SKB

TECHNICAL REPORT 87-33

SKB ANNUAL REPORT 1987

Including Summaries of Technical Reports Issued during 1987

Stockholm, May 1988

SVENSK KÄRNBRÄNSLEHANTERING AB
SWEDISH NUCLEAR FUEL AND WASTE MANAGEMENT CO

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SKB ANNUAL REPORT 1987

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Stockholm, May 1988

FOREWORD

The Annual Report on SKB's activities during 1987 covers planning, building and operational activities as well as research and development work.

During 1987 the construction work of the central repository for final disposal of low and medium level waste — SFR — was completed and SFR started its operations in the spring of 1988.

With 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 the country for a long time ahead.

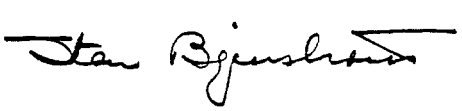
For the remaining work — the final repository for spent nuclear fuel — comprehensive research is well under way, aiming at investigating alternative disposal concepts as well as optimizing proposed systems. A long term programme for this research has been reviewed and accepted during 1987 by the National Board for Spent Nuclear Fuel and the Swedish Government. Such a programme is required in the Swedish Act on Nuclear Activities.

The scientific and political acceptance of the KBS-3 concept with regard to safety and radiation protection, the existing operating systems and the governmental approval of the longterm SKB R&D programme constitute a firm basis for the future activities of SKB.

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 1988

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 1987.

Lectures and publications during 1987 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 1987.

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 1987 in total 630 tonnes of spent fuel (measured as uranium) has been received. Transportation from the nuclear sites to CLAB is made by a special ship, M/S SIGYN.

At Forsmark the first construction phase for the final repository for Radioactive Waste — SFR — is now completed. 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.

SKB is in charge of a comprehensive research and development program on geological disposal of nuclear waste. The total cost for R&D during 1987 was 113.7 MSEK of which 21.4 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.

Geological site-investigations are a substantial part of the program. 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 46 billion which is less than 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. They are coordinated and marketed through SwedPower, which has the same main owners as SKB.

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Part I

Overview of SKB Activities

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1 GENERAL BACKGROUND

1.1 THE SWEDISH NUCLEAR POWER PROGRAMME

Swedens nuclear power programme consists of 12 nuclear reactors located at four different sites and with a combined capacity of 9 650 MW net electric power. Main data and location of the 12 units are shown in Figure 1-1. The nuclear power plants generated 45% of the total Swedish electric power produced in 1987 which is a small decrease compared to 1986. This is mainly due to a very high availability of hydropower in 1987.

Swedish reactors

Reactor		Power MW_e	Commercial operation	Energy availability in 1987 %
Oskarshamn 1	BWR	440	1972	89
Oskarshamn 2	BWR	595	1974	88
Oskarshamn 3	BWR	1050	1985	90
Barsebäck 1	BWR	595	1975	90
Barsebäck 2	BWR	595	1977	92
Ringhals 1	BWR	750	1976	84
Ringhals 2	PWR	800	1975	66
Ringhals 3	PWR	915	1981	83
Ringhals 4	PWR	915	1983	88
Forsmark 1	BWR	972	1980	94
Forsmark 2	BWR	972	1981	90
Forsmark 3	BWR	1050	1985	89

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 outsider 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 45 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

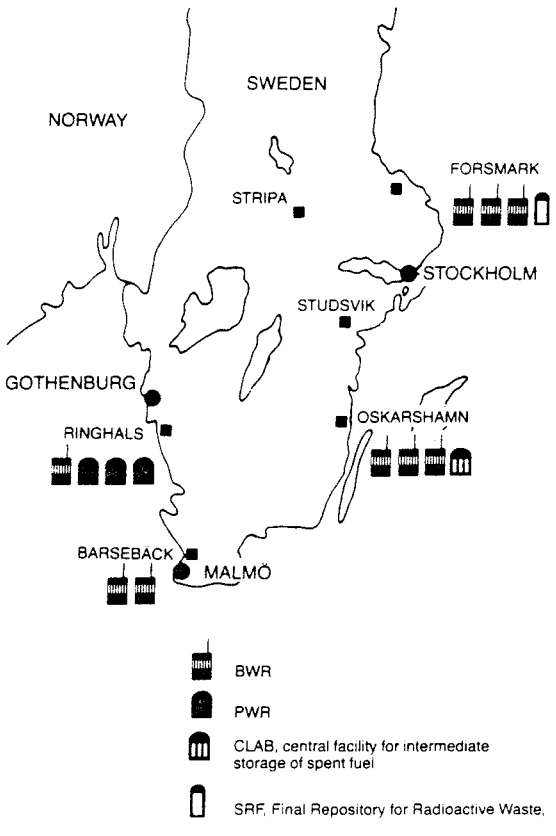

Figure 1-1. The Swedish nuclear power programme

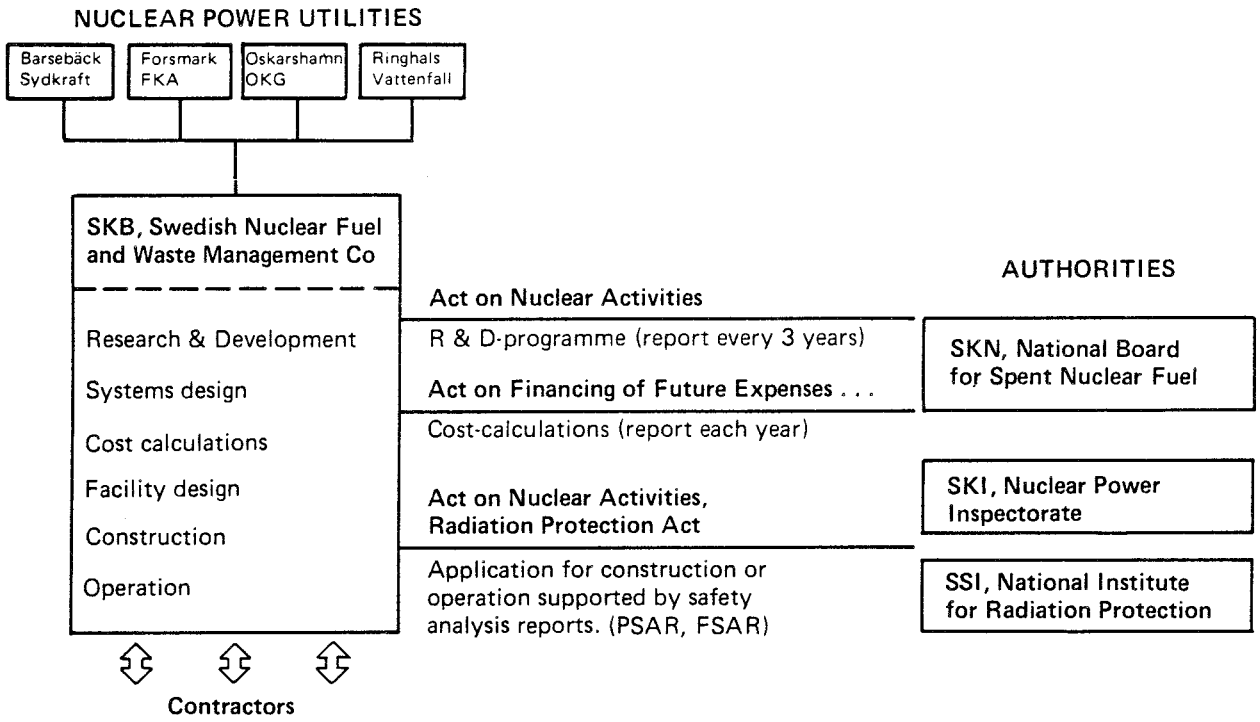

Figure 1-2. Legal framework for activities of SKB.

the most important laws and the corresponding authorities involved.

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 and the first programme was submitted in September 1986.

The authorities for supervision of the safety provisions in the Act on Nuclear Activities are the Swedish Nuclear Power Inspectorate (SKI), and the National Board for Spent Nuclear Fuel (SKN). The National Institute for Radiation Protection (SSI) is supervising provisions of the Radiation Protection Act. The research program 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 a fund built up from fees on the nuclear power production.

The fee is revised annually by SKN, which proposes the fee 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 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 annually on the state of the knowledge in the nuclear waste field /1-2/.

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

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.	19 000 m^3
4 Reactor waste	Operating waste from nuclear power plants etc.	Solidified in concrete or bitumen. Compacted waste	Low- to medium-level. Shortlived	90 000 m^3
5 Decommissioning waste	From dismantling of nuclear facilities	Untreated for the most part	Low- to medium-level. Shortlived	113 000 m^3

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 phase for the Swedish Final Repository for Radioactive Waste, SFR, is now completed. SFR may later on be extended to accommodate also

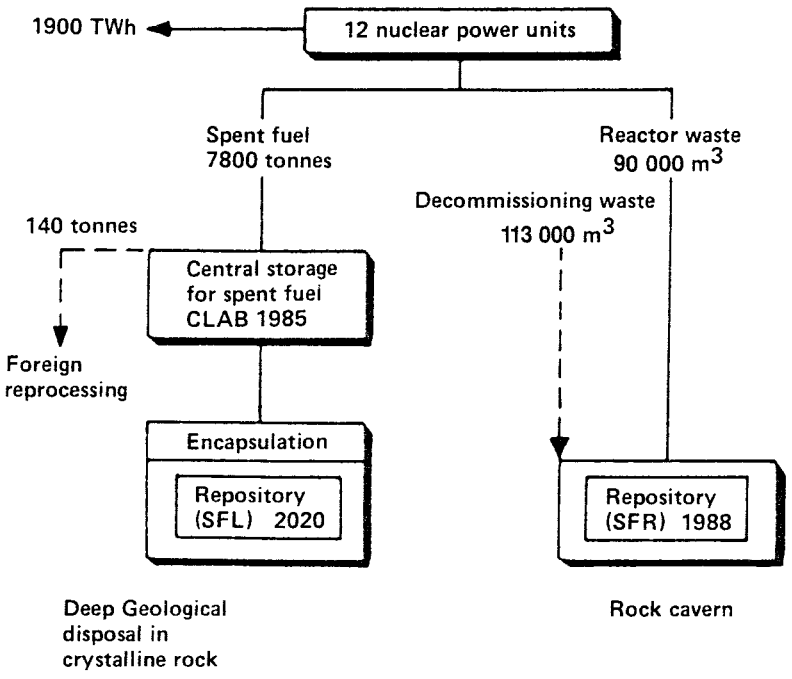

Figure 1-3. Main system for management of radioactive waste in Sweden.

waste 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 used.

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 natural uranium demand of about 1 300 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 1987 up to 1996 is 13 400 tonnes. At the end of 1987, the Swedish utilities had contracts for supply of 10 500 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 1987, some spot quantities were purchased.

Natural uranium is delivered to Sweden mainly from Canada and Australia, but also from Niger, Gabon, People Republic of China (PRC) and USA. Canada is responsible for more than 50% of future deliveries 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 1987.

The average price for long term deliveries in 1984 - 1986 to the European Community was considerably higher than spot prices for the same delivery years.

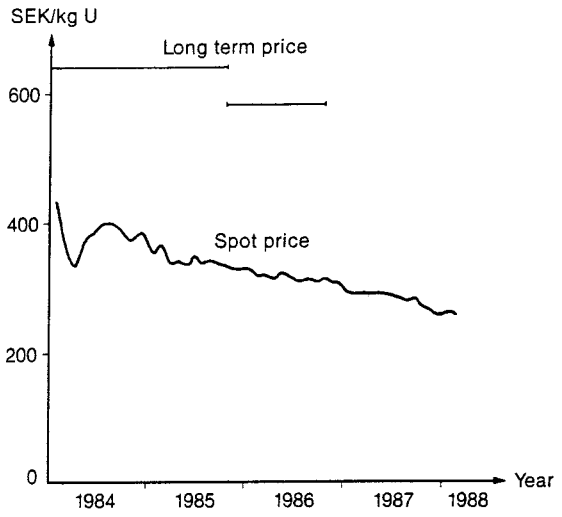

Figure 2-1. Long term and spot prices for uranium.

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

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

2.2 CONVERSION

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

The world conversion capacity is around 54 000 tonnes of uranium per year while the demand is about 37 000 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 1987-1990, most of the deliveries to Sweden will come from EURODIF with an enrichment plant in France and from URENCO with enrichment plants in the Netherlands, the United Kingdom and in Germany. Deliveries from the USSR will continue as earlier, while deliveries from the US will continue on a

reduced scale. PRC may deliver smaller quantities on a spot basis. This situation gives a reliable supply with deliveries from five different companies.

