SKB

TECHNICAL REPORT 89-40

SKB ANNUAL REPORT 1989

Including Summaries of Technical Reports Issued during 1989

Stockholm, May 1990

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FOREWORD

The Annual Report on SKB's activities during 1989 covers planning, building and operational activities as well as research, development and demonstration work.

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 has an operating and well integrated system for handling of all radioactive residues within Sweden for a long time ahead.

For the remaining facilities — 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 1990

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 1989.

Lectures and publications during 1989 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 1989.

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 1989 in total 1070 tonnes of spent fuel (measured as uranium) have been received. Transportation from the nuclear sites to CLAB is made by a special ship, M/S Sigyn.

At Forsmark the the final repository for Radioactive Waste — SFR — was taken in operation in April 1988. The repository is situated in crystalline rock under the Baltic Sea. The first construction phase includes rock caverns for 60 000 m^3 of waste. A second phase for additional 30 000 m^3 is planned to be built and commissioned around the year 2000. At the end of 1989 a total of 3550 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 1989 was 138.4 MSEK of which 20.7 MSEK came from participants outside Sweden.

Some of the main areas for SKB research are:

— Groundwater movements.

— Bedrock stability.

— Groundwater chemistry and nuclide migration.

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

— Characterization and leaching of spent nuclear fuel.

— Properties of bentonite for buffer, backfilling and sealing.

— Natural ageing of recipients in the biosphere.

— Model development and safety assessment.

— Preparations for a new underground research laboratory.

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

Cost calculations for the total nuclear waste management system, including decommissioning of all reactors, are updated annually. The total cost is estimated to SEK 50 billion which is about 10% of the value of the electricity being produced.

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 1989 about 50 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 1989 new successful approaches in public information and media relations were made using mobile exhibitions in a tailor-made trailer and on the SKB ship M/S Sigyn.

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Part I

Overview of SKB Activities

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1. GENERAL BACKGROUND

1.1 THE SWEDISH NUCLEAR POWER PROGRAM

The nuclear power programme of Sweden consists of 12 nuclear reactors located at four different sites and with a combined capacity of 9 900 MW net electric power. Main data and location of the 12 units are shown in Figure 1-1. The nuclear power plants generated 41% of the total Swedish electric power produced in 1989.

Swedish reactors

Reactor		Power MWe	Commercial operation	Energy availability in 1989 %
Oskarshamn 1	BWR	440	1972	88
Oskarshamn 2	BWR	610	1974	88
Oskarshamn 3	BWR	1140	1985	93
Barsebäck 1	BWR	600	1975	90
Barsebäck 2	BWR	600	1977	94
Ringhals 1	BWR	750	1976	83
Ringhals 2	PWR	800	1975	56
Ringhals 3	PWR	920	1981	83
Ringhals 4	PWR	920	1983	86
Forsmark 1	BWR	970	1980	87
Forsmark 2	BWR	970	1981	92
Forsmark 3	BWR	1150	1985	88

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

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

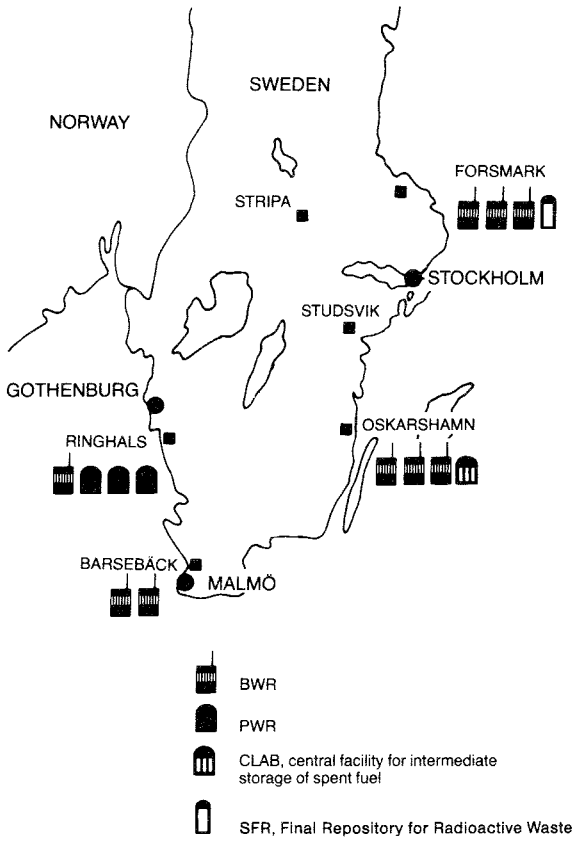

Figure 1–1. The Swedish nuclear power programme

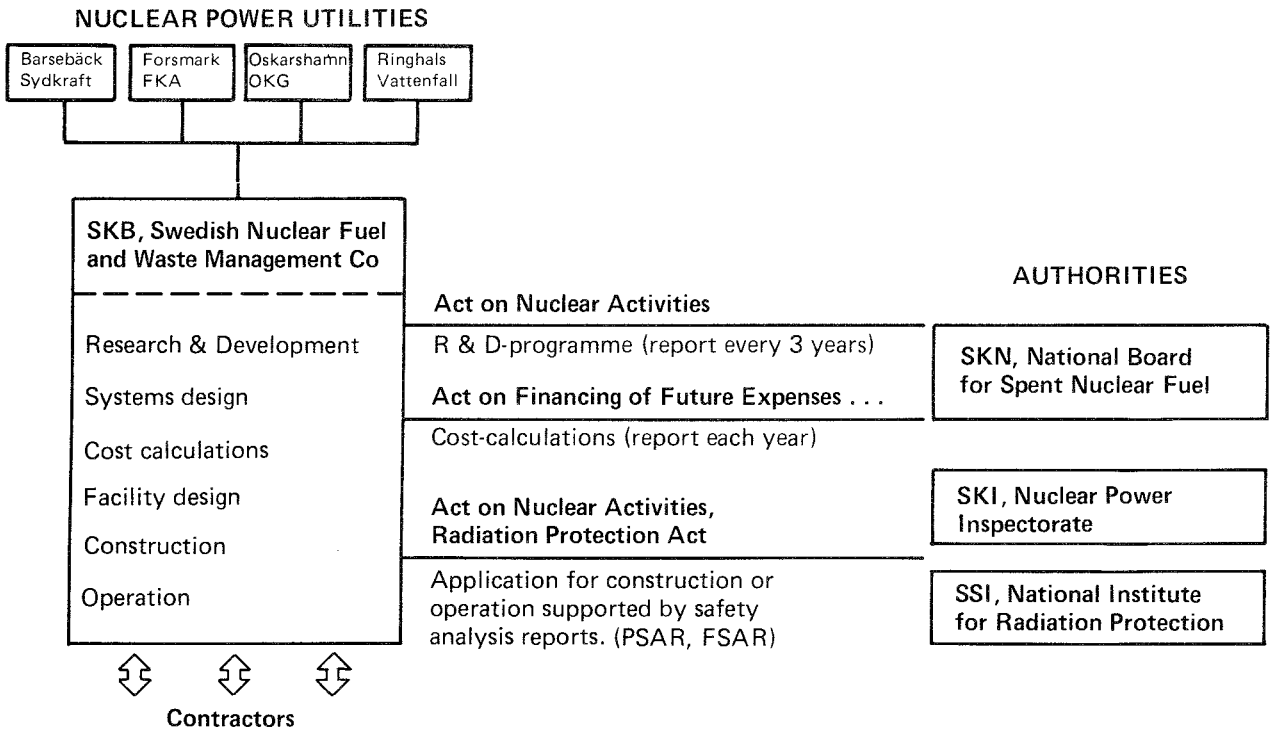

Figure 1–2. *Legal framework for activittes of SKB*

There are three important laws which regulate the nuclear activities:

— The Act on Nuclear Activities.

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

— The Radiation Protection Act.

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

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

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

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

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

— those who work at nuclear installations and other facilities with potential radiation hazards,

— the general public who lives or stays outside such installations or facilities.

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

The three competent authorities have separate funds for the research needed to fulfil their obligations. SKN is also supporting additional waste management research to the SKB-programme. In order to enable a coordination of the research programmes carried out by the authorities a special "Consultative Committee for Nuclear Waste Management" (KASAM) was founded in 1985. The committee shall report to the government bi-annually on the state of the knowledge in the nuclear waste field /1-2/.

Table 1–1. Waste categories

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

1.3 THE SWEDISH NUCLEAR WASTE MANAGEMENT SYSTEM

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

Residues generated by the operation of the reactors are spent nuclear fuel and different kinds of low- and medium level wastes. Furthermore, in the future decommissioning waste will be generated when the reactors 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 are 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 for the Swedish Final Repository for Radioactive Waste, SFR, was taken in operation in 1988. SFR may later on be extended to accommodate waste also from the decommissioning of the nuclear reactors. For spent fuel a central interim storage facility, CLAB, was taken into operation in July 1985. This facility has a capacity of 3 000 tonnes of spent fuel, with a possibility to extend it to cover the total Swedish needs.

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 is contracted for reprocessing.

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

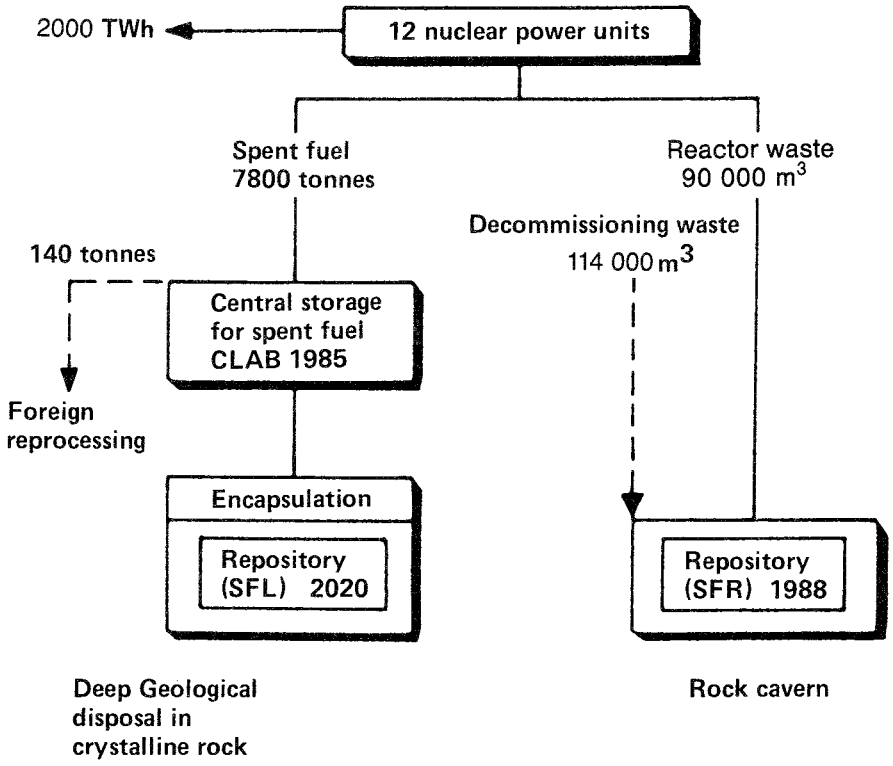

Figure 1–3. *Main system for management of radioactive waste in Sweden*

2. NUCLEAR FUEL SUPPLY

In the front end of the nuclear fuel 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 uranium demand of about 1500 metric tonnes. This demand could be higher or lower depending on a number of factors, which means that the planning of supply must be flexible.

The demand for the period 1989 up to 1998 is 14 500 tonnes. At the end of 1989, the Swedish utilities had contracts for supply of 12 400 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 1989, some spot quantities were purchased.

Natural uranium is delivered to Sweden mainly from Canada and Australia, but also from Niger, Gabon and USA. Canada will deliver around 50% 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 1989.

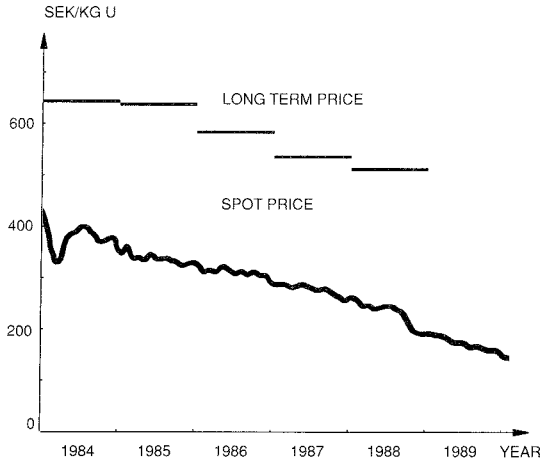

Figure 2–1. Long term and spot prices for uranium.
Long term price = Average price for long term deliveries to the European Community.
Spot price = Average spot price each month published by the German company NUKEM for non US origin uranium.

The average price for long term deliveries in 1984-1988 to the European Community was considerably higher than spot prices for the same delivery years.

2.2 CONVERSION

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

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

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

2.3 ENRICHMENT

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

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

For the period 1988-1990, most of the deliveries to Sweden come from EURODIF with an enrichment plant in France, URENCO with enrichment plants in the Netherlands, the United Kingdom and in Germany and

the USSR. Deliveries from the US (DOE) continues on a reduced scale.

The USSR has delivered enriched uranium. A small quantity of enriched uranium was also delivered from the PRC. This situation gives a reliable supply with deliveries from five different suppliers of enrichment.

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 220 tonnes of uranium in nuclear fuel for BWR and PWR during 1989. Of this volume about 60 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 4x4 or 5x5 rods separated by a water cross, is now the dominating BWR fuel in Sweden. All of the ABB Atom BWR deliveries in 1989 were of this design.

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

2.5 NUCLEAR FUEL STOCKPILE

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

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

2.6 COSTS

The costs for the front end supply and services of the nuclear fuel cycle in 1989 in Sweden were as shown in Table 2-1 (the production of nuclear electricity was 62.7 TWh in 1989):

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

	SEK/kWh	Million SEK in 1989
Natural uranium	0.008	500
Conversion	0.001	60
Isotope enrichment	0.009	560
Fuel fabrication	0.009	560
Strategic stockpile	0.001	60
Total front end	**0.028**	**1.740**

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 1983-1989.

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

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 consists of five underground storage pools for in total 3 000 tonnes of uranium. The reception, auxiliary and office buildings are located on ground level. The facility is designed to receive at least 300 tonnes uranium per year which corresponds to the handling of about 100 transport flasks, see Figure 3-1, and some 10–20 flasks containing reactor core components. For the operation SKB has contracted OKG AB, who is one of the SKB shareholders.

3.2 OPERATING EXPERIENCES

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

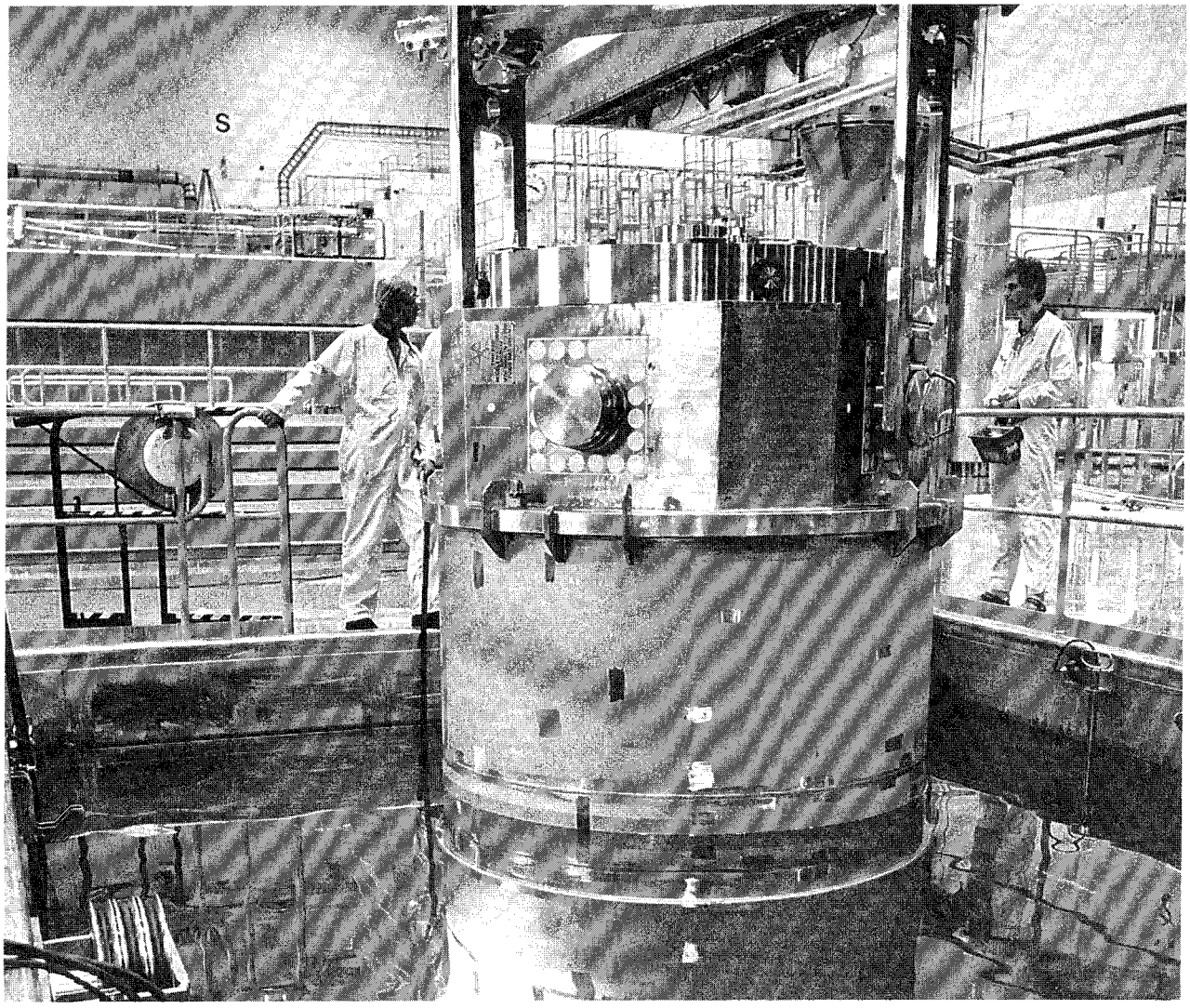

Figure 3–1. *Spent fuel transport cask with protective skirt.*

During the years 1986 to 1989 spent fuel and core components have been received in CLAB on a routine basis from the four nuclear power stations in Sweden. Between July 1985 and the end of 1989 1070 tonnes of uranium have been received.

In 1989 78 flasks containing spent nuclear fuel have been received, 71 of which contained fuel from Swedish BWR and PWR reactors and 7 flasks PHWR fuel from the old dismantled Ågesta reactor. The Ågesta fuel has been stored at the Studsvik nuclear research centre for some 15 years. The first 5 capsules containing residuals from post irradiation examination of fuel at Studsvik have been received. The total fuel quantity shipped to CLAB during the year amounted to 208 tU.

In addition 3 flasks with core components have been received.

The performance of the plant has been excellent and the received amount of fuel has been according to the plans. The total occupational dose in 1989 (86 mmanSv) was 30% of what was expected according to the final safety report.

3.3 INCREASED STORAGE CAPACITY

With the present capacity, 3 000 tU, the storage pools will be full around 1996.

A study on different methods of increasing the storage capacity in the existing pools has been perfomed. It was found that the optimal method is to use new storage canisters with a closer packing of the fuel assemblies. Based on this study SKB applied to the Swedish government for an increase of the maximum permissible amount of spent fuel in CLAB from 3000 to 5000 tU within the existing pools. The government gave its permission in December 1989.

The investment in new storage pools in a second rock cavern will now be postponed by 6-8 years.

In the new storage canisters the number of fuel elements will be increased from 16 to 25 for BWR and from 5 to 9 for PWR. Two methods for maintaining the criticality control were considered, either to take credit for the fact that only spent fuel with a low reactivity will be received in CLAB (burnup credit), or to use neutron absorbing material in the canisters. It was concluded that credit for burnup would lead to too strict control requirements and thus the option with neutron absorbers was chosen.

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, see Figure 4-1. One of the vehicles is specially designed for operation in the SFR repository.

4.2 OPERATING EXPERIENCES

During 1989, 59 casks have been transported by M/S Sigyn from the Swedish reactors to the CLAB facility. 12 on-site spent fuel transports from OKG to CLAB have been performed. 3 casks with core components have been transported to CLAB from Barsebäck.

Transports of low level waste in containers from Studsvik to SFR started during the year. 3 transports with totally 30 containers were performed. In total 40 ATB and 74 containers have been transported with M/S Sigyn from the reactor sites to SFR. 47 on-site waste transports from Forsmark to SFR have also been performed.

In total 87 ATB and 89 containers have been transported to SFR.

During 1989 M/S Sigyn has sailed 26,015 n.m. and been to sea during 96 days. The radiation dose to the ship's crew has been continuously very low, less than 1 mmanSv.

The transport cask TN 17/2 has been licensed for new fuel types with higher enrichment and burn up.

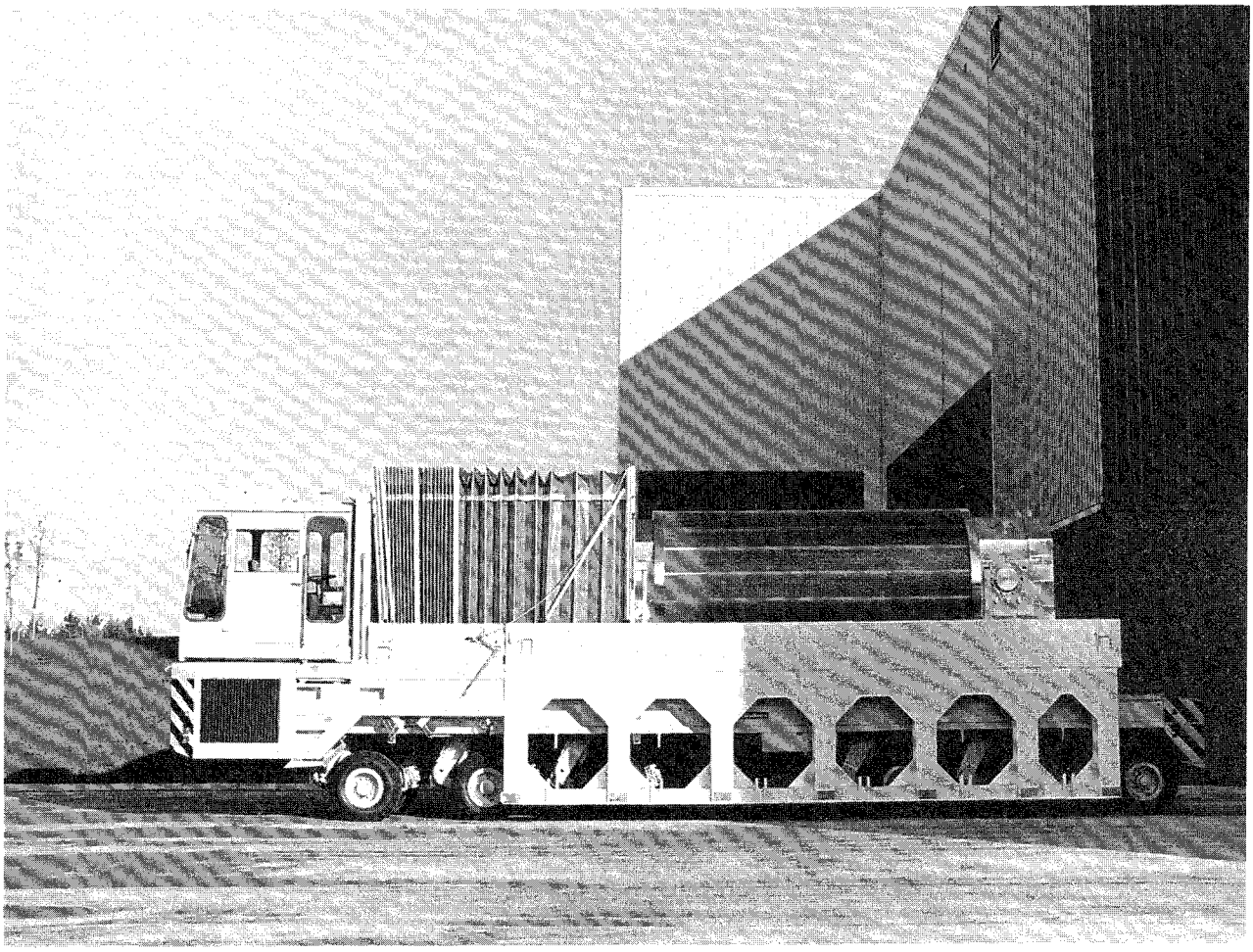

Figure 4–1. *Transport vehicle with fuel cask on its transport frame.*

5. FINAL REPOSITORY FOR RADIOACTIVE WASTE, SFR

5.1 GENERAL

The Swedish Final repository for Radioactive Waste, SFR, was put into active operation on April, 27, 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 construction stage of SFR, which is in operation includes buildings on ground level, tunnels, operating buildings and disposal caverns for 60 000 m^3 of waste. A second stage for approximately 30 000 m^3 is planned to be built and commissioned around the year 2000.

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

All raw waste material are conditioned at the power plants 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.

At the end of 1989 a total of 3550 m^3 of waste have been deposited in SFR. All waste producers have delivered waste. The experiences from the operation have been good and the doses to the personnel have been extremely low.

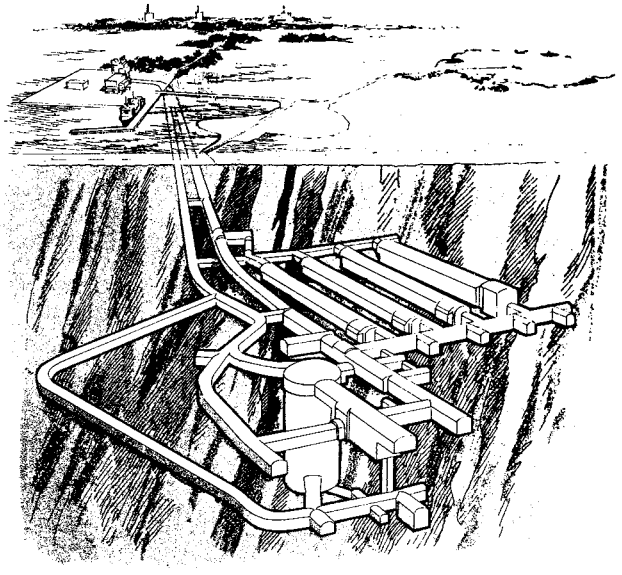

Figure 5-1. *Overview of tunnels and storage chambers in the first construction stage.*

5.2 DESIGN AND CONSTRUCTION

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

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

Waste containing a minor part of the activity content will be disposed of in 160 m long caverns with various cross sections. Three types of caverns are used. The cavern with the largest cross section is equipped with machines for remotely controlled handling, similar to those used in the silo, see Figure 5-2. The waste is deposited in a concrete structure, and finally a concrete lid is put over the waste.

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

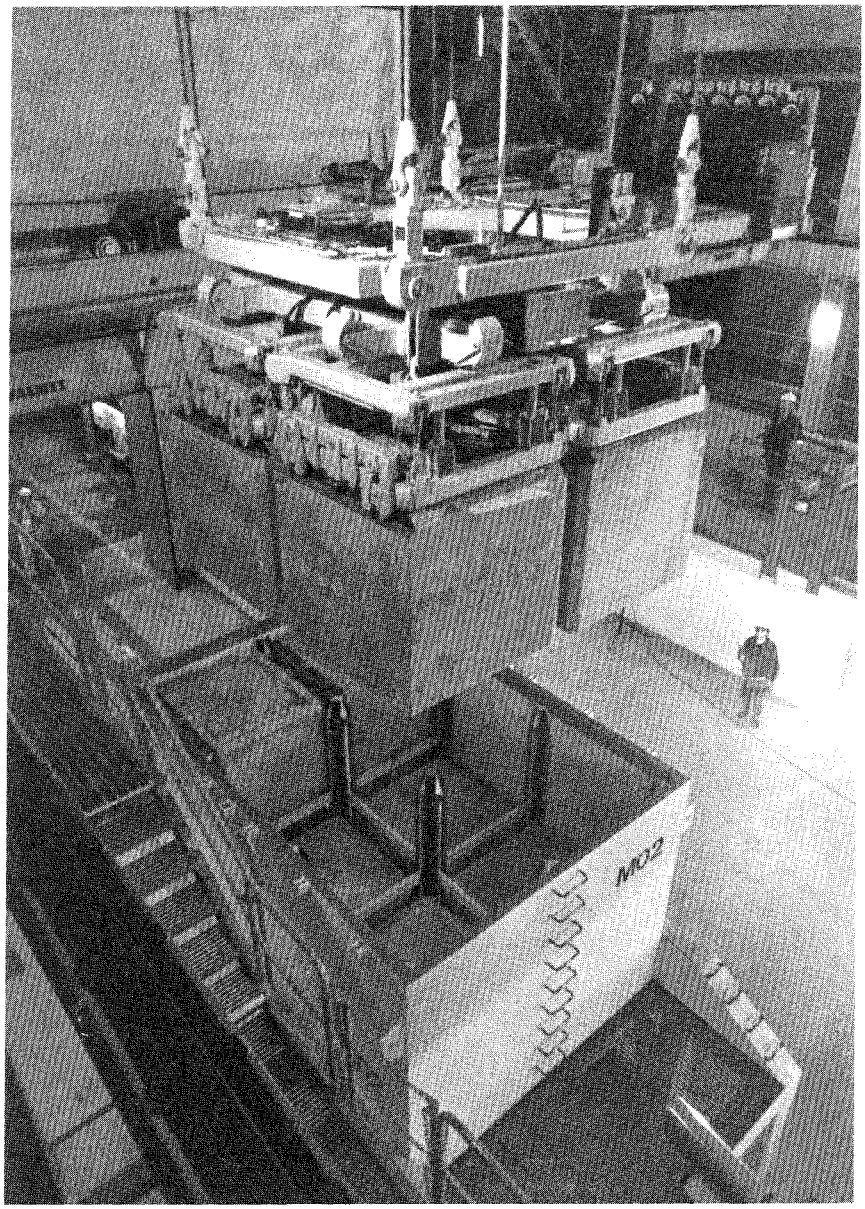

Figure 5–2. Transfer of waste packages from the transport canister to disposal in the rock chamber for ILW.

5.3 OPERATION PERMIT

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

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

5.4 WASTE ACCEPTANCE

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

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

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

The procedure for waste acceptance has been very time consuming. During 1989 nine waste types (of a total of about 40) were accepted for disposal. Disposal was carried out in the rock chambers and in the silo. Further information to the authorities is, however, requested before full scope disposal and grouting will be permitted in the silo. This information was presented to the authorities in November for scrutiny.

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 1989 a total of 3550 m^3 of waste has been deposited. Disposal took place in all caverns and the silo.

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, including the terminal vehicle, and of the auxiliary systems.

The 1989 operating experience is good both with regard to handling and availability. Some problems remains with the automatic operation of the transport vehicle. This has not affected the disposal programme. The doses to the personnel have been very low. The total dose was approximately 0.3 mman Sv in 1989. As all waste that is deposited in SFR is packaged no surface or air contamination has been detected, as expected.

6. RESEARCH AND DEVELOPMENT 1989

6.1 GENERAL

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

The Swedish nuclear utilities have commissioned the Swedish Nuclear Fuel and Waste Management Co. – SKB – to establish the programme required by the law. The programme must be submitted to the National Board of Spent Nuclear Fuel every three years starting 1986. The second programme was submitted by SKB to the National Board of Spent Nuclear Fuel – SKN – in September 1989 /6-1/ and was then sent for review to about 50 organizations in Sweden. SKN shall report to the government before April 1, 1990 on their review.

The work done during 1989 has in general followed the 1986 programme. This chapter gives only a few highlights of the results obtained in 1989. For a more comprehensive account the reader is referred to chapters 10 – 20.

The programme is executed under the leadership of SKBs division for research and development. The staff of the division was increased to 18 persons in 1989. 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 40 technical reports in the SKB-TR-serie, in numerous progress reports and working reports and in communications to several international meetings and to scientific magazines. A list of the more important publications is given in Appendix 2.

The expenditures on research and development within the SKB budget for 1989 were 117.7 MSEK as compared to 104.1 MSEK in 1988. The increase was due to the increasing work at the Hard Rock Laboratory.

SKB is also the managing participant in the international Stripa Project and Poços de Caldas Project. The expenditures for these projects were 32.2 MSEK of which 11.5 MSEK were SKB contributions and 20.7 MSEK came from participants outside Sweden. The total turnover of the R&D-division was thus 138.4 MSEK.

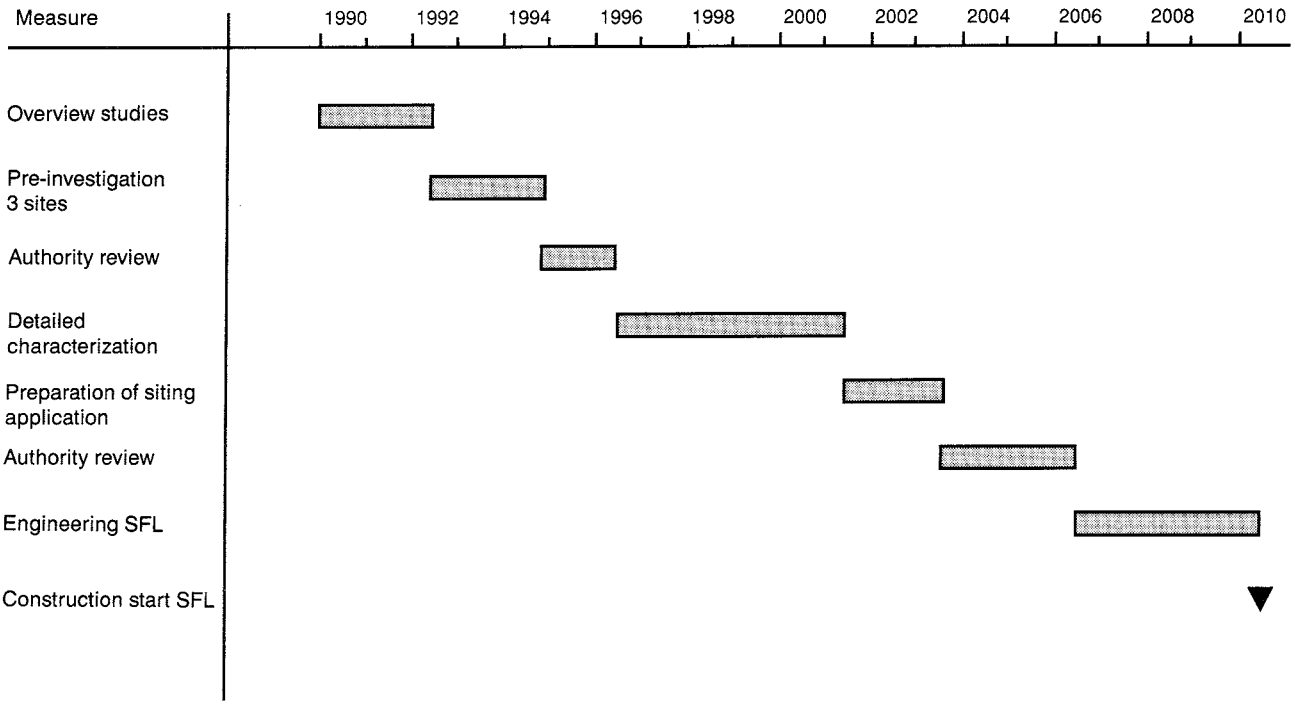

Figure 6–1. *Overall timetable for siting of final repository for spent fuel (SFL).*

6.2 R&D-PROGRAMME 89.

The second R&D-programme according to the requirements in the act of nuclear activities was submitted to SKN on September 27, 1989. The programme has its main emphasis directed towards the final disposal of spent fuel. In the 1990s the work in this area will move from research and development towards development and demonstration. Important general goals of the programme are:

— to select and study suitable sites for a repository,

— to evaluate alternative repository concepts and chose one principal method for further optimization,

— to improve the knowledge and the data base for engineered barriers, geology and bedrock properties to be able to optimize a repository system to a specific site

— to improve and further develop the methods for safety analyses in order to better understand the safety margins and thus contribute to increased acceptance for the final disposal concept.

The siting of a repository for spent fuel and other long lived wastes is a key issue in the programme. Figure 6-1 gives a coarse time schedule for the siting process.

Screening and studies of potential sites for a geologic repository started in Sweden already in the mid-1970s. Through the years an inventory of some 1000 sites have been listed. Several of these sites are shown on Figure 6-2. Measurements in deep drillholes down to 600-1000 meter depth have been made at about 10 of these sites. Experiments and investigations have also been conducted at the Stripa mine since 1977. From these studies we have concluded that there are many places in Sweden where the geological conditions are suitable for hosting a repository for spent nuclear fuel.

In the 1990s the main goal for the activities related to final disposal of spent fuel is to characterize two sites in sufficient detail to be able to submit an application for a siting permit in 2003 and then to start construction in 2010. Announcement of three candidate sites is planned for early 1992. Preliminary field studies of these sites will be made in 1992-94. The detailed characterization will start in 1996 and will include investigations from shafts and/or tunnels down to repository depth. Detailed characterization of a site is expected to take about five to six years.

In order to meet this time schedule for siting through the 1990s the following target dates for the research and development efforts have been identified:

— to develop a programme for preliminary site characterization to 1991.

— to complete a new safety analysis - SKB 91 - to 1991.

— to refine and verify the methodology and to develop a programme for detailed characterization of candidate sites to 1995.

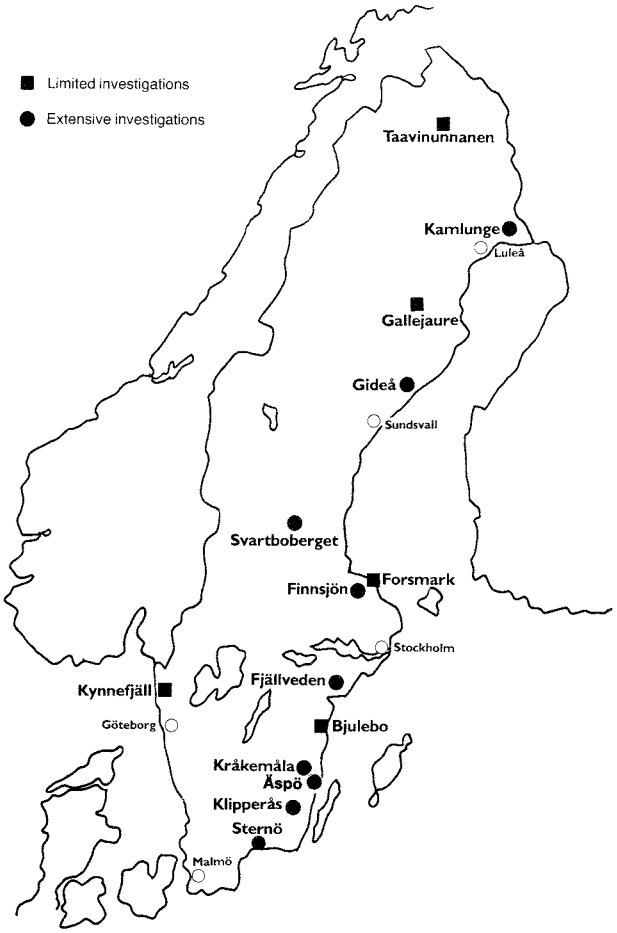

Figure 6–2. *Sites where SKB has carried out geological investigations of varying scope.*

— to complete the studies of alternative principle designs.

— to select a principal repository design as a basis for detailed rock characterization and optimization to 1995.

— to refine and test in different scales the methods and models for describing groundwater flow and transport of dissolved species in the bedrock. Reasonably validated models should be available before start of optimization to specific sites i e in 1998.

6.3 SUMMARY OF R&D-ACTIVITIES DURING 1989

6.3.1 Engineered Barriers and Repository Design

The feasibility study of the Very Deep Hole (VDH) repository concept has continued. Experiences from the deep hole at Gravberg and other deep holes in crystalline rock have been considered. The reference design has been changed to shallower depth (4000 m) and larger diameter (0.8 m) holes. For 7800 tonnes of spent fuel about 35 such deposition holes would be required. In the

Gravberg hole water with 15 % salinity was found. Such high salinity may have a positive influence on the isolation properties of the geologic barrier for this concept. If the heat generation from the waste is moderate the analysis made indicates that the driving force from the heat is insufficient to move the water to the surface.

A rock quality designation process has been applied to the KBS-3 and WP-Cave concepts. It was concluded that the KBS-3 concept is more flexible to adapt to the main waterconducting structures in the bedrock.

The activities on studies of waste form are concentrated to spent nuclear fuel. The work includes fuel characterization, fuel corrosion and modelling. The results obtained throughout 1989 on spent fuel corrosion have been summarized in a technical report. The report emphasizes the consistency in the results obtained by different groups in Sweden and elsewhere. For high burnup BWR and PWR fuel the uranium saturation in synthetic groundwaters is attained at a level of a few ppm whereas plutonium appears to be saturated at a few tenths ppb. The spent fuel modelling efforts are concentrated on oxidative dissolution. The reason for this is that although reducing conditions can be expected in deep granitic groundwaters locally oxidizing conditions may be at hand due to alfa-radiolysis.

Experiments on release and migration of some fission products and actinides from spent fuel in contact with highly compacted bentonite have been initiated. The results from the first tests after 101 and 386 days contact time indicate as expected a high mobility of cesium. The actinides have very low mobility. After one year plutonium had diffused less than 0,5 mm away from the fuel. Very little technetium has been leached from all samples indicating that technetium is present as Tc (IV) or lower valence states.

The investigations on copper during 1989 have been concentrated on creep studies. The tests will continue through 1990.

Since 1986 SKB participates in an EUREKA-project aiming at development of an out-of-vacuum equipment for electron beam welding of thick metallic components. The project is conducted at the Welding Institute in UK. The first stage is now completed and a 500 m^3 welding bay has been built complete with a 10 tonnes crane to manipulate large components. The welding head power supply and control system will be operational in 1990.

A sample of bentonite (MX80) has been taken out of the French facility POSEIDON at Saclay after about one year exposure to intens gammaradiation. Examinations of physical properties are continuing on the irradiated specimens.

In the Stripa mine a test is performed to identify suitable grouts and grouting techniques for sealing fine rock fractures in repositories.

The sealing can improve the isolating properties in the near field, in the adjacent rock to the deposition holes and be an accessory to the measures for diverting groundwater flow from the near field, such as plugging in drifts or shafts. Excavation response in the rock causes a damage zone due to blasting effects and stress redistribution around the opening as well. A series of tests in the Stripa buffer mass test area where simulated deposition holes were earlier tested are planned to be performed in steps so the suitability of grouts and grouting techniques can be evaluated in conjunction with characterizing the rock including permeability tests. These efforts shall form the basis also for an improved knowledge of the variation of damage due to the excavation in granitic rock.

During 1989 a large-scale grouting experiment in two former heater holes was performed. The sealing was effective in rock with an initial hydraulic conductivity higher than 10^{-10} m/s. A heat treatment which simulated the heat pulse after deposition of a canister reduced the sealing effect of grouting due to the induced movement of rock blocks.

In an other part of Stripa rock test volum, the site of the former 3D experiment, a natural major water bearing fracture zone was characterized with a detailed hydrological survey including a ventilation test, a coprehensive sampling of water and pressure recordings in investigation holes drilled in the surrounding rock. The inflow is evaluated and the results from the characterization will form the basis for planning future grouting experiments.

Laboratory experiments in Sweden and Canada and theoretical modelling in USA are directed to longevity issues of bentonitic and cementic grouts considering the hydraulic conductivity and the erosion resistance. Theoretical and experimental studies indicate that the cement dissolution is accompanied by the precipitation of species as long as a relative low hydraulic gradient persists, and that cement grout degration is somewhat sensitive to groundwater composition. Theoretical studies suggest that the rate of grout dissolution is dependent upon the rate of water flow which form the basis for the conclusion that given the conductivity constraint, cement grout may be expected to persist for very long times. The work continues with the objective to evaluate also the rock/cement interactions.

