AB

May 1991

ABSTRACT

A study of near-field radionuclide migration is presented. The study has been performed in the context of the SKB91 study which is a comprehensive performance assessment of disposal of spent fuel. The objective of the present study has been to enable the assessment of which nuclides can be screened out because they decay to insignificant levels already in the near-field of the repository.

A numerical model has been used which describes the transient transport of radionuclides through a small hole in a HLW canister imbedded in bentonite clay into a fracture in the rock outside the bentonite. Calculations for more than twenty nuclides, nuclides with both high and low solubility, have been made. The effect of sorption in the bentonite backfill is included. The size of the penetration hole was assumed to be constant up to time when the calculations were terminated, 500 000 years after the deposition. The mass transport rate is controlled by diffusion. The model is three dimensional.

The report describes the geometry of the modelled system, the assumptions concerning the transport resistances at the boundary conditions, the handling of the source term and obtained release curves.

SKB Technical Report 91-34

SIMFUEL dissolution studies in granitic groundwater

Casas, I 1); Sandino, A 2); Caceci, M S 1); Bruno, J 1); Ollila, K 3)

MBT Technologia Ambiental, CENT, Cerdanyola, Spain 1); KTH, Dpt. of Inorganic Chemistry, Stockholm, Sweden 2); VTT, Tech. Res. Center of Finland, Espoo, Finland 3)

September 1991

ABSTRACT

The dissolution behavior of an unirradiated chemical analogue of spent nuclear fuel (SIMFUEL) has been studied in the presence of two different synthetic groundwaters at 25°C and under both oxic and anoxic conditions. The release of U, Mo, Ba, Y and Sr was monitored during static (batch) leaching experiments of long duration (about 250 days). Preliminary results from continuous flow-through reactor experiments are also reported.

The results obtained indicate the usefulness and limitations of SIMFUEL in the study of the kinetics and mechanism of dissolution of the minor components of spent nuclear fuel. Molybdenum, barium and strontium have shown a trend to congruent dissolution with the SIMFUEL matrix after a higher initial fractional release. Yttrium release has been found to be solubility controlled under the experimental conditions.

A clear dependence on the partial pressure of O_2 of the rates of dissolution of uranium has been observed.

SKB Technical Report 91-35

Storage of nuclear waste in long boreholes

Sandstedt, Håkan 1); Wichmann, Curt 1); Pusch, Roland 2); Börgesson, Lennart 2); Lönnerberg, Bengt 3)

Tyréns 1); Clay Technology AB 2); ABB Atom 3)

August 1991

ABSTRACT

This report constitutes a feasibility study for the storage of high level radioactive waste in long TBM drilled tunnels. The report will form the basis for a comparison with other concepts in future analysis of the isolation performance in a typical Swedish rock structure.

The suggested repository concept consists of three parallel, 4.5 km long, horizontal tunnels at a depth of 500 m constructed using TBM technology. The tunnel diameter will be about 2.4 m for deployment of canisters with a diameter of 1.6 m. The space between the canisters and rock will be totally sealed off by bentonite.

The study comprises the design of canisters, canister handling and deposition, near field design, near field sealing and behaviour, and technical design of the repository. The report also includes a tentative time schedule and cost estimate, incorporating the construction phase and deployment of canisters.

SKB Technical Report 91-36

Tentative outline and siting of a repository for spent nuclear fuel at the Finnsjön site. SKB 91 reference concept

Ageskog, Lars; Sjödin, Kjell

VBB VIAK

September 1991

ABSTRACT

A site in northern Uppland has been selected for a safety assessment of a generic repository for spent nuclear fuel. The site chosen has been thoroughly investigated and documented in previous reports. The repository studied is of the KBS-3 type consisting of a number of deposition drifts with the canisters deployed in holes drilled in the drift floor.

The major fracture zones in the host rock were entered into a 3-dimensional CAD model in which the repository was placed. Two alternative layouts were studied: one with deposition drifts oriented approximately parallel with the hydraulic gradient, the other with drifts perpendicular to the gradient.

The report includes appendices with coordinates for the fracture zones as well as coordinates describing the end-points of the deposition drifts.

SKB Technical Report 91-37

Creep of OFHC and silver copper at simulated final repository canister-service conditions

Auerkari, Pertti; Leinonen, Heiki; Sandlin, Stefan

VTT, Metals Laboratory, Finland

September 1991

ABSTRACT

Results of high-resolution creep rate measurements are described for estimating very long term creep life of copper and silver alloyed copper at room temperature and at stresses approaching the expected service conditions of final repository canisters. The aim was to assess the limiting service stress levels for potential canister wall materials.

The 0.1% silver alloyed copper showed minimum creep rates of 10^{-9} to 10^{-10} l/h, corresponding to 1% strain in about 1000 to 10 000 years, at room temperature and uniaxial stress level of 50 to 75 MPa. The predicted time to 1% strain, when extrapolated from literature data, was at least one order of magnitude shorter. From the results of the present work, the 1% creep life for OFHC copper was at most a few hundreds of years at 50 MPa stress level.

The technique developed and used in this work for measuring very low strain rates appears useful for assessing low temperature creep life of practical structures essentially without accelerating the test from the service conditions.

SKB Technical Report 91-38

Production methods and costs of oxygen free copper canisters for nuclear waste disposal

Rajainmäki, Hannu; Nieminen, Mikko; Laakso, Lenni

Outokumpu Poricopper Oy, Finland

June 1991

ABSTRACT

The fabrication technology and costs of various manufacturing alternatives to make large copper canisters for spent fuel repository are discussed. The capsule design is based on the TVO's new advanced cold process concept where a steel canister is surrounded by the oxygen free copper canister. This study shows that already at present there exist several possible manufacturing routes, which result in consistently high quality canisters. Hot rolling, bending and EB-welding the seam is the best way to assure the small grain size which is preferable for the best inspectability of the final EB-welded seam of the lid. The same route turns out also to be the most economical.