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 the 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 180 tonnes for BWRs and 25 tonnes for PWRs during 1987. Of this volume about 40 tonnes were exported to Finland, Federal Republic of Germany, Switzerland and USA.

In addition, significant quantities of UO_2 powder has been produced for export to the Federal Republic of Germany.

The fuel assembly design, SVEA, where the fuel rods are divided in four minibundles with 4 x 4 rods separated by a water cross, is now the dominating BWR fuel in Sweden. About 80% of the ABB ATOM BWR fuel deliveries in 1987 were of this design.

In 1987 the new type of SVEA-fuel called SVEA-100 was further developed and eight fuel assemblies of this type were loaded in two Swedish BWRs. The SVEA-100 fuel, where the fuel rods are thinner and divided in four groups with 5 x 5 fuel rods in each group, allows for more effective In-Core Fuel-Management and more flexible reactor power control characteristics.

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 tubes corresponding to an electricity production of 35 TWh. This amount has been decided by the Swedish parliament.

Uranium in the abovementioned 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 1987 in Sweden were as shown in Table 2-1 (the production of nuclear electricity was 64.4 TWh in 1987):

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

	SEK/kWh	Million SEK in 1987
Natural uranium	0.008	520
Conversion	0.001	60
Isotope enrichment	0.011	710
Fuel fabrication	0.007	450
Strategic stockpile	0.001	60
Total front end	**0.028**	**1 800**

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

Table 2-2. Costs for nuclear fuel 1983-1987.

Year	SEK/kWh
1983	0.038
1984	0.038
1985	0.035
1986	0.031
1987	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, see Figure 3-1. 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 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.

During the years 1986 and 1987 spent fuel and core components have been received in CLAB on a routine base from the four nuclear power stations in Sweden. Between July 1985 and the end of 1987 630 tonnes of uranium have been received in total.

In 1987 108 flasks containing spent nuclear fuel have been received, see Figure 3-2, 85 of which contained fuel from Swedish BWR and PWR reactors and 7 flasks PHWR fuel from the old dismantled Ågesta reactor, the fuel of which has been stored in Studsvik for some 15 years. In connection with a swap of a minor quantity of spent fuel between Sweden and West-Germany, see Section 7.2, 16 flasks containing MOX-fuel was received. The total quantity shipped to CLAB in these flasks during the year amounted to 272 tU.

In addition 9 flasks with core components have been received.

The receiving of the West-German MOX fuel and the Ågesta fuel involved handling of five different flask types which necessitated some modifications and completions of the handling and flask processing equipment. Installation and tests of the equipment took place in the first 6 months of 1987. The final approvals from the authorities were given in June and the first shipment from West-Germany arrived in July. By the end of the year six of totally 8 shipments had been received as planned.

The performance of the plant has been excellent and the received amount of fuel has been according to the plans. The low total occupational dose in 1986 has been followed with equally good results in 1987, when the dose (67,8 mmanSv corresponding to an individual dose of about 1.1 mSv/person) was 25% of what was expected according to the final safety report.

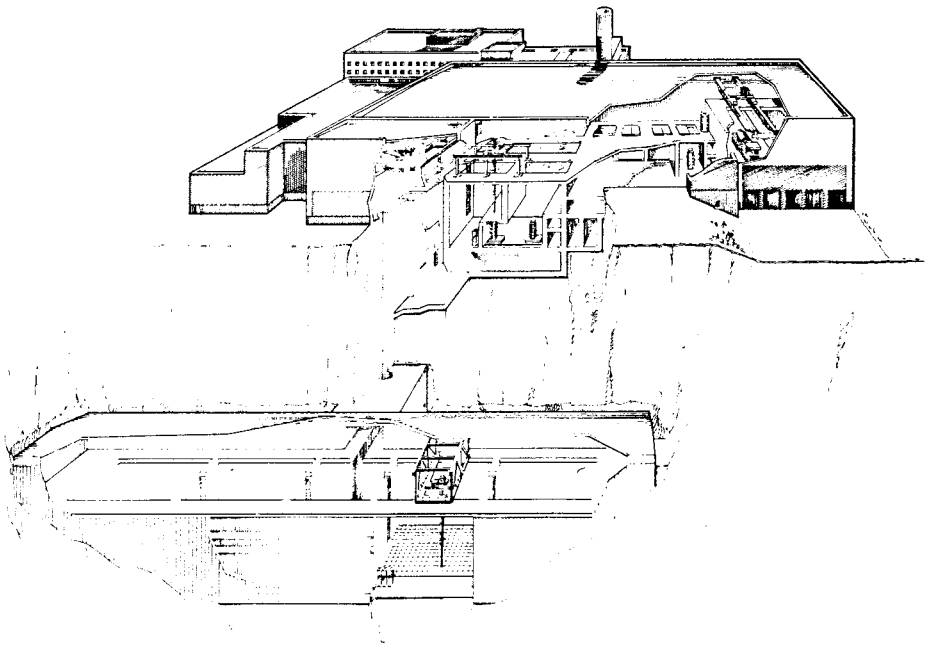

Figure 3-1. Overview of the CLAB facility.

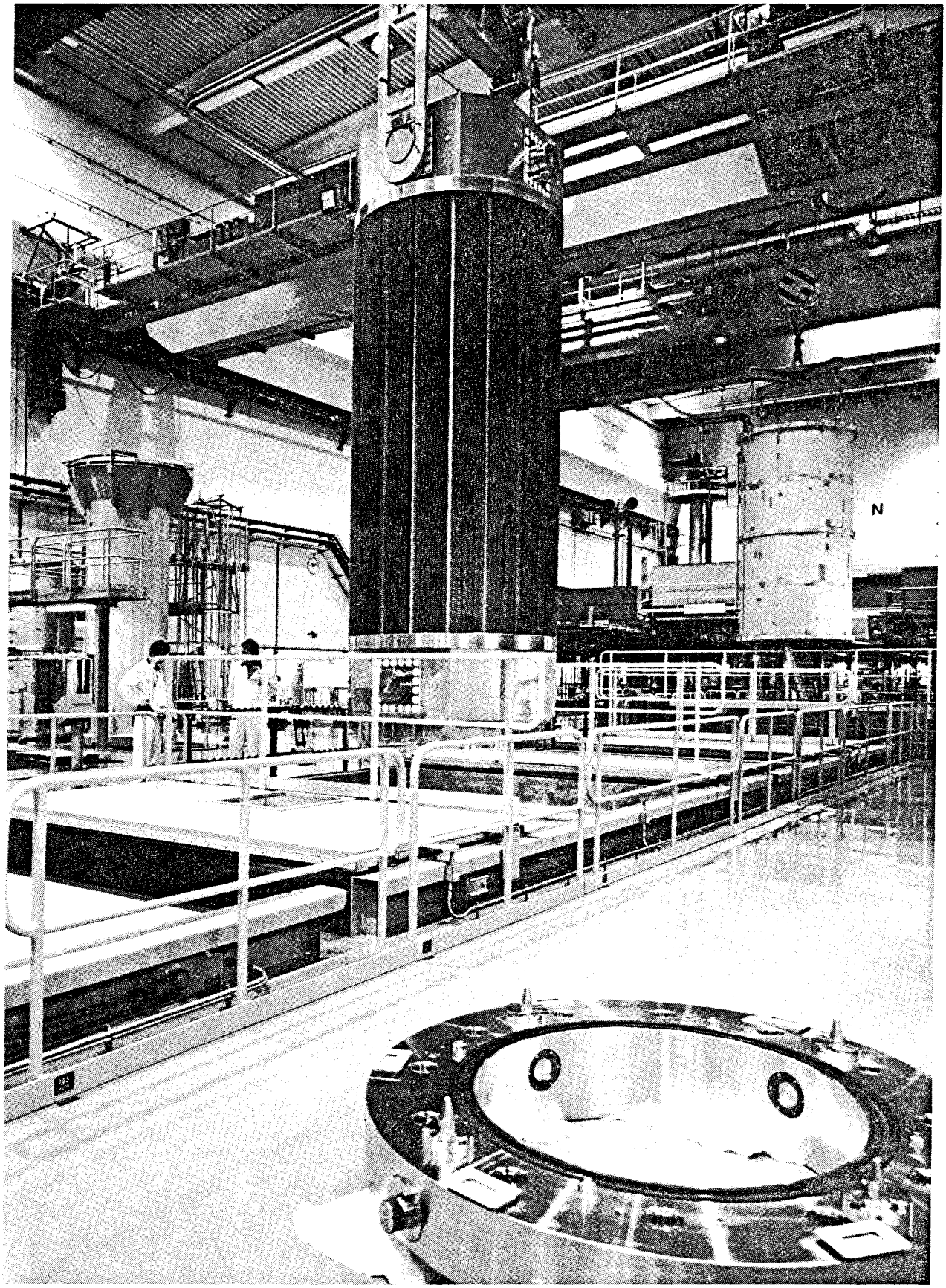

Figure 3-2. Spent fuel transport flask on its way to the cooling down cell in CLAB.

4 TRANSPORTATION SYSTEM

4.1 GENERAL

The sea transportation system consists of the specially purpose built ship M/S SIGYN, 10 transport flasks for spent fuel, 2 flasks for core components, 26 specially designed steel containers for low- and intermediate level waste (ATB) and 4 terminal vehicles.

During 1987 the system has been completed with a fourth terminal vehicle specially designed for operation in the SFR repository. 25 ATB have been manufactured and delivered to SKB during the year, see Figure 4-1.

4.2 OPERATING EXPERIENCES

During 1987 13 sea voyages, each with 4-5 spent fuel casks, have been carried out from the Swedish reactors to the CLAB facility, see Figure 4-2. From West-Germany 6 transports, including 16 flasks with MOX-fuel have been performed. For these transports 4 different types of flasks have been used. The flasks were adopted to the transport system by using special interface equipment between the flasks and the ordinary load carriers. 23 on-site spent fuel transports between OKG and CLAB have been performed. 2 flasks with core components have been transported from Barsebäck to CLAB and 7 from OKG.

The hard winter in the beginning of the year caused problems for the transports from Barsebäck where the harbour was closed due to the ice situation. The transport operations have been successful and the radiation doses to the ship crew have been below the detection limit.

At the end of the year 4 ATB from Barsebäck and 17 ATB from Ringhals with low and medium level waste were transported to interim storage at SFR in Forsmark, waiting for transport down into the repository.

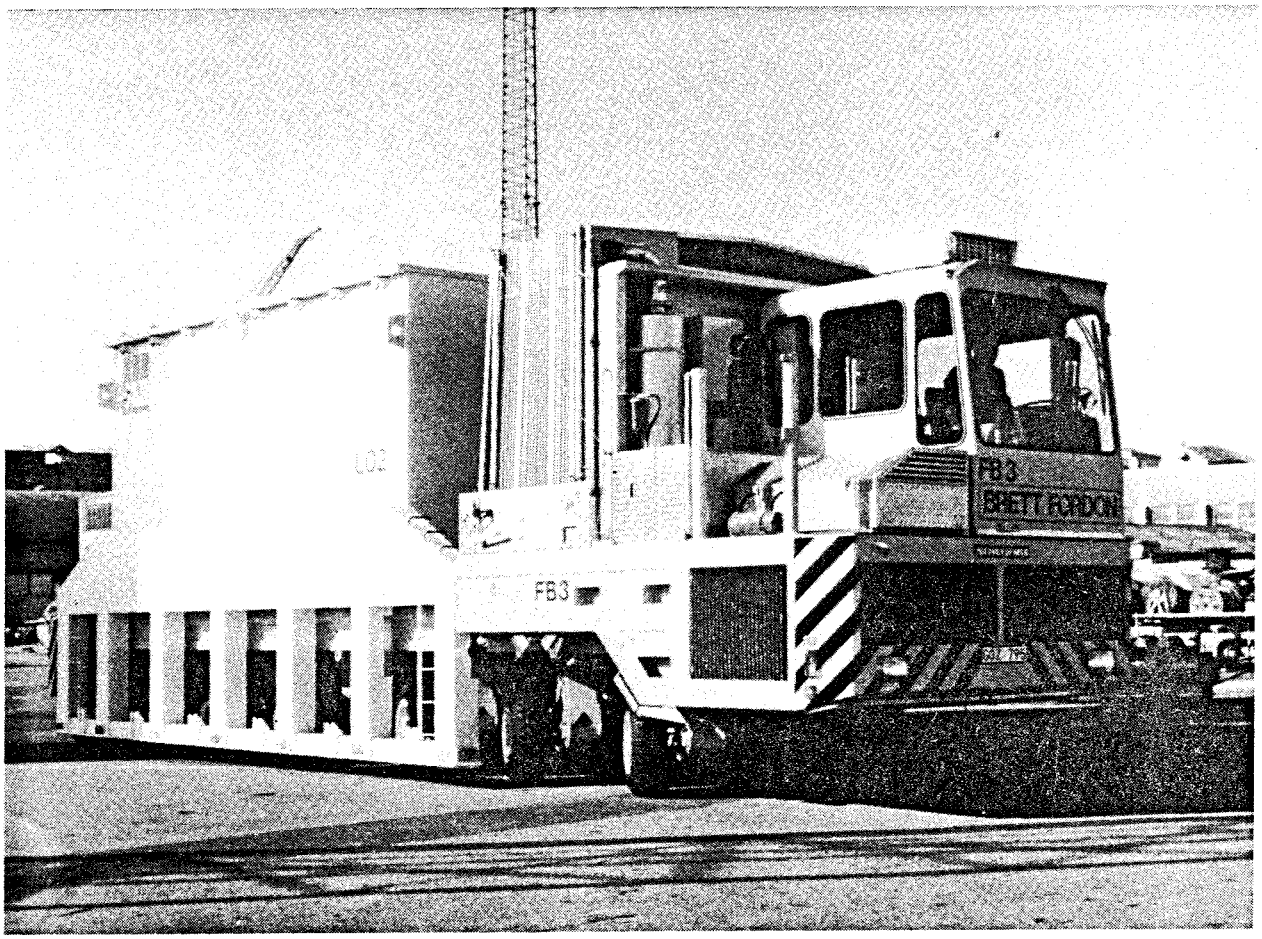

Figure 4-1. The transport vehicle with a transport container containing medium level waste.