6.3.2 Geoscience

The geoscience research has to a great extent been tied to some major projects, which give opportunity for interaction between the various specialized disciplines. The more important projects are

- the international Stripa project
- the planned Swedish Hard Rock Laboratory (HRL)
- the fracture zone study at Finnsjön
- the study on postglacial movements at Lansjärv.

6.3.3 The Stripa Project

The Site Characterization and Validation programme is based around the idea of cycles of data-gathering, prediction, and validation. Hence the programme has stages of work which can be described in these terms. In fact, the

programme contains two cycles of this type where predictions are checked against observation. It is therefore divided into five stages as follows:

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

The programme of work contains a number of different techniques falling within the disciplines of structural geology, geology, geophysics, chemistry hydrogeology, and modelling. These have been combined so that predictions can be made and subsequently validated. The "cycles" of the programme envisage two modelling periods in which predictions would be made. These two periods are very different. In the first (Stage II), a conceptual model is made which is essentially geometrical with preliminary values of the important properties. Modelling at this stage will make primarily geometrical predictions. In the second (Stage IV), modelling will include the detailed properties and will include predictions of inflows to the test drift.

As can be seen Stage III fulfills two functions, that is the data gathered at this point in the programme will be compared against the preliminary predictions resulting from the Stage II work. They will also provide a basis for the detailed prediction in Stage IV. Stages I and II were completed during 1988 and Stage III data collection was completed during 1989 and analysis of these data is currently in progress.

Closely related to the SCV programme is the continued development of the

— high resolution and directional radar antenna

— improved techniques for high resolution borehole seismics

— fracture network modelling

— channelling experiments

The channelling experiments were finalized during 1989 and the results of the experiments will be published in the first half of 1990.

The sealing work of the Stripa Project includes the continued work on the four large scale in-situ tests in Stripa as well as laboratory studies on the physical and chemical long term stability of cement as well as bentonite based grouts. The sealing programme also includes a theoretical investigation into the longevity of cement based grouts using numerical modelling technique, see also section 6.3.1 above.

6.3.4 Hard Rock Laboratory

A rather detailed programme for the Hard Rock Laboratory was presented as a background report to R&D-programme 1989.

Three main goals has been set, that is to

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

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

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

The last goal is common for SKB's entire R&D- programme.

To meet the overall timetable for SKB's research work, stage goals have been set up for the activities at the Hard Rock Laboratory, cf Chapter 19.

The pre-investigations performed during 1988 , including results from several deep cored holes has been evaluated and reported during the year. The results showed that the target area Äspö, a small island north of the CLAB-facility is a suitable site for the laboratory. The investigations have since then continued with additional drilling and testing. An essential part of the investigations is to conceptualize the results to different scales. These descriptions are the basis for several different numerical models that are applied within the project, such as e g fracture flow modelling. Before start of construction planned to occur in fall 1990, predictions will be made on the changes that will occur during construction of the laboratory.

The tunnelling work is expected to start during fall 1990 and end at a depth of 500 m early 1994. Approval from pertinent authorities is expected during summer 1990. In August 1989, the government decided that the Hard Rock Laboratory should be licensed under the Act on the Conservation of Natural Resources. In connection herewith SKB decided to make certain changes in the layout of the laboratory which will reduce the environmental impact. The government approval was granted in April 1990.

During the construction phase, investigations will be carried out to validate expectation models reported during the pre-investigation phase. Furthermore, data will be collected for progressive improvement of previous predictions. The investigations will be carried out both along the surfaces of the access tunnel and in boreholes drilled from the ground surface and from the tunnel.

After the construction phase, the operating phase will begin. The planning for the operating phase will be concentrated on characterization of the rock with tracer tests,

methodology for repository construction and pilot tests of the repository systems.

6.3.5 The fracture zone project

In crystalline rock the groundwater flow is concentrated to zones with an increased frequency of connected water conductive fractures. These fracture zones have much higher hydraulic conductivity than the rock matrix. Therefore any leakage of radionuclides from an underground repository up to the biosphere will preferably occur through such a fracture zone.

In 1984 the fracture zone project was started. The aim of the study was to define the characteristics of importance with respect to radionuclide migration for large fracture zones. In the initial course of the project a suitable subhorizontal fracture zone was identified at the Finnsjön study site. This zone has been extensively characterized by means of geological, geophysical, geohydrological and hydrochemical investigations carried out from the ground surface and from a large number of boreholes.

The third phase of the fracture zone project has included a hydraulic interference test and two separate tracer experiments. One being a radially converging experiment and the other one a dipole experiment.

Based on the very extensive investigations prior to the tracer tests it was attempted to predict the outcome of every new tracer experiment on the basis of the previous ones. In general the results of the experiments are in good agreement with the predictions.

Interpretation and modelling of the results of the tracer tests have shown that the groundwater flow in the highly conducting zone can be described by a layered porous medium model. The vertical connectivity is several orders of magnitude lower than the horizontal one. Whithin the INTRAVAL project the tracer tests in Finnsjön are modelled by several participants using different conceptualizations.

During 1989 the dipole tracer test was carried out. Water was pumped out of the upper highly conducting part of the fracture zone of one borehole and back into another borehole 150 m away. 16 different short lived radioactive isotopes were used as tracers together with stabile tracers. The use of the radioactive isotopes was successfull and the method is planned to be used also in the future.

The data from the Finnsjön tracer tests are very detailed and the modellers within the INTRAVAL project who have been modelling the tracer tests have requested a third tracer experiment, a natural gradient test. An outline of a tentative tracer experiment under natural gradient has been prepared and distributed to tentative participants in an international tracer experiment under natural gradient at Finnsjön.

6.3.6 The Lansjärv study

In 1986, extensive research was begun on the presumed post-glacial faults in the Lansjärv area, northern Sweden The goals of the studies at Lansjärv were to:

— assess the mechanisms that have caused present-day scarps,

— clarify the extent of any recent fracturing,

— clarify the extent of any ongoing movements.

The multi- and interdisciplinary studies carried through 1986–1988 and their evaluations have been published in a summary report during 1989. The general conclusions arrived at are:

1. Since the majority of the fractures that can be observed in the excavated profiles across presumed post-glacial faults (PGFs) are highly chemically altered, it can be assumed that they are of pre-Quaternary age. Similar observations can be made in the upper, approx. 300-metre-long part of the drill core. Furthermore, large portions of the post-glacial faults coincide with magnetically indicated oxidation zones. An indication of a possible new formation of fractures in connection with post-glacial movements has only been observed on one excavated rock surface immediately adjacent to a PGF. The post-glacial movements at Lansjärv are therefore considered to have been released primarily through reactivation of already existing fractures and faults.

2. The pattern and kinematics of the post-glacial faults do not have the radial or tangential extent to be expected as a result of post-glacial uplift. The extent of the faults is more commensurate with the effects of plate-tectonic movements.

3. The post-glacial structures in northern Fennoscandia are prominent tectonic features that were formed in recent time in a bedrock characterized by a relatively large number of regional shear zones with an NW-SE and N-S orientation. The relief in the area is generally low and the present-day rate of land uplift is relatively high.

4. The orientation of older zones of weakness in northern Fennoscandia favours the occurrence of PGFs in the form of thrust faults and reverse faults.

5. The reactivation of PGFs in Lansjärv has taken place through tectonic movements, which may have been released in connection to the deglaciation.

6. The hydraulic conductivity in the cored hole at Lansjärv does not deviate significantly from the conditions measured in a large number of other boreholes in Swedish basement rock.

7. It is deemed that zones of movement of the thickness studied can be avoided by the proper layout of the repository. Even if zones are not located in surface and borehole investigations, they can later be located in connection with detailed investigations and repository construction. Despite the very dramatic formation of the PGFs at Lansjärv, neither hydraulic conductivity nor groundwater chemistry at typical repository levels is remarkable in any way. It has, however, not been possible to specifically distinguish the effects of the last ice age for depths greater than 300 m, since the conditions measured are the result of accumulated disturbances that have taken place in the rock over many hundreds of millions of years and a number of glaciations.

It is planned that the studies at Lansjärv will end during 1990 after some additional field work.

6.3.7 Instrument development

As for 1989 most of the developments of instruments and methods were carried out in connection to the preinvestigations for the Hard Rock Laboratory. The efforts were to a large extent concentrated on measuring technique for characterizing groundwater flow paths in rock volumes between boreholes.

A multilevel monitoring system has been installed in all boreholes within the HRL project for recording natural groundwater level fluctuations as well as piezometric pressure responses, caused by pumping tests or other hydraulically disturbing activities in the surroundings. The system has been improved in such a way that tracer tests and dilution tests can be performed with the same borehole installations.

The technique for 3-dimensional determination of radar structures has taken a great step forward by means of the construction of a directional antenna, as described in last year's Annual Report. During 1989, SKB has improved the directional antenna so that measurements can be performed in vertical boreholes down to a depth of 1000 m.

6.3.8 Chemistry

Groundwater and minerals are being analysed in the course of the preinvestigations for the HRL.

Chemical experiments with radionuclides have been performed with the aim to determine solubility and speciation of actinides and relevant fission products in groundwater, their diffusion and sorption in granitic rock and in engineered barrier materials such as bentonite clay and concrete. Additives to the bentonite (getters) have been tested in order to increase radionuclide retention in the backfill.

The influence of organic groundwater components such as humic and fulvic acids on the migration of radionuclides have been tested. So has the influence of inorganic colloidal particles and microbes in the groundwater.

It may be concluded that groundwater flow characteristics in combination with chemical speciation of dissolved radionuclides are very important for the retention of radionuclides. Concentrations of mobile aggregates and the contact surfaces with the rock along the flow paths are key issues for the assessment of the rock as a barrier to radionuclide migration. The chemical investigations are aimed at this target.

6.3.9 Biosphere

The study of natural ageing of eco systems has been completed. The natural changes occured when the landrise causes brackish water estatuaries to separate from the sea and gradually develop to lakes and finally to farmland. The process has been studied in a coastal area at the Baltic. As expected the transfer of nuclides from ground water to man is strongly influenced by the primary recipient. At large a typical biosphere, as used in previous SKB safety assessments, with a small farm household using a well for drinkingwater, a lake for fishing and irrigation and having live stock as well as cereal production seems to give a reasonable upper estimate of the doses to a hypothetical critical group exposed to radionuclides in the groundwater.

The measurements on the longtime migration of the Chernobyl fallout continues at the Gideå and Finnsjön study sites.

6.3.10 Safety analysis

In the safety assessment area the most interesting development is the initiation of a new comprehensive safety analysis called SKB 91. The main objective is to access the influence of the main geologic parameters and structures and their variability on the performance of the repository. As a reference case the KBS-3 concept and the Finnsjön study site will be used. The variability of the geologic parameters will be taken from the database collected for the SKB study sites throughout the 1980s. The study will be reported by the end of 1991. It will also form a base for continued safety analyses of particular candidate sites for a repository as well as alternative designs to KBS-3.

A cooperative excersize with the Nuclear Power Inspectorate (SKI) has been conducted on scenario identification. The methodology applied will be further implemented in the SKB 91 analysis.

6.3.11 Natural analogues

The studies of natural analogues are important complements to the laboratory and in-situ experiments on radionuclide behaviour and transport in the geosphere. SKB participates in several studies in this area. The Poços de Caldas project started in 1986 on two closely located sites in Brazil. The project is sponsored by organizations in four countries outside Brazil. In 1989 all field work in the project was completed and the efforts were con-

centrated on laboratory analyses, evaluation and reporting of results. The project will be completed in 1990.

In 1989 SKB also joined the project at Cigar Lake conducted by AECL in Canada. Cigar Lake is a very rich uranium ore located at about 450 meters depth in northern Sascatchewan in Canada. The deposit has several very interesting features analogue to a spent fuel repository. The project starts with a preliminary phase up to May 1990 and is then planned to continue with a two year main phase.

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 parts 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. With the present storage technique the available positions in CLAB will be full around 1996. This corresponds to 3000 tonnes of uranium. In 1989 the Government gave a permit to increase the storage capacity within the existing pools to 5000 tonnes, thereby postponing the need for a new storage rock chamber until about 2003. The methods to be used for the expansion is described in chapter 3.

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 actively tried to transfer the existing contracts with COGEMA to other customers.

A part of the contracts were transfered to a Japanese utility in 1985. The same year a swap was made with some utilities in the Federal Republic of Germany, whereby some Swedish fuel delivered to La Hague for reprocessing was exchanged with some German fuel that was sent to Sweden for interim storage in CLAB and subsequent final disposal.

In 1989 the right to use the major part of the remaining contracts with COGEMA has been transfered to a number of German utilities.

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 funds, one for each nuclear power plant, which collect the money via a certain fee on electricity from nuclear power. 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 1989 calculations were presented in PLAN 89 /7-1/. The total future electricity production (from 1989) was estimated to be about 1470 TWh, if all twelve reactors are operated to year 2010. Up to the end of 1988 about 530 TWh have been produced making a total of about 2000 TWh in the Swedish program. For this production a fuel volume of about 7 800 tonnes of U is required.

The total future back-end costs were estimated to be about GSEK 43.0 (price level of January 1989). The figure includes the costs to be paid to COGEMA in accordance with the remaining contracts. This cost will disappear as a result of the transfer of the reprocessing contracts. The spent fuel is assumed to be disposed of in a KBS-3 repository. Up to and including 1989 already SEK 7.4 billion have been spent. The total cost for the back-end of the nuclear fuel cycle is thus about SEK 50 billion. Excluding the reprocessing costs the breakdown of the costs are roughly:

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

Based on SKB's cost calculations and the assumption that each of the twelve nuclear power reactors will be in operation for 25 years only, the government has decided that the fee for 1990 shall be SEK 0.019 per kWh on an average. This is the same fee as for the last six 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 1989 about GSEK 6.2.

7.4 DECOMMISSIONING OF NUCLEAR POWER PLANTS

During 1989 SKB's engagement continued in the international cooperative program, which is sponsored by

OECD/NEA. SKB is responsible for the program coordinator function.

According to the present planning the dismantling of the Swedish reactors will not start until after the year 2010. In 1988 the Swedish Parliament gave guidelines for the start of the phasing out of nuclear power in Sweden. They include that two reactors could be taken out of operation in 1995/96. The two candidates, one at Barsebäck and one at Ringhals, are both integrated with another reactor that will continue in service. A study has been concluded that shows that it for safety reasons is clearly inapropriate to dismantle them before the other reactors have been taken out of service. An early phasing-out would thus not change the planning for dismantling.

This means that there is no immediate need for substantial decommissioning R&D in Sweden. Earlier decommissioning studies have, however, indicated certain areas were early measures are warranted, the most important being methods for taking care of the reactor pressure vessel. In 1989 a study has been initiated about the possibilities to remove the pressure vessel in one piece and transport it intact for disposal.

8. CONSULTING SERVICES

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

From the start in 1985 and up to the end of 1989 about 50 assignments have been accomplished in a variety of areas such as field measurements in boreholes (hydrological, geophysical, rock stresses), canister and buffer material studies, feasibility studies and reviews of investigation programme and facilities. The consulting services performed during 1989 are summarized below.

Taiwan

In August 1989 SKB was contracted by Taiwan Power Co, TPC, to assist in the Phase II of TPC's Spent Fuel Disposal Programme.

According to TPC's instruction the main objective for SKB's advisory function should be to transfer to TPC/INER the know-how and experience gained in the Swedish spent fuel disposal programme. Instruments for this transfer have been informal communication reports, delivery of documents of interest, discussions at meetings in Taiwan combined with visits to various institutions in Taiwan and a field trip to the Peng Hu Islands and meetings in Sweden. Approximately 40% of the work has been carried out during 1989.

Japan

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

Republic of Korea

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

— Waste Inventory and Categorization.

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

— Guidelines for Performance Assessment and Safety Analysis.

— Preliminary Master Time Schedule for the Project.

— QA Programme for Radioactive Waste.

During a part of the joint study some 3-4 Korean engineers will be dispatch to Sweden to work in the project group.

Finland

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

Switzerland

In April 1989 SKB was contracted by NAGRA, Switzerland for conducting borehole radar investigations in the deep borehole at Siblingen, northern Switzerland. Radar measurements were carried out in one meter intervals from 500 m down to approximately 1000 m depth. The purpose of the measurements was to investigate the applicability of the radar technique in the NAGRA deep hole drilling programme. The measurements and interpretations were carried out by staff from SGAB.

9. PUBLIC AFFAIRS AND MEDIA RELATIONS

9.1 GENERAL

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

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

After Chernobyl the debate in Sweden on nuclear energy and waste has been reactivated. As one result, government plans were announced to decommission some of the twelve reactors prior to the year 2010, the deadline decided upon earlier by the Parliament following a 1980 referendum on the future of nuclear energy.

9.2 SKB INFORMATION ACTIVITIES

During 1989 some new approaches were made within the field of public information and media relations. Two different concepts of mobile exhibitions were tried, using the SKB ship M/S Sigyn for harbours and a tailor-made trailer for inland cities. Local media, schools, associations and local politicians were invited by direct mail. The outcome was such a success that full-scale tours will be launched during the next season.

Among the printed material published during 1989 one brochure met special interest. Called "Voices on Nuclear Waste" it featured not the traditional technical details and diagrammes but a series of interviews with different kinds of people, i.e. not only nuclear waste specialists.

On a number of occasions during the year SKB representatives have appeared on Swedish radio and TV programmes. Swedish politicians, other opinion leaders, foreign specialists and politicians, as well as members of the general public, have been frequent visitors to all the different facilities owned by SKB. The local exhibitions were updated during the year, and TV cameras and monitors added in SFR and CLAB to facilitate for visitors to view work in progress without entering controlled areas.

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, like the planned Hard Rock Laboratory.

The in-house magazine SKB-Nytt (SKB News) appeared seven times during 1989. The distribution covers a wide selection of scientists, researchers and consultants working for SKB.

9.3 PRINTED MATERIAL

Currently available printed material in the English language:

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

— Nuclear Waste (annually updated pocket-size folder, order no. C12 E 922 010)

— SFR, Swedish Final Repository for Radioactive Waste (order no. C 003 E 818 025)

— CLAB, Central Interim Storage Facility for Spent Nuclear Fuel

— Transporting Radioactive Waste

— M/S Sigyn

— Stripa, A Deep Underground Facility

— SKB Hard Rock Laboratory (order no. C33 E 834 010)

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

9.4 VIDEO CASSETTES AND FILMS

Currently available video cassettes and films in the English language:

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

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

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

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

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

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

REFERENCES PART I

CHAPTER 1

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

1-2 **KUNSKAPSLÄGET PÅ KÄRNAVFALLSOMRÅDET 1989**
(Present knowledge about nuclear waste 1989)
KASAM, September 1989 (in Swedish)

CHAPTER 6

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

CHAPTER 7

7-1 **Plan 89**
Kostnader för kärnkraftens radioaktiva restprodukter
(In Swedish)
June 1989

SKB ANNUAL REPORT 1989

Part II

Research and Development during 1989

CONTENTS OF PART II

10. REPOSITORY DESIGN

10.1 GENERAL

According to SKB R&D-Programme 89 /10-1/ alternatives to the reference KBS-3 design, see Figure 10-1, will be studied with respect to technical feasibility, cost effectiveness, radiological safety. development potential and confidence in the safety assessment. A good design shall enable available technology for application of the engineered barriers, canister, buffer material and backfill with sealing measures to be adapted to the inherent qualities of the rock as a natural isolating medium. During 1989 a study was finalized on how a rock quality designation process may be used in the alternative designs KBS-3 and WP-Cave. The study forms the basis for an evaluation on the differences in the possibilities to select the site of a canister or group of canisters in the alternatives. A feasibility study and assessment of the economic potential of an alternative repository design based on very deep boreholes was also finalized.

A literature study on the possible influence of the excavation techniques on the adjacent rock to large boreholes was performed and a study on the alternative of very long horizontal deposition holes by fullface boring technique was initiated.

The objectives for the studies on possible alternative designs and construction methods are to:

— form a basis for comparisons of the alternatives to be an isolating system together with canister and rock

— form the basis for cost comparison.

Above mentioned alternative designs can be seen in Figure 10-2.

10.2 ROCK QUALITY DESIGNATION

A strategy for a suitable characterization of the rock, before and during the construction phase, will be a part of the designation process that may form the basis for the selection of a site or group of sites for canisters within the

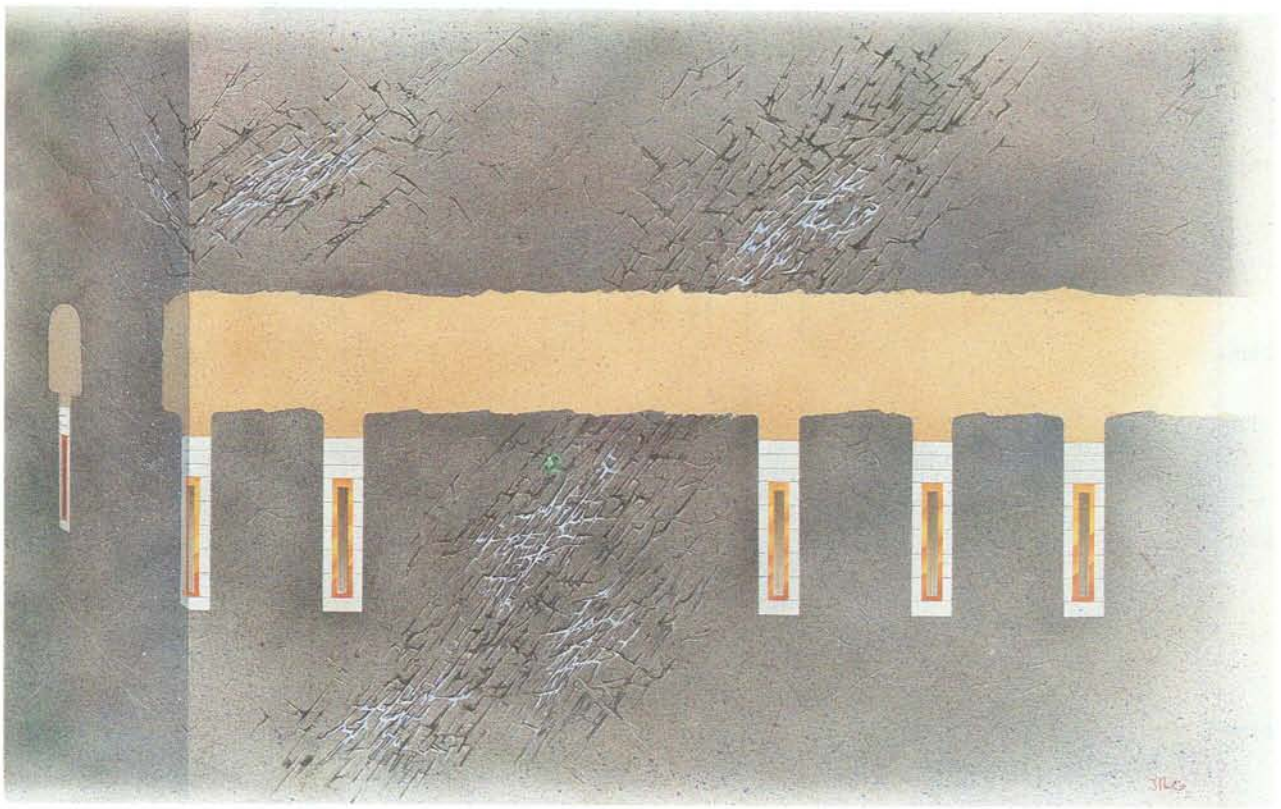

Figure 10–1. *Final repository according to the KBS–3 method*

limits of the layout of a repository. KBS-3 and WP-Cave were used as examples and the rock quality designation process was outlined. Possible types of results were identified when applied to a type of rock based on the experiences from Forsmark and the construction of SFR. The KBS-3 concept was concluded to be more flexible to adapt to the waterways within the rock.

The restrictions with regard to minimum distance between deposition holes and a zone with high conductivity and/or capability of faulting may be tested in the future when the isolation performance is evaluated in realistic rock conditions. This enables relative cost comparison between rejection of a site and alternative isolating measures to be made.

10.3 STORAGE OF SPENT FUEL IN VERY DEEP BOREHOLES

A feasability study and assessment of economic potential of the Very Deep Hole (VDH) repository concept was finalized during 1989. The reference design has been changed to shallower depth (4000m) and larger diameter (0.8 m) holes. For 7800 tonnes of U about 35 such deposition holes would be required.

The study includes a geological model for a Swedish rock column down to 6 km depth based on recent experiences of the Gravberg bore hole. The preliminary data

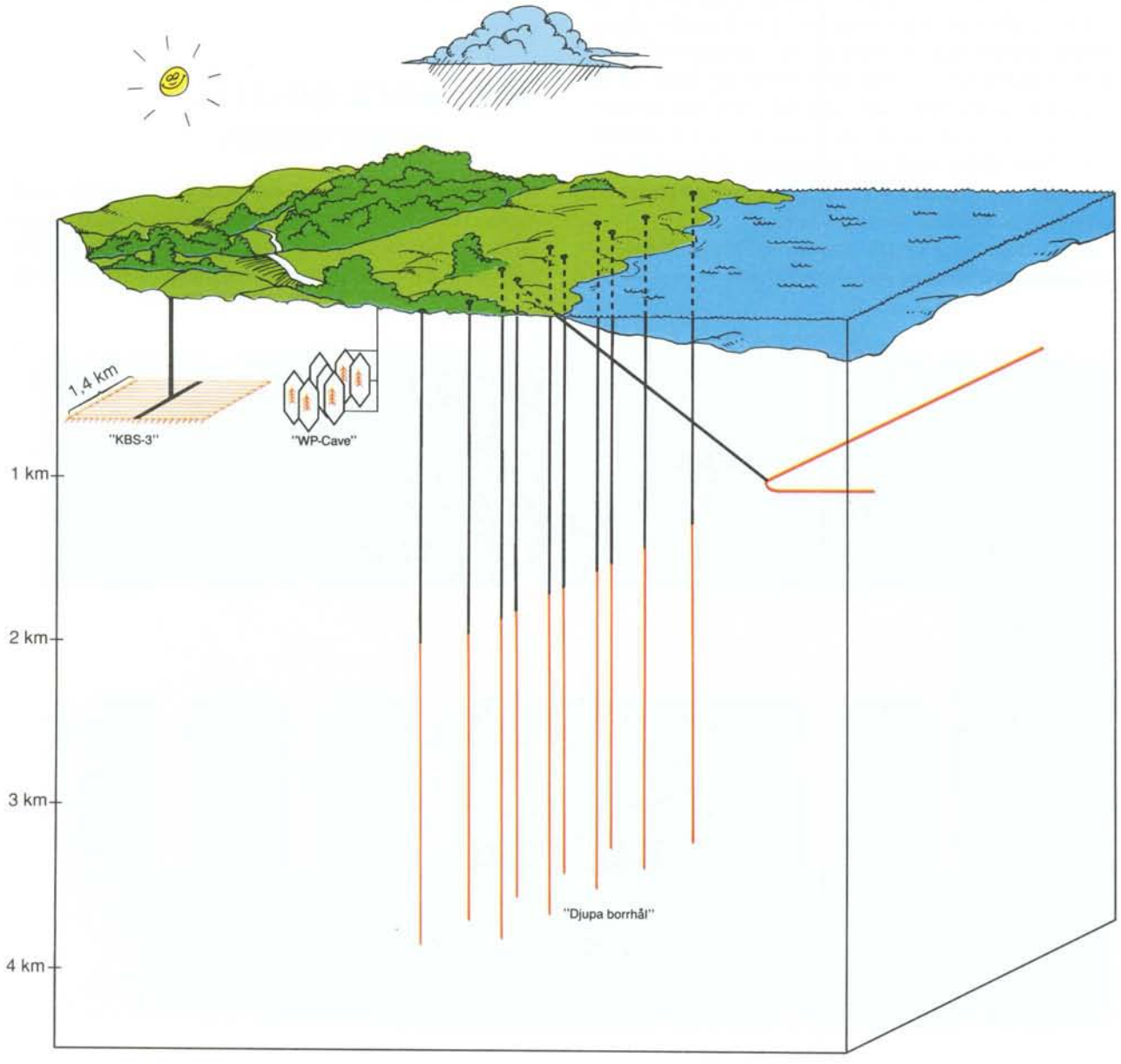

Figure 10–2. Alternative designs

from Dala Djupgas AB were used and the scientific results from other deep boreholes were reviewed as well. The geological investigation methods were discussed with rock mechanic considerations with the objective to form the basis for evaluation of the isolating properties of deep rock.

In the Gravberg hole water with high, 15%, salinity was found. This corresponds to 10% higher density than fresh water.

The influence of an increase in salinity with depth can have a positive effect on the isolation property of the geologic barrier in a multibarrier repository system. Some hydrogeological calculations indicate that the rise of a halocline above a deposition hole may not reach the surface if the heat generation is moderate, see Figure 10–3. From an engineering and economical standpoint the borehole with a large diameter (0,8 m) in 4 km depth was chosen to be feasible for drilling, handling of canisters, plugging and sealing with a special casing system, see Figure 10–4.

10.4 INFLUENCE OF THE EXCAVATION TECHNIQUE OF THE "NEAR FIELD ROCK" AROUND LARGE BOREHOLES

Percussion, rotary and core drilling are techniques which are compared with smooth blasting when the differences of the influences on adjacent rock are evaluated in a study based on data from literature.

The effect of stress release on the hydraulic conductivity of rock is also considered. Core drilling is concluded to have the least effect on the rock structure. Richer fissuring and some generation of new fractures and growth of preexisting fractures is produced within several decimeters from the borehole wall by full-face (rotary) drilling. These effects have importance when the isolating properties in the near field rock are evaluated.

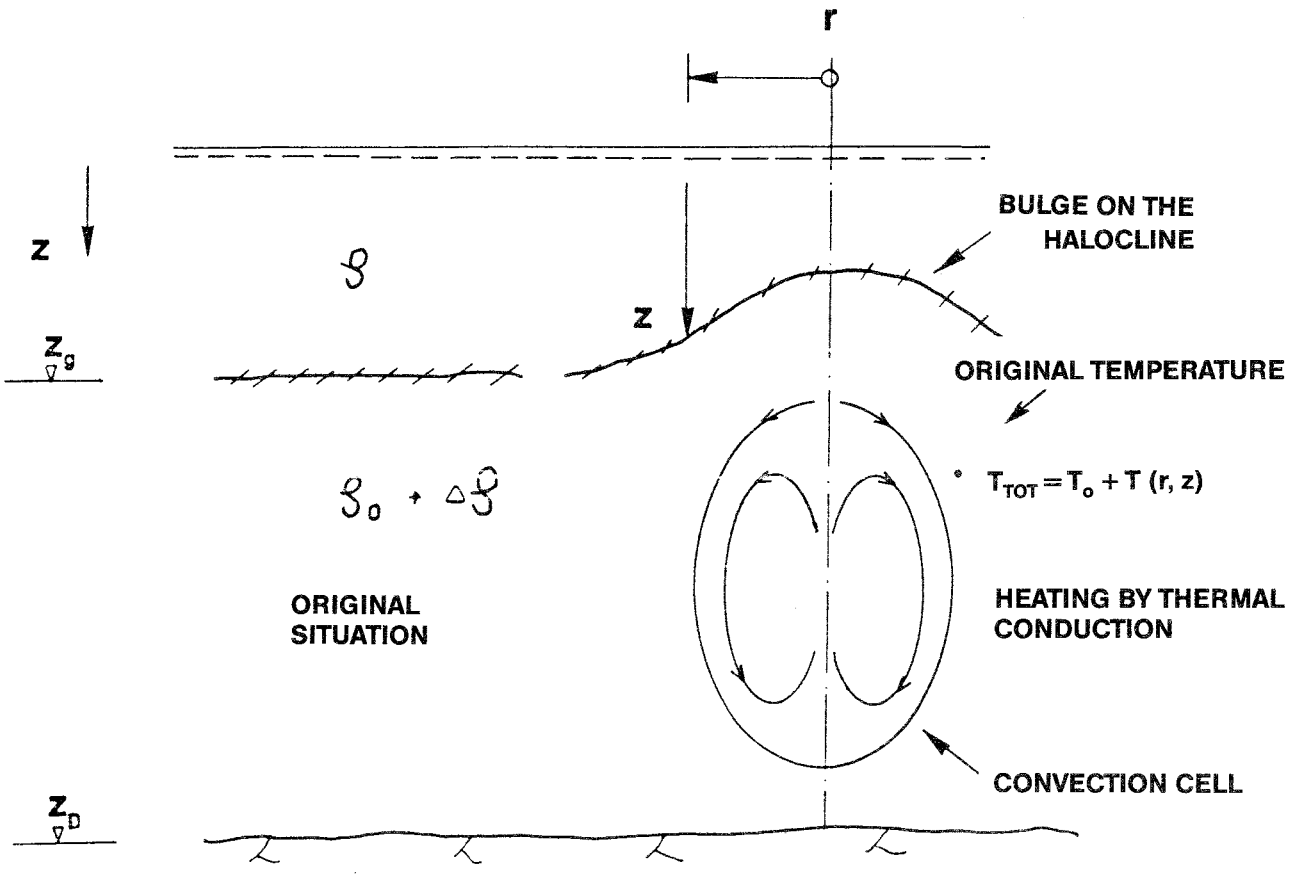

Figure 10–3. The derivation of the bulge of the halocline

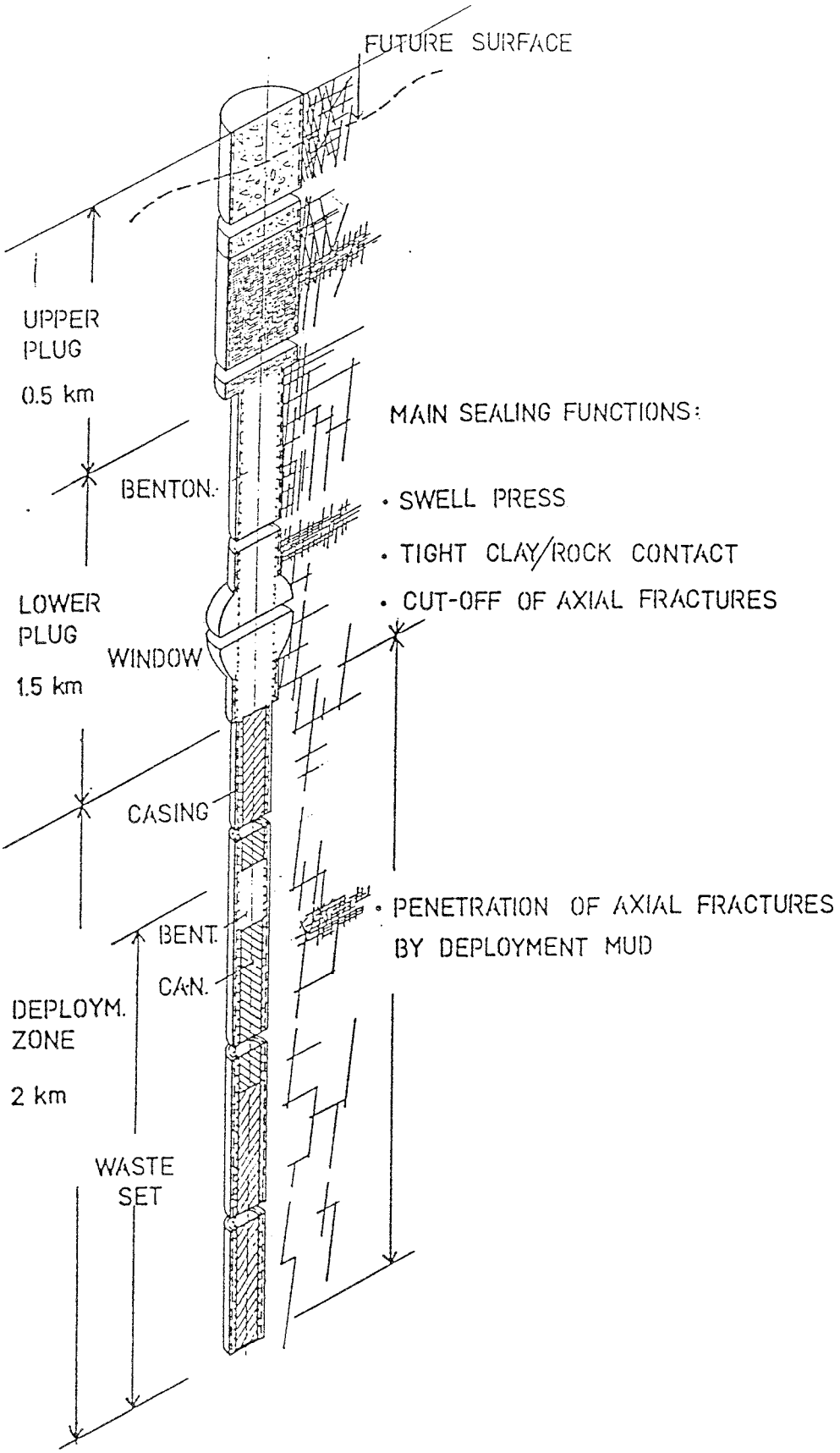

Figure 10–4. General view of a VDH concept

11. WASTE FORMS

11.1 SPENT FUEL EXPERIMENTAL STUDIES

As for 1988, the activities on waste form studies have been concentrated on spent fuel. No experimental work on vitrified waste has been performed. Following the termination of the JSS project with a seminar in May 1988, a final summary report of the results obtained within the project was prepared early 1989 and submitted for publication in Journal of Materials Research, where it is scheduled to appear in late spring 1990.

The close contacts with other groups in the world performing studies on spent fuel have been continued. The 1989 meeting of the annual workshop on spent fuel, the ninth one in the ongoing series, was held in USA and arranged by Battelle Pacific Northwest Laboratory.

11.1.1 Fuel Characterization Studies

The work with scanning electron microscopy and electron micro-probe analysis to characterize the spent fuel at the individual grain level has continued during 1989. Methods for studying both polished surfaces and fracture surfaces have been developed as well as techniques for X-ray diffraction studies of radioactive samples. Identification of secondary alteration products on spent fuel leached in deionized water and groundwater has also started.

Figure 11–1. *Fuel/Clad segment of PWR fuel specimen after 436 days in deionized water and 5 months of air storage*

Secondary alteration products have been observed on fuel specimens leached in deionized water as well as in synthetic groundwater. In Figure 11-1 the end surface is shown of a PWR fuel segment exposed to deionized water for 436 days under oxic conditions and stored in air for about five months. A yellow precipitate is clearly seen in the crack openings at the fuel surface. Figure 11-2 shows a scanning electron microscope photograph at 5,000 times magnification of the precipitate. This deposite is identified by X-ray diffraction as dehydrated schoepite ($UO_3 \cdot 0 \cdot 8H_2O$), or $UO_2(OH)_2$ /11-1/. The same precipitate has also been found to form on defected fuel under reactor conditions. Neither of these two conditions are, of course, representative for repository conditions. Nevertheless, it is important for modelling the fuel dissolution behaviour to be able to identify secondary phases which are expected to control the solution concentrations under laboratory conditions and, more importantly, under repository conditions.

Also on spent fuel exposed to a synthetic groundwater (280 ppm bicarbonate) precipitates have been observed. However, in this case, the material formed still remains unidentified. Figure 11-3 shows a scanning electron microscope photograph of this material formed on a grain boundary (face) of a BWR fuel specimen leached for 1427 days under oxic conditions (magnification 20,000 times). The smaller spherical particles (50 to 100 nm) on the other grain faces are probably 5-metal particles (Mo, Tc, Ru, Rh and Pd).

11.1.2 Spent Fuel Corrosion Studies

The results obtained throughout 1988 within the spent fuel corrosion programme has been summarized during 1989 in a status report /11-2/. The report emphasizes the consistancy in the results obtained within the Swedish programme as well as the agreement between Swedish results and results obtained elsewhere. For high burnup BWR and PWR fuel, uranium saturation in synthetic groundwater (120 ppm bicarbonate) appears to be attained at a level of a few ppm. In deionized water, the saturation level is about a factor of 1000 lower. This large difference is not reflected in the plutonium releases. In groundwater, plutonium reaches saturation at a level of a few tenths of a ppb. In deionized water the concentrations are nearly two orders of magnitude higher, indicating ongoing fuel oxidation/alteration after the leachant has been saturated with uranium resulting in the formation of U(VI) oxides, such as schoepite (see above). Similar alterations are expected to occur also in groundwater, but due to the higher uranium solubilities such alteration products are formed in much smaller quantities during comparable time periods.

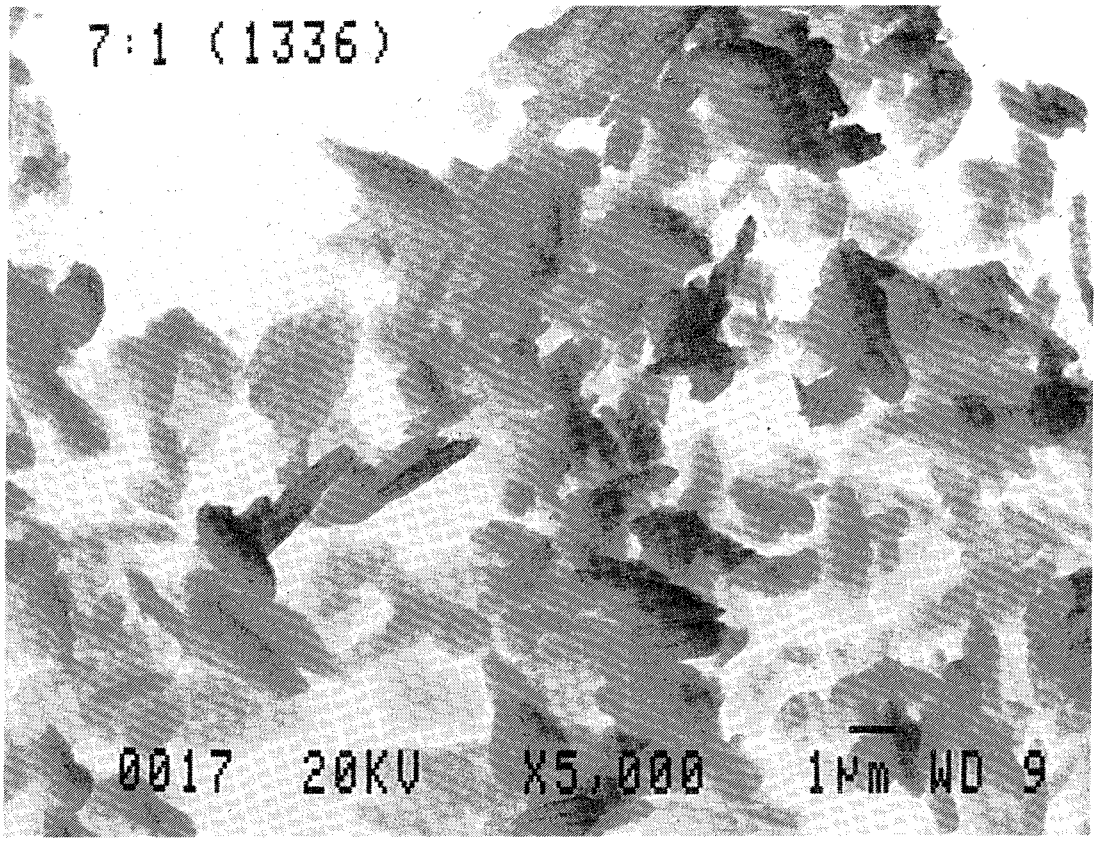

Figure 11–2. *Scanning electron microscop photograph of yellow deposit formed on a PWR fuel specime exposed for 436 days in deionized water. Stored in air for 5 months. Identified by X–ray diffraction as dehydrated schoepite,* $UO_3 \cdot O \cdot 8H_2O$ *or* $UO_2(OH)_2$

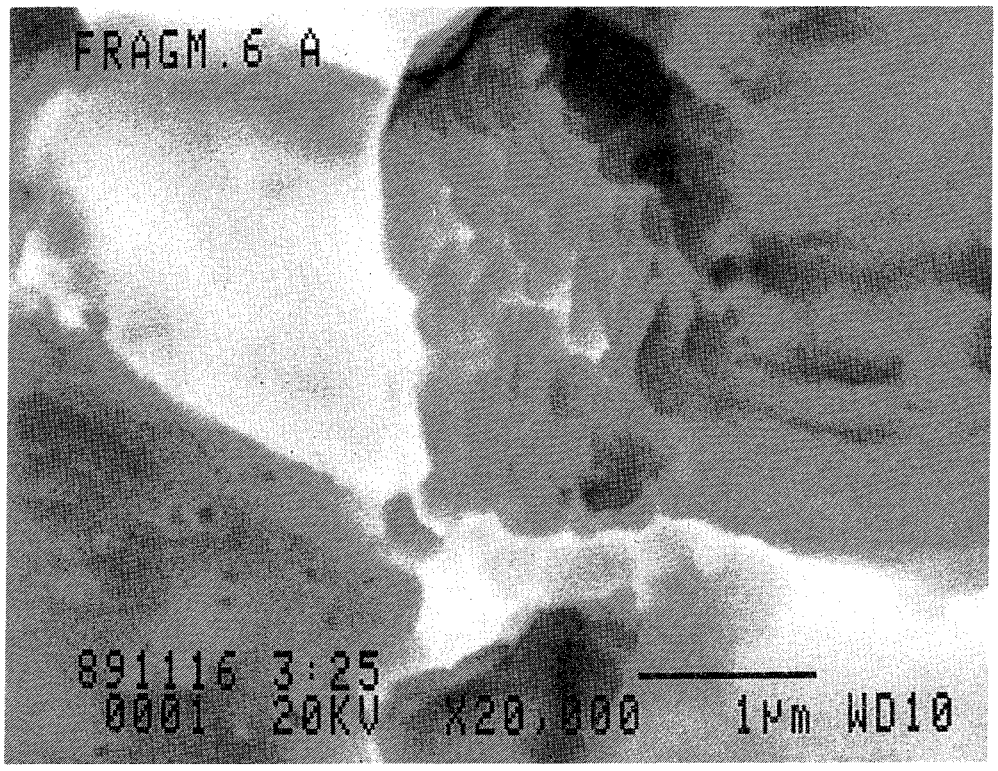

Figure 11–3. *Scanning electron microscope photograph of unidentified material formd at a grain boundary (face) of a BWR fuel specimen exposed to synthetic groundwater (280 ppm bicarbonat) for 1427 days under oxic conditions. The smaller spherical particles (50–100 nm) on the other grain faces are probably 5 metal particles (Mo, Tc, Ru, Rh, and Pd)*

A speciation study performed for uranium and plutonium under conditions relevant for spent fuel corrosion studies /11-3/. It was found that the thermodynamic data agreed sufficiently with the measured solution concentrations that it can be assumed that under oxic conditions (which are expected to prevail in the immediate near-field of the fuel) in natural groundwaters, leachate uranium would be uranyl carbonate complexes, while schoepite would be the solubility limiting solid phase. This is in agreement with previous studies /11-4/. For plutonium, PuO_2^+ would be the solution species and $Pu(OH)_4$ the solubility limiting solid /11-3/.