SKB Technical Report 91-39

The reducibility of sulphuric acid and sulphate in aqueous solution (translated from German)

Grauer, Rolf

Paul Scherrer Institute, Switzerland

July 1991

ABSTRACT

In connection with the Swedish project for the final storage of spent fuel elements it was necessary to assess whether dissolved sulphate can corrode the copper canister without the intervention of sulphate-reducing bacteria. A simple reaction between copper and sulphate is thermodynamically impossible. On the other hand, copper can react to give copper sulphide if an additional electron donor such as iron(II) is available. Because little specific information is available about this subject the problem was extended to the much more general question of the reducibility of sulphur(VI) in dilute aqueous solution.

It is a part of the general knowledge of chemistry, and there is also unanimity about it in the geochemical literature, that purely chemical reduction of sulphate does not take place in dilute solution at temperatures below 100°C. This fact is, however, poorly documented and it was therefore necessary to substantiate it by drawing on numerous individual findings from different areas of pure and applied chemistry.

In experiments on the reduction of sulphates under hydrothermal conditions a reaction only takes place at temperatures above 275-300°C. In the case of the action of sulphuric acid on metals its oxidising action becomes perceptible only at acid concentrations over 45-50%.

From experiments on the cathodic reduction of 74% sulphuric acid it is found that the formation of hydrogen sulphide and elementary sulphur starts, depending on the current density, at 50-130°C, and polarographic measurements lead to the conclusion that the reducible species is not the hydrogen sulphate ion but molecular sulphuric acid. In dilute solutions the latter's concentration is vanishingly small, however.

From corrosion chemistry the resistance of copper to oxygen-free sulphuric acid up to a concentration of 60% is well-known. Copper is also used as a pipe material in the production of iron(II) sulphate; it is thus stable even in the presence of the electron donor iron(II). Although base metals such as iron and zinc can, according to the thermodynamics, reduce sulphate in aqueous solution, such cases are unknown despite the widespread use of these materials.

Numerous processes in industrial electrochemistry take place in sulphuric-acid or sulphate electrolytes, such as the electrochemical extraction and refining of metals, electrochemical deposition of metals and the anodic oxidation of aluminium. Cathodic sulphate reduction would reduce the quality of the products of such processes and there would also be health and safety consequences because of the formation of hydrogen sulphide.

The reversible metal/metal-sulphate electrodes of lead and cadmium are unstable relative to the corresponding metal sulphide. Nevertheless the reversible lead sulphate electrode functions in the starter-battery of 450 million vehicles and in stationary batteries without failing due to sulphide formation. In the Weston cell, which is used as a secondary standard for the electrical voltage, the cadmium-sulphate electrode remains stable for decades, such that these cells can be calibrated.

Finally, sulphuric acid and sulphate solutions are widely used in basic electrochemical research as inert supporting electrolytes. Their instability would make exact and reproducible measurements impossible.

All these facts confirm that sulphur(VI) in dilute solution is completely inert towards chemical reducing agents and also to cathodic reduction. Thus corrosion of copper by sulphate under final-storage conditions and in the absence of sulphate reducing bacteria can be ruled out with a probability verging on certainty.

SKB Technical Report 91-40

Interaction between geosphere and biosphere in lake sediments

Sundblad, Björn; Puigdomenech, Ignasi; Mathiasson, Lena

December 1990

ABSTRACT

One main issue in the safety assessment of nuclear repositories, is which processes influence the distribution pattern of radionuclide elements in the biosphere when released radioactivity is carried with groundwater that penetrates through the bottom sediment of a lake.

To be able to evaluate the transport of elements such as thorium, uranium, and rare earth elements (REE), sampling of lake sediment cores at different Swedish sites with different degrees of groundwater leakage was performed.

Different lake sediment fractions have been identified. One fraction is related to aluminosilicates (clay and sand contents), while the other major fraction contains organic material.

Enrichment of uranium is observed in areas of groundwater seepage, and U-contents is correlated to the levels of organic matter. Besides a higher mobility and enrichment of uranium compared to thorium is observed.

Chondrite normalised REE sediment contents have been found higher in the most reducing sediments.

The weathering and deposition processes are discussed in connection with the degree of mobility of elements. Elements as titanium, zirconium and hafnium are nearly insoluble in aqueous solutions. The immobility of these elements have been confirmed by this study.

Hafnium is selected to study the differentiation of the sediment fraction originating from refractory and other physically weathered minerals.

SKB Technical Report 91-41

Individual doses from radionuclides released to the Baltic coast

Bergström, Ulla; Nordlinder, Sture

Studsvik AB

May 1991

ABSTRACT

Individual doses to critical groups from a continuous unit release of nuclides from high-level waste to a coast area were calculated. The selection of nuclides for this study was based on experience of their importance from a radiological point of view. The coastal area should be representative for average conditions along the Swedish Baltic coast. The coastal area was simulated in the model by compartments for water and sediment, respectively. Six exposure pathways for activity from the water and sediment reservoirs 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. 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 91-42