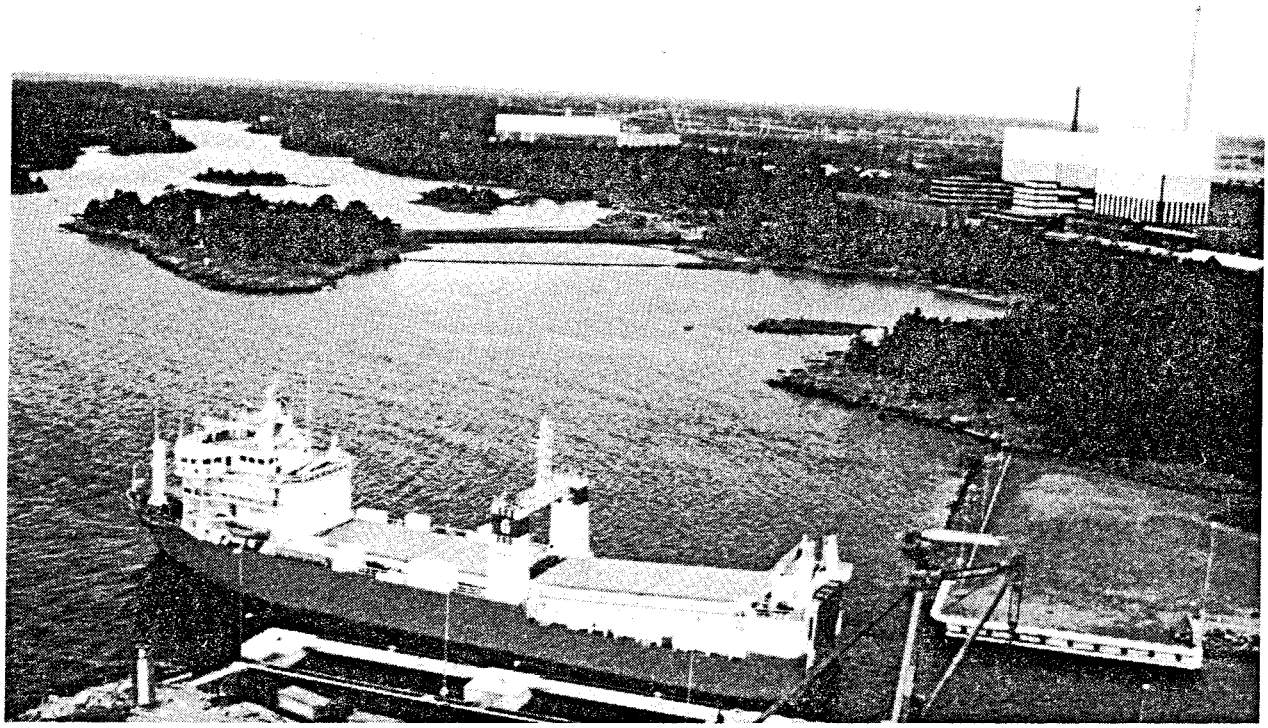

Figure 4-2. M/S SIGYN ready to berth at Simpevarp harbour.

5 FINAL REPOSITORY FOR RADIOACTIVE WASTE, SFR

5.1 GENERAL

The first construction phase for the Swedish Final Repository for Radioactive Waste, SFR, is now completed. It is a repository built in the bedrock under the Baltic sea close to Forsmark nuclear power plant. 60 m of rock covers the repository caverns under the seabed, see Figure 5-1. The first construction phase includes buildings on ground level, tunnels, operating buildings and disposal caverns for 60 000 m^3 of waste. A second phase for additional 40 000 m^3 is planned to be built and commissioned around the year 2000.

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 have been used in order to further reduce the groundwater flow inside the caverns and through the waste. Concrete and bentonite clay is e.g. used in the silo cavern for the waste containing most of the activity. The other caverns have a more conventional design where only concrete is used to reduce water flow.

The waste which will be disposed of in SFR originates from the operation of Swedens 12 nuclear power reactors and CLAB. This waste contains short-lived radionuclides and can be classified as low- and intermediate level waste. A small amount of similar waste from research and medical activities will also be disposed of in SFR. The total amount of waste from the Swedish program up to year 2010 has been calculated to about 100 000 m^3.

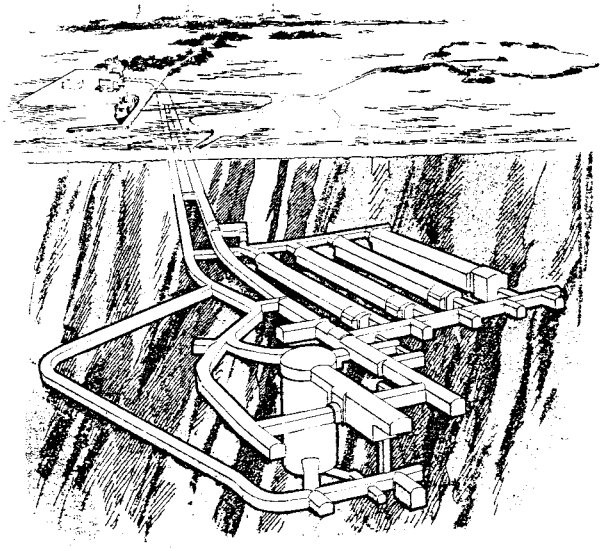

Figure 5-1. Overview of tunnels and storage chambers in the first construction phase.

All wastes are conditioned at the power plants or at the nuclear research center, 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 and need shielding during handling and transport, see Figure 5-2. Low level waste is treated in different ways and finally enclosed in standard freight containers. The total activity content in SFR is calculated to be 3 x 10^6 GBq by year 2010. Dominating nuclides are Co-60 and Cs-137.

Measures have been taken to minimize the exposure of personnel during the operating period by the use of radiation shielding and remote controlled handling of the waste. A specially designed vehicle carries the transport containers through the tunnels to the repository area, see Figure 5-3. The vehicle can be operated by remote control as well as the unloading machines. LLW is transported in standard freight containers and handled with an ordinary forklift in one of the caverns. Safety assessments show that radiological risks during the operational period is very low.

The analyses of post-closure safety is performed for two time periods. The first covers the time during which the seabed above SFR is still covered by the brackish water of the Baltic Sea. The second period covers the time after the drying out of the seabed and after the formation of a freshwater-based ecological system. The radiological impact on the environment will be very low for both periods.

5.2 DESIGN, CONSTRUCTION AND COSTS

SKB has contracted Vattenfall (The Swedish State Power Board) for the design and construction of SFR. The tunnelling work started in October 1983 and the tunnels reached the repository area in the beginning of 1985. All tunnels and caverns were excavated in March 1986. The construction of concrete structures then started subsequently in the various caverns.

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. This cavern is 70 m high and 30 m in diameter. Inside is a 50 m high concrete

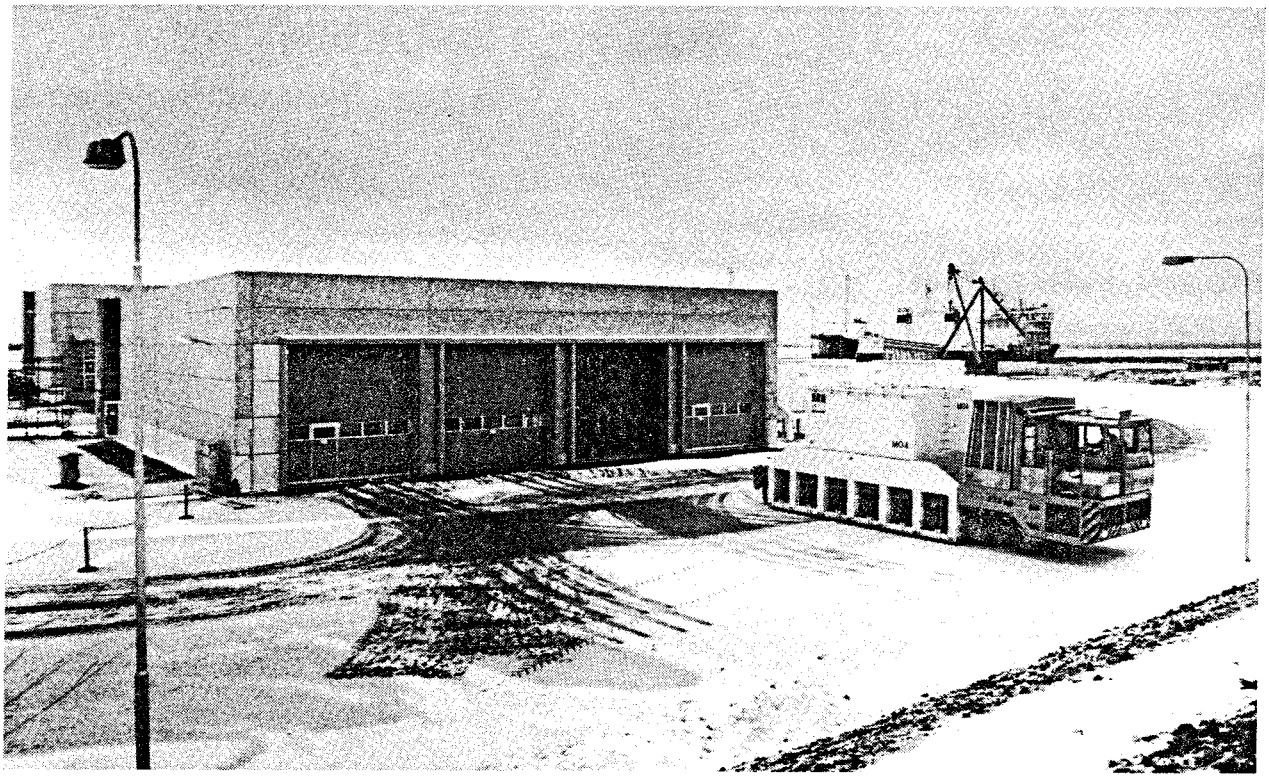

Figure 5-2. The first transport of waste to SFR were carried out in the end of 1987. The shielded waste containers are stored in a terminal building on ground level. When the underground facilities are commissioned and a license for operation is granted the waste in these containers will be disposed of in the caverns.