For the ongoing tests with PWR fuel, cumulative contact times of up to over 1300 days have been achieved. For a soluble fission product, which is not expected to be segregated in the fuel to any major extent, such as strontium, there is a clear similarity in release behaviour for both BWR and PWR fuel. As can be seen in Figure 11-4, the differences between fuel specimens cut from different parts of the same fuel rod are larger than between the two fuel types. It is also worth noting that there is no difference between the strontium releases in deionized water (series 3.1) and groundwater (series 3.2 and 3.5) for specimens cut from the same part of the fuel rod.

Very little, if any, evidence has been found for assuming that strontium is not dissolved in the UO_2 matrix /11-5/. It is therefore reasonable to assume that the release rate of strontium in fact is a measure of the oxidation/alteration rate of the fuel matrix and that fission products and actinides will be mobilized at this rate. Naturally, the release rates of these elements will be controlled also by their solubilities.

11.1.3 Integrated Fuel Tests

The release and migration of the fission products cesium, europium and technetium, the actinides plutonium, americium and curium from spent nuclear fuel pellets in highly compacted bentonite clay has been measured after contact times of 101 and 386 days /11-6/. Experiments at

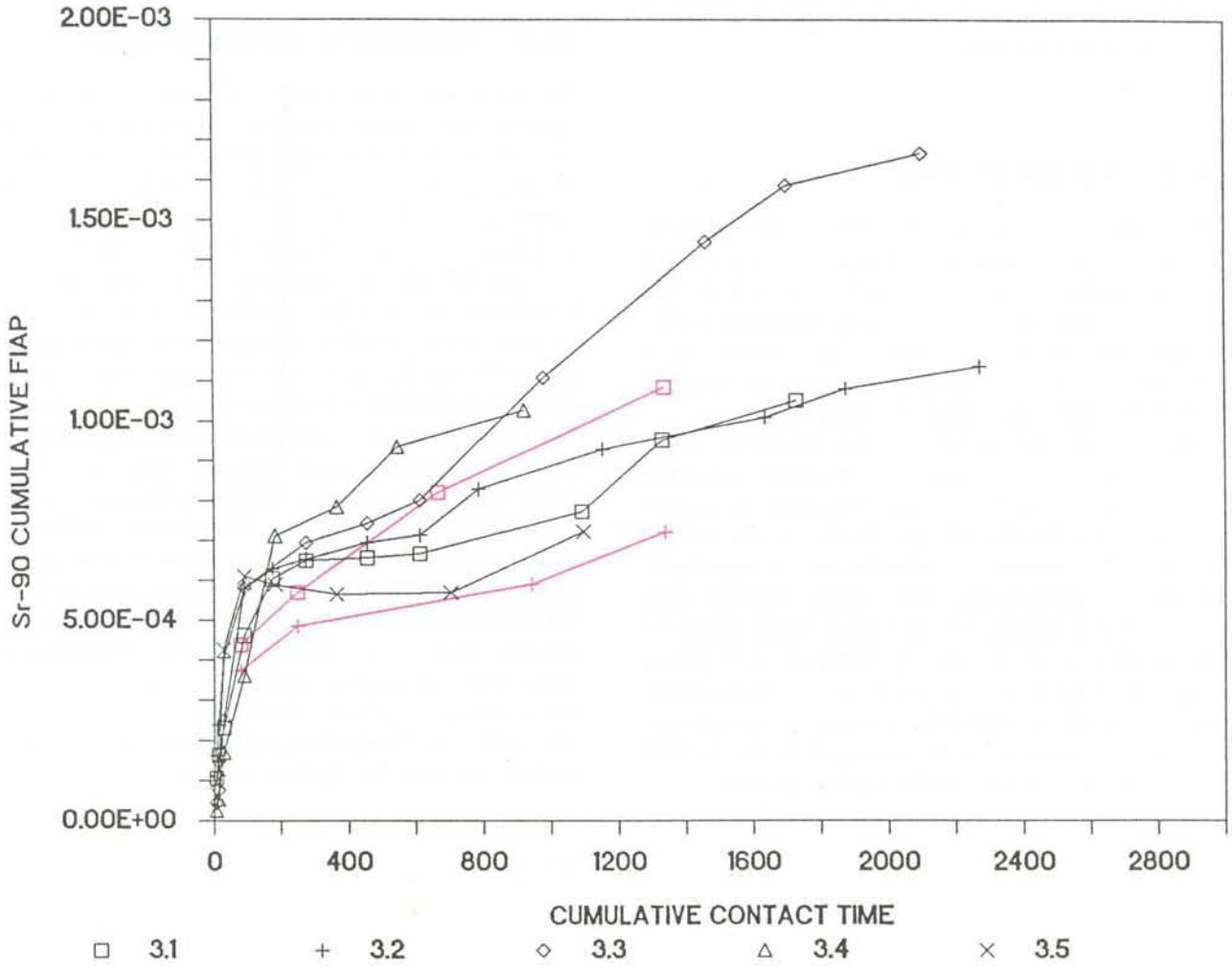

Figure 11-4. *Cumultative strontium release as a function of cumultative contact time. Black symbols denote BWR fuel specimens, red symbols PWR fuel specimens. Series 3.1 corresponds to a fuel specimen sequential leached to deionized water, Series 3.2 and 3.3 to fuel specimens sequentially leached in synthetic groundwater. Series 3.4 and 3.5 corresponds to fuel specimens leached under static conditions in synthetic groundwater. Specimens in the series 3.1, 3.2, 3.5, and 3.2, 3.4 were cut from two different sections of the fuel rod. For the PWR fuel specimens, squares and crosses denote specimens cut from different parts of the fuel rod*

longer contact times are in progress and the analyses of these experiments will start during 1990. Fuel segments, ca 4 mm thick (diameter: 12 mm), weighing about 4.5 g including 1.5 g of the cladding, were placed between two cylinders of bentonite, and put into diffusion cells. The clay had a density of about 2000 kg/m^3. The diffusion cells were submerged in synthetic groundwater that had been pre-equilibrated with clay. In some cases small amounts (0.5 to 1%) of powdered copper or iron metal, or vivianite ($Fe_3(PO_4)_2$) had been mixed with the bentonite clay. A more detailed description of the experiment set-up is given in /11-7/. A schematic view of the diffusion cell placed in a stainless steel water container is shown in Figure 11-5.

The results indicated as expected a high mobility of cesium. The actinides had a very low mobility. After 386 days, plutonium had diffused less than 0.5 mm away from the fuel, while americium and curium appeared to be somewhat more mobile, as can be seen in Figure 11-6. The behaviour of europium was similar to that of trivalent actinides. Very little technetium had been leached from all samples. This indicates that the technetium is present as Tc(IV) or in lower valencies.

11.2 MODELLING

The research activities during 1989 has been concentrated on oxidative dissolution. The reason for this is that although reducing conditions can be expected in deep granitic groundwater, local oxidizing conditions are believed to be at hand at the fuel surface, mainly due to α-radiolysis. The mechanisms that may control oxic matrix dissolution have been discussed /11-5/.

The rates of spent fuel degradation (alteration) under oxic conditions can be controlled by processes such as the growth rate of secondary alteration products, by oxygen diffusion through a product layer, by the rate of formation of radiolytic oxidants or by solubility/mass transport controlled dissolution of the matrix. These processes were discussed and methods for determining upper limits for the mobilization of radionuclides based on Sr-90 release (and hence fuel degradation) were derived from experimental data and consideration of radiolytic oxidant production. This concept will be developed further in 1990 for incorporation into the SKB 91 safety analysis.

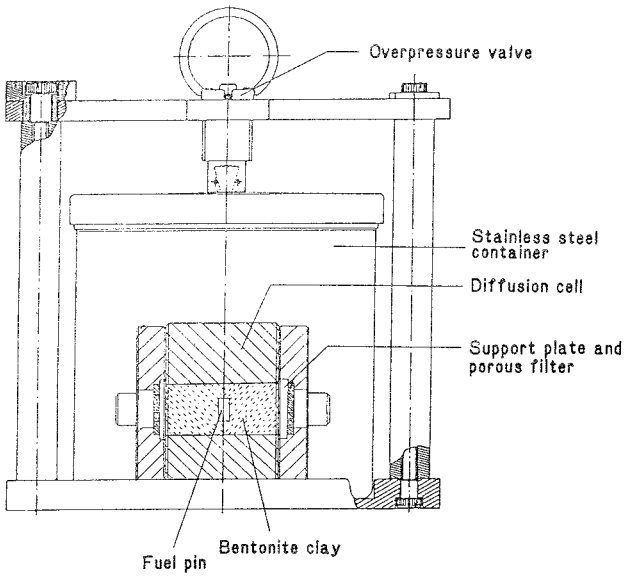

Figure 11–5. A diffusion cell placed in a stainless steel cylinder which contains synthetic groundwater preequilibrated with clay

11.3 NATURAL ANALOGUES

The alteration of uraninite (UO_{2+x}) at Shinkolobwe, Zaire has been found to provide a natural analogue for the corrosion of spent nuclear fuel in contact with oxidizing groundwater and such a study is in progress. A status report has been presented /11-8/. Although the study is still in an early stage, some conclusions can be drawn.

As primary alteration products, oxide phases such as becquerelite and schoepite are formed at the surface of the uraninite as well as other oxide phases incorporating the cations Pb, Cu, Ba and K. All these phases have similar structures and significant solid-solution may exist among them. Uranyl silicates, such as uranophane, replace the more coarse grained oxide hydrates along veins. The uranyl silicates also occur as intimately intergrown crystals within the oxide hydrates. These silicate inclusions appear to be formed concurrently with the oxide hydrates and not by replacement. The uranyl silicates appear to be the most stable long-term phases due to alteration of uraninite exposed to oxidizing siliceous groundwater. These alteration products were formed over periods of time in excess of millions of years and it is interesting to note that a thermodynamic equilibrium has not been reached, but a number of phases coexists.

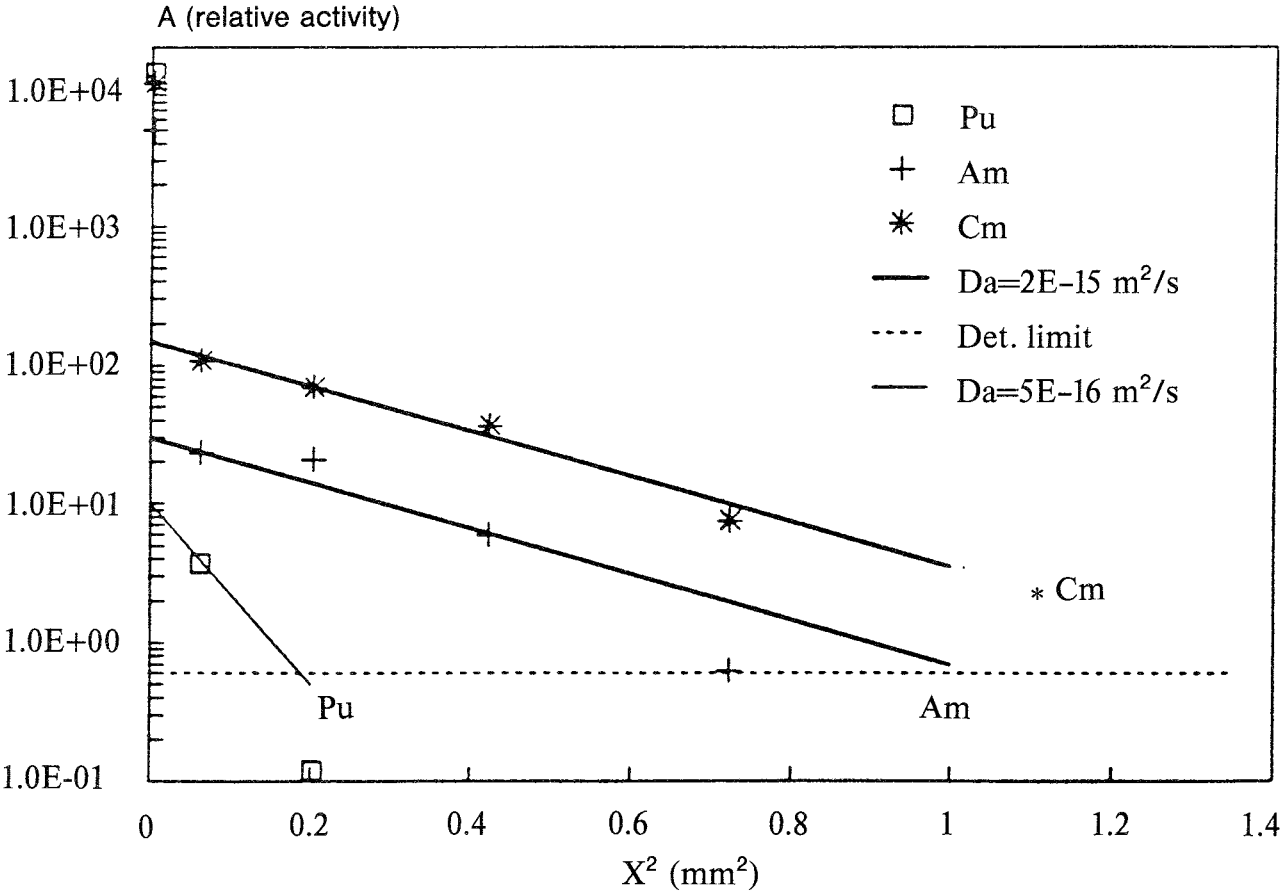

Figure 11–6. *Relative activity profiles of Am–241, Pu–238+239 and Cm–244 after a contact time of 386 days in pure bentonite*

12. CANISTERS

During 1989, three candidate canister materials have been studied in any greater detail: copper, carbon steel and titanium.

12.1 COPPER CANISTERS

12.1.1 Copper Creep Studies

The investigations on copper during 1989 have been concentrated on creep studies. Phase I of the creep studies, including investigations at repository relevant temperatures as well as slightly elevated temperatures (75°C to 145°C) were finalized during 1988. For experimental reasons, these tests had to be performed at rather high stresses (75 MPa to 100 MPa) in order to reasonable rupture times. These tests showed that copper had reasonable ductility at failure (5 to 20 % strain). However, the deformation mechanism in these tests did not correspond to the service deformation mechanism and, therefore, extrapolations to the expected service stress levels are somewhat uncertain.

To enable extrapolation to lower stresses, creep tests were started at higher temperatures (180°C to 250°C) and

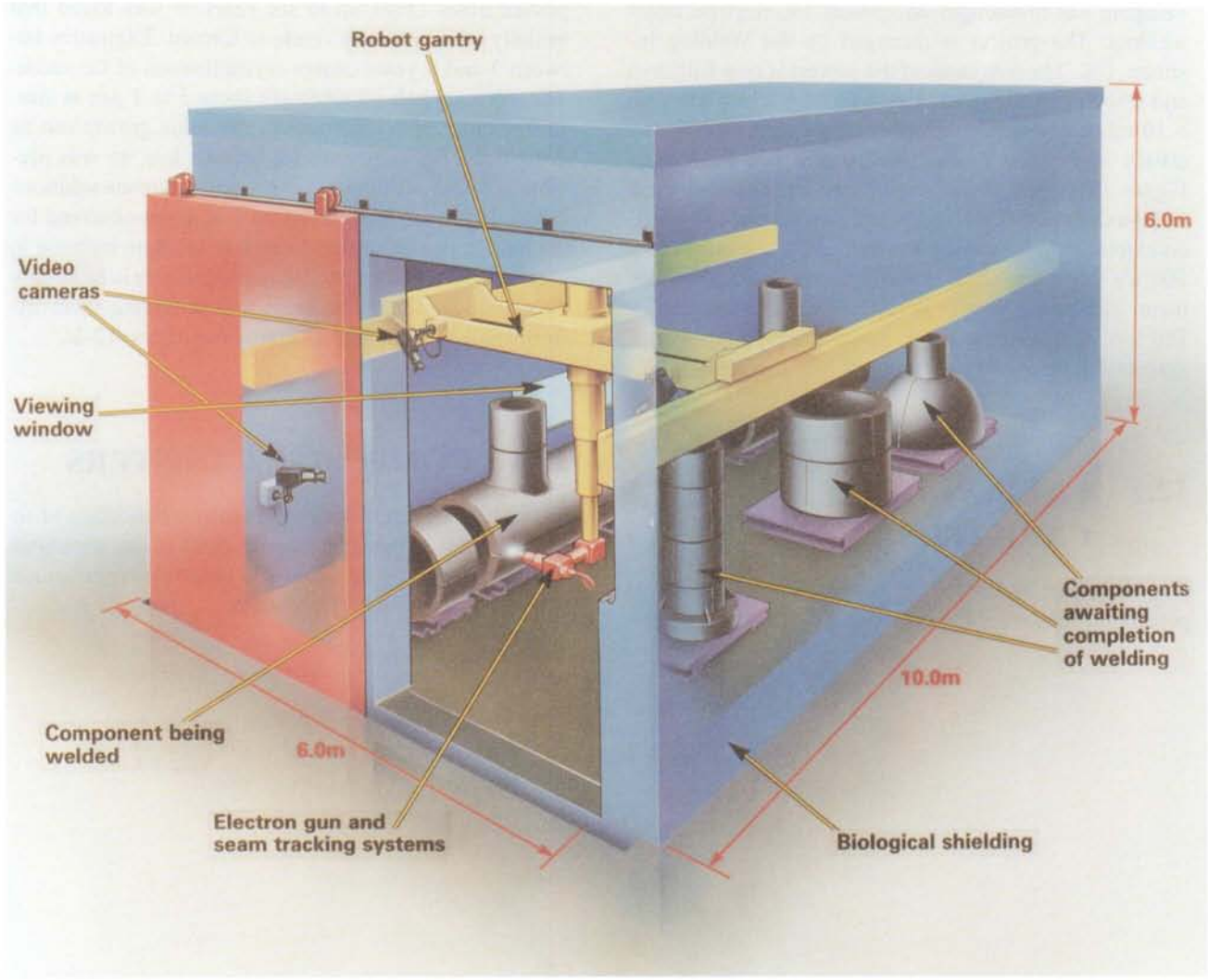

Figure 12–1. Non–vacuum electron beam welding bay: Artist's impression

lower stresses (20 MPa to 100 MPa). These tests have continued during 1989 and the results showed creep failure at extremely low strains, less than 1%. After testing, the samples contained many grain boundary cavities along the gauge length as well as some cavities in the unstressed grip ends of the samples. The presence of cavities in the unstrained material together with the low ductility suggest possible hydrogen embrittlement. The OFHC copper presently used has a hydrogen content of 0.6 to 0.7 ppm. In order to resolve this problem, new tests will be started in 1990 using copper with lower hydrogen contents. Oxygen free copper, phosphorus deoxidized copper and copper containing 0.15% silver, all materials with hydrogen contents lower than 0.1 ppm, have been chosen for this study. The tests are scheduled to start early 1990.

12.1.2 Copper Canister Sealing Techniques

In 1986 SKB joined a EUREKA project aiming at developing out-of-vacuum equipment for electron beam welding. The project is managed by the Welding Institute, UK. The first stage of the project is now finalized and a 500 m^3 welding bay has been built, complete with a 10-tonne crane to manipulate large components. An artist's impression of the construction can be seen in Figure 12-1. The electron gun will be mounted on a multi-axis robot. The power supply, consisting of a semiconductor high frequency inverter (500 V, 11 kHz) and a 300 kV high frequency transformer is under development. The power supply is capable of delivering up to 150 kW. The welding head, power supply and control system will be operational in 1990.

12.2 CARBON STEEL CANISTERS

The major part of the study of corrosion on carbon steel, performed at Harwell Laboratories, UK, has during 1989 been concentrated on anaerobic (hydrogen producing) corrosion. Carbon steel specimens have been corroded at 90°C in anaerobic conditions under a hydrogen pressure 0.1, 1 and 10 MPa. After exposure times of up to 8 months, corrosion rates of 0.5 to 1 m/a have been measured. The corrosion rates are within the experimental uncertainties independent of hydrogen pressure. Such a dependence would be expected if the water reduction reaction is the rate controlling step. However, a literature study performed during 1989 has found that the mechanistic knowledge of the corrosion process is inadequate to clarify this further. This literature survey will be published shortly /12-1/.

12.3 TITANIUM CANISTERS

During 1989, a long term corrosion study of titanium and palladium alloyed titanium exposed to groundwater saturated bentonite at 95°C has been finalized. The exposure times range up to six years. It was found that initially an amorphous oxide is formed. Exposures between 3 and 6 years causes crystallization of the oxide. The microcrystals of rutile are about 5 to 1 μm in size. Before onset of crystallization, the oxide growth can be described with a logarithmic growth law, as was previously found for titanium exposed to aqueous solutions /12-2/. However, a deviation for this law is observed for the long term exposed specimens towards an increase in growth rate. It is suggested that this increase is caused by the crystallization of the oxide thus providing short diffusion paths for the ions in grain boundaries /12-3/.

12.4 COMPOSITE CANISTERS

In 1989, a study of a composite canister consisting of an outer corrosion resistant copper shell given structural support by an inner steel canister. The study is performed in cooperation with TVO, Finland.

13. BUFFER AND BACKFILL

13.1 CLAY CHARACTERIZATION

The reference clay, Mx 80 Na smectite clay, has been investigated with respect to transport properties and rheological behaviour in a Swedish-Finnish cooperative study during 1988 and 1989. The clay dry density was 0,8 and 1,8 g/cm^3 in most of the tests. Diffusion tests with Na, Cu and U were made in room temperature and elevated, 90°C, temperature. Percolation showed only moderate influence on the hydraulic conductivity. Considerable differences were found in the rheological investigations between samples at room temperature and at 90°C, the main reason being the effect of cementation by released silica and aluminium, which are precipitated on cooling before the tests were conducted.

The heater test with French smectite highly compacted clay in a simulated deposition hole in Stripa was running with temperature about 170°C in the interface between the heater and the clay. The test is planned to be finalized in 1990.

A radiated sample of the reference clay Mx 80 was taken out from POSEIDON, SACLAY in April 1989 and examinations are being made with regard to physical properties.

13.2 CLAY RHEOLOGY

A deposition hole of the KBS-3 concept type, is being simulated by a borehole with 40 cm diameter in the Stripa mine. The heater simulating the canister can be loaded in the test arrangement, see Figure 13-1. The test started on June 11, 1986 and is still running. The results and calculations up to November 1989 which use data from laboratory tests and theory of water uptake, swelling, creep and consolidation settlement have been concluded to be:

1. The canister is heaving since the compacted bentonite is swelling upwards thereby compacting the overlying sand/bentonite overfill.

Figure 13–1. *Photo of heater experiment arrangement*

2. The effect of a temperature increase on the surrounding rock can only be explained by block movements. The very high pore pressure induced in the water saturated bentonite when it is suddenly heated is strongly affecting the rock.

3. The total consolidation settlement caused by the weight of the canister is several times larger than the total creep settlement achieved in 100–1000 years.

4. The processes observed during the test are fairly well understood and seem to be predictable.

A prediction of the result of an increased canister load is made and the load step was performed in Nov. 1989.

13.3 MODELLING BUFFER PERFORMANCE

The work with an updated model of water and gasflow through smectite clay buffer /13-3/ is going on.

Finite element code ABAQUS was used in conjunction with the canister settlement test, see section 13.2.

13.4 INTERNATIONAL COOPERATION

In the Stripa Project, phase 3, activities on sealing in the near field of a drift are included, see Chapter 18.

CEA, France and SKB cooperate in the field of clay research, see section 13.1.

9th International Clay Conference was held in Strasbourg, France, Aug 28 - Sept 2, 1989. Clay minerals and nuclear waste disposal was one session with strong Swedish participation. The conference had about 700 participants.

14. GEOSCIENCE

14.1 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 quite in detail in the SKB R&D-Programme 86, /14-1/ and in the current programme 1990 - 1996 /14-2/ that was released in september 1989.

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

— the planned Swedish Hard Rock Laboratory,

— the fracture zone studies at Finnsjön,

— the study on postglacial movements at Lansjärv.

The activities for the Hard Rock Laboratory – HRL – have continued with extensive investigations at the island Äspö. The first interim evaluation from three cored holes has been published. Additional drillings and measurements were carried through during the year to give a more accurate characterization of southern part of the island. Due to discussions on permits for the HRL, SKB decided to make a slight modification of the layout of the laboratory that reduces its environmental impact. The re-design lead to an extension of the investigation area.

The detailed geological, geohydrological and geohydrochemical investigations at the subhorizontal zone at Finnsjön that were carried through during the Phase 2 of the project have been published. Phase 3 of the fracture zone study at the Finnsjön site directed to tracer tests is in progress, see section 16.2.

The inter-disciplinary study of post-glacial movements in the Lansjärv area during 1986 - 1988 has been evaluated and reported as a part of the geoscience programme on bedrock stability. Some general studies on the Swedish bedrock and earthquake effects have been reported as well.

14.2 SWEDISH HARD ROCK LABORATORY – HRL

A detailed programme describing background, objectives and activities has been presented as a background report to the R&D-Programme 89 /14-2/, see Chapter 19, where a summary of the bulk of work executed during 1989 is described.

The results from the first stage in the pre-investigations comprising regional studies and general studies at some taget areas has been published earlier /14-3/.

The second phase of the site investigation programme has been concentrated to more detailed studies on the island of Äspö. The evaluation of the preinvestigations during 1988 has been published /14-4/. The evaluations resulted in conceptualizations of the site to different geometric scales, Äspö scale 1000 m, block scales 50 m and detailed scale 5 m. As the basis for those conceptualizations data all data at hand were used. The evaluations presented in /14-3/ formed the basis for regional studies of groundwater flow. The evaluations of the general studies at Äspö /14-4/ has been the basis for predictive modelling of a long-time pumping test that was carried through during the year. Evaluation of the predictions and outcome of the 3 months pumping test is in progress.

14.3 GROUNDWATER MOVEMENTS IN THE ROCK

14.3.1 Overview

A thorough understanding of groundwater movements is essential for a correct safety analysis of a repository. The groundwater flow affect 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 assessed in performance assessments and safety analyses. One of the factors that have great importance for assessment of radionuclide transport of nonsorbing and sorbing species is the flowrate of water. The flowrate of water in the bedrock is dependent on conductivity, connectivity and the driving forces. The importance of small density contrast for the overall groundwater flow distribution has been recognized. The experiences from SFR, from actual groundwater flow measurements in boreholes and analyses in generic models show that even small variations in the salinity of water have a considerable effect on the flow.

The conceptualization of the groundwater flow distribution is important for the overall assessment of radionuclide transport, both non-sorbing and sorbing. The hypothesis that groundwater flow occur in essentially independent channels or pathways need thorough studies. A project using radar measurements in conjunction with injection of saline water in order to study the potential of

using the technique for characterization of the flow distribution has been published along with some general studies on geophysics and geostatistics.

14.3.2 Fracture Zone Studies at Finnsjön

The rationale for the ongoing fracture zone studies, is to get data and methodology to assess the retention of radionuclides in fracture zones of the bedrock. The first phase of the fracture study at Finnsjön has been reported earlier /14-5/. The second phase – detailed characterization of the fracture zone – was completed late 1987. A total evaluation the geological, geohydrological and chemical work included in the second phase has been evaluated and reported /14-6/. The third phase essentially comprise a series of tracer experiments. The first activity in the third phase was the performance and interpretation of a series of hydraulic interference tests and a tracer test /14-7/. The interference tests were performed by pumping from isolated sections of one borehole and recording the resulting pressure changes in multiple-sections in the borehole. The hydraulic interference test as well as the tracer test documented a very high transmissivity of the subhorizontal Zone 2, particularly in its upper part. A numerical model was used in a series of prediction on more and more detailed data. The final simulation of the interference test show good agreement was achieved between simulated and observed responses from the most distant boreholes. The agreement decreased in the near-region boreholes, a fact attributed to local heterogeneities.

14.3.3 Geostatistical Studies

A pilot study has been published /14-8/ on the possibilities to predict the hydraulic conductivity and conductive fracture frequency in boreholes using multivariate analysis. Data from core mapping, fracture fillings, tubewave measurements and hydraulic tests from five deep boreholes at the Klipperås study-site was used. About 80–90% of the variation of hydraulic conductivity of an input data set could be explained by utilizing 35–40% of the total information contained in the data set. The highest hydraulic conductivities generally occur in borehole intervals with altered and deformed rock with increased fracture density. The frequency of subhorizontal fractures in granite generally correlates best to the hydraulic conductivity.

Multivariate analysis has also been used in order to compare radar data with geological, geophysical and hydraulic data /14-9/. Data from measurements at the study-sites Klipperås, Finnsjön, from the Saltsjö tunnel, Ävrö and Stripa was used as well. The analysis shows a high degree of correlation between highly fractured rock and high radar intensity at all sites. At Klipperås the high fracturing is associated with lithological contacts. The analysis also shows a high degree of correlation for radar intensity and hydraulic conductivity at Stripa and Finnsjön that did not show up from analysis of the other sites. Radar can be seen as an indicator of potentially permeable zones, but is not the ultimate tool as there exist high hydraulic conductivities not identified by the radar.

A joint project between OWTD,US/DOE and SKB on well test statistics is still in progress. A probabilistic model that describes the distribution of a series of transmissivity measurements has been derived. When the parameters of this model were estimated using maximum likelihood estimators, the resulting estimated distribution generally fit the cumulative histogram of the transmissivity measurements very well. Further, estimates of the mean transmissivity of conductive fractures were reasonable.

14.3.4 Studies in Connection to Construction Works

A test for the predictive capacity of radar measurements has been performed in conjunction with the construction of a full-face drilled tunnel situated in central Stockholm. An interpretation of the radar measurements has been arrived at along a section of the tunnel without access to any other geological, geophysical or hydrological data, except a topographic map of the site. The radar model of the site contained one major feature that was identified as a fracture zone. The intersection of the fracture zone with the tunnel was extrapolated from the radar data and found to be in agreement with observations in the tunnel. The radar also identified minor features which were of practically no significance with respect to tunnel construction. There is general agreement between the radar model of the site and the geological-tectonic model of the site, /14-10/.

14.3.5 Flow Distribution in a Fracture Zone

The objective of the project was to characterize the flow distribution in a fracture zone. The idea was to map the water flow paths by taking the difference between borehole radar results obtained prior to and after injection of saline water into the fracture zone. The radar experiment was combined with a more conventional tracer test to provide comparison and calibration of the radar results.

The field experiments were carried out during 1987-1988 in an earlier investigated rock volume with suitable borehole configurations in the Stripa Mine, while the comprehensive interpretation phase of the project have been conducted during 1989 /14-11/. Constant flow rate injection was performed with 0.5% concentration of potassium bromide (KBr) in one of the seven boreholes which are penetrating a fracture zone in the mine. The injection was continously carried out during a period of 38 days. The other boreholes were used for radar investigations; single hole reflexion and cross-hole tomography measurements.

From the differential attenuation tomograms the migration of the injected tracer was mapped and presented both in the fracture zone and in the entire investigated rock

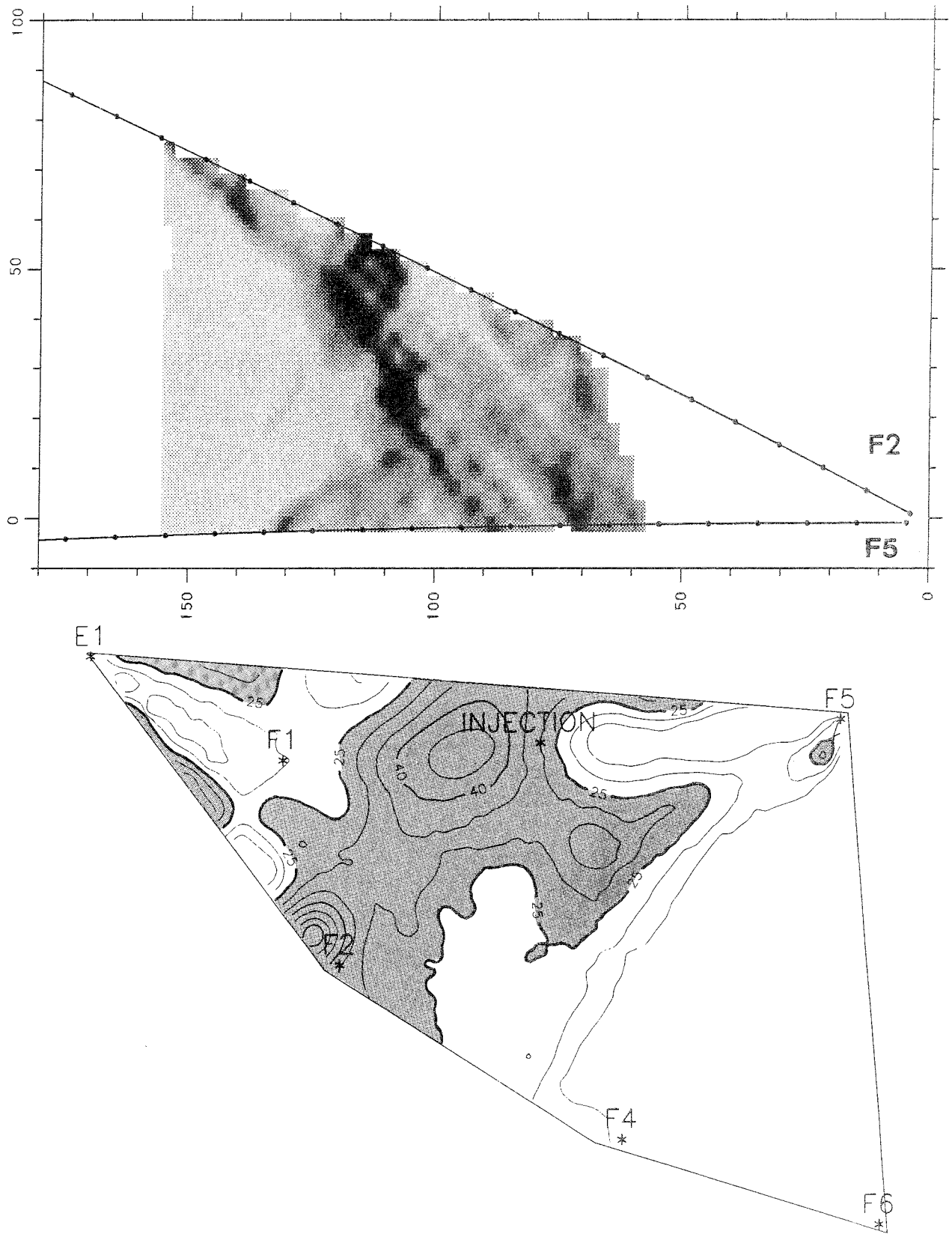

Figure 14–1. *Results from differential attenuation tomograms a) difference tomograms for the section between the boreholes F5 and F2, showing areas with saline tracer b) areas with saline tracer in the plane of the fracture zone intepreted from differential attenuation tomograms in eight sections*

volume, see Figure 14–1. The major tracer migration was found to be concentrated to a few major flow paths. The amount of tracer flow path, defined as the area with tracer transport in relation to the investigated area, was in the range 19-37%. Based on the combined interpretation of radar measurements and migration analysis an attempt was made to give a rough estimate of the wetted surface (the contact area between the flow path and the rock surface). Defined as the area of wet rock per volume of rock the calculation resulted in a wetted surface of 1.8 m^2/m^3.

In order to visualize and present the complex migration results an advanced three-dimensional CAD-system was used. The CAD-generated pictures displays the geological model as well as the tracer migration model in different views of which one can be seen in Figure 14–2. The experiment have shown that the combined method of radar measurements and saline tracer injection can be useful for the characterization of flow distribution in a volume of fractured rock.

14.3.6 Developments in Modelling

Development in modelling is primarily described in section 17.4. This section high-lights some applications. The stochastic continuum concept has been used to study the interface between saline and fresh water. /14-4/. The predictive groundwater flow modelling for the long-time pumping test at HRL was carried through along two avenues. The first approach utilized an three–dimensional equivalent continuum approach with the finite element code NAMMU. The second approach used the stochastic continuum concept recognizing density variations due to the salinity of the groundwater. The calculations were carried through with the PHOENICS code, a finite volume code where mass balance over the volumes is inherent. Evaluation of the two approaches led to the conclusion that modelling for the HRL will continue with the PHOENICS code.

At the scale of a single radioactive waste canister discrete fractures however dominate. The FracMan discrete fracture modelling package was used to analyze discrete feacture and hydrogeological data from the island Äspö, and to quantify heterogeneity and anisotropy. The results of these simulations were used to evaluate flux heterogeneity and anisotropy at the scale of a single nuclear waste canister, and at the 50 m scale to provide the basis for stochastic continuum modelling.The outcome of the calculations is still under evaluation.

14.4 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 move-

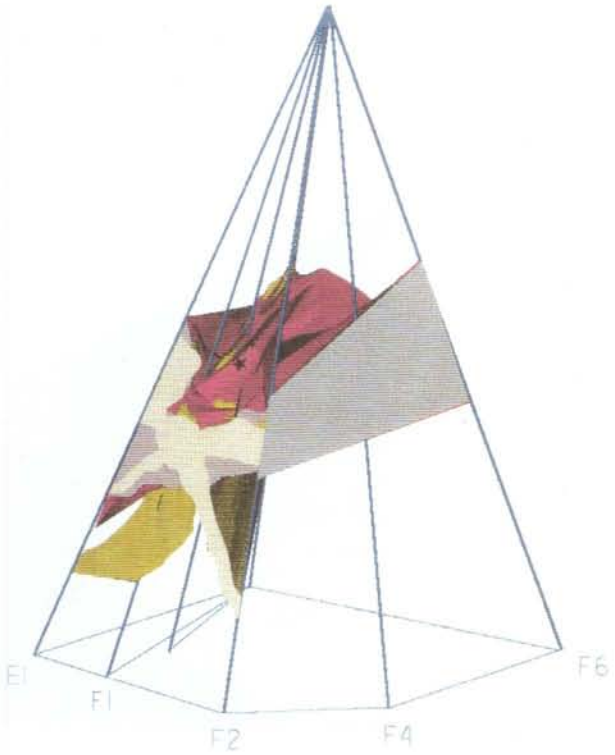

Figure 14–2. 3D CAD–model of the injected saline tracer distribution (yellow) within the investigated volume in combination with the zone model (red)

ments can decisively alter the geohydrological situation around a final repository.

The objectives are to:

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

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

The present major efforts in the project has been directed to the Lansjärv study.

14.4.1 The Lansjärv Study

In 1986, extensive research was begun on the presumed post-glacial faults in the Lansjärv area. Lansjärv is located approximately 150 km north of Luleå. The goals of the studies at Lansjärv were to:

— assess the mechanisms that have caused present-day scarps,

— clarify the extent of any recent fracturing,

— clarify the extent of any ongoing movements.

The multi- and inter-disciplinary studies carried through 1986 - 1988 and their evaluations have been published in

a summary report /14-12./ The general conclusions arrived at are:

1. Since the majority of the fractures that can be observed in the excavated profiles across presumed post-glacial faults (PGFs) are highly chemically altered, it can be assumed that they are of pre-Quaternary age. Similar observations can be made in the upper, approx. 300-metre-long part of the drill core. Furthermore, large portions of the post-glacial faults coincide with magnetically indicated oxidation zones. An indication of a possible new formation of fractures in connection with post-glacial movements has only been observed on one excavated rock surface immediately adjacent to a PGF. The post-glacial movements at Lansjärv are therefore considered to have been released primarily through reactivation of already existing fractures and faults.

2. The pattern and kinematics of the post-glacial faults do not have the radial or tangential extent to be expected as a result of post-glacial uplift. The extent of the faults is more commensurate with the effects of plate-tectonic movements.

3. The post-glacial structures in northern Fennoscandia are prominent tectonic features that were formed in recent time in a bedrock characterized by a relatively large number of regional shear zones with an NW-SE and N-S orientation. The relief in the area is generally low and the present-day rate of land uplift is relatively high.

4. The orientation of older zones of weakness in northern Fennoscandia favours the occurrence of PGFs in the form of thrust faults and reverse faults.

5. The reactivation of PGFs in Lansjärv has taken place through tectonic movements, which may have been released in connection to the deglaciation.

6. The hydraulic conductivity in the cored hole at Lansjärv does not deviate significantly from the conditions measured in a large number of other boreholes in Swedish basement rock.

7. It is deemed that zones of movement of the thickness studied can be avoided by the proper layout of the repository. Even if zones are not located in surface and borehole investigations, they can later be located in connection with detailed investigations and repository construction. Despite the very dramatic formation of the PGFs at Lansjärv, neither hydraulic conductivity nor groundwater chemistry at typical repository levels is remarkable in any way. It has, however, not been possible to specifically distinguish the effects of the last ice age for depths greater than 300 m, since the conditions measured are the result of accumulated disturbances that have taken place in the rock over many hundreds of millions of years and a number of glaciations.

Two background reports to the Lansjärv have been published during the year, /14-13, 14-14/.

It is planned that the studies at Lansjärv will end during 1990 after some additional field work.

14.4.2 SEISMIC EFFECTS ON BEDROCK AND UNDERGROUND CONSTRUCTIONS

R&D-Programme 86 /14-1/ described plans for compiling existing documentation on how underground facilities, mines and wells are affected by seismic events. This part of the programme has been published /14-15/. Geohydrological,geohydrochemical and mechanical changes are of particular interest. As far as mechanical impact is concerned, no damages have been reported for quakes that produce ground accelerations below 0.2 g. It was found, as expected, that the intensity of earthquakes is considerably lower underground than on the surface. There is no record of tunnels collapsing completely due to earthquakes. Minor damage has been reported in cases where a fault intersects the tunnel and very strong earthquakes occur within a kilometer or so of the tunnel. Few observations and published data exist on changes in geohydrological conditions, but inflow into underground facilities has been reported to increase by 40–300% for some events.