Sensitivity analysis of the groundwater flow at the Finnsjön study site

Bao, Yung-Bing; Thunvik, Roger

Dept. Land and Water Resources, Royal Institute of Technology, Stockholm, Sweden

September 1991

ABSTRACT

The object of the present investigation was to study, by means of sensitivity analysis, the impact on the solutions to flow calculations of some major fractures zones and the boundary conditions applied in the previous numerical modelling of the groundwater flow conditions at the Finnsjön site. Sensitivity analysis is a useful complementary tool in groundwater flow modelling by making it possible to analyze qualitative as well as quantitative effects of various flow modelling concepts or model strategies on the flow solutions and to gain a general insight into the geohydraulic behaviour of the flow system studied. The sensitivity of the piezometric head and the sensitivity of the flux across an imaginary region of a hypothetical radioactive waste repository due to perturbations of the permeability in two major fracture zones were analyzed. The influence of uncertainties in the prescribed piezometric head boundary conditions, applied in the previous groundwater flow modelling of the Finnsjön study site, was studied. The uncertainties were due to a procedure used for transferring the boundary conditions from a "regional model" to a "local model" area. The study was performed by means of sensitivity analysis using an adjoint technique. The sensitivity of the piezometric head as well as the Darcy flux, both point-wise and integrated over the imaginary repository region, was calculated. Similarly, the sensitivity at a discharge area of interest was calculated. The groundwater flow calculations are part of

the SKB 91 performance assessment study of a generic high-level waste repository at the Finnsjön site. Two different sensitivity methods, one called the direct method and the other the variational or the adjoint sensitivity method were applied. The numerical method for solving the flow equation or the so-called "primary problem" as well as the sensitivity equation were based on the Galerkin finite element method.

SKB Technical Report 91-43

SKB-PNC – Development of tunnel radar antennas

Falk, Lars

ABEM, Uppsala, Sweden

July 1991

ABSTRACT

Tunnel antennas for the RAMAC borehole radar system have been developed and tested in the field. The antennas are of the loaded dipole type and the receiver and transmitter electronics have been rebuilt to screen them from the antennas. A series of measurements has demonstrated that the radar pulse is short and well shaped and relatively free from ringing, even compared with the existing borehole antennas. Two antenna sets were tested: one centered at 60 MHz and another above-100 MHz. Both produced excellent radar pictures when tested in tunnels in Stripa mine. The antennas have been designed to be easy to carry, since the signal quality often depends on the way the antenna is held relative to electric conductors in the tunnels.

SKB Technical Report 91-44

Fluid and solute transport in a network of channels

Moreno, Luis; Neretnieks, Ivars

Department of Chemical Engineering, Royal Institute of Technology, Stockholm, Sweden

September 1991

ABSTRACT

A three-dimensional channel network model is presented. The fluid flow and solute transport are assumed to take place through a network of connected channels. The channels are generated assuming that the conductances are lognormally distributed. The flow is calculated resolving the pressure distribution and the solute transport is calculated by using a particle tracking technique. The model includes diffusion into the rock matrix and sorption within the matrix in addition to advection along the channel network. Different approaches are used to describe the channel volume and its relation to the conductivity. To quantify the diffusion into the rock matrix the size of the flow wetted surface (contact surface between the channel and the rock) is needed in addition to the diffusion properties and the sorption capacity of the rock.

Two different geometries were simulated: regional parallel flow and convergent flow toward a tunnel. In the generation of the channel network, it is found that its connectivity is reduced when the standard deviation in conductances is increased. For large standard deviations, the water conducting channels are found to be few. Standard deviations for the distribution of the effluent channel flowrates were calculated. Comparisons were made with experimental data from drifts and tunnels as well as boreholes as a means to validate the model.

SKB Technical Report 91-45

The implications of soil acidification on a future HLNW repository. Part I: The effects of increased weathering, erosion and deforestation

Nebot, Josefa; Bruno, Jordi

MBT Tecnología Ambiental, Cerdanyola, Spain

July 1991

ABSTRACT

We have developed a model for soil acidification and granite weathering and erosion caused by the extended use of fossil fuels.

We have explored three different scenarios for depletion of fossil fuel reserves depending on how stringent is the control of the overall fossil fuel cycle.

Fossil fuels reserves are expected to last for the next 300 years. Nevertheless, we have extended our calculations up to next forecasted major glaciation period (58,000 years).

The results of the calculations can be summarized as follows:

- For the best and average scenarios the impact of soil acidification due to fossil fuel burning, lasts only for about 500 years. The overall effect is to increase the net surface lowering (weathering + erosion + denudation) in a few percentage (1–2%).

- In the worst case scenario, the impact of the fossil fuel combustion on the ecosystem is irreversible. The result being that up to 30% of the expected depth of the repository (500 m) would be eroded by year 60,000. The overall ecological impact of this scenario indicates that the safety of a HLNW repository would be a lesser problem for the Southern Sweden ecosystem.

SKB Technical Report 91-46

Some mechanisms which may reduce radiolysis

Neretnieks, Ivars; Faghihi, Mostapha

Department of Chemical Engineering, Royal Institute of Technology, Stockholm, Sweden

August 1991

ABSTRACT

In previous assessments of the rate of radiolysis in the KBS-3 concept, it has been assumed that free liquid water will intrude the canister and form a film around the uranium oxide pellets in the gap between the pellets and the zircaloy tube. The initial water film thickness was further assumed to be maintained forever. The alpha radiation which is emitted from the uranium oxide pellets will radiolyze the water which is dissociated to oxidizing and reducing components. It has, also, been assumed that the reducing components which mostly consist of hydrogen are much more mobile than the oxidizing species and can leave the system either by diffusion or by gas flow.

The studies of the rate of radiolysis, in KBS-3 (1983), indicated that its value is so high that the release rate of the nuclides can be considerably enhanced.

In this report two mechanisms which may considerably decrease the rate of radiolysis are studied. The first main effect is that capillary forces in the very fine pores of the bentonite which surround the canisters do not permit the release of water if there is a gas over pressure inside the canister. Some possible bypassing mechanisms such as gas and surface diffusion are discussed. As long as there is gas inside the canister the gap will partly be gas filled and the alpha-particles will have less water to radiolyze. Because some hydrogen will be dissolved and will escape by diffusion, a rate of radiolysis will be maintained which balances the rate of diffusion. This in turn will be influenced by the geometry of the diffusion path. The size of the hole in the copper canister seems to be one of the critical items which determine the escape of the hydrogen and thus the rate of radiolysis.