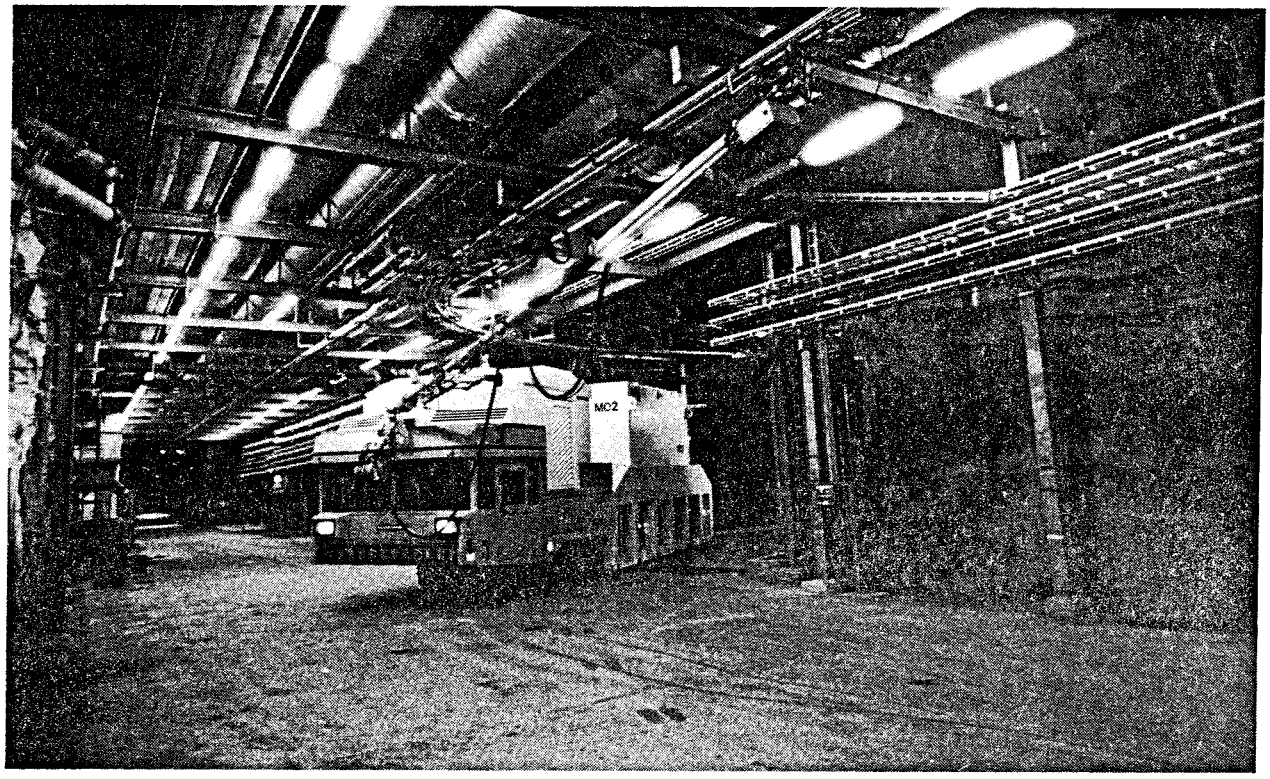

Figure 5-3. The shielded containers are handled with an electrically driven vehicle down in the tunnels. This vehicle can also be operated remotely controlled from the tunnel entrance to the unloading positions in the various caverns.

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 top and bottom and granulated pure bentonite is used for the fill around the silo. The space between the waste packages and the concrete construction in the silo is subsequently filled with concrete.

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

The installation of handling machines in the rock cavern for ILW and in the silo was carried out during 1987. In the autumn the specially designed vehicle for container transport was delivered to the site and commissioned. Almost all the installation work was completed by the end of the year.

The construction and the commissioning of SFR have been carried out on schedule. The total cost for the first construction phase has been 740 MSEK (at current prices).

5.3 SAFETY ASSESSMENT

SFR has been designed to permit a simple and controllable as well as a safe disposal of the radioactive waste. It is intended to ensure isolation of the waste from the biosphere so that exposure to man in the immediate vicinity does not exceed the design dose limit, 100 μSv/y. Safety during the post-closure stage will not be dependent on supervision maintenance and/or corrective measures. Safety assessments have been performed for a fully expanded repository for operating waste, SFR-1 (100 000 m^3 with a total activity content of 10^{16} Bq).

After the operating waste has been deposited, the repository willrbe closed and sealed. According to current plans this will take place at the earliest in 2013, but in the safety assessment it is assumed to take place in 2010.

When the repository is sealed pumping will be interrupted and the repository filled with water. Depending on the waste unit and the manner of deposition in various caverns, the dissolved non-sorbing isotopes may be transported to the groundwater by diffusion or flow. The extent of this transport is determined by the design of the repository and by the groundwater flow in the surrounding rock. The waste packages are designed and emplaced in various caverns in such manner as to prevent the waste from destroying the repository barriers, for example by swelling or production of gases.

5.3.1 Final Safety Report

The final safety report was prepared during 1987 by a working group within SKB.

The safety assessment in this report is made for two time periods. The first covers the time during which the seabed above SFR is still covered by the brackish water of the Baltic Sea, the Salt Water Period. The second covers the time after the drying out of the seabed and after the formation of a freshwater-based ecological system, the Inland Period.

Water flow in the bedrock have been calculated. Two regional 3-D groundwater models have been utilized for the analyses. Model 1 is based on the potential differences between the groundwater level on land and the sea level. Model 2 has been constructed to take into account a single test result from a borehole with pressurized groundwater. This model has been used in order to ensure that the water flow is not underestimated. The model yields water flows of between 0.2 and 0.5 l/m^2y, which have been used as boundary conditions for the local flow model.

For the Salt Water Period it has been pessimistically assumed that the direction of flow is in the least favourable direction, i.e. directly upwards towards the seabed and that the main flow takes place in a few channels. As a result sorption in the surrounding rock gives negligible delay in this case. It has therefore been assumed for the various caverns and for all calculated cases that the radioisotopes leaking into the surrounding bedrock are transported without delay to the biosphere.

The Inland Period is assumed to commence 2 500 years after sealing. Only then sufficient land uplift might have occurred to permit the formation of permanent lakes and shore sediments. At that time a freshwater ecology is assumed to have been established at the depth needed for drinking water wells. During this period, the ground surface above SFR will be a recharge area and the groundwater will reach the biosphere in a small lake situated approximately 1 km from SFR.

The analyses show that the dose which can be imposed on individuals in the most affected group is very low. By a good margin the dose will fall below current design goals for other facilities in the nuclear power cycle, 0.1 mSv per year, see Figure 5-4.

The total dose to an individual in the most exposed group around SFR has been estimated to lie under the level 1 μSv per year during the entire Salt Water Period. For the Inland Period calculations have been done with the use of methods which attempt to determine the upper limits for possible future doses. The analyses indicates that the dose will be maintained well below the continuous level of about 10 μSv per year for a future Inland Period.

Dominating nuclides in the calculations for the Salt Water Period are Co-60, Cs-137 and Sr-90, i.e. isotopes

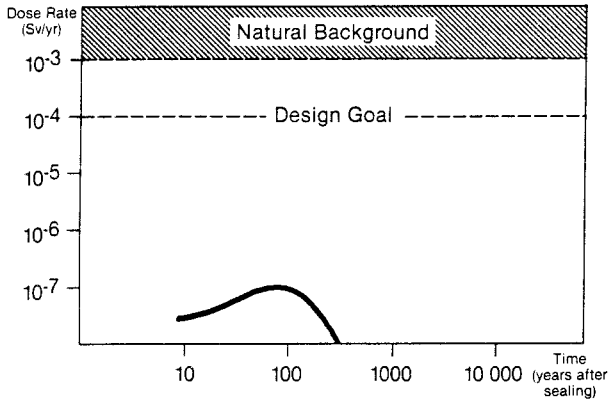

Figure 5-4. Possible maximum individual dose rate during the Salt Water Period.

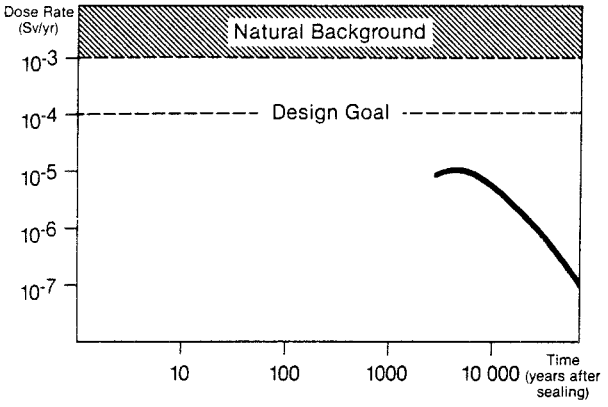

Figure 5-5. Possible maximum individual dose rate during the Inland Period.

which will decay totally during this period. The dose situation for the Inland Period (after 2 500 years) is dominated by the plutonium isotopes 239 and 240, see Figure 5-5.

5.3.2 Research Programme

Three campaigns of geoscientific investigations were performed before and during the construction of the SFR.

The groundwater head registered during construction reflects the drawdown due to drainage by the facility itself. The different boreholes were drilled at different times as the construction advanced and thus the records of head have different period of length. There were some major drainage events recorded during the construction of SFR e.g. crossing of a horizontal fracture zone and drilling and blasting of the silo. These events all gave responses in the groundwater head records.

After completion of construction, the groundwater head in the surrounding bedrock reached a more or less steady state.

The current water inflow to SFR is in the order of 600 l/min.

All boreholes drilled before and during the actual construction of SFR were hydraulically tested by build-up tests in sections sealed off for hydraulic measurements.

Single-hole tests were also performed in investigations comprising the conceived skin-zone close to the silo periphery. In total more than 700 test results were obtained.

When constructing the repository, the predicted fracture zones were penetrated and identified in tunnels and boreholes. The hydraulic conductivity of these zones were needed in the modelling of the groundwater flow in the bedrock at different situations and scenarios. Major fracture zones were tested with interference testing techniques.

The evaluation of the interference tests were carried out under the assumption of equivalent porous media (continuum approach).

A special test was designed to describe the hydraulic conductivity characteristics of the skin zone around the conceived silo. Two boreholes running close to the silo periphery were hydraulically tested in two metre sections by constant head injection prior to excavation. On termination of the excavation, hydraulic testing was repeated in the corresponding sections.

The works performed during the third investigation phase show the usefulness of a network of instrumented boreholes during and after construction of an underground facility.

The analysis performed indicate that validation of hydraulic modelling results in terms of head around, and inflow measurements to, an underground opening must be made with careful consideration to the hydraulic skin conditions in the close proximity of the periphery of the opening.

5.4 MAIN DATA FOR SFR

Table 5-1. SFR-data

First construction phase	
1983-1988	
Excavated rock volume	430 000 m³
Concrete structures	22 000 m³
Steel structures	600 tonnes
Buildings on ground level	28 000 m³
Buildings in rock caverns	22 000 m³
Waste storage volume	60 000 m³
Second construction phase planned	
1995-1998	
Excavated rock volume	120-170 000 m³
Waste storage volume	20- 30 000 m³
Operational phase	
1988-2013	
Operating personnel	20-25 persons
Reception of waste	5-6 000 m³/year
Electrical power supply	4 500 kVA
Ventilation system	65-70 m³/s
Groundwater drainage	30-40 m³/h

6 RESEARCH AND DEVELOPMENT

6.1 GENERAL

The research and development programme of SKB started in 1976—77, when a new law, the Stipulation Act, was passed by the Swedish Parliament. This law was specific to the final disposal of high level waste from nuclear power plants. It stipulated that the owner of a reactor must show to the satisfaction of the government how and where high level waste or spent nuclear fuel can be finally disposed of in a safe manner. The evidence submitted by the owner had to be approved before the first loading of fuel to any new power reactor. The act thus required demonstration of feasibility of a safe disposal method but not an optimized solution. The provisions in the Stipulation Act were replaced by similar provisions in the Act on Nuclear Activities which went into force on February 1, 1984.

To fulfil the legal requirements the utilities with nuclear power plants started the KBS-project in late 1976. The project-group was later organized as a division within SKB and since January 1, 1985 the research and development programme is managed by the "Division of Research and Development". The organization and staff of this division is given in Appendix 1.

The main task of the R&D-staff is the planning, initiation and coordination of the work and compilation and documentation of results. More than two hundred experts and consultants at universities, industry and other companies are engaged in various aspects of the R&D-work. In order to get a thorough review and discussion of results and methods as well as a constructive feedback to the programme, the progress and results are published as SKB Technical Reports and in appropriate scientific publications.

In 1979 and 1980, four new power reactors were granted fuel loading permits according to the Stipulation Act. These permits were based on a report (KBS-1) /6-1/ describing how and where vitrified high level waste from reprocessed spent nuclear fuel could be finally disposed of and also on reprocessing contracts with COGEMA in France. In 1984 two additional new reactors were granted fuel loading permits this time according to the Act on Nuclear Activities. The basis was the KBS-3-report /6-2/ published in May 1983. This study describes a method for final disposal of unreprocessed spent nuclear fuel from light water reactors.

The above mentioned Act on Nuclear Activities (SFS 1984:3) also prescribes that the owners of nuclear power plants must together establish a comprehensive programme for the research and development and other measures that are needed in order to take care of the radioactive wastes from nuclear power plants in a safe way. A revised programme must be submitted to the National Board for Spent Nuclear Fuel, SKN, every three years beginning in 1986. The first such programme, R&D programme 86 /6-3/, was submitted by SKB to SKN on September 29, 1986. The programme gives a general account of all measures that are needed until final disposal of the wastes has been completed. For the period 1987—1992 a more detailed programme is given.