14.4.3 TECTONIC UNITS

Morphology, bedrock geology and the tectonics of Sweden have been compiled /14-16/. Sweden is subdivided into three terrain types, South-East Sweden Terrain, Norrland Terrain and Caledonian Terrain.

The tectonic structures have been evaluated from geological and lineament maps. The new lineament map based on relief shows acceptable correlation with lineaments based on Landsat images, when large tectonic elements, >50 km, are compared in southern Sweden. The correlation is worse for northern Sweden.

A new interpretation is presented of lineaments regarding location, direction and lengths of large lineaments. Based on the compilations, Sweden is divided into tectonic units.

14.5 DEVELOPMENTS OF INSTRUMENTS AND METHODS

The preinvestigation stage of the Hard Rock Laboratory project was intensified during 1989. As for 1988 most of the developments of instruments and methods were carried out in connection with these preinvestigations. The

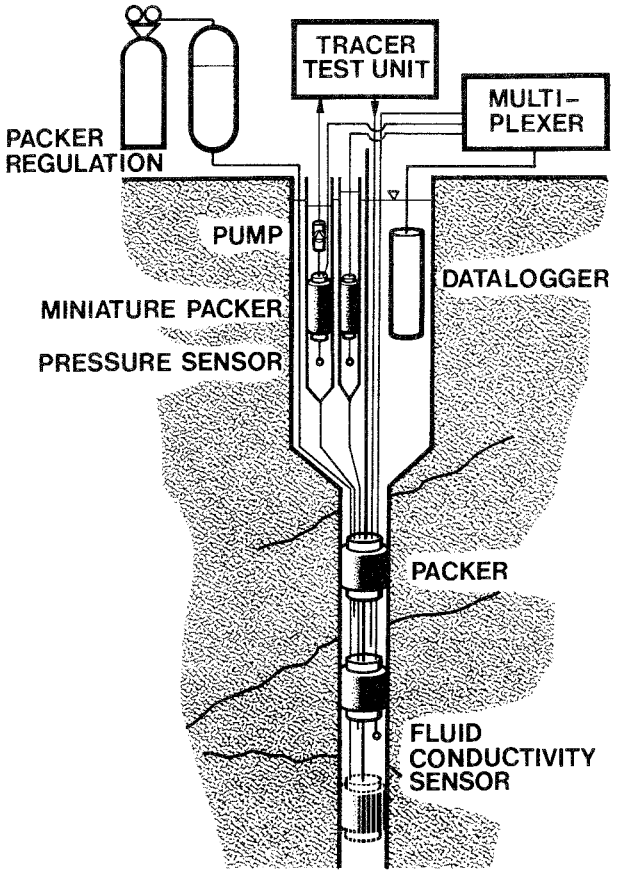

Figure 14–3. Principle of multilevel monitoring system for dilution tests, pressure recordings and fluid conductivity measurements, shown for two of the isolated borehole sections

efforts were to a large extend concentrated on measuring techniques for characterizing ground water flow paths in rock volumes between boreholes.

14.5.1 Hydrological measuring technique

Pumping tests

In order to determine the dominant groundwater conductors in the rock volume interference pumping tests have been made. Based on information from single hole tests, i e hydraulic injection tests and flow meter logging, some highly conductive borehole intervals were selected for these pumping tests. Pumping were performed from packed-off sections using recently developed instruments as described in the Annual Report 1988. The surrounding boreholes were equipped for multilevel monitoring of pressure-head changes, caused by the pumping.

The multilevel piezometric monitoring system have been improved regarding pressure response time through the long tubings. The lag time has been minimized by installing miniature packers in the water stand-pipes.

Dilution tests

Dilution test is a method which has been used for measuring natural ground water flow through a borehole section. For these measurements a special dilution probe has been used. However, these measurements are very time consuming and so are also the demobilization and mobilization of the multilevel monitoring system if such a system previously is installed in the borehole, which is the case in the Hard Rock Laboratory project. Therefore, the multilevel piezometric monitoring system as described in Annual Report 1988 has been modified in a way that dilution tests can be carried out simultaneously with pressure head recordings in two of the packed-off borehole sections. In Figure 14-3 the principle of the measuring equipment is shown, but only for one test section. Two water tubings down to the section and a miniature pump and packer device in the water standpipe are used for circulating water in the test section. In a tracer unit at the ground surface tracers are injected into the circulating water and moreover water samples are taken from the circulating water for analysis of the dilution process.

This kind of dilution experiments have during 1989 been used at undisturbed conditions for the determination of natural groundwater flow but also during the interference pumping tests from isolated sections. By means of dilution tests in observation sections, flow responses have been measured in addition to the pressure head recordings. For a large scale tracer test which is planned for 1990 the circulation system and the tracer unit will be used for tracer injections.

Beside the long term monitoring of the piezometric head a long term program for groundwater chemistry is set up. The borehole installation with the miniature pump and packer device also makes these water sampling possible from some 20 deep borehole sections spread out within the investigation rock volume.

14.5.2 Radar technique

Through years of experience the borehole radar are proven to be a valuable geophysical tool to identify features such as rock type boundaries and fracture zones in the rock outside the borehole or between boreholes. The radar method are being improved regarding technique as well as applicability, see section 14.3.5.

The technique for 3-dimensional determination of radar structures has taken a great step forward by means of the construction of a directional antenna, as described in last year's Annual Report. During 1989, SKB has improved the directional antenna in a way that measurements in vertical boreholes down to 1 000 m depth can be performed. For that purpose a new orientation device with a flux-gate compass has been constructed. Using the directional antenna, the orientation of a fracture zone or other detectable structure can be defined with an accuracy of $\pm 5^{o}$.

In cooperation with PNC, Japan, the development of tunnel radar antennas has been started. The antennas are maybe the most important part of a radar system. In order to provide maximum transmission of radar waves into the rock formation an optimum contact with the bedrock must be achieved. Thus, special antennas must be constructed

for measurements directly from tunnels. Such tunnel antennas must be particularly unsensitive to reflections from tunnel walls and disturbances from tunnel installations. The tunnel antennas are planned to be useful also for measurements from the ground surface.

15. BIOSPHERE

15.1 GENERAL

During the last years the biosphere studies have been concentrated on the transfer of radionuclides from the deep groundwater to man. The investigations have focused on the variability of the transfer of radionuclides from ground water to man due to normal change in the primary recipient of the ground water inflow and on the characteristics of sediments in inflow areas of lakes as compared to other sediments. In 1989 some more effort was given to validation of models and collecting data for this purpose.

15.2 MODELLING - WP-CAVE SAFETY STUDY

Within the safety study for the WP-Cave concept, a modelling of two specific biosphere receptors has been performed to address the doses to critical groups and the uncertainty in these doses /15-1/. The code used was BIOPATH and PRISM. The two biosphere receptors used were a well and a lake with release rates taken from the transport modelling /15-2, 15-3/ and parameters mainly from the KBS-3 study and later revisions /15-4/. The nuclides dominating the dose were found to be C-14, Se-79, Sn-126, I-129, Pa-231, Th-229 and Np-237 with maximum doses at about 5 microSievert per year. The uncertainty for the well case was totally dominated by the volume of the well, reflecting the difficulties of estimating the dynamics of a future well. The factor giving second most uncertainty was the drinking water consumption rate. The uncertainties of the lake case was dominated by sedimentation rate, consumption of and uptake in fish and by migration in soil.

15.3 SKB 91 SAFETY ASSESSMENT

The special safety study SKB 91 will in general not deal with the uncertainties in the biosphere but will use a set of dose conversion factors, relating release rate directly to dose.

The recipients used will be a well and a lake /15-5/.

15.4 NATURAL AGEING OF LAKE ECOSYSTEMS

The natural changes occurring when the landrise is causing the separarion of brackish water estuaries from the sea and slowly turning over to lakes and finally to agricultural land have been studied in two lake/estuary systems in Sweden. The earlier results have been reported in /15-6, 7, 8 and 9/. The final part of that study was to evaluate the effect of that variability when modelling the transport of released radionuclides through the biosphere to man.

As expected the transfer from groundwater to man is strongly influenced by the primary recipient. Depending on the radionuclide the transfer factor will change when a lake is formed, as the lake will get smaller by eutrophication, as the sediments are converted into agricultural land etc. Some nuclides like cesium show a maximum transfer factor when the lake can support a sustained fish population, others like technetium and iodine when producing cereals or letting cattle graze at the shore sediments. The variability with recipient change seems at maximum to be around one order of magnitude.

At large, a typical biosphere as used in the KBS reports and in the SFR licensing, containing a small farmhouse using a well for water consumption, a lake for fishing and irrigation and having both livestock and cereal production, seems to give a reasonable upper estimate of the doses to a hypothetical critical group.

In future comparisons between various repository concepts SKB intends to use such an standardized biosphere in order to simplify the comparison and not to confuse the evaluation with irrelevant uncertainties.

15.5 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 expected to be reported in 1990.

15.6 DISTRIBUTION OF RADIONUCLIDES IN SOILS AND SEDIMENTS

The modelling of transport in soils and sediments have been heavily relying on the sorption assumption expressed as a single K_d-value. There is a strong need for techniques to model this important part of the biosphere models in a better way /15-10, 11, 12/. Thus, a new project is initiated to better understand the long-term modelling of the accumulation of nuclides in sediments and soils. This can be achieved by:

— extending the understanding of sorption phenomena relevant to both the biosphere and the geosphere.

— using thermodynamic data and sorption data to explain and hopefully reduce uncertainty within the biosphere modelling (as the big intervals of uncertainty today mostly are the sequel of the highly variable K_d-values found in the litterature).

The study is expected to be reported in 1990.

15.7 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 /15-13, 14, 15, 16, 17/. SKB is now continuing this work and initiating a model evaluation using both compartment and continuous flow models. Another main issue is the chemical properties of the observed radionuclides.

Measurements of radionuclides originating from the Chernobyl accident in samples of deep and superficial ground water, soil profiles and shallow well sediment from the Gideå and Finnsjön areas have 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 fluctuations and precipitation and temperature fluctuations at different periods during the year.

The measurements of water from the deep core drillhole KGi 02 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 migration of radionuclides in the soil profiles shows that the transport in till is relativly slow compared to sand and peat (the profiles were sampled each year since 1986). Other conclusions from this study are 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-ll0m has moved very moderately but it should be observed that this nuclide is difficult to measure because of the low activity.

— Sb-125 seems to move very fast with 50% of the activity found in the upper 7 cm in till.

— Cs-134/137 can be found with 50% of the activity in the upper 3 cm in sand and till.

Measurements of radionuclide content in sediment profile samples taken in a shallow well indicate a very fast migration through the sediment, shown by an almost straight radionuclide concentration profile versus depth.

15.8 VALIDATION OF MODELS - BIOMOVS

Within the international study BIOMOVS (BIOspheric MOdel Validation Study) BIOPATH has been used in three different scenarios — the B5 scenario "Long-term evolution of a contaminated lake" /15-18/, the B2 scenario "Irrigation with contaminated groundwater" /15-19/ and the B3 scenario "Release of Ra-226 and Th-230 to a lake" /15-20/. In all these scenarios, the most relevant processes and sources of conceptual and parametric uncertainty have been indicated. The BIOMOVS study will be finalized as an open symposium in Stockholm October 1990.

16. CHEMISTRY

16.1 GEOCHEMISTRY

16.1.1 Groundwater analyses

Groundwater samples have been collected from deep core drilled boreholes on Äspö. Water yielding sections down to depths between 100 to 900 m were sampled. During 1989 four additional boreholes were made in order to intersect and verify indicated fracture zones. The groundwater sampling was made in connection with hydraulic pumping tests from isolated borehole sections and short time pumping tests during drilling.

Three different sampling procedures have been used at Äspö. The results of the deep groundwater analyses are compiled in a report discussing the advantages of the different procedures used. /16-1/. Results of analyses are given i Tables 16-1 and 16-2.

Within the site characterization and validation programme in Stripa, groundwater sampling was made in order to verify the earlier results and validate the conclusions.

16.1.2 Fracture mineral studies

Statistical processing of the fracture minerals occuring in the drill cores at Äspö has been made at two different occasions /16-2,16-3/. Calcite, chlorite, epidote, pyrite and hematite are the most common fracture minerals. Flourite, iron oxy-hydroxide, muskovite, quartz and clay minerals are also present. Compared to earlier studies hematized zones are rare especially in the drillholes which are directed towards indicated fracture zones.

Carbon-14 has been analysed on calcite samples from the Klipperås test site /16-4/. Two important results were obtained: 1) Carbon-14 in the infiltrating groundwater is rapidly sorbed in the surficial calcites. 2) The samples are easily contaminated by atmospheric carbon dioxide during storage and preparation.

16.1.3 Groundwater-Rock-Interaction models

Results of the groundwater analyses suggests that the fresh water pillow has a thicknes of approximately 50 m at Äspö /16-5/. Consequently there is a very small infiltration of surface water into the rock mass. This situation is also seen in the fracture minerals of the drill cores /16-3/. In recharge areas there is mostly a significant lack of calcite in the drill cores. The depletion is due to the infiltration of carbon dioxide rich water of low pH which dissolves the calcite. On an average the calcite depletion can be distinguished to 100 m depth. At Äspö the corresponding depth is only 10-20 m. The reason for this is the sea surrounding Äspö which levels out all the pressure gradients that could be the driving force for the percolation of surface water.

16.2 RADIONUCLIDE CHEMISTRY

16.2.1 Solubility and speciation

Solubility and inorganic speciation of radionuclides are described by chemical equilibrium models. The thermodynamic constants needed for these calculations are improved by laboratory measurements /16-6/. Phosphate complexes of uranium have been studied /16-7/ in addition to studies of carbonate and hydroxy complexes of actinides. It has been demonstrated that phosphate ions are of importance for solubility and speciation of uranium at certain groundwater compositions, see Figure 16-1.

International efforts to gather, review and validate the thermodynamic constants are valuable and SKB is supporting the efforts of OECD/NEA (TDB) to compile and quality assure databases for uranium, plutonium, americium, neptunium and technetium. SKB is also participating in the CHEMVAL project organized by CEC with the aim to validate the geochemical codes used. Codes and databases for speciation are also validated as a part of the natural analogue study project Poços de Caldas, see Chapter 20.

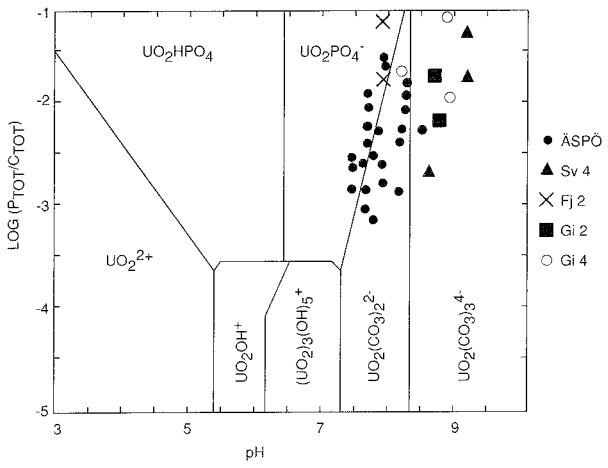

Figure 16–1. Predominace field of carbonate, hydroxide and phosphate complexes of uranium(VI) as a function of phosphate/carbonate ratio and pH. Compositions of deep groundwaters at study sites are included for comparison

Table 16–1.

The concentration of selected major and minor constituents and related parameters of the groundwater sampled from deep boreholes on Äspö. CCC= Complete Chemical Characterization is made by the chemical field laboratory and the downhole measuring and sampling equipment, SPT= Sampling during Pumping Tests, where a small portion of the water is passing the chemical field laboratory

Borehole /section (m)	Sampling method	W.flow ml/min	Drilling water %	Na mg/l	K mg/l	Ca mg/l	Mg mg/l	Sr mg/l	Fe.tot mg/l	Fe(+II) mg/l	SCO_3 mg/l	F mg/l	Cl mg/l	Br mg/l	SO_4 mg/l	S^{2-} mg/l	pH	E_hb mV	TOC mg/l	^{14}C age BP	U^{Tot} ug/1	$^{234}U/^{238}U$	$\delta^{18}O$SHOW	Deut.SHOW	Tri (bq)
KAS02 /202-214.5	CCC	61	0.80	1300	6.6	980	68		0.502	0.483	71.0	1.3	3840	14	108	0.50	7.4		6.0	10435	1.86	3.16	-13.9	-108.9	< 1
KAS02 /308-344	SPT	5000	0.70	1720	8.8	1480	75	27	0.715	0.622	32.7	1.3	5300	29	290	0.16	7.6		2.0		0.79	4.11	-12.7	-99.8	< 1
KAS02 /314-319	CCC	180	0.60	1700	9.0	1540	75	26	0.794	0.788	26.6	1.3	5340	23	270	< 0.01	8.2	-300	2.4	12670	1.36	3.06	-12.3	-100.6	< 1
KAS02 /463-468	CCC	160	0.40	1800	8.2	1570	66	30	0.507	0.505	25.6	1.4	5450	28	290	0.13	8.3	-300	3.0	13910	1.29	2.99	-12.8	-99.9	< 1
KAS02 /530-535	CCC	117	0.30	2100	8.1	1890	42	35	0.228	0.226	10.4	1.6	6370	42	550	0.18	8.3	-300	1.0		0.56	3.25	-12.3	-97.2	- 1
KAS02 /802-924	SPT	15200	0.20	2800	11.7	3690	39	61	0.027	0.023	7.1	1.6	11000	78	522	0.01	8.2		0.5		3.02	3.16	-13.0	-96.8	- 1
KAS02 /860-924	CCC	130	0.22	3000	10.9	3830	30		0.051	0.049	11.0	1.7	11100	74	520	0.72	8.5		<0.5		1.25	4.56	-13.1	-96.8	- 1
KAS03 /129-134	CCC	120	0.07	600	2.4	162	20	3.3	0.120	0.120	61.3	2.1	1230	5	32	0.70	8.0	-260	2.0	31365	0.84	4.56	-15.8	-124.8	< 1
KAS03 /196-223	SPT	10000	2.70	1200	6.3	480	60	10	–	–	60.0	1.8	2900	27	31	0.05	7.7		1.0	21695	0.93	3.54	-14.6	-115.3	- 1
KAS03 /248-251	SPT	4000	1.00	1300	6.6	500	54	10	0.290	0.288	53.0	1.8	3000	18	40	0.17	7.8		0.5	20090	2.63	4.23	-14.5	-118.1	- 1
KAS03 /347-374	SPT	18000	0.80	1730	6.3	1400	45	26	0.200	–	12.0	1.6	5180	30	340	0.05	7.8		0.5		0.34	3.00	-13.3	-104.9	< 1
KAS03 /453-480	SPT	16000	2.10	1710	6.2	1200	40	21	0.196	0.194	27.0	1.5	4600	28	300	0.11	7.8		0.5		1.41	2.90	-13.6	-109.6	< 1
KAS03 /609-623	SPT	18800	2.20	2000	6.3	1740	39	28	0.072	0.068	11.2	1.5	5880	46	470	0.10	8.0		1.1		0.67	3.34	-13.3	-103.4	- 1
KAS03 /690-1002	SPT	13000	2.60	2130	6.6	2660	63	44	0.065	0.059	11.0	1.6	8100	51	680	0.10	8.0		0.5		3.47	4.83	-13.0	-99.7	- 1
KAS03 /860-1002	CCC	120	0.15	3050	7.3	4400	50	75	0.075	0.075	10.6	1.6	12300	85	720	1.10	8.0	-240	0.5		0.98	6.30	-12.7	-96.4	< 1
KAS04 /226-235	CCC	100	0.16	400	2.4	95	6.8		0.040	0.040	215.0	4.0	530	3	180	1.10	8.2	-300	6.9		2.89	5.10	-11.0	-84.8	< 1
KAS04 /334-343	CCC	100	0.55	1180	6.1	750	30	13	0.315	0.315	70.0	2.6	3030	15	210	0.40	7.9	-260	5.3		1.66	4.60	-13.0	-99.6	< 1
KAS04 /440-481	CCC	95	0.06	2000	7.8	1700	60	29	0.260	0.260	20.6	1.5	5900	26	410	0.60	8.0		1.3		229.0	7.20	-11.9	-92.3	< 1
KAS06 /204-277	SPT	15000	0.72	1130	6.9	809	72	15	0.442	0.440	90.0	1.7	3630	17	150	0.17	7.6		4.7	7435	1.43	2.60	-10.7	-94.3	< 1
KAS06 /304-377	SPT	16300	0.03	1850	9.0	1490	119	25	0.430	0.425	49.0	1.6	5680	24	283	0.02	7.5		0.1	13280	1.60	6.00	-9.2	-77.8	< 1
KAS06 /389-406	SPT	15000	0.03	2060	11.8	1410	153	22	0.850		64.0	1.8	5970	23	362	0.01	7.3		0.1		1.45	4.40	-7.4	-69.2	< 1
KAS06 /439-602	SPT	25000	0.05	2200	11.1	1560	130	26	0.627	0.627	50.0	1.8	6150	30	459	0.02	7.3		0.5		1.37	4.90	-8.2	-70.8	< 1
KAS13 /0-100	SPT	115000	–	1880	32.8	1040	219	12	2.730	2.690	132.0	2.0	5070	37	136	<0.005	7.3		1.7		27.70	3.50	-7.2	-69.3	< 1

*E_h measured in the downhole probe

Table 16–2.
Chemical composition of the groundwater sampled during drilling of the boreholes. The samples are collected and sent to external laboratories

Borehole	Sampling method	Sample no	Section (m)	Drilling water %	Cond. mS/m	Density g/ml	Na mg/l	K mg/l	Ca mg/l	Mg mg/l	HCO_3 mg/l	C1 mg/l	SO_4 mg/l	Sio-Si	pH
KAS05	SDD	1	155-388	39.80	1460		1525	12.5	1380	55	29	5400	270	3.3	6.9
		3	387-550	28.40	1804	1.0049	2080	13.5	1980	44	15	6680	535	2.9	6.4
KAS06	SDD	2	106-217	31.60	1476	1.0028	1778	34.0	1022	213	87	5410	152	2.5	7.4
		2	217-317	25.00	1390	1.0027	1570-	1.0	1220	115	61	5000	130	3.6	7.6
		2	319-396	0.93	1484	1.0032	1740	9.3	1430	70	44	5410	240	5.4	7.1
		2	396-505	0.77	1700	1.0043	2190	11.0	1523	158	55	6300	440	5.6	7.4
		2	505-602	8.40	1710	1.0041	2100	17.0	1720	100	48	6300	450	3.7	7.2
KAS07	SDD	2	106-212	22.60	390	0.9980	460	8.2	244	20	231	1100	136	3.6	8.0
		2	212-304	8.76	975	1.0008	1055	10.3	868	57	78	3220	125	4.2	7.6
		2	372-604	41.40	2290	1.0076	2500	11.2	2820	100	11	8700	505	2.3	7.0
		2	462-604	43.80	2350	1.0078	2550	13.4	2860	75	14	8950	500	1.9	7.0
KAS08	SDD	2	106-208	0.64	1420	1.0028	1440	7.3	1430	85	37	5060	210	5.8	7.2
		1	208-306	9.28	1220	1.0016	1300	11.2	1145	89	68	4350	165	3.0	7.3
		1	306-447	29.20	484	0.9986	615	6.8	329	39	195	1470	138	3.7	7.6

SDD = Sampling During Drilling

Coprecipitation may add to the fixation of dissolved radionuclides. This process in connection with calcite formation is being studied /16-8/.

16.2.2 Organic Complexes, Colloids and Microbes

Humic substances have been retrieved from large amounts of deep groundwater from the Stripa mine, drillhole V2. A total of 40 mg was isolated for further experiments. The water contains about 0.1 mg humic material per litre. The study of previously collected humic materials, some of it from deep drillholes at study sites, have resulted in a series of articles in scientific papers on the characteristics and complexing properties of fulvic acids which is the main component /16-9 to 17/. It may be concluded that threevalent cations of radionuclides will mainly occur as complexes with humic substances in natural groundwater.

Colloidal particles have been manufactured by milling of oxides of silica, iron(III), copper(I) and aluminium. Silica oxide and aluminium oxide form rather stable solutions in contrast to the other oxides tested. Uptake of prometium as a model radionuclide have been tested. The K_d-value for silica colloids at pH 7 was 1-20 m^3/kg. Experimental work on radionuclide migration with colloidal particles in groundwater will continue in cooperation with Oak Ridge National Laboratory and Los Alamos National Laboratory in USA.

Groundwater samples for analysis of microbe content have been taken from boreholes in the Simpevarp area. Water conducting sections of the boreholes have been isolated with packers and a special sampler developed for gas sampling, has been used. The sampled levels range from 129 to 860 meter depth. The average total number of bacteria found was $3 \cdot 10^5$ bacteria/ml /16-18/. The bacteria are probably in an inactive state but can be reactivated in a suitable environment.

Experiments on the uptake of the elements cesium, strontium, europium, promethium and neptunium on the bacteria Klebsiella, Pseudomonas and Shewanella have been performed, see Figure 16-2. These investigations are being continued.

Investigations on the formation and mobility of organic complexes and colloids of radionuclides are also part of the natural analogue study project Poços de Caldas, see Chapter 20.

16.2.3 Sorption and Diffusion

Sorption experiments have been performed with radionuclides of cesium, strontium and europium on crushed and intact samples of granitic rock. The effect of diffusion into the rock matrix was demonstrated and a procedure for sorption experiments with strongly sorbing radionuclides was recommended. This included surface area measurements and the use of relatively fine grained samples /16-19/.

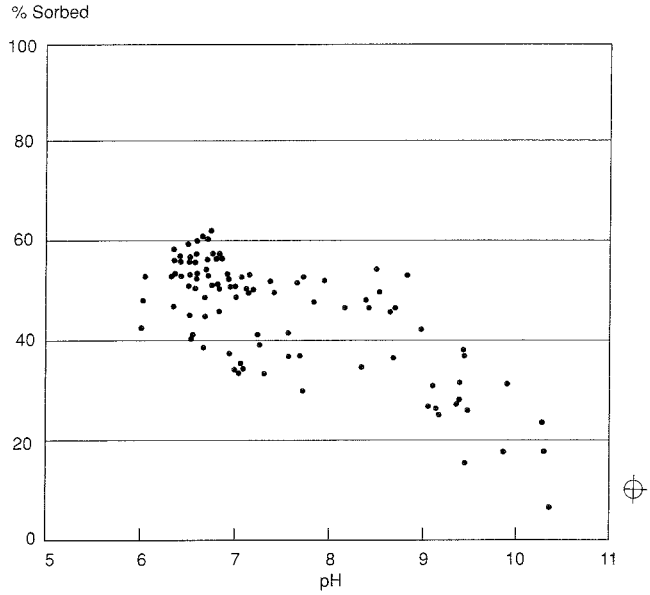

Figure 16–2. *Sorption of neptunium (10^{-6}M) on Shewanella putrefaciens (10^8 cells/ml) as a function of pH*

Results of experiments with diffusion of fission products into the matrix of granitic rock, have been published /16-20/.

Data from earlier diffusion experiments with radionuclides in bentonite clay have been reevaluated. It was found that the diffusion within the solvation sheath of the exchangeable cations in the clay particles is a dominating transport mechanism for Sr^{2+} and Cs^+ /16-21/.

Diffusion experiments with radionuclides of americium, plutonium, uranium, neptunium, cesium, iodine and technetium in 90/10 mixtures of sand and bentonite (MX-80, Wyoming bentonite) have been performed. The apparent diffusivities for all radionuclides are less than about an order of magnitude as compared to the case with pure clay (without sand) /16-22/. It is interesting to note that the apparent diffusivity Da varies from less than 10^{-9} m^2/s for the most mobile anionic species of iodine and technetium to around 10^{-13} m^2/s and below for the threevalent cationic species of americium, see Figure 16-3. Plutonium (threevalent and tetravalent) was diffusing too slow to be measured ($Da=10^{-15}$ m^2/s).

Diffusion experiments have also been performed on bentonite with "getters" i e additives with an expected favourable effect on radionuclide retention. Iron and copper in bentonite reduce the diffusion of technetium, uranium and neptunium. For copper the reduction in diffusivity is a factor of about 10 and for iron about 100 /16-23/. Although the effect is not dramatic it is expected that iron and copper as canister material and also their corrosion products will have a beneficial influence on radionuclide retention in the near-field.

16.2.4 Concrete

Experiments with diffusion of americium and plutonium in different concretes have been performed. Due to the

very slow diffusion the tests have lasted for two and five years respectively. The samples are being measured.

The chemical composition of cement pore water have been investigated and published /16-24/.

The theoretical calculations on possible chemical interactions between bentonite and concrete have been repeated at higher temperatures (150°C).

16.2.5 Radiolysis

Results of experimental investigations and model calculations on the influence of carbonate and chloride ions on the hydrogen peroxide production due to radiolysis by alfa radiation have been published /16-25/.

The rate and yield of radiolysis is governed by a comparatively large number of reaction mechanisms. A literature study has been initiated in order to check the quality of the kinetic constants being used.

16.3 VALIDATION OF TRANSPORT MODELS

16.3.1 Tracer experiments at Finnsjön

The third phase of the Finnsjön fracture zone project includes two types of tracer experiments. One radially converging experiment and one experiment in a dipole flow field, see Figure 16-4. Both these experiments have been carried out within a highly conductive horizontal fracture zone over distances of 100-200 m. The dipole experiment was conducted during 1989. A layered porous media model has been used to explain the results of these two tracer experiments.

Different radioactive and stable tracers have been used. The radioactive tracers have been both weakly sorbing and nonsorbing. The stable ones have been nonsorbing metal complexes and dyes. In Table 16-3 the different types af tracers are listed.

The tracer tests at Finnsjön is one of the test cases in the international INTRAVAL project which is an international exercise managed by SKI, see section 21.6.3.

16.3.2 Modelling of Tests at Stripa and Studsvik

Tracer tests are being conducted in the Stripa Mine within the framework of the international OECD/NEA project, see Chapter 18. A large experiment, the Stripa 3D test, has been carried out to investigate the water flow and mass transport in good, low fractured rock over distances of up to about 50 m /16-26/. The data are compiled and further used as a test case in the INTRAVAL project.

In Studsvik tracer test with nonsorbing tracers: iodine-131, tritium and sorbing tracers strontium-85 and cesium-134 were made in a conductive zone at depths between 60 and 100 m over distances of between 11 and 15 m in granitic rock. The results were reported in 1983 /16-27/. The data from these experiments have been reevaluated and used for the testing of transport models. The possible influence of matrix diffusion and channeling were highlighted /16-28/. It was concluded that more information is needed in order to discriminate between different model approaches.

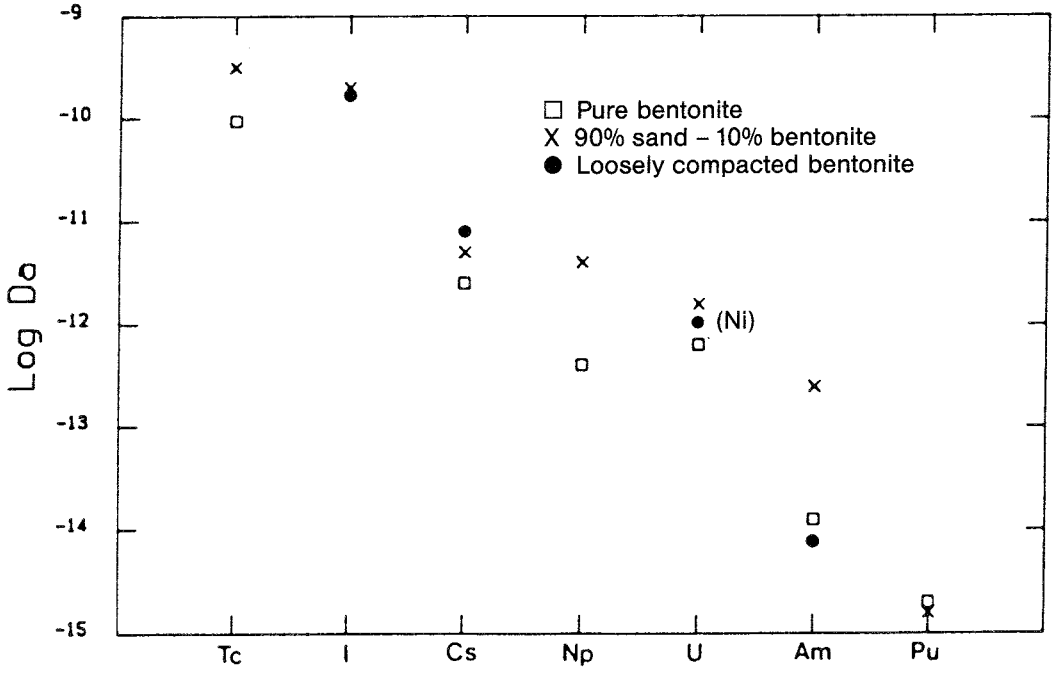

Figure 16–3. Measured diffusivities Da m^2/s for different elements in bentonite and a bentonite sand mixture. The bentonite is MX–80, compacted between 2 g/cm^3 for "pure bentonite" and 1.6 g/cm^3 for "looosely compacted"

16.3.3 Laboratory Experiments

Water conducting fractures in granitic rock are overcored and used in the laboratory for experiments on water flow and radionuclide migration in fractures. Data from earlier experiements have been used as a test case in the INTRAVAL project. Present experiments with overcored fractures are concentrated on effects of redox conditions and rock pressure.

Table 16–3. *The different type of tracers used in the Tracer Tests at Finnsjön*

Substance	Ion	Complex	Radioactive	Sorbing	Ref
Indium		In-EDTA	^{111}In-EDTA	non	
Dysprotium		Dy-EDTA		non	
Holmium		Ho-EDTA		non	
Erbium		Er-EDTA		non	
Thulium		Tm-EDTA		non	
Ytterbium		Yb-EDTA	^{169}Yb-EDTA	non	
Gadolinium		Gd-DTPA		non	
Chromium			^{51}Cr-EDTA	non	
Lutetium			^{177}Lu-EDTA	non	
Iodide	I^-		$^{131}I^-$	non	Stripa, URL, Grim
Bromide			$^{82}Br^-$	non	Stripa, Grimsel
Rhenium	ReO_4^-		$^{186}ReO_4^-$	non	
Technetium			$^{99m}TcO_4^-$	non*	
Sodium			$^{24}Na^+$	weakly	
Cobalt			$^{58}Co^{2+}$	weakly	
Rubidium			$^{86}Rb^+$	weakly	
Thalluim			$^{201}Tl^+$	weakly	
Uranine	dye			non	Stripa
Amino-G acid	dye			non	
Rodamine WT	dye			non	

The tracer tests at Finnsjön is one of the test cases in the international INTRAVAL project.

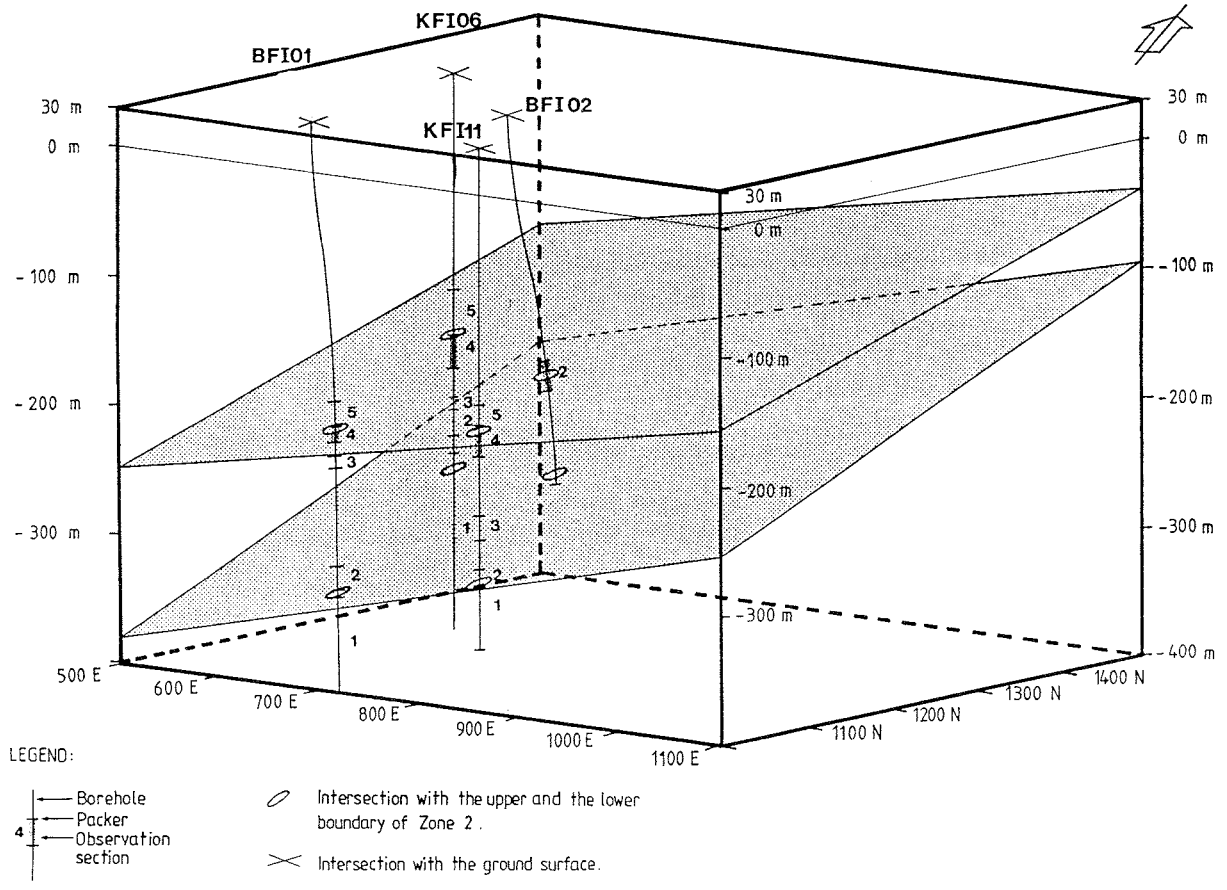

Figure 16–4. *The layout for the radialy concerging and the dipole tracer experiments in a flat highly conducting fracture zone at Finnsjön. For the dipole experiment the water was pumped out of BFi 02 and back into BFi 01 where the tracers were injected. Tracer monitoring was made in BFi 02, KFi 06 and KFi 11. For the radially converging experiment pumping and monitoring was made in BFi 02. Tracer injection was made in BFi 01, KFi 06 KFi 11*

17. SAFETY ANALYSES

The safety assessment activities have during 1989 continued in large along the lines laid down in the R&D-Programme 86. An emphasis has during the second half of the year been given to the planning and organization of a new integrated safety assessment, see section 17.5.

17.1 SCENARIO DEVELOPMENT

The cooperative exercise with SKI on scenario identification has been concluded and reported /17-1/. The work has shown that a systematic approach on scenario development is useful, especially due to the possibilities for documenting all steps and decisions taken during the procedure, but will lead to a great number of final scenarios to evaluate. A final step with expert judgement still will be needed in the scenario development exercise.

Through this cooperative work with SKI a common base for scenario development has been formed. An extensive database of possible events and processes that could influence a repository in the future has been developed. This database, which of course will be updated continously, can be used as a "checklist" for a relative "completeness" in future modelling work and safety analyses.

Another project that has been reported is the C-14 investigation, /17-2/. There a critical examination has been made of the source term of carbon-14 in SFR, the capacity of the repository to isolate the nuclide, the possible release to the biosphere and resulting distribution and doses.

17.2 NEARFIELD MODELLING AND ANALYSIS

The compilation of thermodynamic data for actinides and technetium continues. A Pu-database is in progress and the goal is to have validated data for Np, Tc, Am and Th in time for SKB 91.

In the SKB work it has been found that there is a need to describe the evolution of the chemical changes in the rock as the water flows through it. A development of a coupled transport and chemistry model which is specifically suited to handling the movement of dissolution/precipitation and redox fronts has started.

The model and computer code will incorporate a description of solution and solids chemistry similar to that used in chemical speciation codes (EQ3/6, PHREEQE).

17.3 FARFIELD MODELLING AND ANALYSIS

The work in the farfield area has been directed towards implementation of safety assessment computation programs on the Convex computer at SKB. Furthermore, developement of new concepts for flow and transport in fractured rocks is in progress.

The software package NAMMU /17-3/ will be used for groundwater modelling for future analysis. The program has been installed on the Convex computer. It has been utilized for three different applications during the past year.

SKB is participating in the recently started NAMMU User Group. This is an international effort with aim of coordinating the future developement of NAMMU and also to give the users an opportunity to exchange experiences.

The pre- and postprocessing package HYPAC for groundwater modelling has been implemented on the computer and a users guide has been written /17-4/.

A computer program for sensitivity analysis of groundwater flow GWHRT-S has been developed /17-5/. The model serves as a complement to flow models and may be used to study how different input data parameters and boundary conditions affect the output data.

The channeling model for radionuclide transport calculations has been applied to an in situ tracer test at the Studsvik site /17-6/. Furthermore, the model has been used for evaluating analysis of different test cases within the INTRAVAL project.

A statistical analysis of representative sample sizes in heterogeneous formations has been performed /17-7/. The objective was to estimate the necessary number of hydraulically conductive elements in a fracture network approach, in order to obtain values of the effective hydraulic conductivity, which equal those of continuum approximations.

17.4 THE PROPER CODE PACKAGE

The major emphasis during 1989 in the development of PROPER has been placed on the documentation of the first generation of submodels, development of a second generation of submodels for the SKB 91 project, and development of software and use of PROPER for stochastic modelling of groundwater flow.

Presently, the code package consists of:

— The PROPER monitor used for linking submodels selected from a submodel library at run time, for sampling input data distributions, for controlling and monitoring the transfer of data between submodels.

— A separate computer code for testing the Monitor.

— Postprocessing codes for the graphical presentation of results (POSTMON and GPLOT) and for sensitivity analysis (POSTREG).

— The BATEMAN code for creating radionuclide inventories as a function of time.

— A zero:th-generation library of numerical service routines for submodell designers.

— A library of zero:th- and first-generation submodels containing:

SCFIO, a finite element hydrological model with 2-D and 3-D axisymmetric capabilities adapted to KBS-3 conditions,
NEAR20, a single nuclide, single KBS-3 canister near field model taking canister corrosion, diffusive transport and solubility limitations into account,
NEAR21, a single KBS-3 canister near field model taking canister corrosion, diffusive transport and solubility limitations and chain decay into account,
FARF30, a single nuclide, stream tube far field model taking advective and dispersive transport and matrix diffusion/sorption into account,
FARF31, a stream tube far field model taking advective and dispersive transport, matrix diffusion/sorption and chain decay into account,
BIOS40, a biosphere model computing individual and collective steady-state doses for different primary recipients (based on computations with a detailed compartment model).

17.5 SKB 91

17.5.1 General

The SKB program is currently in a phase where the fundamental feasibility studies have been concluded. Review of alternative sitings and repository designs is in progress and a progressive culling of alternatives with less development potential is being carried out. In this phase the role of the studies of long term performance and safety provide a basis for variation studies whereby the safety role of different barriers or different designs can be assessed.

Compared with KBS-3, whose purpose it was to prove the feasibility of safe disposal, the next major integrated safety assessment, SKB 91, will as far as possible reduce the safety margins in the calculations and avoid highly pessimistic simplifications. The higher realism will permit a better quantification of the effects on safety that a change in design or dimensions will entail. The assessment is planned to be reported in 1991.

A planning of SKB 91 started late 1989. As the general timetable of SKB forsees that three canditate sites will be appointed in 1992, a main role of the assessment is to evaluate the safety role of various characteristics of a repository site. For this purpose site data from the Finnsjön site will be used in the reference scenario. By analysing the effect of variations the importance of existing and possible features will be evaluated.

The overall timetable forsees that the data and models that are to be used in the analysis are defined in mid 1990, whereafter the assessment calculations will be performed during the second half of 1990 and the first half of 1991.

Information has been exchanged between SKB and TVO regarding the planning and scope of SKB 91 and a similar safety analysis exercise that TVO in Finland will report in 1992.

17.5.2 The nearfield

The near field modelling in SKB 91 will be updated compared to the modelling in KBS-3. The following work has been performed or initiated.

A new fuel dissolution model based on the oxidation of the fuel matrix by oxidants formed by the alpha-radiolysis has been developed and is presented in Chapter 11.