The other main effect which will reduce the radiolysis is the accumulation of the corrosion products in the gap. This reduces the water content in the gap. Consequently there will be less water which can be radiolyzed. The presence of corrosion products which have a higher density than water will also consume the energy of the alpha-particles faster.

Both effects seem to, independently, have a potential of reducing the rate of radiolysis by a few orders of magnitude.

SKB Technical Report 91-47

On the interaction of granite with Tc(IV) and Tc(VII) in aqueous solution

Eriksen, Trygve E; Cui, Daquing

Royal Institute of Technology, Department of Nuclear Chemistry, Stockholm, Sweden

October 1991

ABSTRACT

The behaviour of technetium in granite-groundwater systems under reducing conditions was investigated. The anion TcO_4^- was reduced to Tc(IV) and simultaneously precipitated as $TcO_2 \cdot nH_2O$ on the granite surfaces. The electron sources are assumed to be iron oxides and/or iron containing minerals in the granite.

The technetium concentration in ground water under repository conditions may be predicted assuming $TcO_2 \cdot nH_2O$ as the solid phase and $TcO(OH)_2^\circ$ and TcO_4^- as the predominant aqueous complexes using a formation constant for $TcO(OH)_2^\circ$ of log K = -8.16 and a standard reduction potential E° for the reaction $TcO_4^- + 3e^- + 4H^+ = TcO_2 \cdot nH_2O$ of 0.738 V.

The surface related distribution ratio Ka for $TCO(OH)_2^\circ$ between Stripa granite and ground water is approximately 1 cm based on geometrical surface area.

SKB Technical Report 91-48

A compartment model for solute transport in the near field of a repository for radioactive waste (Calculations for Pu-239)

Romero, Leonardo; Moreno, Luis; Neretnieks, Ivars

Department of Chemical Engineering, Royal Institute of Technology, Stockholm, Sweden

October 1991

ABSTRACT

Radionuclides released from a damaged canister for spent fuel will leak through a damage in the canister wall and spread into the surrounding backfill. They will further migrate into water bearing fractures in the rock, through the backfill into the damaged zone around the drift and into the drift itself. Some substances may also diffuse through the rock to adjacent fracture zones. The nuclides will sorb on the materials along the transport paths. This very complex and variable transport geometry has been modelled using a compartment model which is based on simplifying a full three dimensional integrated finite difference model. The simplifications are supplemented by introducing analytical and semianalytical solutions at sensitive locations such as entrances and exits from holes and fractures and in the flowing water.

SKB Technical Report 91-49

Description of transport pathways in a KBS-3 type repository

Pusch, Roland 1); Neretnieks, Ivars 2); Sellin, Patrik 3)

Clay Technology AB, Lund 1); The Royal Institute of Technology, Department of Chemical Engineering, Stockholm 2); Swedish Nuclear Fuel and Waste Management co (SKB), Stockholm 3)

December 1991

ABSTRACT

A descriptive model of the radionuclide transport pathways in the near-field of a KBS-3 type repository has been developed. The model is based on the buffer and backfill properties, a generalized discontinuity model of the undisturbed rock and the effects of drilling and blasting. A reference description of the near-field rock properties is given, with implications for transport modelling.

SKB Technical Report 91-50

Concentrations of particulate matter and humic substances in deep groundwaters and estimated effects on the adsorption and transport of radionuclides

Allard, Bert 1); Karlsson, Fred 2); Neretnieks, Ivars 3)

Department of Water and Environmental Studies, University of Linköping, Sweden 1); Swedish Nuclear Fuel and Waste Management Co, SKB, Stockholm, Sweden 2); Department of Chemical Engineering, Royal Institute of Technology, Stockholm, Sweden 3)

November 1991

ABSTRACT

The concentration of particulate matter such as colloids and microbes in deep Swedish groundwaters has been measured and has been found to be low in all waters. The results are summarized in this paper. The sorption capacity of relevant radionuclides on the particulate matter has been assessed based on many direct measurements and on comparisons with measurements on similar systems. The maximum transport capacity of nuclides by the particulate matter has been estimated for reversible as well as irreversible sorption of nuclides to particles.

SKB Technical Report 91-51

Gideå study site. Scope of activities and main results

Ahlbom, Kaj 1); Andersson, Jan-Erik 2); Nordqvist, Rune 2); Ljunggren, Christer 2); Tirén, Sven 2); Voss, Clifford 3)

Conterra AB 1); Geosigma AB 2); U.S. Geological Survey 3)

October 1991

ABSTRACT

Preface: During the period from 1977-1986 SKB (Swedish Nuclear Fuel and Waste Management Co) performed surface and borehole investigations of 14 study sites for the purpose of assessing their suitability for a repository of spent nuclear fuel. The next phase in the SKB site selection programme will be to perform detailed characterization, including characterization from shafts and/or tunnels, of two or three sites. The detailed investigations will continue over several years to provide all the data needed for a licensing application to build a repository.

Such an application is foreseen to be given to the authorities around the year 2003.

It is presently not clear if anyone of the study sites will be selected as a site for detailed characterization. Other sites with geological and/or socioeconomical characteristics judged more favourable may very well be the ones selected. However, as a part of the background documentation needed for the site selection studies to come, summary reports will be prepared for most study sites. These reports will include scope of activities, main results, uncertainties and need of complementary investigations.

This report concerns the Gideå study site. The report has been written by the following authors; Kaj Ahlbom and Sven Tirén (scope of activities and geologic model), Jan-Erik Andersson (geohydrological model), Rune Nordqvist (groundwater chemistry), Clifford Voss (assessment of solute transport) and Christer Ljungren (rock mechanics).