The R&D programme 86 was sent out by SKN to a large number of Swedish and foreign organizations for review and comments. About 30 Swedish and 9 foreign organizations or groups responded by giving comments after reviewing the programme. These comments were received by SKN in the first quarter of 1987. After that SKN analysed the comments and submitted their own review report to the government by the end of May /6-4/.

The government decided by the end of November that the programme meets the requirements of the law. Through the programme, the review and the government decision a firm base has been given to continue the important work on defining a system and finding a place for a Swedish repository for final disposal of long-lived radioactive wastes.

A condensed summary of the R&D programme 86 was given in the previous Annual Report 1986 Chapter 10. A short summary of the more important review comments is given in Chapter 10 part II of this report.

The R&D-work during 1987 has followed the programme from September 1986. The major activities are briefly highlighted in the following sections and a more comprehensive summary is given in Chapter 11 through 22 of part II in this report.

6.2 SUMMARY OF RESEARCH ACTIVITIES DURING 1987

6.2.1 Engineered Barriers and Repository Design

In early 1986 SKB started a specially organized project for a comprehensive evaluation of the performance, safety and cost characteristics of the so called WP-Cave concept. This concept was originally developed by a group within Boliden WP-Contech AB. Investigations on the concept were supported by SKN during the period 1982—85. The evaluation made by SKB is intended to be finished 1988. The work planned for 1987 was considerably delayed because the final safety assessment for SFR required more efforts and resources than had been anticipated. An analysis of a base scenario for

radionuclide release from a WP-Cave-repository has started late in 1987. The reference design is a WP-Cave consisting of one vertical central shaft surrounded by 12 regularly located channels each with two spent fuel canisters and at 16 levels. The capacity for the cave is 1100 tonne U of spent fuel and is mainly limited by the maximum temperature on the steel canisters. This temperature is not allowed to exceed 150 °C if the repository is closed and sealed after being kept open and supervised for about 100 years. The cave is surrounded by a 5 m thick clay barrier with a mixture of sand and bentonite and also by a hydraulic cage. When the repository is sealed the storage channels and other cavities will be backfilled with sand. The sand will provide a large surface for sorption of radionuclides, which might leach from the fuel. No conclusive results can be given from the analyses made so far.

Preliminary studies of the Very Deep Hole (VDH) repository concept suggest that disposal of spent fuel in several km deep holes in crystalline rock may be feasible. Considering maximum feasible borehole diameter about 30 holes with 5000 m depth would be required for the amount of spent fuel expected from the Swedish programme. The concept does, however, require considerable research, development and engineering work to be mature. A second stage of studies on this concept will be completed in 1988.

The studies of spent fuel as a waste form have continued in accordance with the long term plans. These studies are the dominating ones concerning waste forms in the SKB programme. The work through 1987 was mainly devoted to three areas — leach studies of PWR fuel with 41 MWd/kg burnup, characterization of spent PWR fuel and development of models describing spent fuel dissolution. Results from experiments where high burnup BWR-fuel (42 MWd/kgU) were permitted to corrode in bentonite suspensions indicate that the presence of bentonite has no significant influence on the dissolution of UO_2. The concentrations of plutonium and cationic fission products were, however, considerably decreased, up to a factor 1000 in the case of plutonium.

The development of a model for spent fuel dissolution is still in its initial phase.

The studies of canister materials have during 1987 been concentrated on two candidate materials — copper and carbon steel.

As a result of the review of R&D programme 86 SKN suggested that SKB undertook a study aiming at determining whether or not copper is thermodynamically stable in water. The reason was a short communication by Hultquist in Corrosion Science /6-5/ where he claimed that copper corroded with hydrogen evolution in pure water under reducing conditions. Independent experimental studies performed by SKB and by Sulzer Brothers Ltd in Switzerland /6-6/ have confirmed that no such hydrogen evolution can be detected. In the Swiss experiments the detection limit for hydrogen was three orders of magnitude lower than that reported by Hultquist.

The analysis and evolution of the cannon, a 24-pounder, salvaged in 1985 from the more than 300 year old sunken man-of-war KRONAN has continued and was reported during 1987. The bronze matrix exhibited very little corrosion and a conservative extrapolation of the results give a maximum corrosion rate of copper less than 10 mm in 100 000 years.

In 1986 SKB joined an EUREKA project aiming at development of out-of-vacuum equipment for electron beam welding of thick metals. The project which is managed by the Welding Institute, U.K., is proceeding according to its original plan.

A study of pitting corrosion in carbon steel made at Harwell, U.K., has been reported. The results indicate that previously made estimates of maximum pit depths in full size waste containers are pessimistic.

The research on buffer and backfill material have continued with the main emphasize on bentonites of various type. French smectite rich clays are evaluated in a research program in cooperation with CEA, France, Tests are made in the Stripa mine and in laboratories in France. One of the heater tests at Stripa was ended in April and taken to analyses at Lund and Fontenay-aux-Roses. Measurements of hydraulic conductivities and rheological properties indicate that the French clay, which is a natural calcium smectite, is very similar to sodium bentonite at high densities (above 2000 kg/m^3).

Tests concerning settlement of canisters and the shear effects on canisters from rock movements continued during 1987.

6.2.2 Geoscience

The geoscience programme covers research and developments in geology, geophysics and geohydrology. It also includes the development of new methods, models and instruments for measurements and evaluations. The research is to a great extent organized in projects that give opportunity to interact between specialized disciplines.

A major project initiated during 1986 was the planning of a new underground research laboratory. This was first announced in the R&D programme 86. The laboratory is tentatively planned to be located close to the Oskarshamn nuclear power plant where also the CLAB-facility is located. The final decision on the site must, however, await the results of preliminary geological studies. These were started late 1986 and has continued with comprehensive surface and borehole investigations through 1987. The regional geology, geohydrology and groundwater chemistry have been documented in a number of reports. Pumptests have been performed in three areas of potential interest for siting the laboratory and a reference area. Deep drilling of a few cored holes to 1000 m depth started in late 1987. The preinvestigation phase is planned to go on until 1990 when construction of the laboratory is planned to start. There are three stages in the preinvestigation program — the Siting stage, the Site Characterization Stage and the

Prediction Stage. The first stage will be completed in 1988 and give the basis for a final decision on where to locate the laboratory.

The studies of fracture zone characteristics continued within the Finnsjön area. A subhorizontal zone of about 70 m width is investigated. The zone has been found to have a dominating influence on the ground water flow. The saline content in the groundwater is about 5000 mg/l below the zone and a factor of ten less above the zone.

Phase 2 of the studies were finished and will be reported in 1988, when also phase 3 including tracer tests will start. Some of these tests will be applied in the modelling work of the international INTRAVAL-project.

The study of post-glacial movements in the Lansjärv area has continued as planned. Drillings through a zone with postglacial movements were made in the autumn of 1987. A seismic network was established in the area and started operation in late 1987. A similar network is also operated in south-east Sweden, which has somewhat different tectonic character than the northern part.

The investigations at the Klipperås study site were fully reported in early 1987. Analyses of the data obtained have continued throughout 1987 including statistical treatment of borehole data, a regional groundwater model and planning of a local (site) groundwater model. Results from this modelling work is expected in 1988.

Site selection activities have mainly included a compilation of earlier reconnaissance work. A review of larger basic rock bodies in Sweden has been made by the Swedish Geological Survey. This updated database will be the base for the future work on selecting possible repository sites for spent fuel and long lived wastes. A general plan for the screening and selection of sites will be presented during 1988.

6.2.3 Biosphere

The main thrust in the biosphere studies is in the area of evaluating the variability in the biosphere. This is to a large extent caused by the evolutionary changes of ecosystems with time. Compared to time-periods involved in the possible release scenarios for almost any type of repository, these evolutionary changes are rather rapid. The studies at SKB have been focused on ageing of lakes or estuaries which via eutrophication or land rise are turned into agricultural land. Most of the data for the study have now been collected and are under evaluation.

Another project is attempting to elucidate the differences between sediments in stagnant areas and inflow areas in a lake. Differences in chemical composition and biological activity will have an impact on transport and sorption of radionuclides in the sediments. The study is scheduled for completion in 1989.

The compilation of data concerning the migration of Tjernobyl fallout has continued at Finnsjön and Gideå study sites. Results so far indicate that the data might be useful to test the validity of parts of the nuclide migration models for the biosphere and for shallow groundwaters.

6.2.4 Chemistry

The research in this field spans over a wide range of chemistry related areas like groundwater chemistry, radionuclide chemistry, nuclide transport modelling and validation of models by help of natural analogue studies.

Geochemical modelling have been used to explain ground water composition as measured at the Klipperås study site. The results from this work is briefly summarized in Chapter 17.

The formation and stability of inorganic colloids in groundwater have been studied as part of a redox experiment in Fjällveden. Oxygen saturated water was pumped into a water conducting fracture zone in one borehole. As expected a marked increase in particles containing iron and sulphur was observed in the water. Also the content of silica containing particles increased. However, a few days of pumping restored the original conditions with exception of sulphur particles, which even after a week were higher than normal. The probable explanation is that ironhydroxide particles are sorbed on the fracture walls and not transported over large distances.

The presence of bacteria at low content in deep groundwaters have been confirmed through analysis of microbes.

6.2.5 Safety Assessment

The general safety assessment activities have been related to the following areas:

- Final Safety Analysis Report for the SFR-repository for low and medium level wastes, see Chapter 5.
- Selections of assessment sequence, scenarios and level of conservatism for the evaluation of alternative spent fuel repository designs. This work is coordinated through the integrated performance assessment group (SFG).
- Standard scenarios of post closure safety assessments of HLW repositories.
- Studies of Carbon-14.
- Further development of the PROPER Code Package.

The work on scenarios is coordinated in timing and scope to the international evaluation of scenarios made within OECD/NEA-RWMC.

6.3 INTERNATIONAL COOPERATION

Cooperation and exchange of information on an international or bilateral basis is an integrated part of the R&D-activities of SKB.

International development in the field has been followed through participation in a number of conferences where papers by SKB or its consultants have been presented, see Appendix 2. Staff member of SKB and experts engaged by SKB have also participated in activities within the IAEA and the OECD/NEA.

SKB has since several years bilateral information exchange agreements with DoE in USA, AECL in Canada, NAGRA in Switzerland, CEA in France and with Euratom. A similar agreement was concluded with TVO and IVO in Finland in 1987. Information exchange without formal agreements has been made with organizations in the Federal Republic of Germany, Belgium, United Kingdom, Japan and Spain.

During 1987 Swedish specialists and consultants to SKB have worked for longer or shorter periods of time at research organizations in France (CEA, Fontenay aux Roses), USA (Battelle Memorial Institute) and Canada (Atomic Energy Research Laboratories at Whiteshell, Manitoba). In a similar way foreign experts have been working at Swedish research institutions within the framework of the SKB Research programme.

The largest of the international activities in which SKB is involved is the multinational OECD/NEA Stripa Project managed by SKB. The project completed its first year of phase 3. Seven countries have joined this phase — Canada, Finland, Japan, Sweden, Switzerland, United Kingdom and the United States of America. The phase 3-programme includes an integrated study of a granitic rock mass of 125 x 125 x 50 m size. The study involves characterization and modelling. Characterization methods and techniques developed throughout the previous phases of the project will be used as well as results from some further development of these methods included in the new phase. The programme also includes further studies of channel flow in fractured rock and a major effort to develop and test various materials for grouting and sealing of fractures in crystalline rock. Work on phase 3 started in the autumn of 1986 and will be finished in 1991. The main work during 1987 concerned the preliminary characterization of the selected rock mass by measurements in five horizontal boreholes which bound or penetrate the rock mass. The work on directional radar and high resolution borehole seismics is proceeding according to plans. The channeling experiments have started and will continue until mid 1989.

Two major candidates for rock sealing material have been investigated with respect to all major properties that control their groutability and longevity. The candidates represent smectite based and cementitious grout respectively. The progress on the rock sealing project well meets the objectives and a pilot field test will be made early 1988. It has been demonstrated that clay and cement grouts of considerable density penetrater fractures down to 10—20 μm by using a "Dynamic Injection Technique".

Phase 2 of the Stripa project has been completed and the reports from that work was published.

During 1986 SKB intensified the cooperation with AECL in Canada and reached an agreement that SKB will participate in the URL-project of Whiteshell in Manitoba for a four year period. A Swedish specialist has been attached to the URL-project through a large part of 1987.