The copper corrosion model in KBS-3, based on limitations in corroding species in the near field and ground water, will be used in SKB 91. The pitting factor will be reduced from 25 to 6 to have a modelling that is considered to be more realistic.

A study concerning the transport of nuclides from the canister to the groundwater has been performed /17-8/. Two different situations are modelled in order to compare different nuclide paths. The first is diffusion through the backfill via the rock and further into the mobile water in the fractures. Another pathway is diffusion through the backfill and into the mouth of the fracture. The influence of a possible sealing of fractures is also covered.

The results show that the pathway by diffusion through the pore system of the rock conveys less nuclides than the pathway directly to the fracture mouth. Sealing the fracture for a few tens of cm considerably decreases the release.

A study of the effect of channels on the transport of corrodants and radionuclides in the near field has started.

17.5.3 The farfield

The compilation of the Finnsjön data only started in 1989. The geologic and tectonic conditions on the site have been studied on several scales ranging from regional to site scale. The work has been summarized in an overview report of the Finnsjön area /17-8/.

The hydrogeological information on the site based on measurements in 11 coreholes drilled to between 250 and 750 m depth in Finnsjön during the years 1977 to 1988 have been compiled /17-9/.

Initial calculations of the groundwater flow at Finnsjön have started. The planning of the remaining modelling of groundwater flow and transport of radionuclides in the farfield has been initiated.

17.6 QUALITY ASSURANCE

During 1989 SKB initiated an effort to develop a quality assurance program for performance assessments.

The purpose and scope of the work are to lay down guidelines and formats for assuring that the "right" quality of safety and performance assessments is achieved, which also imposes some guidelines and formats as to quality assurance of software and data used in these contexts. The ultimate goals are to achieve proven correctness, to minimize the risk of mistakes occurring and to increase the confidence in performance assessment predictions.

Another, secondary purpose of the work is to establish procedures which make the handling of data for scientific computations and the production and maintenance of software more efficient. By turning them from a "craft" or "art" into something closer to an engineering methodology, more scientific and engineering creativity can be allocated to more basic and demanding issues.

18. THE INTERNATIONAL STRIPA PROJECT

18.1 SITE CHARACTERIZATION AND VALIDATION

18.1.1 Introduction

The Site Characterization and Validation (SCV) Project focuses on the techniques and approaches used in site characterization. The central aim of the programme is to predict groundwater flow in a specific volume of rock and to compare these predictions with data from field measurements. The distribution of water flow into a drift (tunnel) will be predicted, the drift will be excavated, the inflows will be measured and compared with prediction. Above and beyond the central aim there are a number of subsidiary aims such as assessment of channeling, the small scale hydrogeological effects of drift excavation and tracer tests in the fractured rock mass.

The Site Characterization and Validation programme is based around the idea of cycles of data-gathering, prediction and validation. Hence the programme has stages of work which can be described in these terms. In fact, the programme contains two cycles of this type where predictions are checked against observation. It is therefore divided into five stages as follows:

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

The programme of work contains a number of different techniques falling within the disciplines of structural geology, geology, geophysics, chemistry hydrology, and modelling. These have been combined so that predictions can be made and subsequently validated. The "cycles" of the programme envisage two modelling periods in which predictions would be made. These two periods are very different. In the first (Stage II), a conceptual model is made which is essentially geometrical with preliminary values of the important properties. Modelling at this stage will make primarily geometrical predictions. In the second (Stage IV), modelling will include the detailed properties and will include predictions of inflows to the test drift.

As can be seen Stage III fulfills two functions, that is the data gathered at this point in the programme will be compared against the preliminary predictions resulting from the Stage II work. They will also provide a basis for the detailed prediction in Stage IV. Stages I and II were completed during 1988 and Stage III data collection was completed during 1989 and analysis of that data is currently in progress.

18.1.2 Revision of programme for the SCV Project

The knowledge about the geological and hydrological conditions at the SCV site, acquired from the Stage I and II investigations, called for detailing the remaining parts of the investigation programme. A revision of the programme was also proposed taking into account the experience gained and development of new technology since the definition of the original programme in 1985. A revision of the SCV Project was discussed at the TSG meeting in March 1989 and the following additions and modifications were made to the original programme.

18.1.3 Detailed geological characterization of zone GH

The objective of this programme is to determine the nature of the deformation (fracturing, shearing, etc) within a large and well defined fracture zone, zone GH, and how this deformation varies over distances of 100 m or greater along the vertical and horizontal trends of zone GH. The geometry of the fractures making up the fracture zone will be determined in terms of orientation, trace length, spacing, and interconnectivity/termination characteristics and a description made of the surface characteristics in order to develop a generic model of the fracture zone.

Borehole seismics - Extension of analysis

The analysis of seismic data will be extended to provide detailed information on the rock volume surrounding the Validation drift with special emphasis on the properties and extent of fracture zone GH.

Monitoring of saline tracer transport through rock by borehole radar measurements

The development of the borehole radar technique within the Stripa Project has provided the possibility of locating groundwater flow paths in rock during a flow test. The basic idea is to detect a saline tracer with radar attenuation tomography. If radar measurements are repeated at

regular intervals the spreading of a tracer through rock can be monitored as a function of time.

The objective is to provide data on the geometry of flow paths from an injection point in a hydraulically conductive portion of zone GH. Two separate experiments will be conducted using the same injection point. The first experiment will be performed prior to the excavation of the Validation drift and the second after excavation of the drift. This will make it possible to see if the excavation of the drift causes any changes of the major flow paths.

Water and tracer collection system in the Validation Drift

The system for water and tracer collection has been expanded in order to obtain more accurate measurements of the spatial distribution of water and tracer inflows into the excavated Validation Drift.

Four different techniques will be used to measure water inflow and to collect the tracers:

— collection of wall and ceiling inflows through plastic sheets in a grid system (2x1 m grid),

— lower wall and floor inflow measurements through water collection in sumps located in a grid system,

— total drift measurement using a ventilation bulkhead,

— measurements of small scale inflow variation by the evaporation technique.

Tracer test in the Validation Drift

The objective of the tracer test is to observe and evaluate the movement of tracers from different injection points towards the Validation drift. The original tracer test was due to last for a period of 18 months and occurred at the very end of the period of measurement. The inclusion of salt injection tests with radar detection into the overall proposal has resulted in a shortening of the original schedule from 18 months to 10 months.

Two boreholes will be drilled from the entrance area to the Validation Drift to intersect zone GH. Tracer injection points will be located in the fracture zone and in the "good rock" at distances between 10 to 30 m and 10 to 20 m from the drift, respectively. A different tracer will be used at every injection point. Tracers based on metal complexes will be used.

18.1.4 Current status of Investigation programme

The current status of the SCV programme was presented and a review was given of the latest results.

Stage III of the SCV programme, which comprises the detailed characterization and preliminary validation of the conceptual model produced during Stage II, is now close to completion. Draft reports describing results from most of the experimental tasks are now available. Initially these reports will be distributed to the editorial committee which will produce the Stage IV Detailed Predictions report and the modelers. The Stage IV report will include a summary of the Stage III results and an upgrade of the conceptual model of the SCV site. However, the Stage III results have just recently become available which implies that the commencement of the work on the Stage IV report has been delayed. It is estimated that a draft version of the Stage IV report will be available in June or early July 1990.

Even though there is a delay in the analysis and reporting of the data the experimental activities are on schedule, the Validation Drift has been excavated, fracture mapping of the drift is in progress as well as preparations for inflow measurements and tracer tests.

Preliminary conclusions from the geophysical investigations indicate that the major features GH, GA, and GB exist in approximately the predicted positions. One of the features (GC) is considered insignificant. The fracture mapping work has become more comprehensive than originally envisaged. Steeply inclined boreholes and scanlines have been added to the data set and this has given a better representation of a subhorizontal fracture set. The inflow measurements to the D-holes showed that the inflows was concentrated to two zones (H and B). The variation in magnitude of the inflow between the boreholes was larger than an order of magnitude. The large variation in hydraulic properties on this small scale (2.8 m) was confirmed by the small scale hydraulic crosshole tests. The large scale crosshole tests did not give any significant hydraulic responses for distances between source and receiver greater than 120 m.

The radar/saline tracer tests demonstrated that there is a fast flowpath between the injection point in borehole C2 and the D-boreholes. Most of the transport was found to be confined to the H-zone but the radar data indicated that a minor portion of the saline tracer spreads into fracture systems intersecting zone H.

18.2 IMPROVEMENT OF SITE ASSESSMENT METHODS AND CONCEPTS

18.2.1 Development of the High Resolution and Directional Radar Techniques

During the Stripa Project the RAMAC borehole radar system has been developed and successfully applied to map fracture zones and detect tunnels and boreholes. Many tests have shown that fracture zones can be discovered more than a hundred meters from a borehole in crystalline rock with a resolution of a few meters. Several different measurement techniques have been developed in order to determine the orientation of fracture zones: single hole reflection, crosshole reflection and crosshole tomography. By combining data from different

measurements one can build detailed models of the fracture systems.

If only a single borehole is available these methods are inapplicable and the cylindrical symmetry of the dipole antennas makes it possible to determine the direction to a reflector. In order to solve this problem a directional antenna has been developed. Tests performed in Stripa demonstrate that the resolution of the antenna is better than $\pm 5^{o}$ for well defined fracture zones.

The direction antenna has ben analyzed theoretically to optimize its performance and to investigate the errors induced by small assymmetries of the system. A directional antenna is by necessity inefficient and special care must be taken to avoid contamination by other signals. Tests are in fact regularly performed during measurements to check that the system is functioning well at all times.

The directional antenna has been used in the investigation of the SCV site and the results agree well with the traditional methods used to analyze the fracture zones. During this work has also been tested a recently developed program, which automatically determines the direction to a reflector by a statistical analysis of a selected portion of the radar map.

18.2.2 Improvements of Techniques for High Resolution Borehole Seismics

Techniques for 3-D Seismics Reflection Studies

The Reflection Method has arrived to a relatively standard sequence of processing operations. Besides the data from Stripa, the method has been applied at more than ten other sites with very diverse test scales, measuring configurations and data acquisition systems. The results let us believe the method to be quite robust.

A number of filtering techniques from a "pre-conditioning" package. The aim of pre-conditioning is to suppress the coherent energy of the direct arrivals and of tube-waves. The resulting profile contains therefore only coherent reflected energy and noise.

The "Image Space Transform", which is applied next, is a novel technique aimed at enhancing the coherent events, acting thus as a two-dimensional noise filter. By combining the Image Space Transforms of several profiles, the orientation of the reflectors in 3-D is calculated. A merit of the method is that it can estimate its own artifacts and filter them out.

New Applications of Seismic Tomography

Seismic tomography has to overcome some specific difficulties which arise from the way seismic waves generates and propagate in the rock:

— A realistic model of the energy output by a source placed in a borehole is difficult to compute

— The general algorithm does not account for the anisotropy due to the stress field.

Solving these problems allows the extension of the analysis from velocity to both velocity and attenuation and also makes seismic differential tomography possible. Having two tomograms for the same section increases confidence in the results.

Differential tomography have been constructed from a pilot test performed at the BMT site involving measurements before and after the injection of bentonite. Four differential tomograms are obtained from the sides of a cube. The tomograms connect well along the common borders and there is evidence that the injection of bentonite has produced effects detectable by seismics.

18.2.3 Fracture Network Modelling

General

Phase 3 of the Stripa project provides an opportunity to study a previously undisturbed volume of Stripa granite in great detail. It is important to understand groundwater flow and transport through such rock, since hard, fractured rocks provide possible locations for radioactive waste disposal sites. Field experiments involving tracer transport in fractured rocks have been fully explained using conventional continuum approximations such as Darcy's law. In these rocks, groundwater flow and transport takes place primarily through a network connected fractures and it is hoped that a more direct model might build understanding. One of the goals of Phase 3 of the Stripa project is to validate the fracture network approach. In this approach we calculate flow and transport through fracture networks, which are generated numerically to exhibit the same statistical properties as those measured in the rock. We must show that important properties of the flow field depend only on these statistics and are independent of details of the individual fractures which make up the network. Further, we must show all the necessary input data for the models can be collected and that the results we calculate are accurate and in agreement with the field measurements.

The Stripa project sponsors the fracture network modelling work carried out by the Harwell Laboratory of the UKAEA; a collaborative effort is provided by the US Department of Energy - at Lawrence Berkeley Laboratory and Golder Associates.

Fracture-Flow Modelling of the SCV Site

The major modelling task was to predict the fluxes to the "Simulated Drift Experiment". The fracture network modelling showed that a continuum approach was appropriate for predicting fluxes on scales larger than 8 m. An integrated approach was therefore used: fracture network models predicted effective properties for representative volumes of rock larger than 8 m: a finite-element model used these properties and predicted bulk fluxes through the 100 m long SCV region: finally, this finite-element model provided boundary conditions to a fracture network model which was used to predict the local distribution of flux in the measurement boreholes.

The predictions compared very well with subsequent measurements. Unfortunately, as predicted, the fluxes into short intervals of the measurement boreholes were smaller than the measurement limit: these fluxes are to be remeasured accurately.

The fracture network models currently use a parallel plate approximation for each fracture. Whilst this appears to be acceptable for flux prediction so long as the fracture data is interpreted consistently, it is anticipated that the effects of local aperture variation will be important once velocities are considered. In addition, there is a need to show, understand and account for channeling within fracture planes as observed at Stripa. Over the past few months a facility has been developed to model local aperture variation directly, generating a correlated aperture field on each plane. A parameter study showed that this could account for channelling, did not dramatically affect bulk fluxes, and did not affect computational costs.

Turning to future work, there are immediate tasks. First fluxes into the validation drift experiment must be predicted. This is essentially the same as the SDE experiment but with additional complication of a disturbed zone around the drift due to local stresses and excavation damage. Unfortunately there will be no direct measurement of these effects and no consensus as to the conceptual model to represent them. Therefore, the SDE modelling will be refined and repeated and a sensitivity study will be perormed to account, at least qualitatively, for the disturbed zone.

Finally, the development of a transport facility for the fracture network code, NAPSAC, has started. This is based on a particle tracking approach since it is impractical, and inappropriate, to describe concentration field for the 107 or more finite-elements used in the larger network models. On each plane a representative number of pathlines are calculated from each intersection. These single plane calculations are loaded into a tree structure of connections across the network. Once this tree structure is calculated, very many particles can be followed.

18.2.4 Channeling Experiment

Introduction and Background

Lately it has been recognized that most of the water flows only in a small part of a fracture and that this may have a strong impact on the transport of escaping radionuclides. The water flowpaths in the fractures may connect to form a network of pathways, some of which may be faster than others. The surface area of the fractures which is in contact with the mobile water will determine how much surface area is available for sorption and retardation of the nuclides.

The channelling experiments were designed to study the transmissivity and aperture variations in fractures at depth in crystalline rock. Two types of experiments were designed. In the single hole experiments a hole was drilled more than 2 m into the plane of the fracture and the flowrates were measured in 5 cm sections using a specially designed injection packer. Photographs were also taken inside the hole along the fracture to determine the visible fracture aperture and to obtain other information. In the double hole experiment two parallel holes were drilled in the plane of a fracture at a center distance of 1.95 m. Hydraulic tests and tracer tests were made between the two holes to obtain information on connections in the plane of the fracture and to obtain information on residence time distributions in different paths (channels).

Experimental Design

The design was such that the channeling effects within a fracture plane should be tested along a line without missing any part along this line. It should also be possible to perform a tracer experiment with linear flow where up to five different tracers could be locally injected and monitored along a line "downstream". The conventional technique, penetrating the fracture with a hole perpendicular to the fracture plane, was discarded because this type of injection would give a radial outflow which would make it difficult to determine the exact location and size of the tracer source. Also these injection holes could not be drilled so close together that a line along the fracture plane could be completely covered. It was instead decided that holes, from which water and tracers could be injected, would be drilled along the fracture plane.

Experimental Equipment and Methods

The channeling experiments consist of three different types of tests: (1) the Single hole experiment, (2) the Double hole experiment and (3) the Tracer test.

Single Hole Experiments

To investigate the fracture characteristics along a fracture plane, a large diameter (∅ 200 mm) hole was drilled along the fracture plane to a depth of about 2.5 m. To facilitate the drilling, only planar fractures well seen in the drifts were selected for testing. A multi-pede packer, the Multipede, was inserted into the hole to seal off the hole from the drift. The packer was used to inject all along the intersected fracture plane. Before the actual measurements with the Multipede, the holes were tested with a coarse injection method using a scanning packer. Only holes found suitable in these coarse tests were selected for further testing with the Multipede.

In the Multipede tests, the injection flowrates were monitored separately for the left and right side of the hole over 80 short sections of the fracture plane. The fracture intersection with the borehole was also photographed. These photographs were scrutinized to obtain data on fracture properties such as open fracture area, number of intersections, thickness of infilling. These tests are called "The Single Hole Experiments".

After the drilling of the 200 mm holes, the boreholes were photographed using a system based on a 36 mm standard SLR camera equipped with a macro flash unit.

The following physical properties were measured from these photographs:

— opening area (mm^2/cm)

— total length of all fractures (mm/cm)

— total number of fractures (#/cm)

— average thickness of infilling (mm/cm)

— total number of intersections (#/cm)

The data was collected over small sections with an area of 10x50 mm, with the 10 mm going in the axial direction of the borehole.

To determine if it was meaningful to do detailed water injection tests, implying movement of all measuring equipment, the hole was first scanned with a coarse method giving injection flowrates over 200 mm sections including both left and right side.

The detailed injections were performed using the Multipede packer. Water was injected in twenty 50 mm x 50 mm sections at a time. These sections were located in a row, 50 mm apart. The parts between the sections were sealed off. To cover all parts of the fracture intersections, four sets of measurements had to be performed including one 50 mm movement of the Multipede packer. The injection tests were done with constant injection pressure during 5 to 10 hours. To eliminate the risk of spurious information on inflow from sections due leakage passing the sealing back to the hole, the hole was kept at a slightly higher pressure than the injection sections. During these tests the face of the drift, close to the hole, was observed for emerging water. In some cases the area surrounding the hole were covered with plastic sheets.

As it was required to be able to seal off short (50 mm x 50 mm) sections along the fracture intersection separately on "left" and "right" side, no ordinary inflatable packer could be used. Instead it was decided to use small rubber cushions that were pressed to the wall of the borehole by hydraulic pistons. As the fractures within the hole undulate, it was necessary to have the rubber cups individually adjustable. Figure 18-1 shows the final design of the so called Multipede packer.

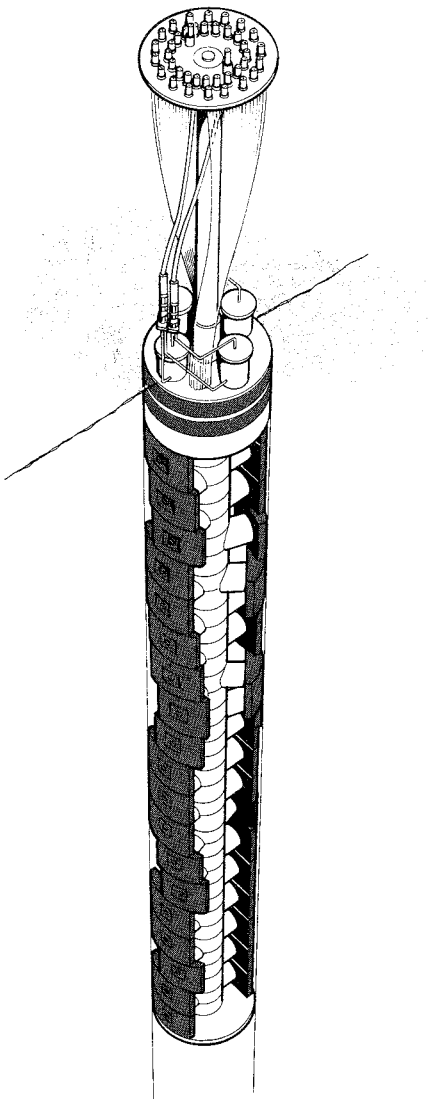

Figure 18–1. *Final design of the Mulitpede packer*

Double Hole Experiment

The double hole experiment was performed in a fracture where earlier a single hole test had shown that channels exist. A second hole was drilled in the same fracture plane at a center to center distance of 1.95 m. The second hole was also subjected to a single hole test before suitable points for the cross hole pressure pulse tests could be selected.

A preliminary tracer test was performed prior to the pressure pulse tests using different salts as tracers to determine the suitability of the fracture for further investigations. One of the injected tracers occurred in the sampling hole, thereby indicating that this fracture plane was suitable for the double hole experiments.

A coarse test was performed to locate suitable sections in which to inject water for the detailed pressure pulse tests. In the test the entire hole was pressurized using a specially designed Scanning packer system and the responses were monitored in the other hole, all along the fracture, using the Multipede packer. This coarse test was reversed, using the receiver hole as the injection hole. Sections which showed pressure responses and also had injection flowrates during the single hole tests were chosen for the detailed pressure pulse tests.

Detailed pressure pulse tests were performed form the selected points, in both directions, with injection at single sections, 50 mm x 50 mm, in one hole and monitoring in twenty sections along the fracture intersection in the second hole. Pressure pulse tests were performed in the double hole experiment using a single point source and a multi point receiver.

Experimental Results

The Multipede was used for injecting water into the fracture at 20 separate 50 mm sections, five of them containing different tracer solutions. Water was collected at 20 different locations in another hole in the same

fracture plane. The injection pressure was the same as during the pressure pulse tests, 2 bar above atmospheric pressure. The tracers are non-sorbing dyes, earlier used in field experiments in Stripa.

The results of the tracer test are indicated in Figure 18-2. The largest amounts of tracers were found at the inner part of the collection hole, but there are differences in the pattern and amount with which they occur. These differences indicate that at least a part of the paths are different for the two tracers, injected only 10 cm apart. As can be seen in this figure, the two outer tracers as well as the innermost have not been found at detectable levels in any location in the collection hole.

In addition to the tracer occurrence in the collection hole, all five injected tracers have emerged in considerable amounts at the face of the drift well outside the sealed off fracture plane. At least 5 points with different proportion of tracers have been found.

Conclusions of the Test

It is at first surprising that there is no obvious correlation between the observed aperture and the injected water flowrate. However, considering that the hydraulic aperture is a few micrometers on average and that the mechanical aperture is more than 10 times larger, obviously the visible local mechanical aperture in not what determines the pressure drop. It has been suggested that the pressure drop is determined by the smaller apertures along the flow path, which form the pinch points for flow. The larger apertures will determine the flow aperture because those are the regions where the water will acquire much of its residence time. This phenomenon will become more noticeable the tighter the fractures are.

The observations on the between hole pressure tests show that the investigated fracture is intersected by other fractures since the pressure responses are more similar to a porous medium with radial flow than flow in a single fracture.

The observations on the tracer movements lead us to conclude that there are dead end channels, that this single fracture has several intersecting fractures which divert the flow from the main fracture and that the channel aperture can be on the order of several hundred m. The flow apertures could not be determined with any accuracy but the values obtained lie in the same range as the visual apertures measured from the photographs.

How much of a fracture that is open to flow and the size of the flow wetted surface is essential information when calculating retardation of radionuclides. When trying to evaluate that number from the results from these experiments it is not possible to achieve an unambiguous result. To start with, one has to define what is meant with a channel. Either one can look at every individual flowpath and get very small channel widths or at a larger scale and identify more or less isolated clusters of small individual flowpaths. The cluster approach will give a more general view of flowpaths within fracture planes.

Based on photographs of totally 50 m of fracture intersections one can say that individual openings within fracture planes are in the range from millimeter to decimeter in length, in rare cases a few decimeters. These openings normally occur in clusters with widths of 0.05 to 1 m with typically 2 to 4 clusters over a length of 2.5 m. The open part in one of these clusters is at most half the cluster width and normally much less. The same results are obtained from the single hole injection tests. Looking at the infilling thickness, a footprint of longtime properties, the result is the same as for the methods mentioned above except for that it is in this case possible to find some distinct narrow channels (50 mm widths). One should, however, keep in mind that the channels now seen as infilling might not have been active at the same time period.

To sum up these observations, on the average 25 percent or less of the fracture plane is open to flow with individual channel widths from centimeter to decimeter. These channels normally occurs in clusters with cluster widths of decimeters. These clusters occur at half meter to meter apart. Individual fractures may however have properties that strongly deviate from the average. These results are based on 12 well defined planar fractures selected from 1500 m mapped drifts. The results may not be applicable on all fractures in a standard fracture mapping.

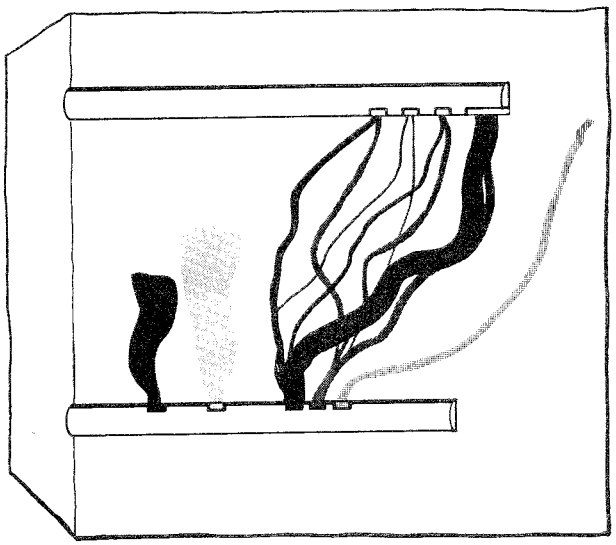

Figure 18–2. Artist's view of flow paths in the fracture. Width of the path correspond to mass flowrates

18.3 ROCK SEALING TEST

18.3.1 General

The general objective of the Rock Sealing Test is to identify suitable grouts and grouting techniques for sealing fine rock fractures in repositories. The grouts have to be sufficiently erosion-resistant and chemically stable to

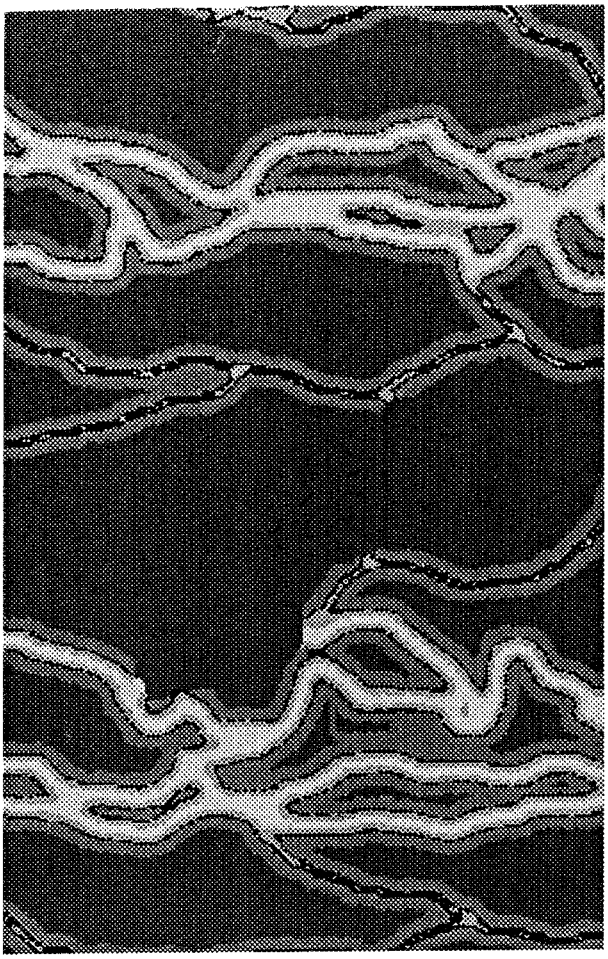

Figure 18–3. Artist's view of single channels and clusters within a fracture plane

make them serve for long periods of time and part of the project is therefore focussed on the testing of candidate materials not only with respect to their initial sealing ability but also to their potential to survive in repository environment.

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

Major activities in 1989

The work in 1989 consisted of three major parts: 1) Large-scale grouting experiment in former heater holes in the BMT area (Test 1), 2) Determination of water inflow and identification of water-bearing structures in the right 3D arm (Test 4), and 3) Laboratory study of the sealing and longevity properties of cement and clay grout candidates.

Grouting of heater holes

Two 76 cm diameter heater holes that are about 3 m deep have been grouted by use of bentonite clay, applying "dynamic" injection technique. For this purpose and for the preceding determination of the hydraulic conductivity a "megapacker" was built see Figure 18-4.

After the grouting, which was made according to somewhat different strategies in the two holes, the hydraulic conductivity was measured again and repeated once more after a heat pulse of about 1 year. The heating of the holes gave a temperature at the periphery of the holes of up to about 90°C while it was about 40°C at 1 m distance. The results of the measurements, which are compiled in Table 18-1 for the hole which was grouted in a way that appears

Table 18–1. Effect of grouting on the conductivity of granite around simulated canister hole (No 2)

Depth	Hydraulic conductivity, m/s		
Interval, m	Initial	After grouting	After heating
0.80-1.35	$k_1=3.7\times10^{-7}$	$k_1/1300$	$k_1/20$
1.30-1.85	$k_2=5.7\times10^{-8}$	$k_2/500$	$k_2/32$
1.80-2.35	$k_3=3.0\times10^{-10}$	$k_3/5$	$2\ k_3$
2.30-2.85	$k_4=3.1\times10^{-10}$	$k_4/2$	$1.7\ k_3$

most practical, show that the best sealing effect was achieved in the upper 2 meters of the hole, i.e. close to the tunnel floor. Here, the conductivity dropped to less than

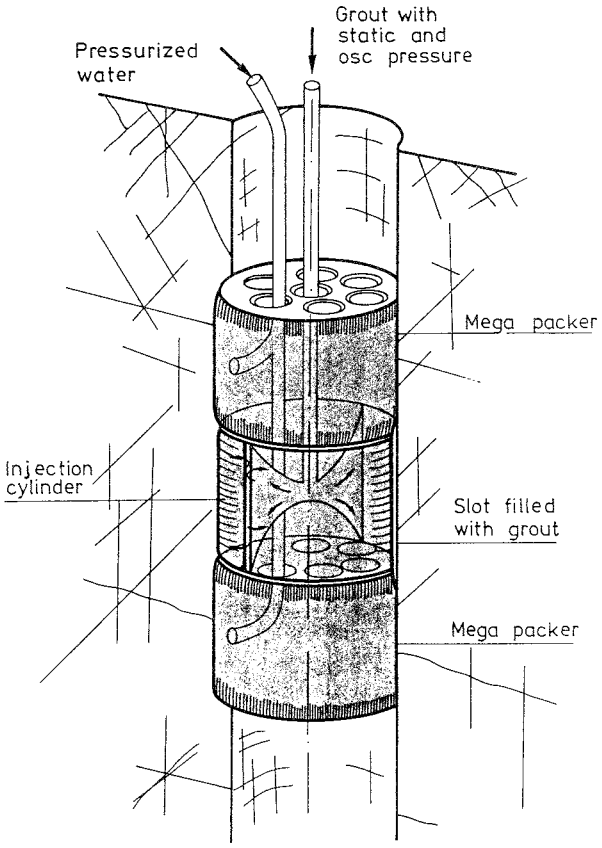

Figure 18–4. "Megapacker" developed for determination of the hydraulic conductivity and for grouting

1/1 000 of the initial value after the grouting, while the subsequent heating increased the conductivity so that the net drop was about 1/20 to 1/30 of the original value.

Deeper down in the holes the sealing effect was smaller and it was concluded that rock with an initial hydraulic conductivity of less than 10^{-9} m/s cannot be effectively sealed. The fact that the heat treatment reduced the sealing effect of the grouting is ascribed to heat-induced movement of rock blocks, by which non-grouted fractures were widened locally.

18.3.2 Characterization of the rock in the 3D arm for planning of grouting

The eastern 3D arm will be used for a field test comprising grouting of a natural major water-bearing fracture zone. In 1989 a detailed hydrological survey has been made through which the rate and amount of water inflow into the drift have been determined. For this purpose, a ventilation experiment and comprehensive sampling of water have been made. In addition, detailed mapping of the distribution of water outflow from the wet northern wall has been made. The measurements show that the daily inflow has been almost constant and about 29 litres from midsummer, which is about three times the figure derived in the 3D experiment. The discrepancy indicates that drainage through the floor was considerable in the 3D experiment and that ventilation experiments must be evaluated with due respect to RH, see Figure 18-5.

Pressure recordings show that the piezometric heads are 1.3-1.8 MPa 3-5 m from the walls of the drift, while they are only about 1 MPa 5-7 m above the roof and below the floor. This indicates rather effective lateral drainage westwards through the abundant subhorizontal fractures. Except for an obvious pressure drop in early May 1989 there is no reaction to draining activities in the vicinity.

Tracer tests were started in the reporting period by injecting Elbenyl Brilliant Flavine in one of the BAT piezometers in the northern wall located about 4 m from the rock surface. Tracer appeared at the lower northeastern corner of the drift in about 1 day indicating the hydraulic importance of the steep fracture zone that strikes N/S.

18.3.3 Accessory tests (Longevity issue)

Clays

Two major types of lab experiments are being conducted: 1) Determination of the hydraulic conductivity of grouts in simulated rock fractures with heating and expansion/consolidation cycles, and 2) Determination of chemical changes in the form of dissolution and mineral alteration as indicated by XRD, chemical analysis, electron microscopy, and rheological testing.

The present state of the study can be summarized as follows:

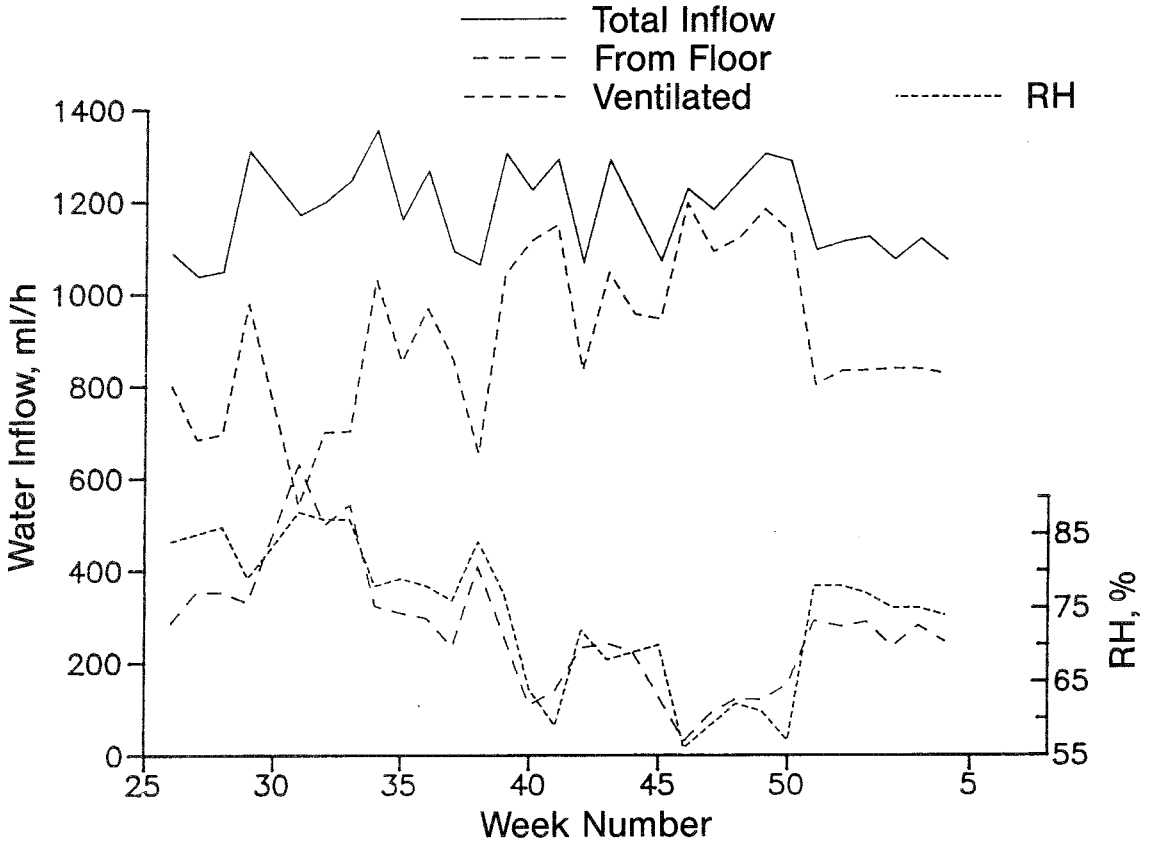

Figure 18–5. Flow diagram showing the contributions to the inflow and total inflow

The groundwater composition is a key parameter for the sealing effect. Under fresh and weakly brackish water conditions Na montmorillonite clay prepared with NaCl to about 10 000 ppm concentration has optimum grouting and sealing properties. Addition of quartz powder improves the sealing effect but makes the grout more sensitive to piping.

When the groundwater is strongly brackish with calcium as major cation, Ca bentonite prepared with fresh water offers the best sealing properties.

At heating to less than 60°C the microstructure and chemical constitution are entirely preserved. In the interval 60-90°C some microstructural changes are induced, giving a stiffer and slightly more permeable gel, while the montmorillonite is affected only by slight congruent dissolution. Stronger microstructural changes, yielding increased stiffening and some additional increase in conductivity, are produced by heating to 120°C, which also yields more rapid dissolution of the montmorillonite. Hydrous mica is neoformed in the presence of potassium.

At higher temperatures non-congruent dissolution of montmorillonite takes place yielding beidellite, which forms hydrous mica by uptake and fixation of potassium. Neoformation of hydrous mica becomes a major process if potassium is available and some kaolinite may be formed as well. K-holding feldspars, occurring as accessory constituents, are dissolved.

Cement

In the last 12 months, tests have been carried out to determine; the general leaching properties of pure cement phases and the hydraulic conductivity and porosity of reference grout.

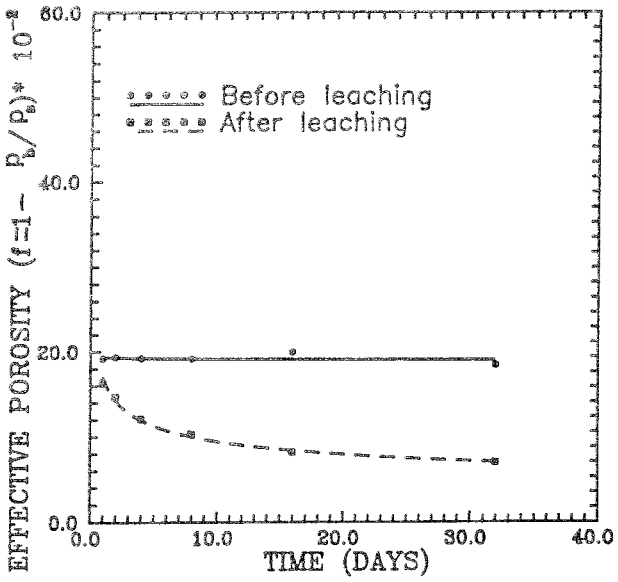

Figure 18–6. The effective porosity of reference grout mixed at 0.4 w/c with 1% superplasticizer and 10% silica fume before and after leaching in distilled deionized water

General Leaching Properties of Reference Grout

Hardened samples of the reference grout mixed at 0.4 and 0.6 w/c and ALOFIX-MC (MC-500) mixed at 0.5 and 0.7 w/c were subjected to a series of static and dynamic leach tests. The leaching performance of grouts was determined by measuring the leach rates of Ca^{2+} and Si^{4+}.

For the reference grout the result from static tests show that the release of Ca^{2+} to solution is virtually constant tending to marginally increase with temperature and groundwater salinity. For MC-500 the release of Ca^{2+} exhibits a marked increase with increasing temperature.

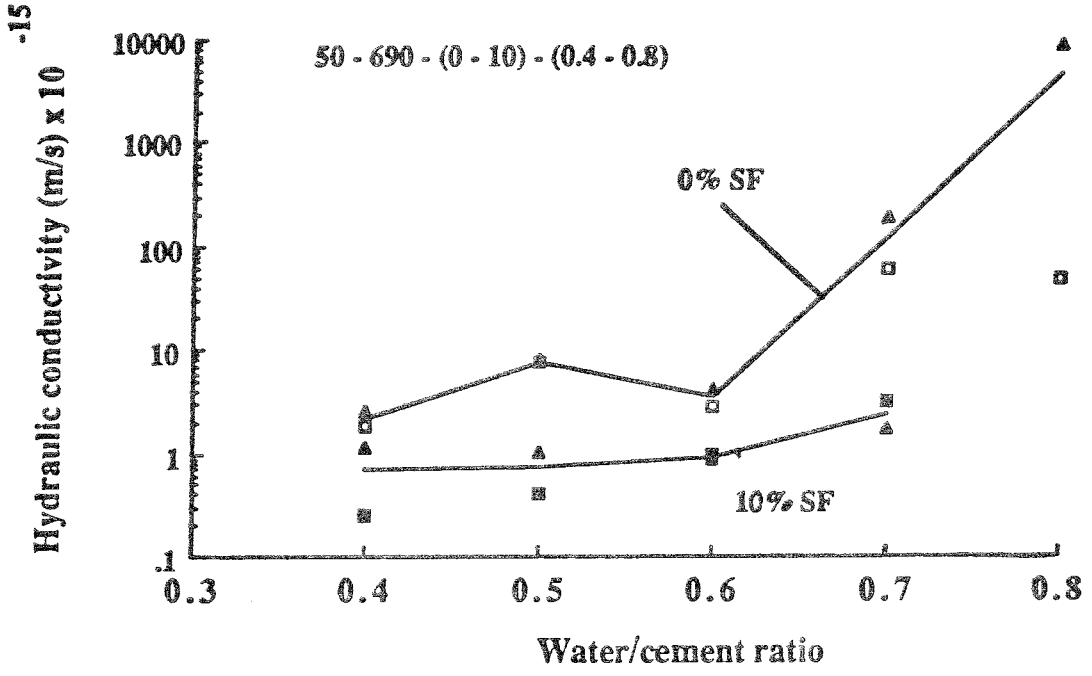

Figure 18–7. The effect of water/cement ratio and silica fume on the hydraulic conductivity of reference grout

At the highest temperature (150°C) and with groundwater with high salinity the MC-500 grout releases Ca^{2+} at approximately six times the rate of the reference grout to leaching can be attributed to the absence of large amounts of free $Ca(OH)_2$ in this material.

In the dynamic leach tests the effects of flow rate and temperature on the leaching properties of grouts were investigated. The leaching behaviour of the grouts mixed at low w/c (0.4) and high w/c (0.6) were found to be similar. Higher leaches rates (10^{-8} kg/m^2·s) were observed at higher w/c. This may reflect a higher proportion of capillary space in the reference grout mixed at high (0.6) w/c.

SEM/EDX examination of the leached samples showed that leaching is accompanied by precipitation and growth of an assemblage of secondary alteration phases. The precipitate layer consisted of two distinct phases; a Ca-phase and a Ca-Si phase. The precipitate layer likely has significant effects on the long-term leach rates of the grouts. It controls the leaching/dissolution behaviour of the cement grout under both static and dynamic conditions.

Leaching of Pure Cement Compounds

The leach tests have also been completed on mixtures of the following pure cement compounds; C_2S, C_3S, C_3A, and C_4AF (C=CaO, A=Al_2O_3, F=Fe_2O_3, S=SiO_4). Results confirm the findings of studies of dissolution and leaching processes in the industrial grade cement.

Hydraulic Conductivity and Porosity of Reference Grout

Static and dynamic leach tests have been carried out to determine the effect of groundwater chemical composition, temperature and time on the porosity of reference grout. Data show, see Figure 18-6, that the effective porosity of the grout decreases with leaching time. The decrease in the effective porosity is assumed to be due to change in the volume of the solids by the continuous hydration, precipitation and associated reactions.

The intrinsic permeability and hydraulic conductivity, K_i, of cement-based grouts are being determined on bulk specimens of grouts and on thin films of grouts. The influence of stress, water content, superplasticizer content and silica fume content on permeability and hydraulic conductivity of grouts are being determined over a range of temperatures and hydraulic gradients. The first series of tests have confirmed the low intrinsic K_i of the reference grout (10^{-14}m/s), see Figure 18-7. Also, the data show that the hydraulic conductivity of the cement grouts decreases by adding silica fume to the mixture and by reducing the value of the water to cement ratio. The decrease in K_i reflects decreases in connected capillary port space in grout.