SKB Technical Report 91-52

Fjällveden study site. Scope of activities and main results

Ahlbom, Kaj 1); Andersson, Jan-Erik 2); Nordqvist, Rune 2); Ljunggren, Christer 2); Tirén, Sven 2); Voss, Clifford 3)

Conterra AB 1); Geosigma AB 2); U.S. Geological Survey 3)

October 1991

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It is presently not clear if anyone of the study sites will be selected as a site for detailed characterization. Other sites with geological and/or socioeconomical characteristics judged more favourable may very well be the ones selected. However, as a part of the background documentation needed for the site selection studies to come, summary reports will be prepared for most study sites. These reports will include scope of activities, main results, uncertainties and need of complementary investigations.

This report concerns the Fjällveden study site. The report has been written by the following authors; Kaj Ahlbom and Sven Tirén (scope of activities and geologic model), Jan-Erik Andersson (geohydrological model), Rune Nordqvist (groundwater chemistry), Clifford Voss (assessment of solute transport) and Christer Ljunggren (rock mechanics).

SKB Technical Report 91-53

Impact of a repository on permafrost development during glaciation advance

Vallander, Per; Eurenius, Jan

VBB VIAK

December 1991

ABSTRACT

The study concerns the development of permafrost during the initial phase of a glaciation period in an area in Sweden, where a generic repository for spent nuclear fuel of type KBS-3 was assumed be located 600 m below the ground surface. The bedrock was assumed to consist of granite which could be superposed by till. An aim of the study was to assess, by calculations, if prerequisites could be developed for a forced ground water flow from an adjacent lake, past the repository and then up to an unfrozen ground surface above the repository. Results from computer calculations, carried out with a finite element program for a total simulation period of 10 000 years, and with varied assumptions regarding final mean air temperature 5 000 years ahead, indicated that permafrost development will be about the same in the ground immediately above the repository as in surrounding ground, and that conditions for the mentioned ground water flow could prevail during less than 10 years. It was also indicated that the impact on permafrost development in a zone with anomalous heat generation would be insignificant in comparison with the impact from a repository.

SKB Technical Report 91-54

Hydraulic evaluation of the groundwater conditions at Finnsjön. The effects on dilution in a domestic well

Axelsson, C-L 1); Byström, J 1); Eriksson, Å 1); Holmén, J 1); Haitjema, H M 2)

Golder Geosystem AB, Uppsala, Sweden, 1); School of Public and Environmental Affairs, Indiana University, Bloomington, Indiana, USA 2)

September 1991

ABSTRACT

The Swedish Nuclear Fuel and Waste Management Company (SKB) is presently performing a safety analysis study, SKB 91, for a final repository for spent nuclear fuel. The study is carried out for a generic repository located to the Finnsjön area, which is one of SKB:s oldest study-areas.

An important part of the safety analysis is the dose calculations. Radionuclides can be transported to the biosphere via the sea, a lake, and via extraction of groundwater from drilled or dug wells. Thus, an important scenario to study is the dilution of radionuclides in a domestic well drilled in the future close to the repository.

The present study is discussing;

* Localization, drilling and construction of wells.
* Specific capacities and chloride content of the rock mass and wells found in the Finnsjön area.
* Risk areas for future drilled wells.
* Dilution in future wells drilled in fracture zones or in the hard rock in the vicinity of the repository.

Saline groundwater with chloride concentrations of about 5000 mg/l is found in the Finnsjön area below a depth of a few hundreds of metre. However, six domestic wells drilled to depths of about 60 m have been found some kilometre northeast of the Finnsjön Rock Block, close to discharge areas, having a maximum chloride concentration of 57 mg/l. Thus, it is likely that a future well for domestic water supply purposes in the vicinity of the repository will be drilled in a waterbearing fracture zone or to shallow depths in the hard rock. The fresh water requirements for a permanent household of four persons is today about 1 m^3/day, while the requirements for a summer residence only is about half of that. A middle sized farm with about 25 – 30 milkcows needs about 6 m^3/day.

The median value of specific capacities found in wells drilled in the rock mass in the Finnsjön area is about 0.3 m^3/day and metre drawdown in the well, and the median depth is 60 m. This is comparable to the lower values calculated for the investigation boreholes drilled in the southern part of the Finnsjön Rock Block. The boreholes drilled in the northern part show specific capacities of 4 – 8 m^3/day and metre drawdown for the upper 60 m of the rock mass. Thus, the specific capacities of the rock mass found in the Finnsjön area indicate that the necessary drawdown is 1 – 20 m for a well with a continuous discharge of 6 m^3/day.

Risk areas for future drilled wells, possibly collecting groundwater that has passed the generic repository, are fracture zone 1 downgradient from the intersection of Zone 4. The regional fracture zone Imundbo as well as the discharge areas, swamps and streams, some kilometre northeast of the Finnsjön Rock Block may also be risk areas for future drilled wells.

Simulations of porous media flow in a two-dimensional vertical section of fracture zone 1 show that a well pumping 6 m^3/day at a depth of 60 m may be as close as 100 m from the discharge area and still pump groundwater not affected by the repository. In order to pump groundwater that has passed the repository, the well has to be located in the discharge area for groundwater from the repository or pump more than 30 m^3/day. In the calculations, no consideration is taken to the channeling character of flow in fractured rock or sorption and matrix diffusion. Thus, the calculations should only be seen as illustrations of hydraulic factors influencing the dilution in a well.

The radius of influence for a well located in the rock mass and pumping 6 m^3/day is about 150 m for a groundwater recharge of 50 mm/year. Three-dimensional analytic calculations show that a well drilled in the rock mass to a depth of up to 100 m gets all of its water from groundwater recharge, if the recharge is greater than about 40 mm/year.