The Japanese — Swiss — Swedish project, JSS, for studies of highly radioactive waste glass has almost reached the end of its final phase V. Experiments made at Studsvik in Sweden and at EIR, Würenlingen in Switzerland has been completed. The modelling effort made at the Hahn—Meitner—Institut in Berlin (West) is also complete and has achieved good results. The project results will be published in the spring of 1988 and a final seminar is planned for May 1988 in Stockholm.

The international Poços de Caldas project participants are SKB, NAGRA in Switzerland, UKDOE in Great Britain and CNEN, Nuclebras and Rio de Janeiro University in Brazil and from 1987 also the USDoE. The scope of the project is studies of natural analogues at a large and rich thorium deposit Morro do Ferro and at the Osamu Utsumi uranium mine. Both are located close to the town Poços de Caldas in Brazil. The programme which covers a three year study is divided in two major tasks:

To evaluate the transport and speciation of natural radionuclides and rare-earth elements in a fissure flow system in crystalline rock under both oxidizing and reducing conditions. This will mainly be done in the uranium mine which has very distinct redox fronts.

To study colloid formation and mobility in natural groundwaters and the role of colloids in radionuclide transport. This will mainly be done at Morro do Ferro.

The first feasibility phase was completed in May 1987 and the main phase of the Poços de Caldas-project started immediately.

SKB is participating in the international HYDROCOIN and INTRAVAL projects which are coordinated by a secretariat set up by the Swedish Nuclear Power Inspectorate and OECD/NEA. INTRAVAL was formally initiated in October 1987. Through the bilateral agreement with Euratom SKB has also got the opportunity to join the Euratom-sponsored studies CHEMVAL and COCO concerning validation of chemical speciation codes and investigation of colloids and organic complexes respectively.

7 SYSTEM PLANNING AND COST CALCULATIONS

7.1 SYSTEM PLANNING ACTIVITIES

The waste management system described in Chapter 1 is the basis for the planning of the work to be performed within SKB concerning R&D and the construction and operation of the necessary facilities. As technological developments are likely during the long time period considered, changes in the system are very probable.

The next step in the implementation of the waste management system is to increase the storage capacity in CLAB, which is necessary before 1996. In 1987 studies have been started on alternative methods of increasing the capacity. One alternative is to build a new rock cavern with pools similar to the existing ones. Other alternatives involve increasing the capacity in the existing pools, e.g. by rod consolidation.

For the disposal of the spent nuclear fuel different alternative concepts are being studied, eg WP-Cave and Very Deep Boreholes, as described in Chapter 6 and 11. The KBS-3 concept is used as the reference concept.

7.2 REPROCESSING

For the Swedish situation the once-through strategy without reprocessing of the spent fuel is the most rational. SKB is therefore actively trying to transfer the existing reprocessing contracts with COGEMA to other customers.

In the early 80-ies a total of 57 tonnes of spent fuel were sent for reprocessing at La Hague. The reprocessing of this fuel would have made it necessary to build separate storage facilities in Sweden for the waste from reprocessing. SKB has therefor made an agreement with four utilities in the Federal Republic of Germany to exchange the Swedish fuel stored at La Hague for about 24 tonnes Mixed Oxide (MOX) fuel from the German utilities that are not easily reprocessible. The amount of plutonium is about the same in the 24 tonnes of German MOX-fuel as in the 57 tonnes of Swedish spent fuel.

The MOX fuel will be stored in CLAB and subsequently finally disposed of in the Swedish final repository for spent fuel. During 1987 the exchange has materialized with the transport of about 20 tonnes of spent Mixed Oxide (MOX) fuel from Germany to Sweden in exchange for the 57 tonnes of Swedish spent fuel stored at La Hague. The transports of the remaining 4 tonnes of MOX-fuel are planned for 1988.

7.3 COST CALCULATIONS AND WASTE MANAGEMENT FEE

According to Swedish law all costs for the management of radioactive waste, including the decommissioning of the nuclear power plants, have to be borne by the owners of these plants. To finance the costs a fee is put on the electricity production from nuclear power plants. The fee is determined annually by the government.

As a basis for the fee calculation a cost calculation is each year presented by SKB, Plan-87 /7-1/. The future costs for the whole waste management system, including the costs for R&D, have been estimated to about SEK 39.5 billion at the price level of January 1987. Up to and including 1987 already SEK 6.1 billion have been spent. The total cost for the back-end of the nuclear fuel cycle in Sweden is thus about SEK 46 billion, which is less than 10 % of the value of the electricity produced in the nuclear power plants.

The costs also include the costs to be paid to COGEMA in accordance with the remaining reprocessing contracts, although it is assumed that no Swedish fuel will be reprocessed under these contracts. If the reprocessing costs are excluded, the breakdown of costs is roughly:

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

Based on the cost calculations the government has decided that the fee for 1988 should be SEK 0.019 per kWh on an average, which is the same as for the last five years. The fee is paid into funds at the Bank of Sweden. The funds are administered by the state authority, SKN (The National Board for Spent Nuclear Fuel), which also allocates money from the funds to the various waste management activities performed by SKB.

7.4 DECOMMISSIONING

SKB has not performed any R&D-work on decommissioning during 1987. To follow the development in

other countries, however, SKB is engaged in an international cooperative programme sponsored by the OECD/ NEA. SKB holds the programme coordinator function.

8 CONSULTING SERVICES

The know-how and experience gained by SKB and its Associated Groups are available to foreign countries on a consultative basis. Consulting services are marketed and coordinated by SwedPower.

The services of the Nuclear Waste Management Division are based on the extensive research and experience of the Swedish national waste development programme and include low- and intermediate level waste, central interim storage, final repository of spent fuel and sea transportation.

SwedPower, which has the same main shareholders as SKB, renders world-wide services based on the entire Swedish power technology, utilizing the relevant resources of the member companies as well as of other power related companies in Sweden. The main objective of SwedPower is to commercially transfer know-how and experience from the Swedish power industry. Formal responsibility to the client rests with SwedPower as the contracting party.

For each assignment a project leader is appointed coordinating a project team of selected individuals (see Figure 8-1).

During 1987 a one-year study was completed for Battelle Memorial regarding assistance in final repository for high level wastes in crystalline rock. The report was presented at a seminar held in Chicago in November.

In 1987 a study was performed for Taiwan Power Co regarding the back-end of the fuel cycle. The study covers all technical items of importance of a nuclear waste management system in Taiwan.

SwedPower was during 1987 commissioned to carry out geophysical loggings in Finland with the objective to determine the various geophysical parameters in boreholes and to evaluate the physical properties of the surrounding bedrock.

In Japan radar reflection surveys were performed in several boreholes.

During 1987 geoscientific measurements in boreholes continued in Switzerland and at the underground Research Laboratory in Canada.

In March 1987 a workshop was held in Sweden with participants from ENRESA in Spain concerning the Swedish Facility for Central Interim Storage (CLAB).

Considerable efforts have also been devoted to the US market regarding progress in the nuclear waste programme.

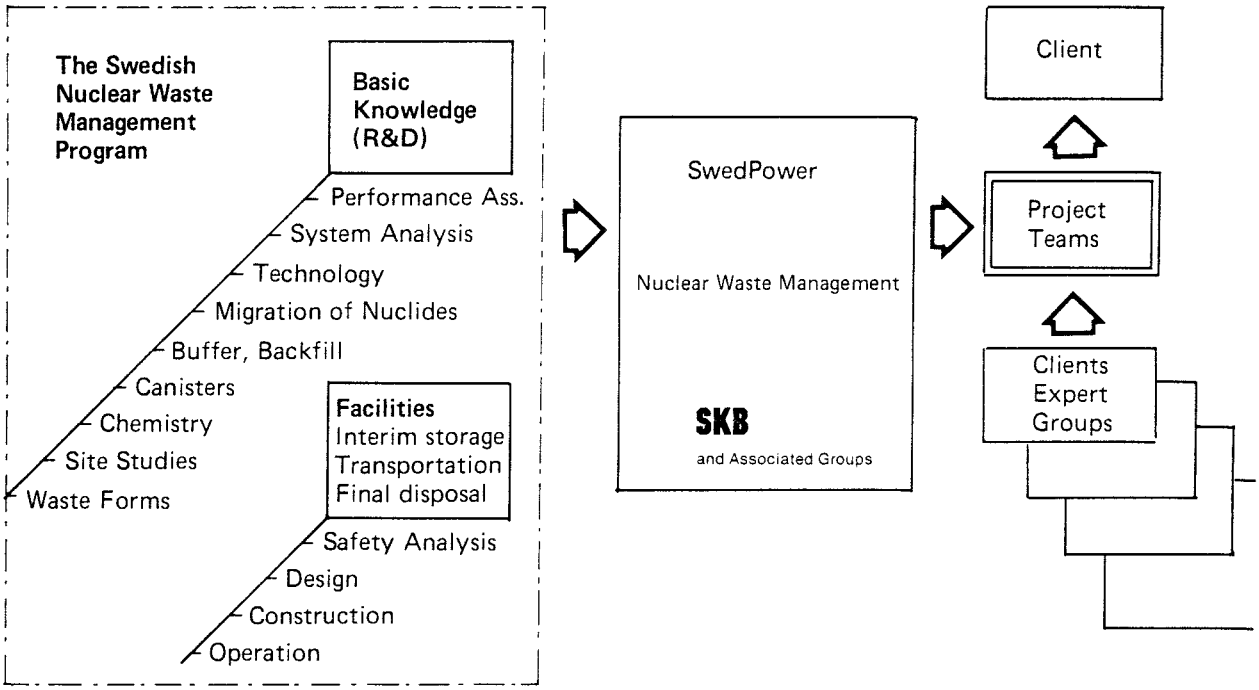

Figure 8-1. Business areas and organization of Nuclear Waste Management.

9 INFORMATION, PUBLIC AFFAIRS AND MEDIA RELATIONS

9.1 GENERAL

The implementation of the SKB nuclear waste management system needs support by the general public. For this reason, a very important part of the waste management program is information activities of all kinds, furnished both locally and on the national level.

The aim, based on the awareness that the public is entitled to open and comprehensible information about the handling and disposal of nuclear waste, has been to give a clear and unbiased description of the main issues.

During 1987 the debate on nuclear energy and waste has been reactivated in Sweden following government plans for decommissioning one or two of the twelve nuclear reactors prior to the year 2010.

9.2 SKB INFORMATION ACTIVITIES

From the start in 1977 of the R&D programme on waste disposal SKB has continuously kept the Swedish public informed on all its activities. Information material, such as printed material and video films, is being produced on a continuous basis. The items currently available in the English language are listed below.

The in-house magazine SKB-nytt (SKB News) was published with seven issues during 1987. It is distributed to the wide selection of scientists, researchers and consultants working for SKB.

Media interest around SKB centered during 1987 on fuel shipments with M/S SIGYN from West-Germany. These were the result of a 1986 agreement between the two countries to exchange spent fuel in order to simplify the waste management systems in both countries. SKB took the opportunity to invite the media to attend the reception of one of the transports at CLAB.

On a number of other occasions during the year representatives from SKB has appeared in Swedish radio and television programmes. The research work being done on different sites around Sweden has been the subject of extensive coverage in local media.

A number of seminars specially arranged for journalists were held when the construction work at SFR reached its final stages.

More than 50 groups of foreign specialists and politicians were received at the SKB facilities CLAB, SFR, Stripa and aboard the M/S SIGYN. In April special news coverage was generated by a visiting group of US senators. Swedish politicians, pupils from local schools as well as members of the general public have also been frequent visitors to the SKB facilities.

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

An Open House arranged at the SFR facility in October could be considered a notable success having more than 3,000 "neighbours" walking through the complete installation and visiting the M/S SIGYN.

9.3 PRINTED MATERIAL

Currently available printed brochures are the following:

- SKB 197 Activities
- Transporting Radioactive Waste
- SFR 197 Swedish Final Repository for Radioactive Waste
- CLAB 197 Central Interim Storage Facility for Spent Nuclear Fuel
- M/S SIGYN
- Stripa 197 A Deep Underground Research Facility
- Data on Nuclear Power and Waste
- Nuclear Waste Management (in collaboration with OECD/NEA)

On request this material can be ordered from SKB Public Affairs and Media Department.

9.4 VIDEO CASSETTES AND FILMS

By SKB produced video films:

- A Final Repository at Forsmark
- CLAB in Action
- Progress of the Stripa Project
- Nuclear Fuel and Waste
- Nuclear Waste on the Way

These films can be lent from SKB Public Affairs and Media Department.