Investigations into the longevity of cement grout seals focused during the year of analyzing increasingly realistic scenarios and incorporating experimentally derived data into the model input. The complexity of the geochemical and hydrologic models was developed in order to analyze realistic conditions anticipated in high-level waste repositories and provide information that may prove useful as input to conceptual seal designs.

The modelling of increasingly complex systems yielded results that continue to corroborate the approach being used to develop the longevity assessment methodology. Besides considering grout models of progressively detailed chemistry, realism was introduced by taking into account: (1) the metastability of grout phases, (2) the uncertainty of the equation relating changes in porosity to changes in hydraulic conductivity, and (3) the inclusion of

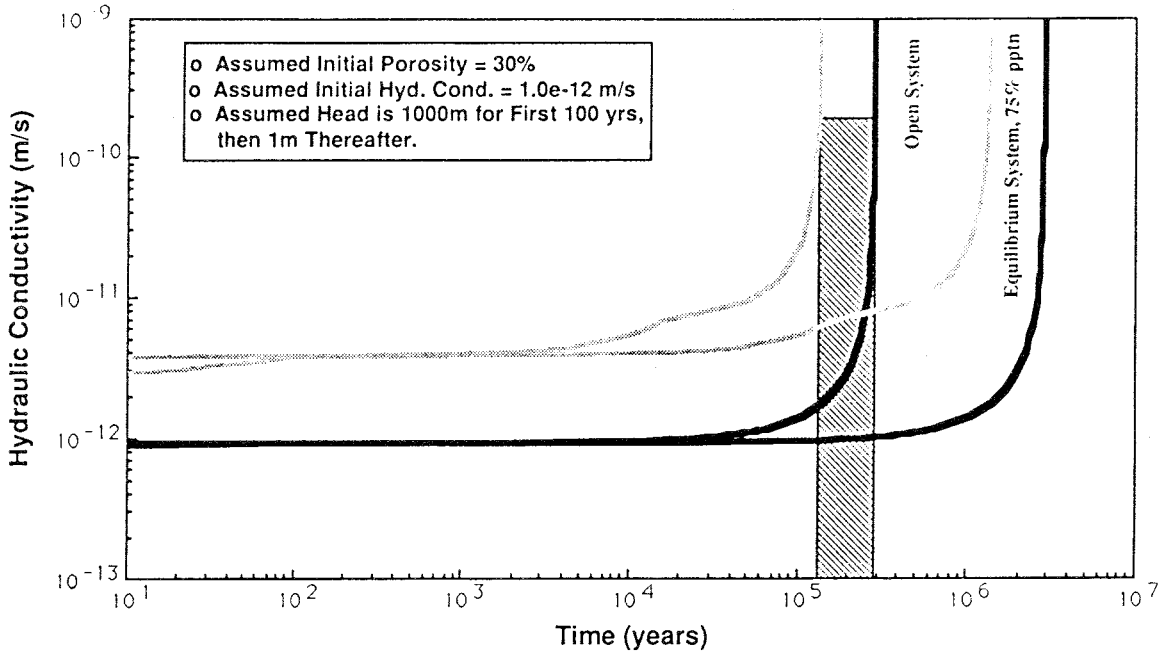

Figure 18–8. Diagram showing changes in hydraulic conductivity of a cement grout seal with time. The vertical bar indicates the minimum estimated useful life of a seal under the conditions analyzed, with uncertainties in the methodology considered

a reasonable amount of portlandite is consistent with the observation that it is observed in cured grout, even in mixes with sufficient silica fume to preclude its formation on a stoichiometric basis. The results continue to suggest that properly engineered portland cement-based grouts, i e those with low initial hydraulic conductivities, can maintain acceptable performance for very long times, up to hundreds of thousands to millions of years, see Figure 18-8.

It has also been found that long-term performance is likely to be influenced by site conditions. Theoretical and experimental studies indicate that cement dissolution is accompanied by the precipitation of calcium-silica-hydrate phases, carbonates, sulfates, clays and zeolites, as long as a relatively low hydraulic gradient at the site permits and approach to steady state conditions. Theoretical and experimental studies also indicate that cement grout degradation is somewhat sensitive to groundwater composition. The theoretical studies suggest that the rate of grout dissolution (and secondary mineral precipitation) is dependent upon the rate at which water flows through the grout, which depends ultimately upon the initial hydraulic conductivity of the grout. These are the bases for the conclusion that, given the conductivity constraint, cement grout may be expected to persist for very long times.

The development of a methodology for assessing the potential for fracture development in grout due to dissolution-induced stresses was initiated. The approach shows considerable promise for estimating the transition between a porous (Darcy or Darcy-like) flow-dominated regime and a fracture flow-dominated one. Very preliminary results from coupling chemical modeling data with fracture-potential analysis suggest that porous flow may predominate for long periods of time.

19. HARD ROCK LABORATORY

19.1 GENERAL

In 1986 SKB started pre-investigations for an underground research laboratory in the vicinity of Oskarshamn nuclear power plant. The work has been divided into three separate stages namely; siting, characterization and prediction. The siting stage ended with the choice of the island of Äspö as a potential site for the laboratory. The island is positioned 2 km north of the Simpevarp peninsula where the power plant is located see Figure 19-1. The characterization stage indicated that Äspö was suitable for construction of the planned facility and the planned research-activities. Further investigations of geology, geohydrology and geochemistry have then been carried out during the prediction stage.

The field-investigations for the laboratory have continued during 1989. Evaluation of the results has confirmed that the geological conditions on the southern part of the island are suitable for the planned research activities. The tunnelling work is planned to commence in the autumn 1990 and to be completed down to 500 m level during 1994.

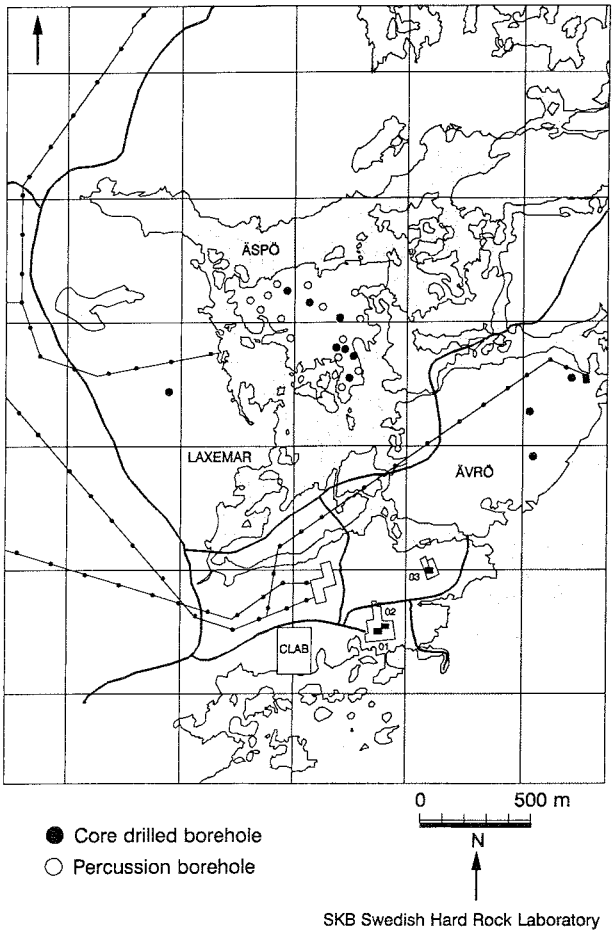

Figure 19–1. The island of Äspö and its environs

19.2 BACKGROUND AND MOTIVES

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

A balanced appraisal of the facts, requirements and evaluations presented in connection with the preparation of R&D-Programme 86 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.

The most important reasons for pertinent the Hard Rock Laboratory are:

— verification of methods for surface and borehole investigations,

— testing of methods for detailed site investigations with shaft sinking or tunnelling,

— opportunity, in a realistic environment and on a large scale, to investigate conditions of importance for safety, eg groundwater flow and associated transport of solutes,

— opportunity, in a realistic environment, to carry out demonstration tests and long-term tests of the interaction between engineered barriers and rock,

— method development for rock construction works, waste handling and backfilling.

These motives are examined in greater detail in the R&D-Programme 89.

19.3 SITING AND LAYOUT OF THE HARD ROCK LABORATORY

In R&D-Programme 86, 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 in 1987, 1988 and the spring of 1989. On the

basis of the results obtained, SKB has made a decision in principle to locate the Hard Rock Laboratory on the southern part of the island of Äspö. This has been found to be a suitable site for the Hard Rock Laboratory primarily for the following reasons:

— It meets the requirement on undisturbed conditions in the bedrock and the groundwater. Locating the Hard Rock Laboratory in an area exempted from industrial establishment should ensure that other activities will not disturb the research during the time required for certain long-term experiments.

— Äspö provides access, within a geographically limited area, to the different geological and hydrological conditions required for planned tests and their evaluation. The results of investigations of the bedrock on Äspö show a suitable variation between volumes of sound rock and fracture zones of varying character. The composition of the groundwater is representative of Swedish coastal rock and provides an opportunity for studies of prevailing conditions and changes in these conditions resulting from the construction work.

This siting presumes the approval of the concerned authorities, which is expected to be obtained during 1990.

The exact site of the 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 is subjected to detailed investigation prior to the final siting of the final repository.

Studies of alternative layouts of the underground portion of the Hard Rock Laboratory were performed during 1987. A tunnel ramp was found to be preferable to the sinking of a shaft to a depth of about 500 m. The tunnel alternative was chosen primarily because it provides better flexibility and a greater opportunity for collection of data and characterization of the rock mass. In August 1989, the Government decided that the Hard Rock Laboratory should be reviewed under the Act on the Conservation of Natural Resources. In connection therewith, SKB has decided to make a slight modification of the layout of the laboratory that reduces its environmental impact. The new layout is shown in Figure 19-2, where the tunnel entrance is located on the Simpevarp peninsula instead of on the island of Äspö as previously planned. This entrance tunnel will also provide opportunities to study the zones indicated between Simpevarp and Äspö.

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

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

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

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

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

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

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

1 **Verify pre-investigation methods**

2 **Finalize detailed investigation methodology**

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

3 **Test models for groundwater flow and transport of solutes**

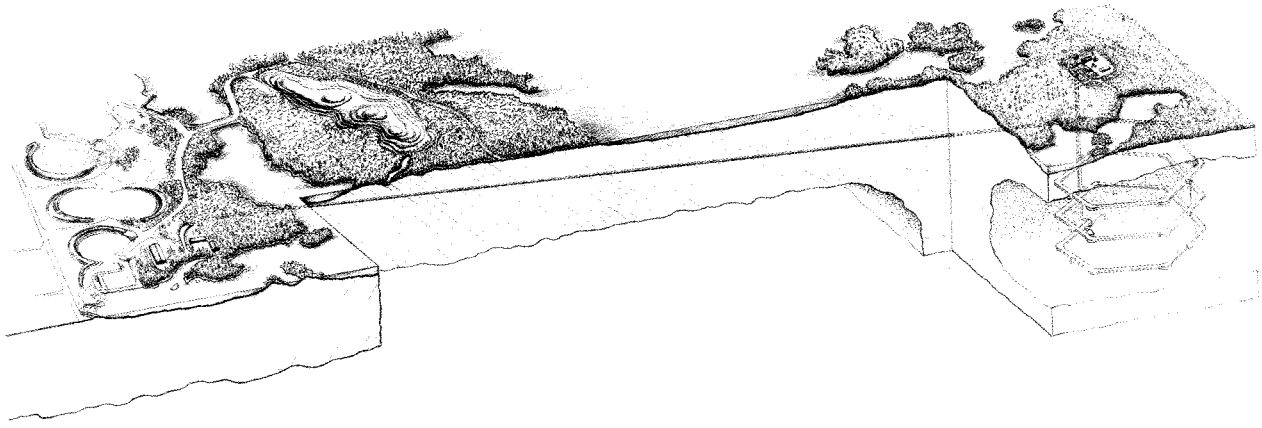

Figure 19–2. *Schematic design of the Hard Rock Laboratory*

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

4 **Demonstrate construction and handling methods**

and

5 **Test important parts of the repository system**

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

The properties of the rock that are of importance in different phases will vary. The testing of the quality of methods for rock characterization that is done at the Hard Rock Laboratory will be coupled at an early stage to the ability to determine the flow and chemistry of the groundwater at repository depth on the basis of pre-investigations. As the decision-making process progresses and as the prediction models and the safety assessments become more detailed, specific requirements will be made on the detailed information.

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

In the pre-investigation phase, a site will be chosen for the laboratory. The natural conditions in the bedrock will be described. In parallel with the preliminary investigations, the project's construction and operating phases will be planned.

During the construction phase, 1990–1994, a number of investigations and tests will be conducted in parallel with the construction activities. The tunnel will be excavated down to the 500 m level in stages.

19.4 OVERVIEW OF WORK 1986 – 1988

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

The pre-investigation phase is divided into the following stages:

— siting,

— site description and

— prediction,

The results from the siting stage have been reported /19-1/. The regional-scale rock description shows that the Simpevarp area consists primarily of granitic bedrock (Småland granite) with intrusions of basic rock types, greenstones. The information from the geological and geophysical surveys shows a tectonic picture of the Simpevarp area dominated by a nearly orthogonal system of first-order fracture zones in the N-S and E-W directions. Aside from this system, there are second-order zones running in the NW and NE directions that also form a nearly orthogonal system. There are probably also low-dipping, subhorizontal zones.

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

The site description stage has been described in /19-1/. The continued investigations for siting were focussed primarily on Äspö. Laxemar will be used as a reference area where, for example, natural variations in groundwater levels can be followed and compared with the disturbed conditions that will exist on Äspö after the laboratory has been built. Four holes were cored, the deepest down to a depth of 1 km. In addition to high-quality core mapping, extensive geophysical measurements have been carried out, along with hydro tests on several scales and hydrochemical analyses. Thorough surface investigations have been carried out on Äspö, including outcrop mapping, magnetic and electric measurements and seismic reflection and refraction measurements. In the cored holes drilled on southern Äspö, Småland granite is the dominant rock type down to a depth of more than 300 m. Below this, it is surplanted by a quartz-poorer version of the Småland granite called diorite. A large number of zones of different character exist on Äspö.

19.5 OVERVIEW OF WORK 1989

Evaluation of the siting stage led to the conclusion that four additional cored holes were drilled to depths of about 500 m. During the year measurements have been carried out, both in these holes and between the holes. A long-time pumping test, in total 3 months, was carried out. This test was preceeded by predictive modelling utilizing two different approaches. The first approach used three-dimensional finite elements. The second used a three-dimensional finite volume code incorporating the saline/fresh water interface. The major flow paths were described deterministically whereas the rest of the rock mass was treated as a stochastic continuum. After evaluation of the approaches it was decided that predictive modelling in site scale will continue using the finite volume code PHOENICS. The code will be used for predictive modelling of a tracer test utilizing radioactive tracers that will be carried out during 1990. The code will

as well be used for the final predictions before construction starts.

Based on surface mapping and borehole measurements fracture network models have been applied. The objective of the modelling was basically to simulate heterogeneity on the scale of canisters and at the scale of elements within a stochastic continuum model.

The seismic reflection data reported in /19-2/ has been reprocessed and analyzed by two additional organizations in Houston, Texas and University of Manitoba. The processors at Houston question whether the data contain any useful information whatsoever, while the University of Manitoba see numerous reflections in their final sections.

The work during 1989 has been summarized in close to 30 Progress Reports, six Borehole Reports and several Technical Notes.

In August 1989 the goverment decided that the laboratory should be reviewed under the Act on the Conservation of Natural Resources. A goverment approval was obtained in April 1990. In connection herewith SKB decided to make changes in the layout of the laboratory. Due to the new layout, see Figure 19-2, new drillings and surface investigations was launched late 1989. These will be evaluated spring 1990.

20. NATURAL ANALOGUE STUDIES

20.1 THE POÇOS DE CALDAS PROJECT

The overall aim of the project is to validate models for the release and dispersal of radionuclides in the geosphere. The field studies were performed at two sites close to the town of Poços de Caldas in Minas Gerais, Brazil. One site comprises a thorium and rare earth mineralization (Morro do Ferro) and the other a uranium mineralization (Osamu Utsumi uranium mine). A laboratory has been in operation in Poços de Caldas for rock and groundwater sample preparation and distribution.

Participants in the project are Sweden (SKB), Great Britain (UK DOE), Switzerland (NAGRA), USA (US DOE) and Brazil, Federal University of Rio de Janeiro, Pontificial Catholic University of Rio de Janeiro (PUC), University of Sao Paulo, CNEN and NUCLEBRAS). The project is managed and coordinated by SKB.

The project started in May 1986 and was originally planned to last for three years. An extension of the project to the end of March 1990 was formally decided in January 1989. The extension phase was motivated by the extent of data obtained and the extra time needed for the evaluation.

The field investigations were finalized in June 1989. An international group of about 10 experts have been assigned the task to coordinate the interpretation of the data and its use for the validation of safety related models. A modelling workshop has been convened twice during 1990 in Saanen in Switzerland. Results of analyses and preliminary evaluations were presented and modelling work initiated. Complementary geological evaluations and chemical analyses were recommended.

The validation exercise is concentrated on the following four objectives.

— Thermodynamic codes and databases for rock/water interaction and solubility/speciation of elements

— Natural groundwater colloids: their uptake of radionuclides and their retention in the rock due to instability, sorption etc.

— Geochemical transport across redox fronts

— Migration of REE/U-Th series radionuclides during hydrothermal activity.

A total of 14 quarterly reports have been issued in addition to the two annual reports. A plan for the reporting of all data and modelling results from the Poços de Caldas project was decided in September 1989 and expected to be fulfilled by May 1990. Some results of the redox front movement have already been presented /20-1,2/.

20.2 THE CIGAR LAKE PROJECT

The Cigar Lake uranium mineralization is situated in northern Saskatchewan in Canada and is one of several uranium ore bodies in the area. The Cigar Lake deposit, located entirely underground at a depth of about 430 m, is in contact with sandstone and underlying basement rock. The ore body is 2 km long, 25-100 m wide and 1-20 m deep, see Figure 20-1. It is surrounded by a 5-30 m thick clay-rich halo that consists for the most part of illite, kaolinite and quartz. The ore and the surrounding clay zone were formed hydrothermally about 1.3 billion years ago when reducing hydrothermal solutions from the basement rock have discharged into the sandstone. The uranium content of the ore is exceptionally high with 12% of weight uranium as the average grade and with local concentrations in excess of 55% There are no direct indications; radiological, thermal, geophysical or geochemical, at the surface that the ore deposit exists /20-3/.

SKB have signed an agreement with AECL in Canada to investigate the Cigar Lake Uranium deposit as a natural analogue to a repository for spent nuclear fuel. Cooperation started in April 1989 and a three year project is foreseen. The investigation programme contains the following tasks:

— Geochemistry/mineralogy

— Hydrogeochemistry

— Colloids

— Hydrogeology

— Organic material and microbes

— Radiolysis

— Nuclear reaction products

— Modelling

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

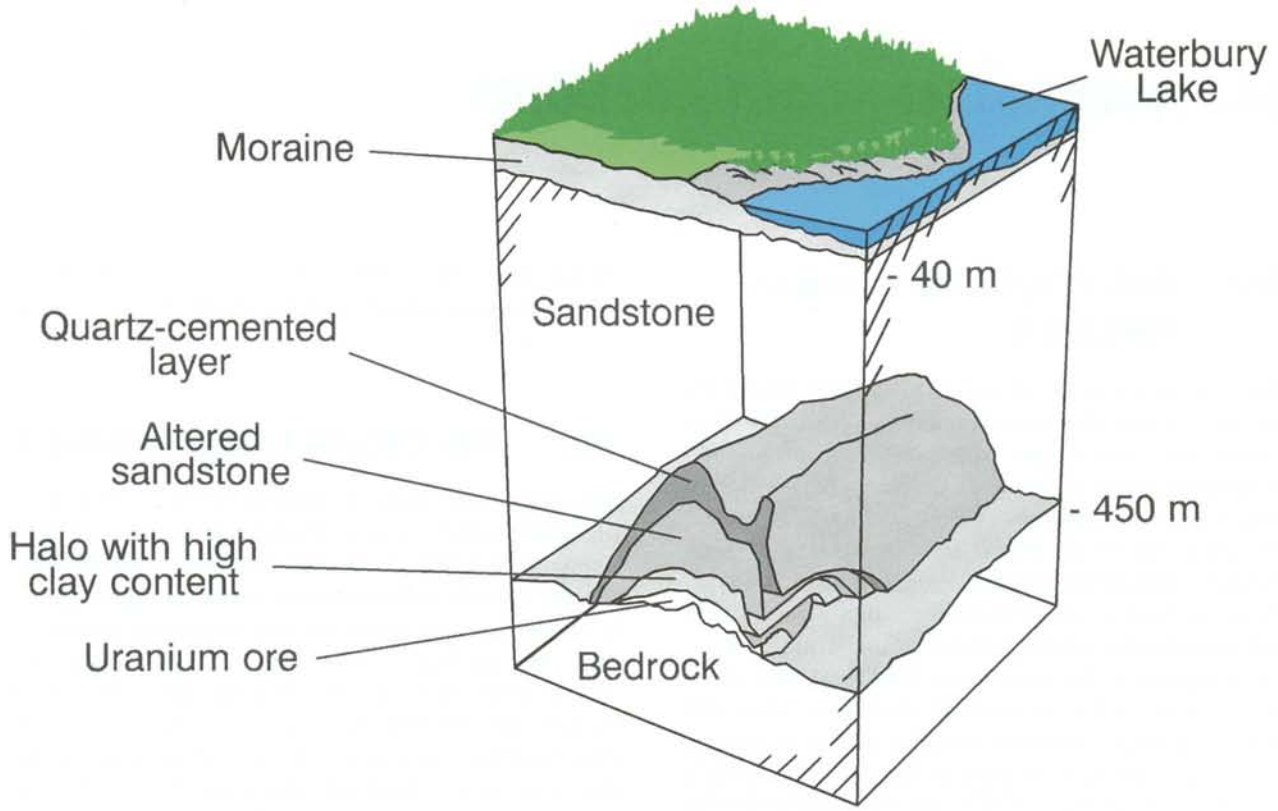

Figure 20–1. *Schematic illustration of the Cigar Lake Uranium deposit*

21. INTERNATIONAL COOPERATION

An important part of SKBs programme is to follow the correspondent 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 aspects i e:

— contributions to method– and model development

— broadened and strengthened databases

— exploration of other alternatives for repository and barrier design, material selection etc.

— insights in programmes to broaden the public confidece in repository 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.

21.1 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),

— EC – EUROATOM,

— Finland – TVO and IVO,

— Soviet Union – SCUAE (State Committee on the Utilization of Atomic Energy),

— Japan – JNFI (Japan Nuclear Fuel Industries Company, Inc.).

Information exchange without formal agreements also with:

— West Germany,

— Belgium,

— Great Britain,

— Other Nordic countries.

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.

21.2 COOPERATION WITH TVO, FINLAND

Cooperation with TVO was initiated in 1988 regarding studies of the relationship between the microstructure and diffusion properties of clays. During 1989 measurements were made at room temperature and elevated temperature with samples in measuring cells prepared at Clay Technology in Lund. Measurements with tracers was performed at VTT in Helsinki, while rheology and conductivity was studied in Lund.

A regular exchange of experience and technology for site investigation is taking place. Furthermore, Finnish representatives are included in the reference groups for the Lansjärv study and for the Hard Rock Laboratory.

TVO and SKB are jointly compiling existing knowledge on the importance of ice ages and related phenomena for the assessment of the repository's safety. Aside from this organized cooperation, information has been exchanged regarding deposition methodology, canister design, see Chapter 12, safety assessment and quality evaluations.

21.3 COOPERATION WITH CEA, FRANCE

21.3.1 Clay

SKB is currently cooperating with CEA in clay studies. The cooperation has included coordination of research projects and information exchange regarding relation-

ships between the microstructure, mineralogy etc of smectite clays and the influence of temperature and irradiation. Hydrothermal tests and irradiation have been carried out during year-long experiments in the laboratory. The irradiation tests have been carried out on SKB's reference clay Mx 80 and French smectite clay in a simulated canister environment in the laboratory at Saclay. Tests are being conducted at Stripa with highly compacted French smectite clay in a simulated deposition environment at approx. 170°C. Studies of rheological properties have been carried out in the laboratory in Sweden. 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.

21.3.2 Chemistry

Within the framework of the bilateral cooperation agreement between CEA and SKB, experiments have been conducted to collect basic data on actinides. Similarly, experiments have been conducted regarding complexation between actinides and humic substances. Researchers from the Department of Inorganic Chemistry at KTH in Stockholm and Tema Vatten ("Theme Water") at the University of Linköping have during 1989 participated on behalf of SKB.

21.4 COOPERATION WITH AECL, CANADA

21.4.1 Characterization of the 240 level of URL

AECL and SKB signed in April 1987 an agreement on cooperation for characterization of the 245 Level in the Underground Research Laboratory situated in a granitic batholite in Manitoba, Canada. The agreement expires 1991. SKB regularly attach staff or designated representatives to follow and participate in the work. The work performed has addressed discrepancies between calculated and in-situ measured hydraulic response as a part of a post-excavation analyse of the test. Already existing hydraulic conceptual models were revised and any available information was included in the new model. By altering the permeability in the floor and along the walls and roof of the periphery of the tunnel, a better correspondence between calculated and measured drawdown was obtained. The same also applied for measured inflow in quantity, though not for the actual distribution of inflow. As causes for the skin around the tunnel, partial unsaturation, propulsion of debris into fractures and effects of blasting were deemed to be of importance /21-1/.

21.5 COOPERATION WITH EURATOM, CEC

21.5.1 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.

21.5.2 CHEMVAL

CHEMVAL is a CEC project for verification and validation of chemical equilibrium calculation programs and coupled models for geochemistry transport.

SKB had during 1989 a group participating in the project.

21.5.3 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.

21.6 COOPERATION WITHIN OECD NUCLEAR ENERGY AGENCY

21.6.1 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 Tönis Papp. Some work is carried out in joint international projects, and work groups are formed to facilitate information exchange or prepare material as a basis for joint decisions 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 1989 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

ISAG (Advisory Group on In Situ Research and Investigations) functions in an advisory capacity to RWMC in matters pertaining to the activities of the various underground research laboratories.
Member from SKB: Bengt Stillborg

PSAC (Probabilistic Safety Assessment Code) Users 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. The project manager and head of project administration is Bengt Stillborg.
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)

21.6.2 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, uranium, neptunium, plutonium, americium and technicium are being reviewed. There are plans to include palladium, iodine, cesium, strontium, radium and lead as well.

The TDB Project is a very important effort to develop a well-documented, reviewed and internationally accepted database. SKB is supporting the activity and Swedish experts are participating in the review work. For SKB, as well as for other participants, it will naturally be necessary to have an operational database available before TDB for different calculation purposes. However, the results from TDB will be incorporated as they become available. A good example of this is the Uranium Database at SKB.

21.6.3 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 are included in the project, which involves evaluating the results of selected laboratory tests, field tests and studies of natural analogues. In many of the cases, it is possible for different model groups to perform predictive modelling before the measurement results have become available.

Five of the fourteen test cases are 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.

INTRAVAL is planned to continue until the end of 1990, with an option for extension for an additional three years.

21.7 COOPERATION WITHIN IAEA

Cooperation has during 1989 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 appointed during 1989 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.

SKB often participates with experts in the compilation or review of the above kinds of reports and has an observer, Per-Eric Ahlström, in INWAG.

22. DOCUMENTATION

The scientific work in the R&D programme of SKB are documented at different levels:

- in reports requested by law and submitted to the Swedish Government or its authorities such as KBS-3, R&D-Programme 89 and Plan 89,
- in the series of SKB Technical Reports,
- in contributions to scientific journals, symposia and conferences in different subject areas,
- in SKB Working Reports (Arbetsrapporter),
- in internal SKB memos,
- in technical memos and notes.

Further, the bulk of basic data from geological site characterization activities, spent fuel studies etc. are collected and stored in data base systems at SKB.

22.1 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 microfish at IAEA in Vienna and are available through them. Abstracts of the 1989 Technical Reports are included in part IV of this Annual Report.

22.2 CONTRIBUTIONS TO PUBLICATIONS, SEMINARS ETC

The contributions to conferences, symposia and scientific journals have been extensive during 1989, see Appendix 2.

Both SKB own staff as well as the contractors of SKB have been involved in this work.

22.3 SKB GEOLOGICAL DATA BASE SYSTEM

The data from the geological site investigations is managed by and brought together in GEOTAB, a common database system. 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 /22-1, 2, 3, 4/. As new measuring methods and data acquisition techniques are applied the documentation is completed with working reports /22-5,6,7,8/. All documentation is in English.

The database now contains surface data from 42 sites and data from 339 boreholes in many of these. Data are structured in 9 subject areas, 86 different methods and 589 tables containing 5704 columns. Total data volume is about 150 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.

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 10.000 records in each. Plans exist to port it to SKBs new Convex C210 computer, a supermini running UNIX. These plans now have even more been brought to the fore, as the MIMER company has been bought by an other company selling the database manager INGRES. This means that the MIMER system probably cannot be used after about 3 years from now.

Despite large efforts to make the programs user friendly, retrieval is mostly done by the same personnel that stored the data. Some working documents have been prepared to give an overview of GEOTAB /22-9/. An operators manual /22-10/ has also been distributed. All documentation is in English. The small amount of direct user retrieval is partly due to the relatively high complexity in some of the measuring methods and data evaluation.

Statistical and graphical presentation is currently better provided on personal computers. The output from GEOTAB can be correctly formatted for these programs and automatically transferred to the PC.

22.4 COMPUTERS AT SKB

22.4.1 Minisupercomputer

SKB has during 1989 purchased a minisupercomputer CONVEX C 210 in order to achive better computing capacity and lower costs. Several other computers were used before with converting problems between them. The CONVEX C 210 from Databolin was delivered and passed all tests with flying colors in the beginning of June. Since then the CONVEX has been running 24 hours a day with no major problems and with the expected vector capacity of about 12 Mflops (floating point operations per second). The operating system is a 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 from the VAX 11/750. This software enabled all consultants with access to the VAX system to directly access the CONVEX as well. The hardware configuration is 64 Mbyte main memory, 3 Gbyte on 3 disks, a 6250 bpi tape drive, 2 ethernet transcievers and 16 asyncronous ports.

22.4.2 Minicomputer

The VAX 11/750 is now conceptually more than 10 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 Gbytes on 5 disks, a 2.3 Gbyte Exabyte and a 1600 bpi tape station, ethernet transciever 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.

22.4.3 Workstations and local area network

The personal computers at SKB have been connected to a common local area network (LAN). The main advantage is that a common file system is used, making document transfer very easy and the common software consistent throughout the company. The networking software used in this LAN is PCNFS from SUN Microsystems. This is the communication part of a true UNIX implementation, including telnet, rsh and NFS. The servers can be one or several UNIX computer with NFS and currently 2 SUN386i workstations with 1 Gbyte on 3 disks, a 2.3 Gb Exabyte and a QIC tape station are used. The difference to a conventional LAN (as Novell) is that no computer is central but communication is direct between for example a PC and the VAX. One PC is in this LAN served by several file servers simultaneously. The LAN is extended to include the CONVEX and the VAX computers via a pair of ethernet bridges.

REFERENCES PART II

Chapter 10

10-1 R&D-Programme 89
Handling and final disposal of nuclear waste.
Programme for research development and other measures
SKB, September 1989

10-2 Carlsson H, Carlsson L and Pusch R 1989
Rock quality designation of the hydraulic properties in the near field of a final repository for spent nuclear fuel.
SKB Technical Report TR 89-21, Stockholm

10-3 Juhlin C and Sandstedt H 1989
Storage of nuclear waste in very deep boreholes: feasibility study and assessment of economic potential.
Part I Geological consideration
Part II Overall facility plan and cost analysis
SKB Technical Raport TR 89-39, Stockholm

10-4 Pusch R 1989
Influence of various techniques on the structure and physical properties of "near-field" rock around large boreholes
SKB Technical Report TR 89-32, Stockholm

Chapter 11

11-1 Forsyth R S et al. 1990
To be published 1990.

11-2 Werme L O and Forsyth R S 1989
The SKB spent fuel corrosion programme
Status report 1988
SKB Technical Report Tr 89-14, Stockholm

11-3 Choppin G R 1990
Actinide speciation in spent fuel leaching studies
in: Proc. Mater. Res. Soc. 13th Symp. on Scientific Basis for Nuclear Waste Management, Boston, 1989, eds. V M Oversby and P W Brown (Materials Research Society, Pittsburgh, in press).

11-4 Forsyth R S, Werme L O and Bruno J 1986
The corrosion of spent UO_2 fuel in synthetic groundwater, J. Nucl. Mater. 138 (1986) 1.

11-5 Grambow B, Werme L O, Forsyth R S and Bruno J 1990
Constraints by experimental data for modelling radionuclide release from spent fuel
in: Proc. Mater. Res. Soc. 13th Symp. on Scientific Basis for Nuclear Waste Management, Boston, 1989, eds. V M Oversby and P W Brown (Materials Research Society, Pittsburgh, in press).

11-6 Albinsson Y, Forsyth R S. Skarnemark G, Skålberg M, Torstenfelt B and Werme L O 1990
Leaching/migration of UO_2-fuel in compacted bentonite, in: Proc. Mater. Res. Soc. 13th Symp. on Scientific Basis for Nuclear Waste Management, Boston, 1989, eds. V M Oversby and P W Brown (Materials Research Society, Pittsburgh, in press).

11-7 Skålberg M, Eliasson L, Skarnemark G, Torstenfelt B, Forsyth R S, Holmér A, Winqvist B and Allard B 1988
Diffusion of radionuclides from spent oxide fuel into compacted bentonite
Sci. of Tot. Environm. 69 (1988) 347.

Chapter 12

12-1 Platts N and Marsh G P 1990
To be published 1990

12-2 Mattsson H and Olefjord I 1984
General corrosion of Ti in hot water and water saturated bentonite clay
SKB Technical Report TR 84-19, Stockholm

12-3 Mattsson H, Olefjord I and Li C 1990
Titanium exposed in water saturated bentonite clay: Exposures ranging up to six years
To be published 1990

Chapter 13

13-1 Pusch R, Karnland O and Muurinen A 1989
Transport and microstructural phenomena in bentonite clay with respect to the behabiour and influence of Na, Cu and U
SKB Technical Report TR 89-34, Stockholm

13-2 Börgesson L and Pusch R 1989
Interim report on the settlement test in Stripa
SKB Technical Report TR 89-29, Stockholm

13-3 Pusch R and Hökmark H
1989
Outline of models of water and gas flow through smectite clay buffers.
SKB Technical Report TR 87-10, Stockholm

Chapter 14

14-1 R&D- Programme 86
Handling and final disposal of nuclear waste.
Programme for research development and other measures
SKB, September 1986

14-2 see 10-1

14-3 Gustafson G, Stanfors R and Wikberg P
1988
The Swedish Hard Rock Laboratory: First evaluation of pre-investigations 1986-1987 and target area characterization.
SKB Technical Report TR 88-16, Stockholm

14-4 Gustafson G, Stanfors R and Wikberg P
1989
Swedish Hard Rock Laboratory: Evaluation of 1988 year pre-investigations and description of the target area, the island of Äspö.
SKB Technical Report TR 89-16, Stockholm

14-5 Ahlbom K, Andersson P, Ekman L, Gustafsson E, Smellie J and Tullborg E-L
1986
Preliminary investigations of fracture zones in the Brändan area, Finnsjön study site.
SKB Technical Report TR 86-05, Stockholm

14-6 Ahlbom K and Smellie J (eds)
1989
Characterization of fracture zone 2, Finnsjön study-site.
SKB Technical Report TR 89-19, Stockholm

14-7 Andersson J E, Ekman L, Gustafsson E, Nordqvist R and Tirén S
1989
Hydraulic interference tests and tracer tests within the Brändan area, Finnsjön study site. The Fracture Zone Project - Phase 3
SKB Technical Report TR 89-12, Stockholm

14-8 Andersson J E and Lindqvist L
1989
Prediction of hydraulic conductivity and conductive fracture frequency by multivariate analysis of data from the Klipperås study site.
SKB Technical Report TR 89-11, Stockholm

14-9 Carlsten S and Olsson O
1989
Comparison between radar data and geophysical, geological and hydrological borehole parameters by multivariate analysis of data.
SKB Technical Report TR 89-15, Stockholm

14-10 Olsson O and Palmqvist K
1989
Radar investigations at the Saltsjötunnel - predictions and validation.
SKB Technical Report TR 89-18, Stockholm

14-11 Andersson P, Andersson P, Gustafsson E and Olsson O
1989
Investigation of flow distribution in a fractur zone at Stripa mine, using the radar method, results and interpretation
SKB Technical Report TR 89-33, Stockholm

14-12 Bäckblom G and Stanfors R (eds) 1989
Interdisciplinary study of post-glacial faulting in the Lansjärv area, northern Sweden.
SKB Technical Report TR 89-31, Stockholm

14-13 Wahlström R, Linder S-O, Holmqvist C and Mårtensson H-E
1989
Near-distance seismological monitoring of the Lansjärv neotectonic fault region. Part II: 1988.
SKB Technical Report TR 89-01, Stockholm

14-14 Slunga R
1989
Earthquake measurements in northern Sweden Oct 1987 – Apr 1988.
SKB Technical Report TR 89-28, Stockholm

14-15 Röshoff K
1989
Seismic effects on bedrock and underground constructions. A literature survey of damages on constructions; changes in groundwater levels and flow; changes in chemistry in groundwater and gases.
SKB Technical Report TR 89-30, Stockholm

14-16 Röshoff K
1988
Characterization of the morphology, basement rock and tectonics in Sweden.
SKB Technical Report TR 89-03, Stockholm

Chapter 15

15-1 Bergström U and Nordlinder S.
1989
Individual radiation doses from nuclides contained in a WP-cave repository for spent fuel.
SKB Technical Report TR 89-06, Stockholm

15-2 Moreno L, Arve Sue and Neretnieks I.
1989
SKB WP-Cave project: Transport of escaping radionuclides from the WP-Cave repository to the biosphere.
SKB Technical Report TR 89-05, Stockholm

15-3 Moreno L and Neretnieks I.
1989
SKB WP-Cave Project Some notes on technical issues Part 3: Transport of escaping nuclides from the WP-Cave repository to the biosphere. Influence of the hydraulic cage.
SKB Technical Report TR 89-07, Stockholm

15-4 Bergström U, Andersson K and Sundblad B.
1986
Biosphere data base revision.
SKB Technical Report TR 86-15, Stockholm

15-5 Papp T, Sellin P, Ström A and Nilsson S.
1989
Arbetsbeskrivning för SKB 91.
SKB Arbetsrapport 89-18, Stockholm

15-6 Agnedal P O Andersson K, Evans S, Sundblad B, Tham G and Wilkens A-B.
1984
The dynamics of Lake Bog and Bay - Consequences of exposure to man related to final storage of spent nuclear fuel.
SKB Technical Report TR 84-17, Stockholm

15-7 Evans S.
1986
Quantitative estimates of sedimentation rates and sediment growth in two Swedish lakes.
SKB Technical Report TR 86-29, Stockholm

15-8 Sundblad B.
1986
Recipient evolution - transport and distribution of elements in the lake Sibbo-Trobbofjärden area.
SKB Technical Report TR 86-30, Stockholm

15-9 Sundblad B, Bergström U, Evans S and Puigdomenech I.
1988
Long-term dynamics of a lake ecosystem and the implications for radiation exposure.
SKB Technical Report TR 88-31, Stockholm

15-10 Kelmers A D, Meyer R E, Blencoe J G and Jacobs G K.
1987
Radionuclide sorbtion methodologies for performance assesements of high-level nuclear waste repositories: A perspective gained from an NRC workshop.
Nuclear Safety vol.28 No.4 (1987) 515

15-11 Elert M and Argärde A-C.
1985
Modelling of the interface between the geosphere and the biosphere - Discharge through a sediment layer.
Project SSI P295-84.
Swedish National Institute of Radiation Protection, Stockholm

15-12 Elert M, Argärde A-C and Ericsson A-M.
1988
Modelling of the interface between the geosphere and the biosphere - Discharge through a soil layer.
Kemakta AR 88-23.
Swedish National Institute of Radiation Protection, Stockholm

15-13 Gustavsson E, Skålberg M, Sundblad B, Karlberg O, Tullborg E-L, Ittner T, Carbol P, Eriksson N and Lampe S.
1987
Radionuclide deposition and migration within the Gideå and Finnsjön study sites, Sweden: A study of the fallout after the Chernobyl accident. Phase I, initial survey.
SKB Technical Report TR 87-28, Stockholm

15-14 Ittner T and Gustavsson E.
1989
Lägesrapport avseende 1988 års aktiviteter inom projektet: Nedfallsstudier i Gideå och Finnsjöområdet efter Tjernobylolyckan 1986 (in Swedish).
SKB Arbetsrapport 89-27, Stockholm

15-15 Carbol P and Skålberg M.
1989
Rapport avseende 1987-88 års aktiviteter inom projektet nedfallsstudier i Gideå och Finnsjönområdet efter Tjernobylolyckan 1986 (in Swedish).
SKB Arbetsrapport 89-28, Stockholm

15-16 Carbol P, Ittner T and Skålberg M.
1988
Radionuclide Deposition and Migration of the Chernobyl fallout in Sweden.
Radiochimica Acta 44/45,207-212 (1988).

15-17 Liljenzin J O, Skålberg M, Persson G, Ingemansson T and Aronsson P O.
1988
Analysis of the Fallout in Sweden from Chernobyl.
Radiochimica Acta 43,1-25 (1988).