Thus, the evaluations show that a well pumping 6 m^3/day, located in a fracture zone or in the rock mass, has no influence on the local groundwater flow system except for the very vicinity of the well. Consequently, a well may be drilled in the hard rock without any risk of pumping groundwater that has passed the repository. Wells may also be located anywhere in fracture zones, except for in the very discharge area, without any risk of getting groundwater affected by the repository. Modelling indicate that a well drilled in the discharge area for contaminated groundwater, may collect all groundwater from the repository. However, this is based on assumptions of homogeneous continuous fracture zones with a high hydraulic conductivity compared to the rock mass, which will give rise to a concentrated discharge area.

Inhomogenieties in the rock mass and fracture zones together with the areal extent of the repository might give rise to a spreading of pathlines from the repository over the discharge area, swamps and streams, northeast of the Finnsjön Rock Block. This implies that all groundwater that passes the repository will not converge to a single well pumping less than 6 m^3/day, even if it is located in the discharge area. However, with the present knowledge of groundwater flow in fractured rock, it can not be excluded that a well drilled in the future in a discharge area could get all of its water from groundwater that has passed the repository. The dilution in such a well is just a function of the pumping rate of the well. Thus, a high capacity well

will result in a larger dilution giving a smaller dose to more people, while a low capacity well will be less diluted and give a higher dose to fewer persons.

Assuming that the groundwater flow interacting with each canister is about 1 l/year, gives a total groundwater flow interacting with the canisters of 5 m^3/year. If all canisters are destroyed and leaking and this flow is collected by a well pumping 6 m^3/day, it will be diluted at least 400 times. However, considering the unrealistic scenario with all canisters leaking, the dilution of activity-contaminated groundwater will be much higher.

SKB Technical Report 91-55

Redox capacity of crystalline rocks. Laboratory studies under 100 bar oxygen gas pressure

Pirhonen, Veijo; Pitkänen, Petteri

Technical Research Center of Finland

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ABSTRACT

The excess amount of dissolved oxygen has been used as a reducible species in order to determine reducing ability (redox capacity) of crystalline rocks and minerals in an aqueous granite solution. Both crushed and whole rock samples were used. The oxygen pressure was set to 100 bar both to promote diffusion and accelerate the surface reactions. The redox capacity was obtained as a function of the decrease of Fe (II) in the solid phase. The decrease of ferrous iron near the reaction surface ranged from about 2% up to 39%. All reacted samples showed a decrease of between 5 – 30% in the ratio of Fe II/Fe total within a reaction zone at the rock surface. The reaction depth varied from about 0.1 cm up to more than 2.5 cm in rocks that were artificially ruptured and in naturally fractured granitic rocks, respectively. The redox capacity calculated from the average decrease of iron in profile varied from about 18 to 620 mol FeII/m^3 and 320 to 580 mol FeII/m^3 for the ruptured and the natural fracture samples, respectively.

SKB Technical Report 91-56

Microbes in crystalline bedrock. Assimilation of CO_2 and introduced organic compounds by bacterial populations in groundwater from deep crystalline bedrock at Laxemar and Stripa

Pedersen, Karsten; Ekendahl, Susanne; Arlinger, Johanna

Department of General and Marine Microbiology, University of Göteborg, Sweden

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ABSTRACT

The assimilation of CO_2 and of introduced organic compounds by bacterial populations in deep groundwater from fractured crystalline bedrock has been studied. Three depth horizons of the subvertical boreholes KLX01 at Laxemar in southeastern Sweden, 830-841 m, 910-921 m and 999-1078 m, and V2 in the Stripa mine, 799-807 m, 812-820 m and 970-1240 m were sampled. The salinity profile of the KLX01 borehole is homogeneous and the groundwaters had the following physicochemical characteristics: pH values of 8.2, 8.4 and 8.5; Eh values of 270, no data and -220 mV; sulphide: 2.3, 11.0 and 5.6 µM; $CO_3 2-$: 104, 98 and 190 µM; CH_4: 26, 27 and 31 µl/l and N_2: 47, 35 and 18 ml/l, respectively. The groundwaters in V2 in Stripa were obtained from fracture systems without close hydraulic connections and had the following physico-chemical characteristics: pH values of 9.5, 9.4 and 10.2; Eh values of +205, +199 and -3 mV; sulphide: 0, 106 and 233 µM; $CO_3 2-$: 50, 57 and 158 µM; CH_4: 245, 170 and 290 µl/l and N_2: 25, 31 and 25 ml/l, respectively. Biofilm reactors with hydrophilic glass surfaces were connected to the flowing groundwaters from each of the 3 depths with flow rates of approximately $3 \cdot 10^{-3}$ m/sec over 19 days in Laxemar and 27 to 161 days in Stripa. There were between 0.15 to $0.68 \cdot 10^5$ unattached bacteria/ml groundwater and 0.94 to $1.2 \cdot 10^5$ attached bacteria/cm^2 on the surfaces in Laxemar and from $1.6 \cdot 10^3$ up to $3.2 \cdot 10^5$ bacteria/ml groundwater and from $2.4 \cdot 10^5$ up to $1.1 \cdot 10^7$ bacteria/cm^2 of colonized test surfaces in Stripa. Assuming a mean channel width of 0.1 mm, our results imply that there would be from 10^3 up to 10^6 more attached than unattached bacteria in a water conducting channel in crystalline bedrock. The assimilations of $^{14}CO_2$, ^{14}C-formate, 1,2,3-3H-acetate, U-^{14}C-lactate, U-^{14}C-glucose and L-4,5-3H-leucine by the Laxemar and Stripa populations were demonstrated with microautoradiographic and liquid scintillation counting techniques. The measured CO_2 assimilation reflected the in situ production of organic carbon from CO_2. Assimilation of formate followed that of CO_2 and indicated the presence of bacteria able to substitute formate for CO_2 e.g. methanogenic bacteria. The presence of sulfate reducing bacteria