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CHAPTER 1

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

1-2 **KUNSKAPSLÄGET PÅ KÄRNAVFALLS-OMRÅDET 1987**
(Present knowledge about nuclear waste 1987)
KASAM, November 1987 (in Swedish)

CHAPTER 6

6-1 **KBS. Handling of Spent Nuclear Fuel and Final Storage of Vitrified High Level Reprocessing Waste**
Volumes I-V
Kärnbränslesäkerhet, December 1977

6-2 **SKBF/KBS. Final Storage of Spent Nuclear Fuel — KBS-3**
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SKBF/KBS, May 1983

6-3 **SKB. Handling and Final Disposal of Nuclear Waste. Programme for Research, Development and other Measures**
R&D programme 86
Svensk Kärnbränslehantering AB, September 1986

6-4 **SKN. Management and Disposal of Spent Nuclear Fuel. Review of a Programme for Research, Development and other Measures.**
National Board for Spent Nuclear Fuel, May 1987

6-5 **See ref. 13-1**

6-6 **See ref. 13-3**

CHAPTER 7

7-1 **PLAN 87**
— Kostnader för kärnkraftens radioaktiva restprodukter.
(Costs for the management of radioactive waste from nuclear power production)
SKB June 1987 (in Swedish)

SKB ANNUAL REPORT 1987

Part II

Research and Development during 1987

CONTENTS OF PART II

10 R&D PROGRAMME 87

10.1 GENERAL

According to the Act on Nuclear Activities (SFS 1984:3) the owners of Swedish nuclear power plants must together establish a comprehensive programme for the research and development and other measures that are needed 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 pertinent authority every three years starting 1986. The first such comprehensive programme was submitted by SKB to SKN in September 1986 /10-1/.

The R&D programme 86 was sent out by SKN to a large number of Swedish and foreign organizations for review and comments. About 30 Swedish and 9 foreign organizations or groups responded by giving comments after reviewing the programme. These comments were received by SKN in the first quarter of 1987. After that SKN analysed the comments and submitted their own review report to the government by the end of May /10-2/.

The government decided by the end of November that the programme meets the requirements of the law. Through the programme, the review and the government decision a firm base has been given to continue the important work on defining a system and finding a place for a Swedish repository for final disposal of long-lived radioactive wastes.

10.2 COMMENTS FROM REVIEW OF R&D PROGRAMME 86

An overall timetable for all measures that are needed up to the start of construction of a final repository for long lived wastes including spent fuel was presented in the R&D programme 86, see Figure 10-1. Key points in this schedule are:

— selection of sites for detailed investigations 1992,
— selection of barrier system 1995,
— selection of candidate site 1998,
— siting application 2000,
— start of construction 2010.

In general this timetable was accepted by the authorities. It was pointed out that the work for the first period i.e. 1987—1992 should be carried out according to the schedule but that it is not necessary at this stage to fix the remaining parts of the schedule up to 2020.

The nuclear opponent groups in Sweden had in their review requested that a from the nuclear industry independent organization should be given the responsibility

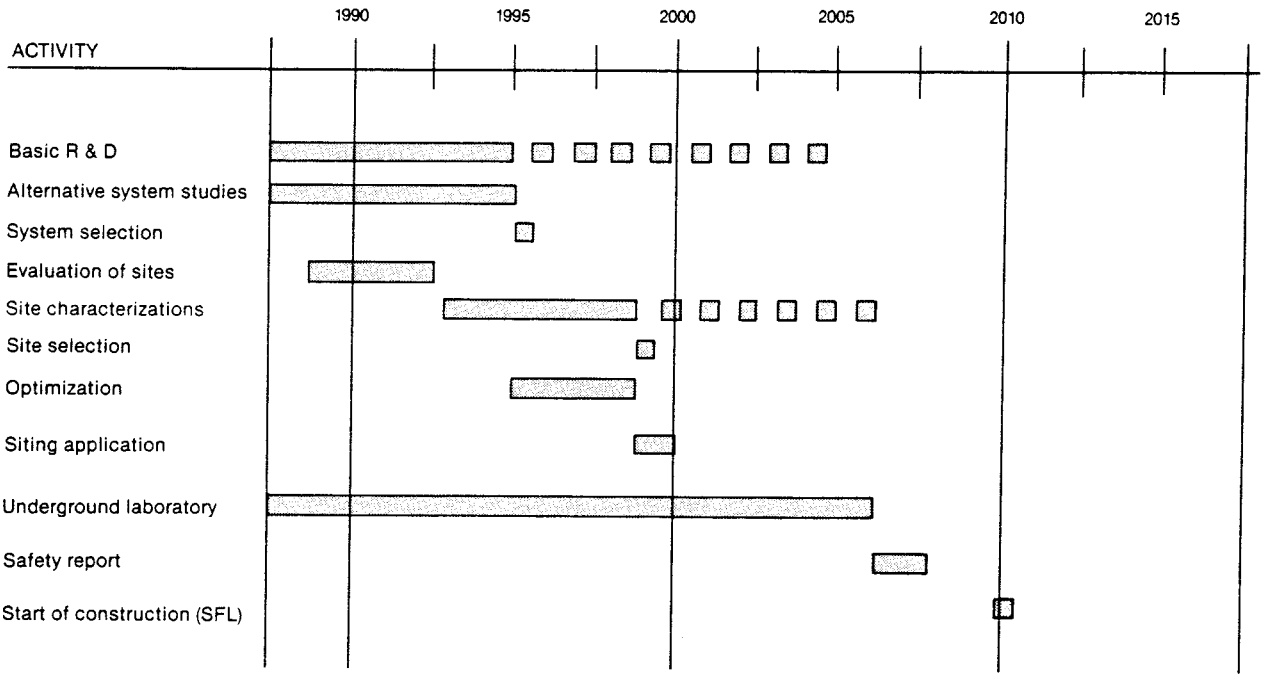


Figure 10-1. Overall timetable for measures up to the start of construction of the final repository and the treatment plant.

for the waste management programme rather than SKB. The SKN responded that the experiences from the review of the R&D programme 86 gave no reason to make any extensive change in the basic rules concerning the division of responsibilities in this area.

A general comment from SKN was that in future programmes the goals and priorities and necessary resources in terms of money and time should be specified in greater detail. Further more results from the ongoing research should be presented more comprehensively and unified than in R&D programme 86.

According to the law the research programme must be comprehensive in the sense that various possible alternatives should be investigated. This is also an important part of the programme up to the mid-1990s. Various basic concepts will be evaluated as well as different materials and designs for the engineered barriers. Concerning these studies of alternatives the general comment was that the programme had the breadth that is motivated by the present state of the art.

The proposed programme on engineered barriers only received a number of detailed comments and some remarks concerning the priorities for various types of studies.

In the review SKN also made some very important comments concerning resources for safety analyses. As a response to these comments SKB has decided to increase its inhouse staff for such analyses. SKN also requested that an easy to read and illustrative booklet about methods and tools for safety and performance assessments should be produced. Further both SKN and SKI requested that updated and comprehensive safety analyses for "generic" repositories should be worked out within the next few years.

The geoscientific programme was generally well received. In particular the announcement of a plan to build a new underground research laboratory — called the Swedish Hard Rock Laboratory — got very favourable comments from almost all reviewers. SKN concluded that SKB had given satisfactory reasons to construct the laboratory but that more data and analyses were needed before deciding on its siting. This is in accordance with SKBs opinion. Present plans foresee that such data and analyses will be presented late 1988 or early 1989. A site close to the Oskarshamn nuclear power plant is still being extensively investigated.

10.3 COMMENTS CONCERNING SITE SELECTION PROCEDURE

The most conspicuous comments in the SKN reviewreport concern the site selection procedure. SKB had proposed that the studies of sites should be concentrated on the rock types granite and gneiss. No further studies of gabbroic rock should be made. The investigations already made should be supplemented and a couple of more sites should be included before a small number of sites are selected for detailed characterization.

SKN finds that the planned work to establish a base for site selection should be expanded. The whole country should be screened, possible sites should be evaluated and ranked based on available data and the more promising sites should then be reserved (temporarily) according to the planning procedure in the different communities as given by the recently ratified Planning and Construction Act (PBL). This phase, called the screening phase, should be completed during the 1980s. In the next phase, called the selection phase, a more thorough evaluation is made of the sites previously selected and a few are chosen as candidates for detailed characterization. These are reserved by the authorities as having "national interest" according to the law. At least two sites are then characterized in detail. According to SKN the application for a siting permit could be made for more than one site. This would postpone the final selection of one site to the last phase, the licensing phase. During this phase the application(s) would be reviewed and evaluated according to procedures set forth in the acts on Natural Resources (NRL) and Nuclear Activities (KTL). Decisions according to these laws are made by the government.

In the NRL there is, however, a provision that gives the local community board a veto right against locating large facilities such as a nuclear plant or a repository within the community borders. SKN recommends that this local veto should be softened by amending the legislation.

The comments made by SKN on the site selection procedure are supported by a special appendix to their review report. The appendix, called "Report from the site selection group" gives a comprehensive summary of the new legislation in PBL and NRL that is applicable to this procedure /10-3/.

10.4 EXECUTION OF THE R&D PROGRAMME

The programme is executed under the leadership of the division of research and development at SKB. The staff of the division averaged 12 persons during 1987. Some 250—300 scientists, engineers, specialists and technicians were engaged under contracts with universities, technical institutes, research laboratories, engineering firms and industry. The results were reported in 32 technical reports in the SKB-TR-serie, in numerous progress reports and working reports and in communications to various international meetings and scientific magazines. A list of the more important publications is given in Appendix 2.

The expenditures on R&D within the SKB budget for 1987 were 92.3 MSEK as compared with 66.3 MSEK in 1986. The main part of the large increase is for the new underground laboratory, for increased Swedish contri-

bution to the Stripa Project and for other geological investigations. SKB was also the managing participant in the international projects Stripa, JSS and Poços de Caldas. The expenditures for these three projects were 31.0 MSEK of which 9.6 MSEK were SKB contributions and 21.4 MSEK came from participants outside Sweden. The total turnover of the R&D-division was thus 113.7 MSEK.

11 REPOSITORY DESIGN

11.1 GENERAL

According to the R&D programme 1986, an evaluation of available alternatives will be made before a site and repository system is selected for the Swedish spent fuel. The order in which the R&D-work will be focused is:

- limitation of the number of most promising sites to 3-5 for detailed investigations at repository depth, around 1992,
- selection of one (or a few) suitable system(s) of engineered barriers for these sites around 1995,
- selection of the most favorable site, around 1998,
- optimization of the repository system to the selected site.

This means that most of the comparison of alternative designs for the layout of the repository and the engineered barrier system in the repository will be made during the period 1993-1996. Some design alternatives involve, however, specific features that have special demands on the sites or on how the investigations must be done. An example of such a concept is disposal in very deep drilled holes (VDH). Another is the WP-Cave where the units of waste that are independently protected by unaltered host rock are very large, 1000 tons of U. In order to make it possible to decide whether special geologic or investigational aspects should be taken into account in the site screening stage, it is necessary to evaluate such repository concepts at an early stage.

During 1987 both the WP-Cave and the VDH have been under investigation with regard to how such a repository concept could be applied in Swedish bedrock, what safety potentials it may have, and what the confidence in the results of a safety assessment might be — based on the validity of models and the quality of data available.

11.2 WP-CAVE

11.2.1 General on Project Work

The overall goal of the current work is to outline the safety potential of the WP-Cave design. Summing up and reporting have been postponed for six months and are scheduled for mid 1988. The reason for this postponement is that the safety assessment of the SFR facility has required increased personnel resources during the year.

The work in 1987 has been concentrated on defining a Base Scenario for the initial calculations on nuclide release rates. The most important barriers have been identified and the most plausible chemical environment outlined.

The initial calculations have used the multidimensional integrated finite difference code TRUMP. In 1987 only fission and activation products have been considered. Calculations on actinides are scheduled to be carried out in 1988.

11.2.2 Base Scenario

The design of the central part of the repository, where the canisters with the spent fuel are to be stored, is shown in Figure 11-1. It consists of one vertical central shaft with 12 regularly located canister channels at 16 levels. Each canister channel passes through a vertical inner ventilation shaft and ends in an outer ventilation shaft. No change has been made in this design during 1987.

After the canisters have been placed in their positions in the storage, the storage will be kept ventilated for a time period of 100 years. After this period the repository is sealed off. In the Base Scenario it is assumed that channels and other openings are refilled with a hydraulic fill in a manner similar to that used in cut-and-fill mines. The fill of fine grained sand has such a particle size that it prevents circulation of water in the channels.

The large supply of iron material in the storage — in outliners and canisters — will result in a rapid consumption of dissolved oxygen in the water and the establishing of a stable anaerobic chemical environment.

The mild steel canisters isolate the fuel for 200 years after refilling, whereafter corrosion break-through is assumed to occur. When water reaches the fuel, the fuel starts to dissolve. The ionizing alpha-radiation of the fuel will cause radiolysis of the water near the surface of the fuel. The effect of this radiolysis and the rate with which the fuel will be oxidized are being evaluated.