15-18 Smith G.
1989
Scenario B5: Ageing of a Lake.
BIOMOVS TR 5
National Institute of Radiation Protection, Stockholm

15-19 Grogan H A.
1989
Scenario B2 Irrigation with Contaminated Groundwater.
BIOMOVS TR 6
National Institute of Radiation Protection, Stockholm

15-20 Bergström U.
1988
Scenario B3 : Release of Radium-226 and Thorium-230 to a Lake.
BIOMOVS TR 1.
National Institute of Radiation Protection, Stockholm

Chapter 16

16-1 Nilsson A-C
1989
Chemical Characterization of Deep Groundwaters on Äspö
SKB Progress Report PR 25-89-14, Stockholm

16-2 Wickman, Kornfält, Riad, Munier and Tullborg
1988
Detailed Investigations of the Drillcores KAS 02, 03, 04 on Äspö Island and KLX 01 at Laxemar.
SKB Progress Report PR 25-88-11, Stockholm

16-3 Tullborg E-L
1989
Fracture fillings in Drillcores KAS 05 - KAS 08 from Äspö.
SKB Progress Report PR 25-89-16, Stockholm

16-4 Possnert G and Tullborg E-L
1989
Carbon-14 analyses of calcites from Klipperås
SKB Technical Report TR 89-36, Stockholm

16-5 Laaksoharju M and Nilsson A-C
1989
Models of groundwater composition and of hydraulic conditions based on chemometrical and chemical analyses of deep groundwater at Äspö and Laxemar.
SKB Progress Report PR 25-89-04, Stockholm

16-6 Bruno J and Sandino A
1989
The solubility of amorphous and crystalline schoepite in neutral to alkaline solutions.
Materials Research Society Symposium
Proceedings Vol 127(1989) p 871

16-7 Bruno J, Sandino A and Fredlund F
1989
The solubility of $(UO_2)_3(PO_4)_24H_2O(s)$ in neutral and alkaline media.
Migration-89 Symposium in Monterey, California, November 6-10, 1989

16-8 Bruno J, Charlet L, Karthein R, Sandino A and Wersin P
1989
Adsorption, precipitation and co-precipitation of trace metals on carbonate minerals at low temperatures.
Water Rock Interaction Symposium, WRI/-6. Ed. by Miles D L and Balkema, Rotterdam, Brookfield 1989

16-9 Ephraim J, Borén H, Pettersson C, Arsenie I and Allard B
1989
A novel description of the acid-base properties of an aqueous fulvic acid.
Environmental Science and Technology Vol 23 (1989) p 356-362

16-10 Pettersson C, Arsenie I, Ephraim J, Borén H and Allard B
1989
Properties of fulvic acids from deep groundwaters
Sci. Tot. Environ. Vol 81/82 (1989) p 287-296

16-11 Ephraim J, Borén H, Arsenie I, Pettersson C and Allard B
1989
A combination of acid-base titrations and derivatization for functional group determinations of an aquatic fulvic acid
Ibid. p 615-624

16-12 Arsenie I, Borén H and Allard B
1989
Effects of gamma irradiation on an aquatic fulvic acid
International Symposium on Humic Substances in the Aquatic and Terrestrial Environment
Linköping, August 22, 1989

16-13 Ephraim J, Roddy M M and Marinsky J A
1989
Ion binding by humic substances: Considerations based on the solutio chemistry and heterogeneity of the humic substances
Ibid

16-14 Nordén M, Ephraim J and Allard B
1989
Interaction of strontium and europium with an aquatic fulvic acid
Ibid

16-15 Pettersson C and Allard B
1989
Dating of groundwater from ^{14}C-analysis of dissolved humic substances
Ibid

16-16 Ephraim J
1989
Non-aqueous titration of a fulvic acid sample with use of an internal reference compound
Talanta Vol 36 (1989) p 379-382

16-17 Ephraim J, Marinsky J A and Cramer S J
1989
Complex forming properties of natural organic acids: Fulvic acid complexes with cobalt, zinc and europium
Talanta Vol 36 (1989) p 437-443

16-18 Karsten P
1989
Deep groundwater microbiology in Swedish granitic rock and its relevance for radionuclide migration from a Swedish high level nuclear waste repository
SKB Technical Report TR 89-23, Stockholm

16-19 Eriksen T and Locklund B
1989
Radionuclide sorption on crushed and intact granitic rock. Volume and surface effects
SKB Technical Report TR 89-25, Stockholm

16-20 Ittner T, Torstenfelt B and Allard B
1989
Migration of fission products in granitic rock
Radiochim. Acta 46 (1989) In press

16-21 Eriksen T
1989
Some notes on diffusion of radionuclides through compacted clays
SKB Technical Report TR 89-24, Stockholm

16-22 Albinsson Y and Engkvist I
1989
Diffusion of Am, Pu, U. Np, Cs, I and Tc in compacted sand-bentonite mixture
SKB Technical Report TR 89-22, Stockholm

16-23 Albinsson Y, Christiansen B, Engkvist I and Johansson W
1989
Transport of actinides and technetium through a bentonite backfill containing small quantities or iron or copper Radiochemica Acta (1989). In press. Also presented at Migration-89 Symposium in Monterey, California, November 6-10, 1989

16-24 Andersson K, Allard B, Bengtsson M and Magnusson B
1989
Chemical composition of cement pore solutions
Cement Concrete Research Vol 19 (1989) p 327-332

16-25 Eriksen T, Ndalamba P, Christensen H and Bjergbakke E
1989
Radiolysis of groundwater: Influence of carbonate and chloride on hydrogen peroxide production
J. Radioanal. Nucl. Chem. Vol 132:1 (1989) p 19-35

16-26 Abelin H, Birgersson L, Gidlund J, Moreno L, Neretnieks I, Widén H and Ågren T
1987
3-D Migration experiment - Report 3,
Part I and II Stripa Project,
SKB Technical Report TR 87-21, Stockholm

16-27 Landström O, Klockars C-E, Persson O, Tullborg E-L, Larsson S Å, Andersson K, Allard B and Torstenfelt B
1983
Migration experiments in Studsvik
SKB Technical Report TR 83-18, Stockholm

16-28 Moreno L, Neretnieks I and Landström O
1989
An evaluation of tracer tests performed at Studsvik
SKB Technical Report TR 89-09, Stockholm

Chapter 17

17-1 Andersson J, Carlsson T, Eng T, Kautsky F, Söderman E and Wingefors S
1989
The joint SKI/SKB scenario development project
SKB Technical Report TR 89-35, Stockholm

17-2 Hesböl R, Puigdomenech I and Evans S
1990
Source terms, isolation and radiological consequences of carbon-14 waste in the Swedish SFR repository
SKB Technical Report TR 90-02, Stockholm

17-3 Atkinsson, R et al
1989
NAMMU users guide (to be published)

17-4 Grundfelt B, Boghammar A and Lindberg H
1989
HYPAC User's Guide
SKB Arbetsrapport 89-22, Stockholm

17-5 Thunvik R, Bao Y-B
1988
GWHRT-S - Documentation of computer program for sensivity analysis of groundwater flow. Version 1.0
SKB Arbetsrapport 88-55, Stockholm

17-6 Moreno L, Neretnieks I and Landström O
1989
An evaluation of tracer tests performed at Studsvik
SKB Technical Report TR 89-09, Stockholm

17-7 Follin S
1989
Statistical analysis of representative sample sizes in heterogeneous formations
SKB Arbetsrapport 89-35, Stockholm

17-8 Ahlbom K and Tirén S
1989
Overview of geologic and hydrogeologic character of the Finnsjön site and its surroundings
SKB Arbetsrapport 89-08, Stockholm

17-9 Andersson J-E, Nordqvist R, Nyberg G, Smellie J and Tirén S
1989
Hydrological conditions in the Finnsjön area. Compilation of data and conceptual model
SKB Arbetsrapport 89-24, Stockholm

Chapter 19

19-1 see 14-3

19-2 Gustafsson G, Stanfors R, Wikberg P
1989
Swedish Hard Rock Laboratory
Evaluation of 1989 year preinvestigations and description of the target area, the island of Äspö
SKB Technical Report TR 89-16, Stockholm

Chapter 20

20-1 Romero L, Moreno L and Neretnieks I
1989
Poços de Caldas. The location of the redox front. Presented as Test Case 7 (Natural Analogues) in the INTRAVAL Workshop, Helsinki, Finland, June 12-16 1989

20-2 Cross J, Haworth A, Neretnieks E, Sharland S M and Tweed C J
1989
Modelling of redox front movement in a uranium mine at Poços de Caldas.
Presented at the Migration 89 Symposium in Monterey, California, November 6-10, 1989

20-3 Goodwin B W, Cramer J J and McConnell O B
1988
The Cigar Lake uranium deposit: An analogue for nuclear fuel waste disposal
Third CEC meeeting of the Natural Analogue Working Group (NAWG) Snow bird, Utah, June 15-17, 1988.

Chapter 21

21-1 Winberg A, Chan T, Griffiths P and Nakka B
1989
Post-excavation analysis of a revised Room 209 hydraulic fracture model. A part of the joint AECL/ SKB characterization of the 240 level at the URL, Manitoba, Canada.
SKB Technical Report TR 89-27, Stockholm

Chapter 22

22-1 Gentzschein B
1986
Description of hydrogeological data in SKBs database GEOTAB.
SKB Technical Report TR 86-22, Stockholm

22-2 Sehlstedt S
1988
Description of geophysical data in SKBs database GEOTAB.
SKB Technical Report TR 88-05, Stockholm

22-3 Stark T
1988
Description of geological data in SKBs database GEOTAB.
SKB Technical Report TR 88-06, Stockholm

22-4 Eriksson E. and Sehlstedt S
1989
Description of background data in SKBs database GEOTAB.
SKB Technical Report TR 89-02, Stockholm

22-5 Gerlach M
1989
Status of hydrogeological tables in the SKB database GEOTAB
SKB Arbetsrapport 89-29, Stockholm

22-6 Eriksson E
1990
Status of background tables in the SKB database GEOTAB
SKB Arbetsrapport 90-01, Stockholm

22-7 Sehlstedt S
1990
Status of Geophysical tables in the SKB database GEOTAB
SKB Arbetsrapport 90-02, Stockholm

22-8 Stark T
1990
Status of Geological tables in the SKB database GEOTAB
SKB Arbetsrapport 90-03, Stockholm

22-9 SKB
1990
GEOTAB Overview
SKB Arbetsrapport 90-04, Stockholm

22-10 SKB
1990
GEOTAB Operators manual
SKB Arbetsrapport 90-09, Stockholm

SKB ANNUAL REPORT 1989

Part III

Appendices

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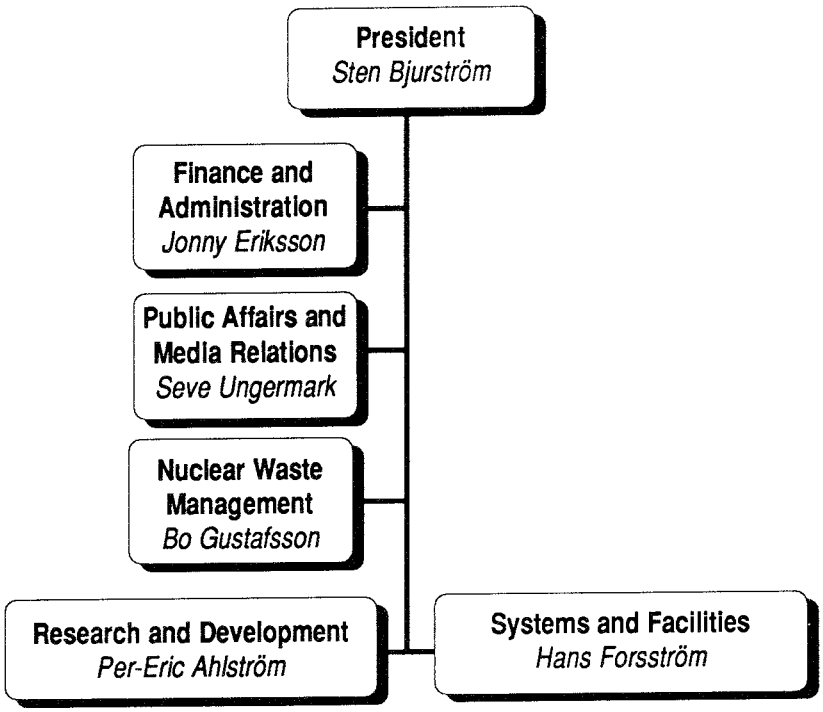
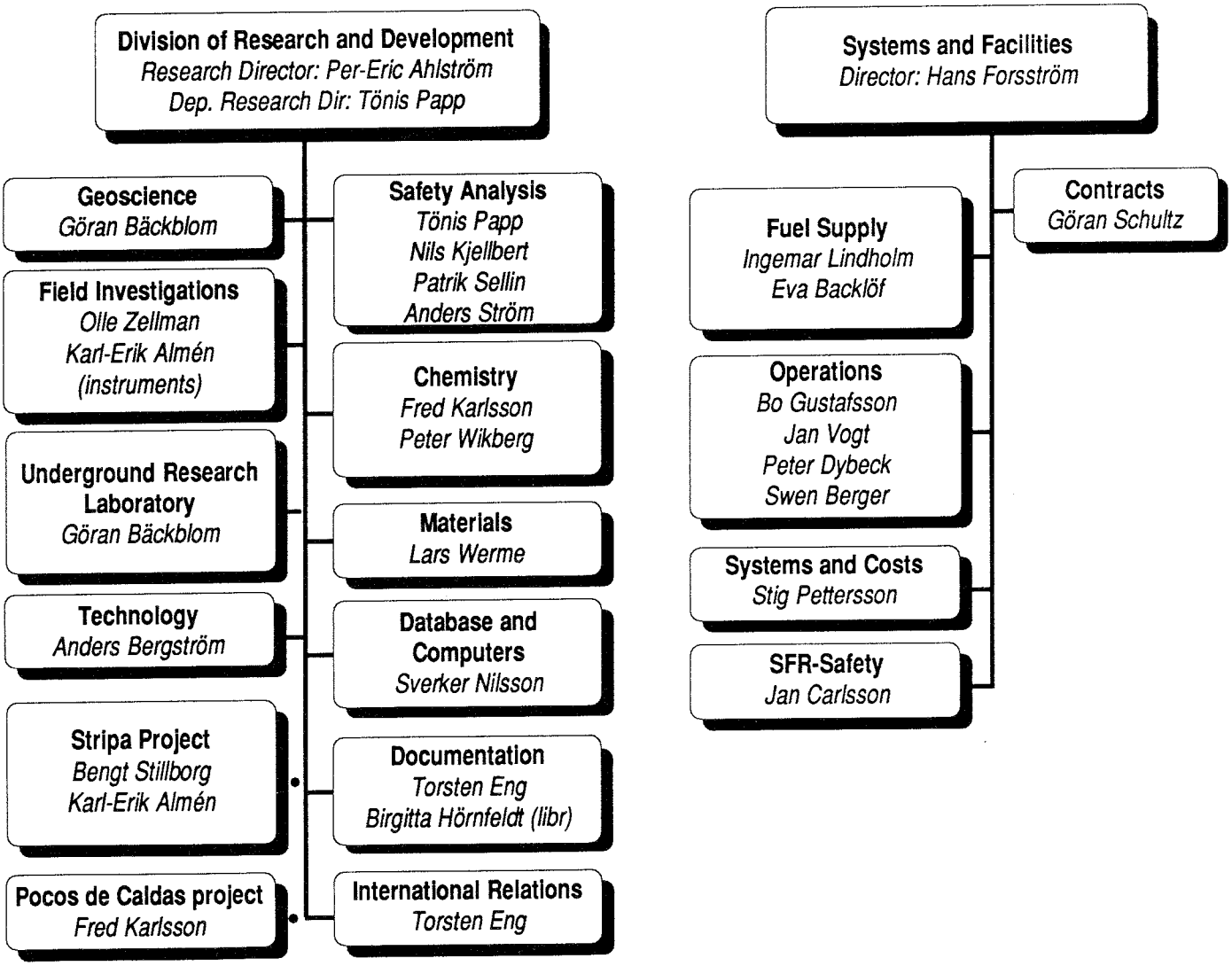
Appendix

Organization charts for SKB and its divisions





LECTURES AND PUBLICATIONS 1989

A channeling experiment to study flow and transport in natural fractures
Abelin,H; Birgersson, L; Ågren, T
OECD/NEA Workshop, Stockholm
October 1989

Management of spent nuclear fuel in Sweden
Ahlström, P; Forsström, H
High Level Radioactive Waste and Spent Fuel Management Vol II Book No. 10292B
1989

Diffusion of Am, Pu, U, Np and Tc in compacted sand-bentonite mixture
Albinsson, Y; Engkvist, I
Submitted to Radioactive Waste Management and the Nuclear Fuel Cycle
1989

Transport of actinides and Tc through a bentonite backfill containing small quantities of iron or copper
Albinsson, Y; Engkvist, I
Migration '89, Monterey, California
November 1989

Transport of actinides and Tc through a bentonite backfill containing small quantities of iron or copper
Albinsson, Y; Christiansen, B; Engkvist, I; Johansson, W
Radiocemica Acta (1989). In press

Leaching/migration of UO_2-fuel in compacted bentonite.
Albinsson, Y; Forsyth, R; Skarnemark, G; Skålberg, M; Torstenfelt, B; Werme, L
MRS fall meeting in Boston, Massachusetts
November 27 - December 2 1989

Leaching/migration of UO_2-fuel in compacted bentonite.
Albinsson, Y; Forsyth, R; Skarnemark, G; Skålberg, M; Torstenfelt, B; Werme, L
Scientific Basis for Nuclear Waste Management (1989). In press.

Mapping groundwater flow paths in crystalline rock using differential radar crosshole tomography measurements utilizing saline tracers
Andersson, K. P.; Andersson, P. M.; Gustavsson, E; Olsson, O
MGLS 3rd Symposium on Borehole Geophysics for Minerals, Geotechnical, and Groundwater Applications, Las Vegas, USA
October 1989

Chemical composition of cement pore solutions
Andersson, K; Allard, B; Bengtsson, M; Magnusson, B
Cement Concrete Res. 19 (1989) 327-332

Effects of gamma radiation on an aquatic fulvic acid
Arsenie, I; Borén, H; Allard, B
International Symposium on Humic Substances in the Aquatic and Terrestrial Environment, Linköping
August 1989

The Solubility of amorphous and crystalline schoepite in neutral to alkaline solutions
Bruno, J; Sandino, A
Mat. Res. Soc. Symp. Proc. 127, 871 (1989)

Adsorption, precipitation and co-precipitation of trace metals on carbonate minerals at low temperatures
Bruno, J; Charlet, L; Karthein, R; Sandino, A; Wersin, P
Water Rock Interaction, WRI-6.
ed by D.L. Miles, A.A Balkema, ed./Rotterdam/Brookfield 1989

Work on the kinetics of UO2(s) dissolution
Bruno, J; Carroll, S; Casas, I; Sandino, A; Östhol, E
Conference on Aquatic Surface Kinetics
Ittingen (Switzerland), March 1989

Swedish programme for disposal of radioactive waste. Site characterization for high level waste.
Bäckblom, G; Ahlström, P-E
28th International Geological Congress.
Washington D. C.,
July 9-19, 1989

Swedish programme for radioactive waste - geological aspects
Bäckblom, G; Karlsson, F
Geological Society Winter Meeting, Stockholm University Radioactive waste disposal - The geologists' responsibility
January 31, 1989

The Swedish final repository for radioactive waste (SFR) - Safety Assessment and Quality Assurance
Carlsson, J
Waste Management '89, Tucson
March 1989

Appendix 2

Saftey assessment of SFR - A Swedish repository for low- and intermediate level radioactive waste
Carlsson, J; Papp, T; Forsström, H
IAEA/OECD/NEA - International symposium on Safety Assessment of Radioactive Waste Repositories.
Paris October 1989

Modelling of redox front movement in a uranium mine at Pocos de Caldas.
Cross, J; Haworth, A; Neretnieks, I; Sharland, S. M.; Tweed, C. J.
Migration '89, Monterey, California
November 1989

Contribution to the IAEA Technical Committee on Decontamination of Transport Casks and of Spent Fuel Storage Facilities
Dybeck, P; Grahn, P
Vienna 4-7 April, 1989

Inservice inspection and maintenance of transport casks at the CLAB facilities in Sweden
Dybeck, P; Gustafsson, B; Frykman, S
Patram 89, Washington D.C.,
June 11-16, 1989

The undersea location of the Swedish final repository for reactor waste, SFR - Human intrusion aspects.
Eng, T
OECD/NEA Workshop on Assessment of the Risks Associated with Human Intrusion at Radioactive Waste Disposal Sites. Paris
June 1989

The role of International cooperation regarding saftey assessment development in the SKB research programme.
Eng, T; Ahlström, P-E
Waste Management '89, Tucson
March 1989

Non-aqueous titration of a fulvic acid sample with use of an internal reference compound
Ephraim, J
Talanta 36 (1989) 379-382

A combination of acid-base titrations and derivatization for functional group determinations of an aquatic fulvic acid
Ephraim, J; Borén, H; Arsenie, I; Pettersson, C; Allard, B
Sci. Tot. Environ. 81/82 (1989) 615-624

A novel description of the acid-base properties of an aqeous fulvic acid
Ephraim, J; Borén, H; Pettersson, C; Arsenie, I; Allard, B
Environ. Sci. Technol. 23 (1989) 356-362

Complex forming properties of natural organic acids: Fulvic acid complexes with cobalt, zinc and europium
Ephraim, J; Marinsky, J A; Cramer, S J
Talanta 36 (1989) 437-443

Ion binding by humic substances: Considerations based on the solution chemistry and heterogeneity of the humic substances
Ephraim, J; Reddy, M M; Marinsky, J A
International Symposium on Humic Substances in the Aquatic and Terrestrial Environment, Linköping
August 1989

On the corrosion of copper in pure water
Eriksen, T E; Ndalamba, P; Grenthe, I
Corrosion Science 29:10 (1989) 1241-1250

Radiolysis of ground water: Influence of carbonate and chloride on hydrogen peroxide production
Eriksen, T E; Ndalamba P; Christensen, H; Bjergbakke, E
J Radioanal. Nucl. Chem. 132:1 (1989) 19-35

Plans for expanding the capacity of the Swedish Away From Reactor Storage Facility, CLAB
Forsström, H
Technical Committee on Methods for expanding Spent Fuel Storage Facilities
June 12-15, 1989

Chemical aspects of radwaste disposal
Grenthe, I
Geological Society Winter Meeting, Stockholm University Radioactive waste disposal - The geologists' responsibility
January 31, 1989

Development, Implementation and Experience of the Swedish Spent Fuel and Waste See Transportation System
Gustafsson, B; Dybeck, P; Pettersson, S
Patram 89, Washington D.C., June 11-16, 1989

Design, Construction and safety assessments for a repository in bedrock
Hedman, T; Aronsson, I; Pettersson, S
Reprint from Symposium on Management of low and intermediate level radioactive wastes
IAEA, Stockholm, May 16-20 1988, published 1989

Migration of fission products in granitic rock
Ittner, T; Torstenfeldt, B; Allard, B
Radiochim. Acta 46 (1989)

The need and necessity for the M/S Sigyn's advanced communication and navigation system adopted for marine transportation of radioactive material
Josefsson, J; Gustafsson, B; Dybeck, P
Patram 89, Washington D.C., June 11-16, 1989

Utilization of certain chemical and physical properties of smectite for isolation of radioactive waste
Karlsson, F
IXth International Clay Conference, Strasbourg, France
August 28-September 2, 1989

Preliminary evaluation of some uranium migration tests
Kjellbom, K; Moreno, L; Neretnieks, I
INTRAVAL Workshop, Helsinki
June 1989

Pressure head calculations based on groundwater composition
Laaksoharju, M
Poster presentation at Migration '89, Monterey, California
October 1989

Site characterization and validation Stage 1 - Hydrochemical investigations at the Stripa mine
Laaksoharju, M
Stripa TSG-meeting
March 1989

Postglacial faulting and palaeoseismicity in northern Sweden and adjacent parts of Finland and Norway
Lagerbäck R
Geological Society Winter Meeting, Stockholm University Radioactive waste disposal - The geologists' responsibility
January 31, 1989

The influence of fracture mineral/groundwater interaction on the mobility of U, Th, REE and other tracer elements in different redox env.
Landström, O; Tullborg, E–L
Poster at the 6th International Symposium on Water-Rock Interaction WRI-6, Malvern, England
August 1989

The development and status of performance assessment in radioactive waste disposal
McCombie, C; Papp, T, Coplan S
International Symposium on the Safety Assessment of Radioactive Waste Repositories, Paris
October 1989

Preliminary evaluation of tracer tests in Finnsjön. Radial convergent experiment
Moreno, L; Neretnieks, I
INTRAVAL Workshop, Helsinki
June 1989

A note on data needs for assessment of radionuclide transport
Neretnieks, I
OECD/NEA Workshop, Paris
October 1989

A large scale flow and tracer experiment in granite
Neretnieks, I; Abelin, H; Birgersson, L; Moreno, L; Widén, H; Ågren, T
OECD/NEA Workshop, Stockholm
October 1989

A large scale flow and tracer experiment in granite
Neretnieks, I; Abelin, H; Birgersson, L; Moreno, L; Widén, H; Ågren, T
28th Geological Congress, Washington D. C.
July 1989

Interaction of strontium and europium with an aquatic fulvic acid
Nordén, M; Ephraim, J; Allard, B
International Symposium on Humic Substances in the Aquatic and Terrestrial Environment, Linköping
August 1989

Numerical predictions of a dipole tracer test in a fracture zone in the Brändan area, Finnsjön
Nordqvist, R
Third INTRAVAL Workshop, Helsingfors,
June 1989

Radar crosshole tomography using saline tracers to map groundwater flow paths
Olsson, O; Andersson, Per; Andersson, Peter; Gustavsson, E
EAEG Conference , Berlin
1989

Borehole radar – a new technique for characterization of rock at great depth
Olsson O; Falk L
International symposium on Rock at Great Depth
Pau, France
August 1989

Borehole radar applied to characterization of fracture zones
Olsson, O; Falk, L; Forslund, O; Niva, B; Sandberg, E
7th ASEG Conference, Melbourne, Australia
1989

Appendix 2

Radar measurements with a directional borehole antenna
Olsson, O; Falk, L; Sandberg, E; Forslund, O; Lundmark, L
SEG Annual Conference in Dallas, USA
1989

Radar crosshole tomography using saline tracers
Olsson, O; Niva, B; Sandberg, E; Andersson, P
URSI International Symposium on Electromagnetic Theory
1989

Dating of groundwaters from c-14-analysis of dissolved humic substances
Pettersson, C; Allard, B
International Symposium on Humic Substances in the Aquatic and Terrestrial Environment, Linköping
August 1989

Properties of fulvic acids from deep groundwaters
Pettersson, C; Arsenie, I; Ephraim, J; Borén, H; Allard, B
Sci. Tot. Environ. 81/82 (1989) 287-296

Poços de Caldas. The location of the redox front.
Romero, L; Moreno, L; Neretnieks, I
INTRAVAL Workshop, Helsinki
June 1989

Combined interpretation of fracture zones in crystalline rock using single hole, crosshole, tomography and directional borehole radar data
Sandberg E; Olsson, O; Falk, L
MGLS 3rd Symposium on Borehole Geophysics for Minerals, Geotechnical, and Groundwater Applications, Las Vegas, USA
1989

Swedish earthquakes and fault movements
Slunga, R
Geological Society Winter Meeting, Stockholm University
Radioactive waste disposal - The geologists' responsibility
January 31, 1989

Swedish natural analogue studies and their applications
Smellie, J
Geological Society Winter Meeting, Stockholm University
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Modelling of bedrock stability
Stephansson, O
Geological Society Winter Meeting, Stockholm University
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Problems posed to a bedrock radwaste repository by gently dipping fracture zones
Talbot, C. J.
Geological Society Winter Meeting, Stockholm University
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Rock block configuration in southern Sweden and crustal deformation
Tirén, S; Beckholmen, M
Geological Society Winter Meeting, Stockholm University
Radioactive waste disposal - The geologists' responsibility
January 31, 1989

Block faulting in southeastern Sweden interpreted from digital Terrain models
Tirén, S; Beckholmen, M
GFF Vol 111
1989

The influence of recharge water on fissure filling minerals - a study from Klipperås, southern Sweden
Tullborg, E–L
Chemical Geology, Vol. 76
1989

---

^{18}O and ^{13}C in fracture calcite used for interpretation of recent meteoric water circulation
Tullborg E-L
6th International Symposium on Water-Rock Interaction WRI-6, Malvern, England
August 3-8 1989

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TR 121
KBS Technical Reports 1–120
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Summaries.
Stockholm, March 1980

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KBS Technical Reports 80-01—80-25.
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Summaries.
Stockholm, April 1982

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KBS Technical Reports 82-01–82-27.
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Stockholm, July 1983

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KBS Technical Reports 83-01–83-76.
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Annual Research and Development Report 1984
Including Summaries of Technical Reports Issued during 1984. (Technical Reports 84-01 – 84-19)
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TR 89-01
Near-distance seismological monitoring of the Lansjärv neotectonic fault region. Part II: 1988
Wahlström, Rutger; Linder, Sven-Olof; Holmqvist, Conny; Mårtensson, Hans-Edy
Seismological Department, Uppsala University
January 1989

TR 89-02
Description of background data in the SKB database GEOTAB
Eriksson, Ebbe; Sehlstedt, Stefan
Swedish Geological Co, Luleå
February 1989

TR 89-03
Characterization of the morphology, basement rock and tectonics in Sweden
Röshoff, Kennert
August 1988

TR 89-04
SKB WP-Cave project. Radionuclide release from the near-field in a WP-Cave repository
Lindgren, Maria; Skagius, Kristina
Kemakta Consultants Co, Stockholm
April 1989

TR 89-05
SKB-WP-Cave project. Transport of escaping radionuclides from the WP-Cave repository to the biosphere
Moreno, Luis; Arve, Sue; Neretnieks, Ivars
Royal Institute of Technology, Stockholm
June 1989

TR 89-06
Individual radiation doses from nuclides contained in a WP-Cave repository for spent fuel
Bergström, Ulla; Nordlinder, Sture
Studsvik Nuclear
July 1989

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SKB-WP-Cave project. Some notes on technical issues. Part 1: Temperature distribution in WP-Cave: when shafts are filled with sand/water mixtures. Part 2: Gas and water transport from the WP-Cave repository. Part 3: Transport of escaping nuclides from the WP-Cave repository to the biosphere. Influence of the hydraulic cage
Björklund, Stefan (part 1) 1); Josefson, Lennart (part 1) 1); Moreno, Luis (part 2 and 3) 2); Neretnieks, Ivars (part 2 and 3) 2);
Div. of solid mechanics, Chalmers University of Technology 1); Dep. av chemical engineering, Royal Institute of Technology 2)
August 1989

TR 89-08
NAK WP-Cave project. Thermally induced convective motion in groundwater in the near field of the WP-Cave after filling and closure
Hopkirk, Robert J
Polydynamics Ltd., Zuerich, Switzerland
April 1989

TR 89-09
An Evaluation of tracer test performed at Studsvik
Moreno, Luis 1); Neretnieks, Ivars 1); Landström, Ove 2)
Department of Chemical Engineering, Royal Institute of Technology 1); Studsvik Nuclear 2)
March 1989

TR 89-10
Copper produced from powder by HIP to encapsulate nuclear fuel elements
Ekbom, Lars B; Bogegård, Sven
Swedish National Defence Research Establishment, Materials department, Stockholm
February 1989

TR 89-11
Prediction of hydraulic conductivity and conductive fracture frequency by multivariate analysis of data from the Klipperås study site
Andersson, Jan-Erik 1); Lindqvist, Lennart 2)
Swedish Geological Co, Uppsala 1);
EMX-system AB, Luleå 2)
February 1988

TR 89-12
Hydraulic interference tests and tracer tests within the Brändan area, Finnsjön study site. The fracture zone project phase 3
Andersson, Jan-Erik; Ekman, Lennart; Gustafsson, Erik; Nordqvist, Rune; Tirén, Sven
Swedish Geological Co, Uppsala
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Spent fuel, dissolution and oxidation. An evaluation of literature data
Grambow, Bernd
Hanh-Meitner-Institut, Berlin
March 1989

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The SKB spent fuel corrosion programme. Status report 1988
Werme, Lars O 1); Forsyth, Roy S 2)
SKB 1); Studsvik Nuclear 2)
May 1989

TR 89-15
Comparison between radar data and geophysical, geological, and hydrological borehole parameters by multivariate analysis of data
Carlsten, Serje; Lindqvist, Lennart; Olsson, Olle
Swedish Geological Company, Uppsala
March 1989

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Swedish Hard Rock Laboratory Evaluation of 1988 year preinvestigations and description of the target area, the island of Äspö
Gustafson, Gunnar; Stanfors, Roy; Wikberg, Peter
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Field instrumentation for hydrofracturing stress measurements. Documentation of the 1000 m hydrofracturing unit at Luleå University of Technology
Bjarnason, Bjarni; Torikka, Arne
Luleå University of Technology
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Radar investigations at the Saltsjötunnel - predictions and validation
Olsson, Olle 1); Palmqvist, Kai 2)
Abem AB 1); Bergab 2)
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Characterization of fracture zone 2, Finnsjön study-site.
Part 1: Overview of the fracture zone project at Finnsjön, Sweden.
Part 2: Geological setting and deformation history of a low angle at Finnsjön, Sweden. Part 3: Hydraulic testing and modelling of a low-angle fracture zone at Finnsjön, Sweden
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Ahlbom, K 1); Smellie, JAT 1); Tirén, Sven A 1); Andersson, J-E 1); Ekman, L 1); Nordqvist, R 1); Winberg, A 2); Gustafsson, E 1); Andersson, P 1); Wikberg, P 3)
Swedish Geological Company, Uppsala 1);
Swedish Geological Company, Gothenburg 2);
Swedish Nuclear Fuel and Waste Management Co 3)
August 1989

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WP-Cave - assessment of feasibility, safety and development potential
Swedish Nuclear Fuel and Waste Management Co
September 1989

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Rock quality designation of the hydraulic properties in the near field of a final repository for spent nuclear fuel
Carlsson, Hans 1); Carlsson, Leif 1); Pusch, Roland 2)
Swedish Geological Co (SGAB), Gothenburg, 1);
Clay Technology AB, Lund, 2)
June 1989

TR 89-22
Diffusion of Am, Pu, U, Np, Cs, I and Tc in compacted sand bentonite mixture
Albinsson, Yngve; Engkvist, Ingemar
Department of Nuclear Chemistry, Chalmers University of Technology, Gothenburg
August 1989

TR 89-23
Deep ground water microbiology in Swedish granitic rock and it's relevance for radio-nuclide migration from a Swedish high level nuclear waste repository
Pedersen, Karsten
Department of Marine microbiology,
University of Gothenburg
March 1989

TR 89-24
Some notes on diffusion of radionuclides through compacted clays
Eriksen, Trygve E
Department of Nuclear Chemistry,
Royal Institute of Technology
May 1989

TR 89-25
Radionuclide sorption on crushed and intact granitic rock. Volume and surface effects
Eriksen, Trygve E; Locklund, Britta
Department of Nuclear Chemistry,
Royal Institute of Technology
May 1989

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Performance and safety analysis of WP-Cave concept
Skagius, Kristina 1); Svemar, Christer 2)
Kemakta Konsult AB 1);
Swedish Nuclear Fuel and Waste Management Co 2)
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TR 89-27
Post-excavation analysis of a revised hydraulic model of the Room 209 fracture, URL, Manitoba, Canada. A part of the joint AECL/SKB characterization of the 240 m level at the URL, Manitoba, Canada
Winberg, Anders 1); Chan, Tin 2); Griffiths, Peter 2); Nakka, Blair 2)
Swedish Geological Co, Gothenburg 1); Computations & Analysis Section, Applied Geoscience Branch, Atomic Energy of Canada Limited, Pinawa, Manitoba, Canada 2)
October 1989

TR 89-28
Earthquake mechanisms in Northern Sweden Oct 1987 - Apr 1988
Slunga, Ragnar
October 1989

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Interim report on the settlement test in Stripa
Börgesson, Lennart; Pusch, Roland
Clay Technology AB, Lund
November 1989

TR 89-30
Seismic effects on bedrock and underground constructions. A literature survey of damage on constructions; changes in groundwater levels and flow; changes in chemistry in groundwater and gases
Röshoff, Kennert
June 1989

TR 89-31
Interdisciplinary study of post-glacial faulting in the Lansjärv area Northern Sweden 1986 - 1988
Bäckblom, Göran (ed.); Stanfors, Roy (ed.)
December 1989

TR 89-32
Influence of various excavation techniques on the structure and physical properties of "near-field" rock around large boreholes
Pusch, Roland
Clay Technology AB and Lund University of Technology and Natural Sciences, Lund
December 1989

TR 89-33
Investigation of flow distribution in a fracture zone at the Stripa mine, using the radar method, results and interpretation
Andersson, Per; Andersson, Peter; Gustafsson, Erik; Olsson, Olle
Swedish Geological Co., Uppsala,
December 1989

TR 89-34
Transport and microstructural phenomena in bentonite clay with respect to the behavior and influence of Na, Cu and U
Pusch, Roland 1); Karnland, Ola 1); Muurinen, Arto 2)
Clay Technology AB (CT) 1); Technical Research Center of Finland, Reactor Laboratory (VTT) 2)
December 1989

TR 89-35
The joint SKI/SKB scenario development project
Andersson, Johan (ed. and author) 1); Carlsson, Torbjörn 1); Eng, Torsten 2); Kautsky, Fritz 1); Söderman, Erik 3); Wingefors, Stig 1)
Swedish Nuclear Power Inspectorate, SKI, Stockholm, 1);
Swedish Nuclear Fuel and Waste Management Co
SKB, Stockholm, 2); ES-Konsult, Bromma, 3)
December 1989

TR 89-36
^{14}C-Analyses of calcite coatings in open fractures from the Klipperås study site, Southern Sweden
Possnert, Göran 1); Tullborg, Eva-Lena 2)
Svedberg-laboratory, Uppsala 1); Swedish Geological Co, Gothenburg 2)
December 1989

TR 89-37
Alteration of natural UO_2 under oxidizing conditions from Shinkolobwe, Katanga, Zaire: A natural analogue for the corrosion of spent fuel
Finch, R J; Ewing, R C
Department of Geology, University of New Mexico
November 1989

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TR 89-38

An estimation of nuclide release rate near the canister (Near Field Model 91)

Lee, Han-Soo 1); Moreno, Luis 2); Neretnieks, Ivars 2)
Dept. of Radwaste Disposal, Korea Advanced Energy Research Institute, Choong-Nam, Korea 1); Dept. of Chemical Engineering, Royal Institute of Technology, Stockholm, 2)
December 1989

TR 89-39

Storage of nuclear waste in very deep boreholes: feasibility study and assessment of economic potential. Part I Geological considerations 1); Part II Overall facility plan and cost analysis 2)

Juhlin, Christopher 1); Sandstedt, Håkan 2)
Swedish State Power Board
December 1989

AUTHORS OF SKB TECHNICAL REPORTS 1989

Appendix 5

SKB ANNUAL REPORT 1989

Part IV

Summaries of Technical Reports Issued During 1989

SKB Technical Report No 89-01

Near-distance seismological monitoring of the Lansjärv neotectonic fault region. Part II: 1988

Wahlström, Rutger; Linder, Sven-Olof; Holmqvist, Conny; Mårtensson, Hans-Edy
Seismological Department, Uppsala University

January 1989

Keywords: Seismology, Lansjärv, Postglacial faulting, Sweden, Nuclear waste, Seismic network

ABSTRACT

During five months in 1988, a mobile seismic network (six stations) was operated near the Lansjärv neotectonic fault in Swedish Lapland. This was a continuation of an investigation in the same area in 1987. Some 30 local earthquakes were recorded, 18 of which have been located. A restrained focal depth has been obtained for six of these, and the depths range from 5 to 12 km.

There is no clear spatial association of the earthquakes with the lateglacial fault segments, but many epicentres lie close to an older fault with the trend perpendicular to that of the lateglacial fault segements. Seismic moments from 10^{10} to 10^{12} Nm, fault radii 30 - 100 m, average dislocations 0.03 - 3 mm and stress drops 0.01 - 4 MPa have been computed from Sg-wave amplitude spectra. Focal mechanisms are not well constrained due to the small number of stations, and their tectonic interpretation is uncertain.

SKB Technical Report No 89-02

Description of background data in the SKB database GEOTAB

Eriksson, Ebbe; Sehlstedt, Stefan
Swedish Geological Co, Luleå

February 1989

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. Here, the data is organized into six groups (subjects) as follows:

— Background data
— Geological data
— Borehole geophysical data
— Ground surface geophysical data
— Hydrogeological data
— Hydrochemical data

Except for the case of borehole and ground surface geophysical 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 BGR, 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 No 89-03

Characterization of the morphology, basement rock and tectonics in Sweden

Röshoff, Kennert

August 1988

Keywords: Tectonics, Sweden, Geology, Nuclear waste

ABSTRACT

This report is a compilation of the knowledge of the morphology, the bedrock geology and the tectonics of Sweden. The compilation is mainly based on published articles and maps. The result is presented on seven maps.

Sweden is subdivided into three terrain types, South-East Sweden Terrain, Norrland Terrain and Caledonian Terrain.

South-East Sweden Terrain is dominated by the sub-Cambrian peneplain, the elevated and fractured sub-Cambrian peneplain and Tertiary denudation surfaces. The dominating landforms are plains and fissure-valleys, with a relative relief of 20-50 meters.

The Norrland terrain is characterized by an undulating hilly landscape with a relative relief of more than 100 meters. The most northern part is dominated by monadnock plains.

The Caledonian Terrain has not been included in the study.

Sweden is a part of the Baltic Shield, a Precambrian craton area.

The bedrock is predominated by Precambrian hard rocks. The geology is subdivided into three large domains, mainly based on the geological deformation history. The oldest rocks of Archaean age are found in northern Sweden, where they are related to the Archaean domain, the nucleus of the Baltic Shield.

The Svecofennian domain covers most of Sweden. The domain is subdivided into four subdomains the North, Central and South subprovinces and the Transscandinavian granite-porphyry belt. The latter is thought to represent the later stages of the Svecofennian orogeny.

The Southwest Scandinavian domain represents rocks found on the southwest part of the country. The boundary between the Southwest Scandinavian Domain and the Transscandinavian granite-porphyry belt is an extensive tectonic zone, the Protogine zone.

The dominating rocks within the different domains are granites, gneissic granites and gneisses. Supracrustal rocks of both sedimentary and volcanic origin are locally observed. In some areas they predominate.

The tectonic structures have been evaluated from geological and lineament maps. The latter based on Landsat III images and the Relief map of Sweden.

A new lineament map based on the Relief map is presented. This map shows an acceptable correlation with the lineaments based on Landsat images, when large tectonic elements, more than 50 km, are compared in southern Sweden. The correlation is worse for north Sweden.

The paper presents a new interpretation of lineaments regarding location, direction and length of large lineaments, a regional density map of lineaments and the regional distribution of orientations of lineaments.

SKB Technical Report No 89-04

SKB WP-Cave project. Radionuclide release from the nearfield in a WP-Cave repository

Lindgren, Maria; Skagius, Kristina
Kemakta Consultants Co, Stockholm

April 1989

Keywords: WP-Cave, Near-field release, Safety analysis, Bentonite buffer mass

ABSTRACT

The release of radionuclides from the bentonite-sand barrier (near-field) in a WP-Cave repository for high level radioactive waste has been studied. Calculations were made for two cases; a Low Flow Through Case and a High Flow Through Case. The difference between the two cases lies in the assumed hydraulic properties of the bentonite-sand barrier and the system inside the barrier. The effect on the nuclide release of solubility limitations, sorption capacity of the barriers, radiolytic fuel oxidation rate as well as the thickness of the bentonite-sand barrier, were also investigated for the Low Flow Through Case.

SKB Technical Report No 89-05

SKB-WP-Cave project. Transport of escaping radionuclides from the WP-Cave repository to the biosphere

Moreno, Luis; Arve, Sue; Neretnieks, Ivars
Royal Institute of Technology, Stockholm

June 1989

Keywords: WP-Cave, Far-field release, Safety analysis, Channel flow

ABSTRACT

Far-field release rates for radionuclides that have escaped from the WP-Cave repository (excluding the surrounding hydraulic cage) are calculated using the channeling model. The model considers flow in channels with different flowrates. The channeling model is based on the assumption that the channels are independent over a certain distance. In each channel the model takes into account the advective transport of the nuclide along a fracture with dispersion in the fracture and diffusion and sorption in the rock matrix. Preliminary calculations are performed to determine which parameters influence the release rate of the nuclides from the repository. These parameters are the travel length, channel width, and flowrate. The final results show that most of the radionuclides are not retarded to any great extent (if any) in the surrounding rock. The nuclides that are retarded in the rock are those that have a high sorption coefficient and/or short half-life. The calculations are performed for fractures that are 1 m in width, travel distance of 100 m and a flowrate of 0.3 l/m^2a.

SKB Technical Report No 89-06

Individual radiation doses from nuclides contained in a WP-Cave repository for spent fuel

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Studsvik Nuclear

July 1989

Keywords: WP-Cave, Biosphere dispersion, Safety analysis, Individual doses

ABSTRACT

The individual radiation doses to man were calculated from leakage of radionuclides from a WP-Cave repository for spent nuclear fuel. This study is a part of a safety analysis of a WP-Cave repository performed by SKB.

It was assumed that the nuclides reach the biosphere by inflow to a well and/or a lake. Therefore calculations were performed for three different critical groups. The turnover in the biosphere and the exposure to man was modelled by a compartment model using the BIOPATH-code. The nuclides dominating the total dose were identified. These were C-14, Se-79, Sn-126, I-129, Pa-231, Th-229 and Np-237. Maximum doses were about $3 \cdot 10^{-6}$ Sv/year.

Uncertainty analysis was carried out using the PRISM-code for the dose dominant nuclides. For all nuclides and cases the ranges of the doses are within three orders of magnitude for 90% confidence interval. The main parameters to the uncertainty in the case with outflow to a well are the volume of the well, the amount of water consumed or the migration in the soil. For the lake case major contributions to the uncertainty arise from the sedimentation, bioaccumulation in fish and the amount of consumption of fish.

SKB Technical Report No 89-07

SKB-WP-Cave project. Some notes on technical issues.
Part 1: Temperature distribution in WP-Cave: when shafts are filled with sand/water mixtures.
Part 2: Gas and water transport from the WP-Cave repository.
Part 3: Transport of escaping nuclides from the WP-Cave repository to the biosphere. Influence of the hydraulic cage

Björklund, Stefan (part 1) 1); Josefson, Lennart (part 1) 1); Moreno, Luis (part 2 and 3) 2); Neretnieks, Ivars (part 2 and 3) 2);
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August 1989

Keywords: WP-Cave, Temperature distribution, Gas transport, Hydraulic cage

ABSTRACT

PART 1:
The temperature field inside the sand-bentonite barrier of the WP-Cave has been computed numerically by the use of a three dimensional finite element model and the code SOLVIA-TEMP. In the calculations the cave is assumed to be filled with a sand/water mixture after the completion of the ventilation period. The highest calculated temperature is 250 °C, which is found in the filling material at the inner end of the canister column 50 years after the storage has been sealed. The spent fuel is then 190 years old.