(SRB) is suggested by the observed assimilation and respiration of lactate by up to 74% of the bacterial populations. The recorded uptake of acetate and glucose indicates the presence of heterotrophic bacteria other than SRB. Up to 99% of the populations assimilated leucine which showed that major fractions of the populations were viable. Incubation in air compared to N_2 indicated that portions of the studied populations were obligate anaerobes as their ability to assimilate the added compounds was sensitive to oxygen. The results show that the use of several different compounds for assimilation experiments, reduces the risk for false conclusions about the viability and the metabolic activity of the deep groundwater populations. The Stripa results implies that deep groundwater bacteria have a CO_2 assimilating potential that may have a profound influence on the groundwater chemistry, through its action on the carbonate system.

SKB Technical Report 91-57

The groundwater circulation in the Finnsjö area – the impact of density gradients.

Part A: Saline groundwater at the Finnsjö site and its surroundings.

Part B: A numerical study of the combined effects of salinity gradients, temperature gradients and fracture zones.

Part C: A three-dimensional numerical model of groundwater flow and salinity distribution in the Finnsjö area

Ahlbom, Kaj (Part A) 1); Svensson, Urban (Part B and C) 2)

CONTERRA AB 1); CFE AB 2)

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ABSTRACT

Part A: Introduction: Saline groundwater is found in many boreholes at the Finnsjön site. The occurrences and depths to the saline water vary however greatly between different boreholes. This report presents a conceptual model which can explain most of these differences. The model is based on several assumptions. The background and relevance for using these assumptions are discussed and estimated depths to the interface between non-saline and saline groundwater, based on the conceptual model, are presented.

Part B: Introduction: The Finnsjö area, in the north-eastern part of Uppland Sweden, has been subject to comprehensive field studies. Reviews of these studies can be found in Ahlbom and Tiren /1-1/ and Andersson et al /1-2/. One striking result of these field measurements is that the depth to the salinity interface varies significantly. In the studied area, called the Finnsjö Rock Block, salt water is sometimes found 100 meters below the surface while in other areas no salt water has been encountered in boreholes at a depth of 700 meters.

It is the purpose of the present report to explain some of the complex interactions which are due to fracture zones, salinity gradients and temperature gradients from a potential repository. The study is carried out with idealized conditions but the reference to the Finnsjö Rock Block is clear. As the study is two-dimensional it is however not to be expected that we can simulate the Finnsjö Rock Block in detail, as strong three-dimensional effects can be expected in the area.

Part C: A numerical simulation model of the groundwater flow and salinity distribution in the Finnsjö Rock Block is presented. The model is three-dimensional and includes, in addition to the Darcy equations, the salinity equation and gravitational forces.

A conceptual model is first discussed in order to provide likely boundary conditions and motivate why a steady state analysis can be used.

The main result of the study is that the circulation below zone 2, at a depth of a hypothetical repository (500 or alternatively 600 meters), is strongly influenced by the presence of salt water. Typically the salt makes the water more stagnant.

SKB Technical Report 91-58

Exploratory calculations concerning the influence of glaciation and permafrost on the groundwater flow system, and an initial study of permafrost influences at the Finnsjön site – an SKB 91 study

Lindbom, Björn; Boghammar, Anders

Kemakta Konsult AB, Stockholm

December 1991

ABSTRACT

The present report describes some exploratory calculations concerning the potential groundwater flow during the recession phase of a future glaciation. The exercise forms part of the SKB 91 performance assessment project, and aims at qualitatively illustrating the prevailing hydrological phenomena under extreme glacier conditions, and at quantitatively indicating the order of magnitudes for the groundwater flows that can be expected during the withdrawal of an ice-sheet. The interest has been focussed on the deglaciation phase, since it can be expected that large amounts of water are available for infiltration at this time.

Conditions assuming either intact or melted away permafrost were considered within the project.

Apart from the exploratory calculations mentioned above, an initial attempt at modelling a permafrost situation at the Finnsjön site was carried out. This part of the study did not include the presence of melting-water, but was focussed on the potential occurrence of permafrost and its impact on the groundwater flow as a potential barrier. These calculations are reported separately in an Appendix.

Neither part of the project addressed the conceptual uncertainties like potential crustal downwarping, thermal buoyancy effects by the heat evolution from the repository, fracture zone conductivities being affected by the overburden from the ice-shelf, etc, etc.

The project made use of the finite element code NAMMU for solving the equation system, while the program package HYPAC was used for pre- and postprocessing purposes.

SKB Technical Report 91-59

Proceedings from the Technical Workshop on Near-Field Performance Assessment for High-Level Waste held in Madrid October 15-17, 1990

Sellin, Patrik (ed.) 1); Apted, Mick (ed.) 2); Gago, José (ed.) 3)

SKB, Stockholm, Sweden 1); Intera, Denver, USA 2); ENRESA, Madrid, Spain 3)

December 1991

ABSTRACT

This report contains the proceedings of "Technical Workshop on Near-Field Performance Assessment for High-Level Waste" held in Madrid October 15-17, 1990. It includes the invited presentations and summaries of the scientific discussions.

The workshop covered several topics:

- Post-Emplacement Environment
- Benchmarking of Computer Codes
- Glass Release
- Spent-Fuel Release
- Radionuclide Solubility
- Near-Field Transport Processes
- Coupled Processes in the Near-Field
- Integrated Assessments
- Sensitivity Analyses and Validation

There was an invited presentation on each topic followed by an extensive discussion.

One of the points highlighted in the closing discussion of the workshop was the need for international cooperation in the field of near-field performance assessment. The general opinion was that this was best achieved in smaller groups discussing specific questions.

SKB Technical Report 91-60

Spent fuel corrosion and dissolution

Forsyth, R S 1); Werme, Lars 2)

Studsvik AB, Nyköping, Sweden 1); Swedish Nuclear Fuel and Waste Management Co., Stockholm, Sweden 2)

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ABSTRACT

The paper presents the current status of the Swedish programme for the study of the corrosion of spent fuel in bicarbonate groundwaters. Results from the on-going experimental programme are presented and compared with the data base accumulated over the past ten years.

Release of uranium and the other actinides was solubility-controlled under the semi-static type of experiments performed: the limiting solubility for uranium under oxic conditions was found to be consistent with the hypothesis that the fuel surface can be considered to have the U_3O_7/U_3O_8 redox potential.

The measured release fractions for ^{137}Cs, ^{90}Sr and ^{99}Tc are discussed and used to exemplify the probable dissolution and corrosion processes involved. A substantial part of the Swedish programme is directed to the characterization of spent fuel before and after corrosion tests, and some recent results are presented on identification of possible corrosion sites.

SKB Technical Report 91-61

Heat propagation from a radioactive waste repository. SKB 91 reference canister

Thunvik, Roger; Braester, Carol

Royal Institute of Technology, Stockholm, Sweden

March 1991

ABSTRACT

A study of heat propagation around a hypothetical radioactive waste repository is presented. The investigated flow domain was limited to a quarter of the flow domain around a single canister due to symmetry by vertical planes passing through the centre of the canister, half distance between the adjacent tunnels and the adjacent canisters. Strictly speaking, such an approach is applicable to a repository of infinite extent. However, from a practical point of view this assumption applies to all canisters but the ones close to the edge of the repository. The following different material regions were considered: (i) Canister containing the spent fuel, (ii) Buffer (bentonite) around the canister, (iii) Backfilled (mixture of bentonite and sand) tunnels, and (iv) host Rock. The canister material was represented by a "homogenized" medium obtained by weighted averaging of the main constituents of the canister, viz. spent fuel, copper and lead. A geothermal gradient of 13°C/km was assumed. The initial heat effect per canister was 1066 W. The total vertical extent of the flow domain considered was about 1500 metres. The base case, with 6.2 m canister spacing and 30 m tunnel spacing, resulted in a maximum temperature at the canister/buffer interface of about 66°C (corresponding to a temperature rise of about 54°C), and about 50°C (about 38°C temperature rise) in the rock.

SKB Technical Report 91-62

The kinetics of pitting corrosion of carbon steel applied to evaluating containers for nuclear waste disposal. Final report 1991

Marsh, G P 1); Taylor, K J 2); Harker, A H 3)

Strategic Studies Department, AEA Environment and Energy, AEA Technology, Harwell Laboratory 1); Applied Electrochemistry Department, AEA Industrial Technology, AEA Technology, Harwell Laboratory 2); Theoretical Studies Department, AEA Industrial Technology, AEA Technology, Harwell Laboratory 3)

July 1991

ABSTRACT

This is the final summary report on a project, funded by SKB, investigating the pitting corrosion of carbon steel containers for high level nuclear waste or spent reactor fuel under granite disposal conditions. The study has covered a statistically based experimental programme to establish the pit growth kinetics, and a modelling study to determine the maximum pitting period subsequent to repository closure. It is shown that the rate of pit propagation is slower than that suggested by earlier work and that the maximum pitting period is only a small fraction of the target container life of 1000 years. An illustrative example of the methodology for estimating the corrosion allowance needed to prevent pit penetration is given. This could be applied to specific repository conditions as defined by SKB. Finally some limited recommendations are made for further studies to test and validate the methodology.

SKB Technical Report 91-63

An electrochemistry-based model for the dissolution of UO_2

Shoesmith, D W; Sunder, S

AECL Research, Whiteshell Laboratories, Pinawa, Manitoba, Canada

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ABSTRACT

A model to predict the dissolution of UO_2 fuel under both oxidizing and non-oxidizing conditions is presented and compared with other available models for fuel dissolution. Dissolution rates under oxidizing conditions are predicted by extrapolating steady-state electrochemical currents for the anodic dissolution of UO_2 to the corrosion potentials measured in solutions containing various oxidants, including dissolved oxygen, hydrogen peroxide, and the products of the gamma or alpha radiolysis of water. Where possible, these predictions are compared with dissolution rates measured chemically and available in the literature. With a few exceptions, the agreement between our predictions and published rates is good.

For non-oxidizing conditions, the dissolution rate of UO_2 is not well known. Attempts to measure this rate are fraught with difficulties, and the published values are difficult to rationalize within the framework of our model. Consequently, we briefly reviewed the literature on the dissolution of similar p-type semiconducting oxides and chose to estimate the chemical dissolution rate of UO_2 by analogy to the well-studied oxide NiO. In this manner we have managed to establish a threshold rate below which the rate of oxidative dissolution becomes negligible in comparison with the rate of chemical dissolution. This

threshold agrees quite well with that established electrochemically.

Using these extrapolated rates we predict that the rate for oxidative dissolution of CANDU (CANada Deuterium Uranium) fuel due to gamma radiolysis will fall below this threshold after ~200 a, a time period that is short in comparison with the anticipated lifetimes of titanium waste containers, which are expected to last for a period greater than ~1200 a. For dissolution due to alpha radiolysis, oxidative rates are uncertain, but could be above this threshold for a period of 500 to 10 000 a for CANDU fuel, and 500 to 30 000 a for pressurized water reactor (PWR) fuel. The uncertainty in these ranges reflects the poor quality and limited number of corrosion potential measurements in the presence of alpha radiolysis. Experiments are in progress to obtain additional data to ascertain the impact of alpha radiolysis.