PART 2:
Gas and water transport from the WP-Cave repository has been calculated. The gas production has been estimated to be in the interval 3 500 to 74 000 Nm^3/y. The water flow during the initial period will occur with a maximum overpressure in the interior of the repository of 0.75 MPa. The gas flow requires an initial high overpressure. The gas flow through the bentonite-sand barrier starts only if the overpressure is greater than the critical pressure. The critical pressure for a mixture bentonite-sand 50/50 is about 0.5 - 1.5 MPA. An alternative design is discussed, the use of a mixture bentonite-sand with a lower content of bentonite (e.g. 10/90). In this case the critical pressure is lower and the pressure needed to maintain a given flow is lower as well.

PART 3:
Transport of radionuclides escaping from the WP-Cave repository to the biosphere is calculated. The effect of the hydraulic cage is taken into account. It is found that the hydraulic cage may play an important role if the transport distance to the biosphere is short. For longer distances the effect of the hydraulic cage is smaller.

SKB Technical Report No 89-08

NAK WP-Cave project. Thermally induced convective motion in groundwater in the near field of the WP-Cave after filling and closure

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April 1989

ABSTRACT

The WP-Cave concept for the storage and final disposal of high level radioactive wastes involves the hydraulic isolation of an essentially cylindrical storage volume from passing groundwater by means of a two-stage barrier. The first (inner) stage is a diffusive barrier formed by a 5 m

thick enclosure of backfilled bentonite in an excavated annular space surrounding the storage volume. The second stage is a hydraulic "cage" formed by a network of drillholes and ring galleries. Figure 1 is a reproduction of this overall geometry. The purpose of the present report is to present the results of preliminary calculations of coupled thermo-hydraulic processes in the near field. These have been undertaken to check whether thermally induced circulations within either of the two barriers could diminish the effectiveness of the barriers themselves. The work has been carried through in two stages. In the first stage a uniform distribution of the heat source intensity within the storage region was assumed. A more detailed model of the heat source was introduced in the second stage calculations. In both stages, the WP-Cave was modelled with and without the presence of the hydraulic cage. The following parameters have been varied:

— the magnitude of the heat source
— hydraulic conductivity of the bentonite barrier
— hydraulic conductivity of the inner rock mass.

SKB Technical Report No 89-09

An Evaluation of tracer test performed at Studsvik
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Landström, Ove 2)
Department of Chemical Engineering, Royal Institute of Technology 1); Studsvik Nuclear 2)

March 1989

Keywords: Sweden, Nuclear waste, Radar statistics, Multivariate analysis, Crystalline rock, Geophysics

ABSTRACT
In situ tracer tests performed with nonsorbing tracers, as well as with sorbing tracers, in crystalline rock at the Studsvik site in Sweden have been analysed. Three different models were used: Advection-Dispersion model, Advection-Dispersion-matrix Diffusion model, and Advection-Channeling-matrix Diffusion model. Tests with a nonsorbing tracer were used to obtain information on hydraulic properties and tests with a sorbing tracer were used to determine the sorption properties of the fractured rock.

SKB Technical Report No 89-10

Copper produced from powder by HIP to encapsulate nuclear fuel elements
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February 1989

Keywords: HIP, Hot isostatic pressed, OFHC copper, Copper, Canister

ABSTRACT
In the Swedish nuclear waste management program, nuclear fuel elements are proposed to be encapsulated in copper canisters. To fill the space between the fuel elements two methods have been proposed. Originally lead was proposed to be cast into the canister. According to a second method the space between the fuel rods is filled with copper powder and hot isostatic pressed (HIP) to seal the canister lid and to densify the powder to homogeneous copper. The latter method has the advantage that each fuel rod is individually encapsulated in a very corrosion resistant material.

This investigation was performed to find out to what extent pure copper powder can be hot isostatic pressed to full density and to achieve properties comparable to that of the oxygen free high conductivity (OFHC) copper of the canister.

OFHC copper was molten under helium gas protection an atomized to a fine spherical powder in a pilot plant. The powder was transferred to a glove box with an argon atmosphere. The powder was filled into a steel container, which was evacuated and sealed. HIP was done at 550 °C and 200 MPa for one hour. The resulting copper was found to have a good ductility an mechanical properties comparable to that of ordinary copper. The constant strainrate stress corrosion test used to test the canister copper showed that the HIP-ed copper has the same good properties as OFHC copper.

SKB Technical Report No 89-11

Prediction of hydraulic conductivity and conductive fracture frequency by multivariate analysis of data from the Klipperås study site

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February 1988

Keywords: Nuclear waste

ABSTRACT

The present study is a pilot study on the possibility to predict the hydraulic conductivity and conductive fracture frequency in boreholes in crystalline rock using multivariate data analysis. The data set used was very extensive and included data from core mapping, fracture fillings, geophysical logs, tubewave measurements and hydraulic tests from five deep boreholes at the Klipperås study site. In the study, multivariate data analysis proved to be a powerful technique to systematically analyze an extensive data material and to study different correlation structures within the data set. With the models derived, about 80-90% of the variation of hydraulic conductivity of an input data set (consisting of 233 conductivity values in 1 m-sections) could be explained by utilizing 35-45% of the total information contained in the data set. The hydraulic conductivity of about 4500 one meter sections was predicted. The predicted transmissivity was generally in good agreement with measured transmissivity values in 20 m-sections. The predicted values in 1 m-sections provided a more detailed picture of the hydraulic conductivity distribution along the boreholes. The predicted conductivities were found to be very unevenly distributed. The highest values generally occur in borehole intervals with altered and deformed rock with increased fracture density.

The predicted conductive fracture frequency (CFF) was also unevenly distributed. Fissure fillings, in particular iron minerals, are regarded as useful information in predicting the CFF. The predicted average CFF of the rock mass varied between 0.17 and 0.25 (conductive) fractures per meter. This corresponds to an average fracture spacing of about 4-6 m. The frequency of subhorizontal fractures in granite generally correlates best to the hydraulic conductivity.

The study also showed that both the geological and hydrogeological properties of different rock types may vary considerably within a site.

SKB Technical Report No 89-12

Hydraulic interference tests and tracer tests within the Brändan area, Finnsjön study site. The fracture zone project - phase 3

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June 1988

Keywords: Nuclear waste, Sweden, Finnsjön, Hydrogeology, Fracture zones, Tracer tests, Interference tests, Crystalline rock

ABSTRACT

The report covers the perfomance and interpretation of a series of hydraulic interference tests and a tracer test in fracture Zone 2 within the Brändan area, Finnsjön. The interference tests were performed by pumping from isolated sections of one borehole and recording the resulting pressure changes in multiple-observation sections (generally five) in adjacent boreholes as well as in the pumping borehole. The tracer test was performed by pulse injection of tracers in isolated sections of the near region observation boreholes and monitoring the break-through of tracers in the pumping borehole.

The interference tests showed that different response patterns were generated in the near-region and in the more distant region from the pumping borehole. In the near-region, primary responses in high-conductive, low-porosity flow paths between the boreholes generally dominate. The tracer test also indicates that the primary responses may be strongly influenced by local hetero-geneities. At longer distances more averaged responses generally occurred with similar responses in the multiple-sections in the boreholes.

The hydraulic interference test as well as the tracer test documented a very high transmissivity of Zone 2, particulary in its upper part.

The interference tests indicated hydraulic interaction between Zone 2 and the over- and underlying rock. Zone 2 was found to be bounded and may be represented by a triangular-shaped area. Inflow to Zone 2 occured during pumping, possibly via other zones. Responses due to the pumping occurred at long distances (up to about 1.5 km) from the pumping borehole.

A numerical model was used to simulate the responses of the interference tests. Good agreement was achieved between simulated and observed responses from the most distant boreholes but decreased agreement in the near-region boreholes. This fact was attributed to local heterogeneities in the nearregion.

SKB Technical Report No 89-13

Spent fuel, dissolution and oxidation. An evaluation of literature data

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March 1989

Keywords: Spent fuel, Spent fuel oxidation, UO_2, Uraninite, Schoepite, Uranium solubility, U solubility

ABSTRACT

Data from studies of the low temperature air oxidation of spent fuel were retrieved in order to provide a basis for comparison between the mechanism of oxidation in air and corrosion in water. U_3O_7 is formed by diffusion of oxygen into the UO_2 lattice. A diffusion coefficient of oxygen in the fuel matrix was calculated for 25 °C to be in the range of 10^{-23} to 10^{-25} m^2/s.

Reported rate data for the dissolution of UO_2, uraninite and spent fuel where compiled as a function of environmental variables. Within the scatter of data, resulting from uncertainties in the effective surface area, the initial rates of U release from spent fuel and from UO_2 appeared to be similar. The lowest rates (at 25 °C more than 10^{-4} g/(m^2d)) were observed under reducing conditions. Under oxidizing conditions the rates depend mainly on the nature and concentration of the oxidant and/or on carbonate. In contact with air, typical initial rates at room temperature were in the range between 0.001 and 0.1 g/(m^2d).

A study of apparent U solubility under oxic conditions was performed and it was suggested that the controlling factor is the redox potential at the UO_2 surface rather than the Eh of the bulk solution. Electrochemical arguments were used to predict that at saturation, the surface potential will eventually reach a value given by the boundaries at either the U_3O_7/U_3O_8 or the U_3O_7/schoepite stability field, and a comparison with spent fuel leach data showed that the solution concentration of uranium is close to the calculated U solubility at the U_3O_7/U_3O_8 boundary. Nevertheless, a true thermodynamic equilibrium may never be achieved, because the U_3O_7 surface will remain unstable with respect to schoepite or other U(VI) phases if the concentration of oxidants in bulk solution is high enough.

The difference in the cumulative Sr and U release was calculated from data from Studsvik laboratory. The results reveal that the rate of Sr release decreases with the square root of time under U-saturated conditions. This time dependence may be rationalized either by grain boundary diffusion or by diffusion into the fuel matrix.

Hence, there seems to be a possibility of an agreement between the Sr release data, structural information and data for oxygen diffusion in UO_2. If this correlation is substantiated by comparison with other experimental data and by surface analytical techniques, the release of soluble radionuclides from spent fuel can in part be described as a transport process under moving boundary conditions.

SKB Technical Report No 89-14

The SKB spent fuel corrosion programme. Status report 1988

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May 1989

Keywords: Spent fuel, Spent fuel corrosion, Pu, Plutonium, U, Uranium, Solubility

ABSTRACT

The results of the Swedish spent fuel corrosion programme from 1982 to 1988 are reviewed. Areas where additional research will be required are identified.

The major findings and conclusions after the first six years of the programme are that uranium attains relatively rapidly a constant solution concentration of about 1 mg/l. This is probably solubility controlled. Also plutonium, after initially higher concentration appear to reach a constant concentration of about 0.3 µg/l in groundwater. In DI water, the normalized Pu release is higher than the U release, indicating ongoing fuel oxidation/alteration after the leachant has been saturated with U.

Under reducing conditions, the absence of fuel oxidation and the very low U solubility lead to a stronger tendency towards congruent releases, controlled by the solubility of the fuel matrix.

The fission products Cs, Sb, Tc and Mo appear to selectively leached, probably from inclusions or from fuel cracks, fissures and grain boundaries.

SKB Technical Report No 89-15

Comparison between radar data and geophysical, geological, and hydrological borehole parameters by multivariate analysis of data

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March 1989

Keywords: Radar, SIMCA, Multivariate data analysis, Fracture zones, Hydraulic conductivity

ABSTRACT

The borehole radar technique has been developed to its present status by a group at the Swedish Geological Company (SGAB), funded by the International Stripa Project and SKB. Several radar measurements have been per-

formed at different sites Klipperås, Finnsjön, Saltsjö-tunnel, Stripa, and Ävrö.

The object of the present work is to study the correlation between radar reflectors and geopysical, geological and hydraulical parameters from the boreholes. An additional objective is to show what information can be gained by the borehole radar with respect to waterflow and geological structures in crystalline rock. The tool for making the data modelling is Multivariate Data Analysis (SIMCA). For the data modelling there are two algorithms available in the SIMCA software. One for Principal Component analysis and one for Partial Least Squares regression analysis (PLS and PLS2). The PLS method gives the best results for the purpose of correlation between radar intensity and other variables.

The result from the Principal Component, PLS, and PLS2 analysis shows that the strongest correlations results in a division beweeen highly fractured rock and low fractured rock at all sites. Also, PLS and PLS2 analysis show that there is a good correlation between high radar intensity and highly fractured rock in the boreholes at all sites. The correlation between radar intensity and hydraulic conductivity is more ambiguous. Two of the investigated sites, Stripa and Finnsjön, exhibit good correlation between radar intensity and hydraulic conductivity, while the correlation at Ävrö is lower and at Saltsjötunnel it is poor. Hydraulic conductivity was not included in the analysis of the Klipperås data. The best correlation in the data from Klipperås was obtained between radar intensity and fractured lithological contacts. The degree of correlation between radar intensity and lithological contacts at the other four sites was lower than for Klipperås.

SKB Technical Report No 89-16

Swedish Hard Rock Laboratory Evaluation of 1988 year preinvestigations and description of the target area, the island of Äspö

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June 1989

Keywords: Hard Rock Laboratory, Geology, Geohydrology, Site characterization, Äspö

ABSTRACT

The site investigations for the Swedish Hard Rock Laboratory have been focussed on the southern part of the Äspö island. Geological, geohydrological and chemical investigations have been made in three deep boreholes on Äspö. The results are used to evaluate previous predictions of the properties of the rock mass and to set up new predictions, more detailed than the previous ones.

At the southern part of Äspö a basic rock type called the Äspö diorite dominates at the depths of 300 - 600 m. The hydraulic conductivity is lower here than in the surrounding Småland Granite. The groundwater chemistry in contact with the Äspö Diorite has a high iron content. The methods and techniques used for the investigations have been optimized and integrated. During the drilling operation both hydraulic tests and groundwater sampling were performed.

SKB Technical Report No 89-17

Field instrumentation for hydrofracturing stress measurements

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August 1989

Keywords: Hydrofracturing, Rock stress measurement, Instrumentation, Straddle packer, Multihose, Breakdown pressure, Shut-in pressure, Reopening pressure, Fracture orientation, Impression packer

ABSTRACT

The hydrofracturing method for rock stress measurements was introduced at Luleå University of Technology in the year 1982. It began with a loose component field instrumentation of multihose type for measurements to a maximum borehole depth of 500 m. It was later mounted on a field truck. Measurements were conducted in a number of sites in Sweden and in Finland by this first version of the hydrofracturing equipment.

The experience from this first equipment was good. The possibility of measuring rock stresses in continuous vertical profiles in existing field boreholes was new in Scandinavia. The results from the measurements added new and unique data to the knowledge of the state of stress in the upper part of the Baltic crust.

In the light of this experience and due to the needs for rock stress measurements within the Swedish Nuclear Waste Program, a contract of cooperation between Luleå University of Technology and SKB was signed in late autumn 1986. The new 1000 m hydrofracturing field instrumentation documented in this report is the outcome of this cooperation.

SKB Technical Report No 89-18

Radar investigations at the Saltsjötunnel - predictions and validation

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June 1989

Keywords: Nuclear waste, Sweden, Geophysics, Radar, Geohydrology, Conceptual model, Tunnel, TBM

ABSTRACT

Borehole radar investigations have been performed in two boreholes drilled along the extent of the Saltjö-tunnel in Stockholm, Sweden. Singlehole and crosshole radar measurements were made in the two boreholes which outlined an equilateral triangle. The crosshole data was used to produce tomograms showing the distribution of radar attenuation and slowness (inverse of velocity) in the plane between the boreholes.

There is general agreement between the radar model of the site and the geologic-tectonic model of the site. The radar model of the site contained one major feature which was identified as a fracture zone and the intersection with the tunnel was correctly predicted.

This project has demonstrated the capability of the borehole radar technique to predict the existence, location, and orientation of geologic features (e.g. fracture zones) which can be of significance to the cost and safety when excavating a tunnel. However, further development is needed to be able to use the technique cost effectively for continuous prediction ahead of the tunnel front.

SKB Technical Report No 89-19

Characterization of fracture zone 2, Finnsjön study-site.
Part 1: Overview of the fracture zone project at Finnsjön, Sweden.
Part 2: Geological setting and deformation history of a low angle fracture zone at Finnsjön, Sweden.
Part 3: Hydraulic testing and modelling of a low-angle fracture zone at Finnsjön, Sweden.
Part 4: Groundwater flow conditions in a low angle fracture zone at finnsjön, Sweden.
Part 5: Hydrochemical investigations at Finnsjön, Sweden.
Part 6: Effects of gas-lift pumping on hydraulic borehole conditions at Finnsjön, Sweden

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August 1989

Keywords: Nuclear waste, Sweden, Finnsjön, Fracture zone, Characterization, Geology, Geohydrology, Geophysics, Chemistry, Trace-tests

ABSTRACT

The Swedish Nuclear Fuel and Waste Management Company (SKB) has performed site selection studies for an underground repository of spent nuclear fuel since 1977. The Finnsjön site, situated in northeastern Uppland, and dominated by rocks of Precambrian age, has been a target area for such site selection studies. The area was mainly investigated from 1977-1982 when the surface and subsurface geology and hydrogeology were characterised. A few years later, in response to an increasing interest to study groundwater flow and transport in major fracture zones to evaluate the safety performance of geosphere barriers, the Finnsjön Fracture Zone Project was initiated in 1984. These later generic studies were restricted to a single fracture zone, Zone 2, which is gently dipping with an almost planar upper surface located between 100 m to 240 m below the ground surface.

This report is a compilation of the main scientific investigations carried out in and around Zone 2 during a four year period (1984-1988); some tracer experiments are still in progress. The objective of these studies was to characterise the geology, hydrology and hydrochemistry of Zone 2, so as to provide an invaluable input into the various safety assessment performance codes for model validation.

SKB Technical Report No 89-20

WP-Cave– assessment of feasibility, safety and development potential

Swedish Nuclear Fuel and Waste Management Co

September 1989

ABSTRACT

According to SKB R&D-programme 1986, alternative disposal methods will be investigated to provide a basis for selecting a site and a repository system for the Swedish spent nuclear fuel.

The present report is a comparison between the WP-Cave and the reference concept KBS-3.

The evaluation was made jointly by the SFG (the integrated performance group) and the WP-Cave project.

The task of the group has been to recommend to SKB which of the two alternative repository concepts should be prioritized in the future R&D efforts.

The comparison between the WP-Cave and KBS-3 concept has resulted in the following conclusions:

— Both concepts are judged to be able to provide adequate safety.

— A utilization of the potential of the WP-Cave requires, however, extensive development in areas where the current state of knowledge and available data are incomplete.

— The higher temperatures in the WP-Cave lead to greater uncertainty as to long-term performance. Reducing this uncertainty would require many years of research and substantial resources.

— Both repositories, including the barriers they incorporate, could be built with a normal adaptation of available technology.

— It is not possible to say today whether it would be simpler to find suitable sites for one design or the other.

— The WP-Cave is considerably more expensive.

A future research direction based on a concentrated emplacement of spent fuel along the lines of the WP-Cave is therefore judged to entail greater uncertainty as regards the possibilities of achieving acceptable safety and to require greater resources for research and development, at the same time as the costs of building the repository would be higher.

The studies of the WP-Cave as an integral system should therefore be discontinued. The research should be focused on distributed systems with lower temperatures, in accordance with the basic KBS-3 concept.

Certain barrier designs in the WP-Cave could also be utilized in repository designs with lower temperatures, for example the reduction potential of the steel canisters and the hydraulic cage's diversion of groundwater. Studies within these areas are being conducted within SKB and should continue.

SKB Technical Report No 89-21

Rock quality designation of the hydraulic properties in the near field of a final repository for spent nuclear fuel

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June 1989

ABSTRACT

Quality assurance of a final repository for spent nuclear fuel requires detailed information on the characteristics of the rock, backfill, canisters and the waste itself. Furthermore, and of fundamental importance, is the knowledge on the behaviour of the integrated system of the waste and the different barriers. The in-situ characteristics of the rock must therefore be assessed and their influence on and interactions with the remaining barriers must be predicted and verified.

A rock quality designation process of the hydraulic properties in the near-field is out-lined both for the KBS-3 system as well as for the WP-Cave system. The process, once updated and approved, will be included in a Quality Assurance Program for the final repository for spent nuclear fuel.

Some of the available methods for the near-field designation process are presented as well as techniques that need further development or are not developed at all.

Finally, a presentation is given of a generic designation process of the KBS-3 and WP-Cave repository systems in the previously investigated area in Central Sweden where the final repository for reactor waste, SFR, is located. Geological and hydrogeological data are here at hand and it is therefore possible to carry out a simulation of how the designation process would be accomplished.

SKB Technical Report No 89-22

Diffusion of Am, Pu, U, Np, Cs, I and Tc in compacted sand-bentonite mixture

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August 1989

Keywords: Diffusion, Buffer material, Backfill, Bentonite, Migration (near-field), Actinides, Radionuclide chemistry

ABSTRACT

In order to predict the diffusion of actinides and fission products through a backfill mixture of sand and clay from a high-lewel waste repository, the diffusion of the actinides ^{241}Am, ^{239}Pu, ^{237}Np and ^{233}U and the fission products ^{134}Cs, ^{131}I and ^{99}mTc have been measured in a mixture of 90% silica sand-l0% bentonite (MX-80, Wyoming bentonite). The sand/bentonite mixture was compacted to a density of 2000 kg/m^3. The water phase used was an artificial groundwater representative of Swedish deep granitic groundwater (pH approx. equal to 8, I approx. equal to 0.0l). The apparent diffusivity is in all cases slightly higher than in pure clay.

SKB Technical Report No 89-23

Deep ground water microbiology in Swedish granitic rock and it's relevance for radio-nuclide migration from a Swedish high level nuclear waste repository

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March 1989

Keywords: Microbiology (microbes), Geochemistry, Hard Rock Laboratory, Ävrö, Äspö, Laxemar

ABSTRACT
Data on numbers, species and activity of deep ground water microbial populations in Swedish granitic rock have been collected. Specific studies are performed on radio-nuclid uptake on bacteria judged to be probable inhabitants in Swedish nuclear waste repositories.

An integrated mobile field laboratory was used for water sampling and for the immediate counting and inoculation of the samples from bore holes at levels between 129 and 860 m. A sampler adapted for the collection of undisturbed samples for gas analysis was used to collect samples for bacterial enumerations and enrichments. The sampler can be opened and closed from the surface at the actual sampling depth. The samples can subsequently be brought to the surface without contact with air and with the pressure at the actual sampling depth.

The number of bacteria were determined in samples from the gas sampler when this was possible. Else numbers are determined in the water that is pumped up to the field lab. The average total number of bacteria is $3 \cdot 10^{-5}$ bacteria/ml. The number of bacteria possible to recover with plate count arrays from 0.10 to 21.9 %.

SKB Technical Report No 89-24

Some notes on diffusion of radionuclides through compacted clays

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May 1989

Keywords: Diffusion, Buffer material, Bentonite, Migration (near-field), Radionuclide chemistry

ABSTRACT
The apparent diffusivities of some simple cations i.e. Sr^{2+}, Cs^{+} in water saturated bentonite indicates that diffusion takes place both in the pore solution and within the solvation sheath of the exchangeable cations. Data from some earlier diffusion experiments have been re-evaluated and the results suggest that diffusion within the solvation sheath of the exchangeable cations is the dominating mechanism for Sr^{2+} and Cs^{+}.

SKB Technical Report No 89-25

Radionuclide sorption on crushed and intact granitic rock. Volume and surface effects

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May 1989

Keywords: Sorption, Radionuclide chemistry, Migration (geosphere)

ABSTRACT
The specific surface areas and distribution ratios for sorption of ^{85}Sr, ^{137}Cs and ^{152}Eu were measured for crushed and intact granitic rock.

The experimental data can be accommodated by a sorption model encompassing sorption on outer and inner surfaces. It is clearly demonstrated that the time required to obtain reliable K_d-values for the sorption of strongly sorbing radionuclides like ^{252}Eu is very long due to solution depletion and slow diffusion into the rock.

A combination of surface area measurements and batch sorption with small particles may therefore be preferable when studying strongly sorbing nuclides.

SKB Technical Report No 89-26

Performance and safety analysis of WP-Cave concept

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August 1989

Keywords: Spent nuclear fuel, Final disposal, Performance evaluation, Safety evaluation, WP-Cave

ABSTRACT
This report presents a performance, safety, and cost analysis of the WP-Cave, WPC concept. In the performance analysis, questions specific to the WPC have been addressed which have been identified to require more detailed studies. Based on the outcome of this analysis, a safety analysis has been made which comprises of the modeling and calculations of radionuclide transport from the repository to the biosphere and the resulting dose exposure to man.

The result of the safety analysis indicates that the present design of a WPC repository may give unacceptably high doses. By improving the properties of the bentonite/sand barrier such that the hydraulic conductivity is reduced, or by changing the shortlived steel canisters to more long-lived canisters, eg, copper canisters, it is judged possible to achieve a sufficiently low level of dose exposure rates to man.

The cost for a WPC repository of the studied design is significantly higher than for a KBS-3 repository considering the Swedish conditions and the Swedish amount of spent fuel. The major costs are connected to the excavation and backfilling of the bentonite/sand barrier. The potential for cost savings is high but it is not judged possible to account for savings in such a way that the WPC concept shows lower cost than the KBS-concept.

SKB Technical Report No 89-27

Post-excavation analysis of a revised hydraulic model of the Room 209 fracture, URL, Manitoba, Canada. A part of the joint AECL/SKB characterization of the 240 m level at the URL, Manitoba, Canada

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Keywords: Canada, URL, Nuclear waste, Rock mechanics, Geohydrology, Disturbed zone

ABSTRACT

An excavation response test was conducted in the Room 209 on the 240 m level of the AECL Underground Research Laboratory.

Model predictions prior to excavation were made of the geomechanical response of the rock mass and the hydraulic response of an intercepted fracture. The model results were compared with excavation response data collected in a comprehensive instrument array.

The work performed has addressed discrepancies between calculated and in-situ measured hydraulic response as part of a post-test analysis. Already existing hydraulic conceptual models of the fracture were revised and any available information was included in the new model.

The model reproduced the pre-excavation hydraulic head distribution and hydraulic test results in terms of normalized flow rate within 5% and 75%, respectively. It was also found that the model reproduced the results of cross-hole hydraulic interference tests at least from a qualitative standpoint.

The next stage of the modelling addressed the response of the model to a simulation of the excavated pilot tunnel. The preliminary results suggested the presence of a skin of different permeability in a thin zone around the periphery of the tunnel. By altering the permeability in the floor and along the walls and roof of the periphery, a better correspondence between calculated and measured drawdown was obtained. The same also applied for measured groundwater inflow in quantity, though not for the actual distribution of inflow.

As probable causes for the interpreted positive skin in the crown and wall, temporary partial unsaturation and propulsion of debris into the fracture were suggested. The negative skin in the floor was interpreted as an effect of the dense and high energy charges used in the excavation process.

SKB Technical Report No 89-28

Earthquake mechanisms in Northern Sweden Oct 1987 - Apr 1988

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October 1989

Keywords: Nuclear waste, Sweden, Lansjärv, Seismic networks, Seismology, Tectonics, Geodynamic

ABSTRACT

A network of six vertical short-period seismometers distributed over an area 200 · 100 km in northern Sweden has been in operation since Oct 1987. During the first six months 38 earthquakes within or close to the network have been located and analysed. The focal depths are in the range 4-30 km, the most frequent depths are 7-9 km which is 5 km shallower than in southern Sweden. The boundary between the upper and middle crust seismicity thus seems to be at about 13 km in comparison to about 18 km in southern Sweden. The stresses released by the earthquakes have the horizontal principal compression in or close to the NW-SE quadrant. The most likely regional stress component has the principal compression in the direction N60W (N120E). If one interprete all Baltic Shield earthquake data one gets the same most likely orientation for the regional stress component.

The relation between the surface faults and the earthquake fault plane intersections with the surface is preliminary investigated. There seems to be a good agreement between the fault plane strikes of the upper crustal earthquakes and the surface fault strikes.

The dominating type of fault movements is strike-slip at subvertical planes. This is in agreement with the fault plane solutions for other areas in the Baltic Shield. There is also a reverse faulting component indicating the possibility that there exists a plate tectonic uplift component in Sweden. Finally an alternative view on the Baltic Shield

seismicity is given. It is based on the Baltic Shield earthquake studies and on the results of geodetic levellings in Finland and Norway. It assumes the earthquakes to be preceeded by aseismic sliding (normally called stable sliding or creep) episodes over large parts of the faults, the earthquakes are unstable sliding events at small locked parts (asperities) of the faults. This view means for instance that for the geodynamical interpretation of the earthquakes the peak slip is a more relevant parameter than the seismic moment. It also leads to estimates of the crustal deformations over southern Sweden of the order of 1 mm/year.

SKB Technical Report No 89-29

Interim report on the settlement test in Stripa
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November 1989

ABSTRACT
A deposition hole, of the KBS-3 concept type, is being simulated by a borehole with 40 cm diameter in the Stripa mine. The canister is heated and different vertical loads applied to the canister. The resulting canister displacement, rock displacements and swelling and compression of the compacted bentonite and sand/bentonite overfill are studied.

The test is still running. So far the results and calculations have yielded the following main conclusions:

1. The canister is heaving since the compacted bentonite is swelling upwards, thereby compacting the overlying sand/bentonite overfill.

2. The effect of a temperature increase on the surrounding rock can only be explained by block movements. The very high pore pressure induced in heated bentonite is strongly affecting the rock.

3. The total consolidation settlement caused by the weight of the canister is several times larger than the total creep settlement achieved in the initial 100-1 000 years.

4. The processes observed during the test are fairly well understood and seems to be predictable.

The report ends up with a suggestion of how to continue and finish the test, and with a prediction of the result of an increased canister load at the present high temperature.

SKB Technical Report No 89-30

Seismic effects on bedrock and underground constructions. A literature survey of damage on constructions; changes in groundwater levels and flow; changes in chemistry in groundwater and gases
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June 1989

Keywords: Nuclear waste, Earthquakes, Geohydrology, Bedrock stability, Groundwater chemistry, Seismic effects

ABSTRACT
This report is a literature review of direct and indirect effects of earthquakes on underground constructions as tunnels, caverns and mines. The direct damage will cause vibrations, shaking and displacements, which may lead to partial or total destruction of the underground facility.

The damage effects, reviewed in Chapter 2, on underground constructions are either caused by displacement along an existing fault intersecting the underground facility or by shaking. A third type of damage observed mainly for shallow tunnels is ground failure or landslides which will damage the tunnel portals.

Damage caused by shaking has been reported in several studies, and several hundreds of events have been reported both from mines and tunnels. These reports are mainly from active earthquake areas.

There are very few reports of damage caused by displacements on an existing fault. The damage, which may be severe, is generally concentrated to the vicinity of the fault zone.

The report also includes a review of the effects caused by earthquakes on groundwater level, flow, pressure, chemistry and constituents in the ground. Such changes are mainly reported from studies in wells near active faults. The interesting cupling of changes in groundwater characteristics around an underground construction is, unfortunatly, very seldom reported.

The ground water level and pressure changes are discussed in Chapter 3. The bases for this part of the review is taken from the Alaska earthquake 1964, which turns out to be the most recorded and studied single seismic event in relation to a world wide ground water change. Still further work and analyses can be expected from this event. Other observations are reported from wells and reservoirs located near existing faults. Water level changes have in few cases been correlated with aseismic creep events, but the normal case as an earthquake.

Changes of the geochemistry in ground water and soil gases are reviewed in Chapter 4. The mechanisms of seismochemical anomalies are discussed and examples of short and long term monitoring are given from USA, Soviet Union and China.

Gases in ground eater and soil is reported in Chapter 5. Radon is so far one of the most studied species and its

variation in short, medium and long term with seismic activity is rather well understood. Other gases or isotopes that have been studied include helium, carbon dioxide, hydrogen, argon and methane, radium and uranium.

The paper also includes same statements for repository design based on the result of the review.

SKB Technical Report No 89-31

Interdisciplinary study of post-glacial faulting in the Lansjärv area Northern Sweden 1986 - 1988
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December 1989

ABSTRACT
Post-glacial faults have been recognized in the northern Baltic shield for several decades.

It is important to evaluate whether such neotectonic movements can lead to new fracturing or decisively alter the geohydrological or geohydrochemical situation around a final repository for spent nuclear fuel.

The post-glacial Lansjärv fault was chosen for interdisciplinary study because of its relative accessibility.

The goals of the study were to assess the mechanisms that caused present day scarps, to clarify the extent of any recent fracturing and to clarify the extent of any ongoing movements. All these objectives were reasonable met through a series of studies.

This report describes achievements that have been gained since the study was initiated by SKB 1986. Analysis of geology and geophysics over a 150x200 km region supplemented with seismic networks and field studies at outcrops and trenches set a framework for a cored borehole down to a depth of 500 m at the fault. The core has been studied in detail with respect to fracture-infillings in order to analyse mineralogical and geochemical alteration. The borehole has been logged for geophysics, stress, hydraulic conductivity, groundwater pressure and the chemical constituents of the groundwater. Numerical modelling has been undertaken in order to understand the effects of glaciation on the behaviour of a blocky rock mass. Several general conclusions have been made by the interdisciplinary research group. One of the major conclusions is that pre-existing old structures were reactivated by tectonic movements, possibly triggered by deglaciation. In spite of a major earthquake that may have occurred during the deglaciation, and in spite of the anomalous tectonic setting compared to study-sites within SKB:s site investigation programme, the hydraulic conductivity and groundwater chemistry are comparable with results from those sites.

SKB Technical Report No 89-32

FARF31 - A far field radionuclide migration code for use with the proper package
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January 1990

ABSTRACT
The far feld radionuclide migration computer code FARF31 has been developed as a submodel to the probabilistic package PROPER, and can be considered a refined and less CPU-time consuming version of the far field models used in the KBS-3 study.

FARF31 constitutes the numerical equivalent of a dual porosity model for radionuclide migration along a stream tube in fractured rock. It calculates the migration rate of the radionuclide chains at the exit of the tube given the input rates at the entrance. Advection, dispersion and one dimensional matrix diffusion is taken into account as well as chain decay.

The underlying equations are formulated in terms of groundwater travel time and Peclet number, thus allowing for the groundwater travel time to be computed outside FARF31 by a separate submodel fitted to handle Darcy velocities and kinematic porosities which vary in space.

Input migration rate boundary conditions are arbitrary.

SKB Technical Report No 89-33

Investigation of flow distribution in a fracture zone at the Stripa mine, using the radar method, results and interpretation

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Keywords: Radar, Tomography, Crosshole, Fracture zones, Migration, Saline tracer

ABSTRACT

The objective of the current project was to map the steady state flow distribution in a fracture zone when water was injected into the zone from a borehole. The basic idea was to map the flow paths by taking the difference between radar results obtained prior to and after injection of a saline tracer into the fracture zone. The radar experiments were combined with a more conventional migration experiment to provide validation and calibration of the radar results.

The Crosshole Site in the Stripa mine was selected as the experimental site as the geological and the hydrological conditions were well known. The site is located at the 360 m level where seven boreholes were used for this experiment.

Difference tomography using borehole radar was a valuable and successful tool in mapping groundwater flow paths in fractured rock. The data presented were of good quality and sufficiently consistent throughout the investigated rock volume. The interpreted results verified previous findings in the surveyed granite volume as well as contributed to new and unique information about the transport properties of the rock at the site. The inflow data and the tracer breakthrough data has served as a useful aid in the interpretation of the flow distribution within the investigated zone and also within the surrounding rock mass.

From the differential attenuation tomograms the migration of the injected tracer was mapped and presented both in the fracture zone of interest and in the entire investigated granite volume.

From the radar tomographic model, the major tracer migration was found to be concentrated to a few major flow paths. Two additional fracture zones originally detected within this project, were found to transport portions of the injected tracer.

The radar results combined with the tracer breakthrough data were used to estimate the area with tracer transport as well as flow porosity and the wetted surface.

SKB Technical Report No 89-34

Transport and microstructural phenomena in bentonite clay with respect to the behavior and influence of Na, Cu, and U

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December 1989

ABSTRACT

MX-80 Na smectite clay, essentially consisting of montmorillonite, was investigated with respect to major transport properties and rheological behavior. Diffusion and percolation tests using sodium, copper, and uranium solutions were conducted both at room temperature and at 90°C. In the latter case the clay samples had been hydrothermally pretreated at 90°C and 10-20 MPa pressure for 10 days. The clay dry density was 0.8 and 1.8 g/cm^3 in most of the tests.

The diffusion tests showed that sodium migrates very rapidly by pore diffusion as well as by surface diffusion. Copper appears to migrate at the same rate as many other cations, the major diffusion mechanism being surface diffusion. Copper tends to replace initially sorbed sodium and exchangeable protons and charges the clay to yield "Cu-bentonite" even on contacting the clay with rather dilute solutions (100 ppm Cu).

Uranium was found to migrate approximately as copper but precipitation of sodium- or calcium uranium compounds forming a front zone appeared to be a rate-controlling mechanism. Thus, the diffusion profile had a very steep front, identified also by a SEM/EDX investigation, and this indicates that the rate of advancement of the front is determined by the reaction rate. Although not being a true diffusion process, it can approximately be regarded as one, the coefficient of diffusion being 10-100 times lower than that of copper. Behind the high concentration front, the clay becomes fully charged with uranium to form a "U-bentonite" even at low concentration of the uranium solution (100 ppm U).

The percolation and rheological investigations showed only moderate influence on the hydraulic conductivity and creep properties by an increased sodium content (10 000 ppm) or partial uptake by copper or uranium. However, considerable differences were found between samples investigated at room temperature and at 90°C, the main reason being the effect of cementation by released silica and aluminum, which were precipitated on cooling before the tests were conducted.

The microstructure was concluded to control a number of practically important physical properties. Thus, it determines the hydraulic conductivity and the rheological behaviour, and it has a very substantial influence on diffusive transport ions in the porewater.

SKB TR 89-35

The joint SKI/SKB scenario development project

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Abstract

The Swedish Nuclear Power Inspectorate (SKI) and the Swedish Nuclear Fuel and Waste Management Co. (SKB) have carried through a joint scenario development exercise of a hypothetical repository for spent nuclear fuel and high level waste based on the KBS-3 concept as disposal method.

The starting point of the scenario development strategy has been the "Sandia methodology", but the actual implementation of the steps in this method has required new strategy development. The work started with a relatively large internationally composed group meeting, which identifed an extensive list (approximately 150 items) of features, events and processes (FEPs) that might influence the long term performance of a repository. All these FEPs and a memotext containing a description of the FEP as well as its possible causes and consequences have been entered into a computer database.

The next step in the development was to remove from the list approximately 30 FEPs of low probability or negligible consequence. In a following step a large number of the FEPs on the original list were assigned to the "PROCESS SYSTEM". The PROCESS SYSTEM comprises the complete set of "deterministic" chemical and physical processes that might influence the release from the repository to the biosphere. A scenario is defined by a set of external conditions which will influence the processes in the PROCESS SYSTEM.

Approximately 50 FEPs were left representing external conditions. These remaining FEPs have been grouped (lumped) into a few (10) primary FEPs of external conditions. The remaining FEPs could all be combined to form scenarios, but it is concluded that it is not meaningful to discuss combinations without first analyzing the consequence and probability of the individual conditions.

An important aspect of the work is that the developed strategy includes a framework for the documentation of the complete chain of scenario development. Such a transparent documentation makes possible an extensive review and updating of the set of scenarios.

A reviewing process, open to very broad groups in the society, is probably the best means of assuring reasonable completeness and of building up a general consensus on what are the critical issues for the safe disposal of radioactive waste.

In conclusion, the strategy developed within the project appear to be a feasible approach to scenario development, but it must be stressed that the present project is a first stage and that the complete analysis must be reiterated several times.

SKB Technical Report No 89-36

^{14}C-analyses of calcite coatings in open fractures from the Klipperås study site, Southern Sweden

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ABSTRACT

Carbonate samples from open fractures in crystalline rock from the Klipperås study site have been analysed for their ^{14}C contents using accelerator mass spectrometry. This technique makes it possible to analyse very small carbonate samples (c. 1 mg C). The analyses show low but varying contents of ^{14}C. However, contamination by CO_2 have taken place affecting small samples more than others. Attempts have been made to quantify the contamination and thus evaluate the analyses of the fracture samples.

The obtained low ^{14}C values can be due to:

1) An effective retention of ^{14}C by sorption/fractionation forcing ^{14}C onto the calcite surfaces in the near-surface zone which means that the ^{14}C contribution to the deeper levels is diminished or

2) the penetration depth of surface groundwater is very shallow. The former is suggested as more probable based on evaluations of the hydrochemical conditions (Smellie et al 1987) and the fracture mineral studies (Tullborg 1986).

SKB Technical Report No 89-37

Alteration of natural UO_2 under oxidizing conditions from Shinkolobwe, Katanga, Zaire: A natural analogue for the corrosion of spent fuel

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Keywords: Natural analogue, Spent fuel, Alteration, Corrosion, Uraninite, UO_2

ABSTRACT

The alteration of uraninite (UO_{2+x}) at Shinkolobwe, Zaire provides a natural analogue for the corrosion of spent nuclear fuel in contact with oxidizing groundwater. Characterization of the uranium-containing solid alteration phases is required for predictive modeling of groundwater chemistries over long term periods of time. An integrated analysis of uraninite alteration products using optical microscopy, scanning electron microscopy (SEM), analytical electron microscopy (AEM), x-ray diffraction analysis (XRD), and electron microprobe analysis (EMPA) demonstrates the presence of coexisting phases at all analytical scales. The uranyl silicates (uran-ophane $(H_3O)_2Ca(UO_2)_2(SiO_4)_2 \cdot 3H_2O$ and cuprosklodowskite $(H_3O)_2Cu(UO_2)_2(SiO_4)_2 \cdot 4H_2O$) are ubiquitous in the samples studied and replace the Pb-uranyl oxide hydroxides (becquerelite $Ca(UO_2)_6O_4(OH)_6 \cdot H_2O$, compriegnacite $K_2(UO_2)_6O_4(OH)_6 \cdot 8H_2O$, vandendriesscheite $PbU_7O_{22} \cdot 22H_2O$, fourmarierite $PbU_4O_{13} \cdot 6H_2O$, billietite $Ba(UO_2)_6O_4(OH)_6 \cdot 8H_2O$, and schoepite $UO_3 \cdot 2H_2O$) by reaction of the oxide hydrates with silicarich groundwater. An overall reduction in grain size is apparent as alteration proceeds. Electron microscopy holds the greatest promise for the detailed characterization of the alteration products because of the extremely small sizes (1 micron to 5 microns) typical of the mineral grains.

SKB Technical Report No 89-38

An estimation of nuclide release rate near the canister (Near field model 91)

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December 1989

ABSTRACT

Radionuclide release from the degraded canister to the mobile water in the rock has been modelled and several different pathways have been investigated. They include transport through the rock to the water by diffusion as well as directly into the mouth of the fractures via the backfill. The importance of the different paths and the various resistances to transport are discussed and numerical sample calculations are given.

SKB Technical Report No 89-39

Storage of nuclear waste in very deep boreholes: Feasibility study and assessment of economic potential. Part I: Geological considerations 1). Part II: Overall facility plan and cost analysis 2)

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December 1989

ABSTRACT

This report constitutes a feasibility study for storage of radioactive high-level waste in deep boreholes. The basic idea is to deploy the waste at such a great depth that the time for migration of radionuclides to the biosphere becomes so long that either adequate decay has taken place or sufficient dilution of the waste has occurred to eliminate any safety hazard. In the interim report, Stage A, it was concluded that disposal of radioactive waste in deep boreholes may be feasible and economical using today's technology. It was also concluded that considerable engineering and development work will be needed in a number of fields.

Part I of this feasibility study concentrates on quality assurance-related questions such as geological prerequisities at great depth.

Part II of this feasibility study concentrates on the engineering aspects of the very deep borehole concept (VDH).