The temperature around the canisters is an important parameter when considering the determination of thermodynamic equilibrium constants. In order to stay below a temperature, which is considered to be reasonable, in the sense of providing accurate thermodynamic data, a temperature of 150 °C has been adopted. This limit has in the Base Scenario been met by a decrease of the amount of fuel stored in the repository.

Nuclides in solution at the fuel surface will start to migrate out from the corroded canister. The redox sensitive nuclides will be reduced by the present iron before escaping from the canisters. The result will be, that nuclides with low solubility in the reduced state will precipitate inside or just outside the canister.

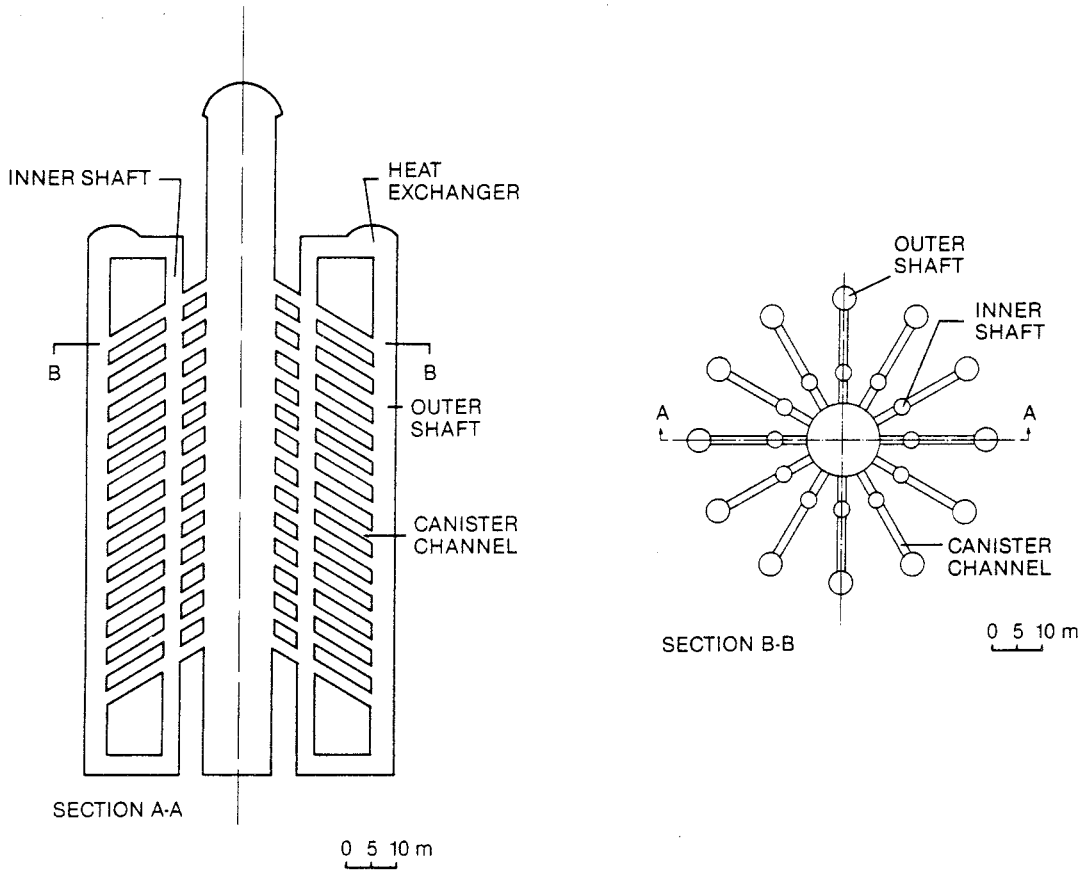


Figure 11-1. Central part of WP-Cave repository.

Once outside the canister the nuclides will migrate in direction away from the central part of the repository. The three main barriers retarding this migration in the near field will be:

— the refilled sand in the canister channels,
— the bentonite-sand barrier, see Figure 11-2,
— the "diffusion" or "film" resistance in the rock mass just outside the bentonite-sand barrier.

The hydraulic cage, see design in Figure 11-2, is meant to by-pass the groundwater (decrease the hydraulic gradient over the rock mass inside) and thus decrease the water flow in the area around the bentonite-sand barrier. This effects the amounts of nuclides escaping through the bentonite-sand barrier. The decreased water flow rate will further delay the transportation of nuclides in the rock between the bentonite-sand barrier and the hydraulic cage. The performance of the hydraulic cage will be analysed in 1988.

The far field is modelled as a barrier with the characteristic properties known for the Swedish bedrock. The retention effect for migrating nuclides are therefore not specific for the WP-Cave design but general for any repository placed underground.

11.2.3 Near Field Barriers

Sand-water in canister channels

With a negligible circulation of water in the material, diffusion will be the main release process. Due to sorption, the nuclides will be retarded in the fine grained sand material. Many of the available nuclides will decay to a negligible level before they reach the outer boundary of the fill.

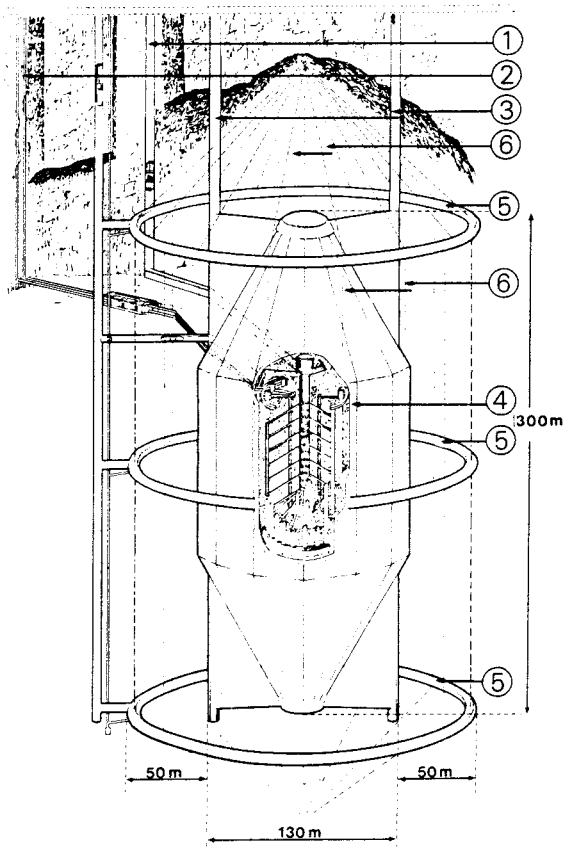
From the result of the calculations the most important fission and activation products released to the rock mass have been identified.

No retardation effect of the inner rock mass is considered in the Base Scenario. The release outside the canister channels are considered to be immediately transferred to the inside of the bentonite-sand barrier.

Bentonite-sand barrier

The bentonite-sand barrier, which is assumed to be 5 m thick, has according to the calculations a far higher retardation potential for the studied nuclides than the sand-water mixture around the canisters.

The design of the barrier is seen in Figure 11-2. It consists of a mixture of bentonite and sand with an assumed proportion of 10% bentonite and 90% sand in the



1. *Transportation shaft*
2. *Ventilation shaft*
3. *Main shaft for excavation and refilling of slot*
4. *Bentonite-quartz barrier with thickness of 5 m.*
5. *Drift for hydraulic cage.*
6. *Drillhole for hydraulic cage.*

Figure 11-2. Overview of WP-Cave design.

bottom cone. The cylindrical part is considered to have a somewhat higher bentonite grade; 20%, as such an increase would decrease the hydraulic conductivity and improve the swelling properties. The top cone was initially designed for a mixture with about 50% bentonite, so that the decreased hydraulic conductivity of the material would compensate for the higher groundwater flow at the top compared with the flow at the bottom part of the bentonite-sand barrier.

The low hydraulic conductivity, however, has turned out to be a drawback with respect to the question of hydrogen gas migration. Anaerobic corrosion of iron is expected to produce hydrogen gas, which if not escaping through the bentonite-sand barrier would form a gas bubble and press out an equivalent amount of water through the barrier at levels below the gas bubble. Laboratory tests of bentonite-sand mixtures indicate, however, that a sufficiently high gas penetration rate is maintained in a low bentonite graded mixture; 10% of bentonite. Such a mixture is therefore assumed in the Base Scenario.

The calculation on migration through the bentonite-sand barrier, has resulted in a list of the fifteen fission and activation products, which have an impact on the total dose rate released outside the barrier.

"Diffusion resistance" in rock outside bentonite-sand barrier

This barrier comprises the most significant barrier of the three mentioned. The function is shown in Figure 11-3. As the water flow passes the repository, the concentration in the water increases. Nuclides migrate by diffusion from the outer boundary of the bentonite-

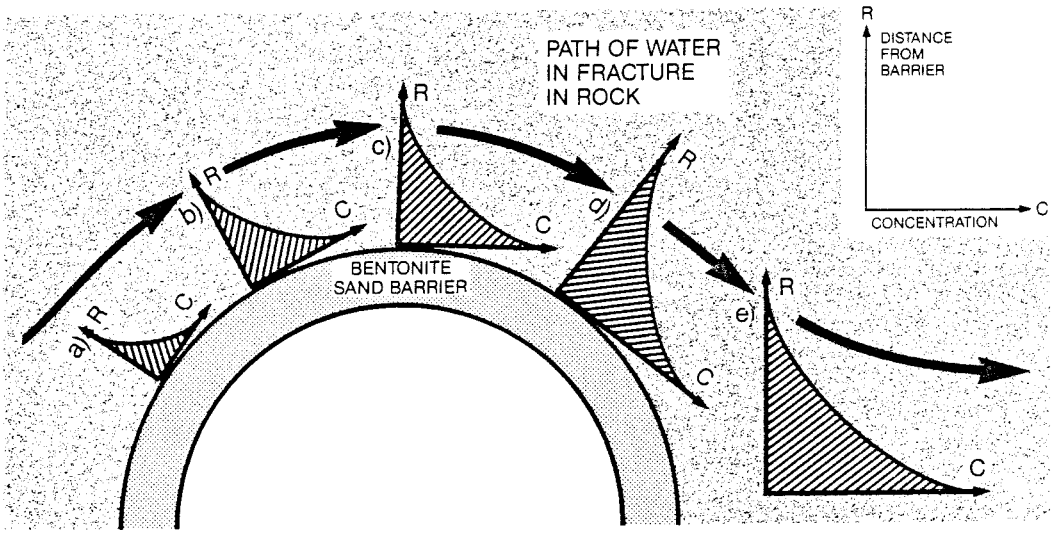


Figure 11-3. The water passes the bentonite-sand barrier as is shown by the black arrows. At a) nuclides escaping from the barrier have got into contact with the water and have reached a short distance out into the water. At b) the nuclides have diffused farther out into the water. The concentration closest to the bentonite-sand barrier has increased. During the progressively longer contact time c) and d) the concentration closest to the bentonite-sand barrier increases further. The concentration in the water farther out also increases. As the difference in concentration is the driving force for diffusion, the transportation of nuclides out into the water will be lower at d) than at a).

sand barrier to the water flowing in fissures. The "diffusion resistance" increases the higher the concentrations from nuclides get. The important parameters are the distance between fractures and the aperture of these fractures as well as the magnitude of the virgin ground water flow.

The TRUMP calculations for fission and activation products have shown that more than 90 % of the total transport resistance for these nuclides lies in the nuclide transfer from the bentonite-sand barrier to the flowing water outside the barrier. This is valid as long as the rock mass has about the same water flow rate and overall flow porosity as that in average have been found in the Swedish bedrock in site investigations at 200 meters depth.

11.2.4 Deficiencies in Present Basis of Calculation

Several important questions have not yet been considered and it is therefore not possible for the time being to draw detailed conclusions on the safety potential of the WP-Cave structure with any degree of accuracy.

The major work left is the evaluation of the release of actinides, of which several may have an impact on the total radioactive dose rate released to man.

The study on thermo-induced groundwater flow has given some preliminary results in 1987. These indicate that an additional release of importance can be expected initially through the top part of the bentonite-sand barrier.

The hydraulic cage has theoretically a great impact on the water flow rate in the rock mass around the bentonite-sand barrier. The cage stands, however, also in contact with fissures which may provide quick transport pathways for the nuclides from the repository to the biosphere. A sensitivity analysis on the effect of different properties of the rock on the performance of the hydraulic cage is therefore considered necessary.

11.3 THE VDH REPOSITORY

An alternative repository concept is based on very deep holes (VDH), see Figure 11-4 /11-1/. A preliminary review of previous studies /11-1/ was made early 1987 by the group in the Swedish State Power Board organiza-

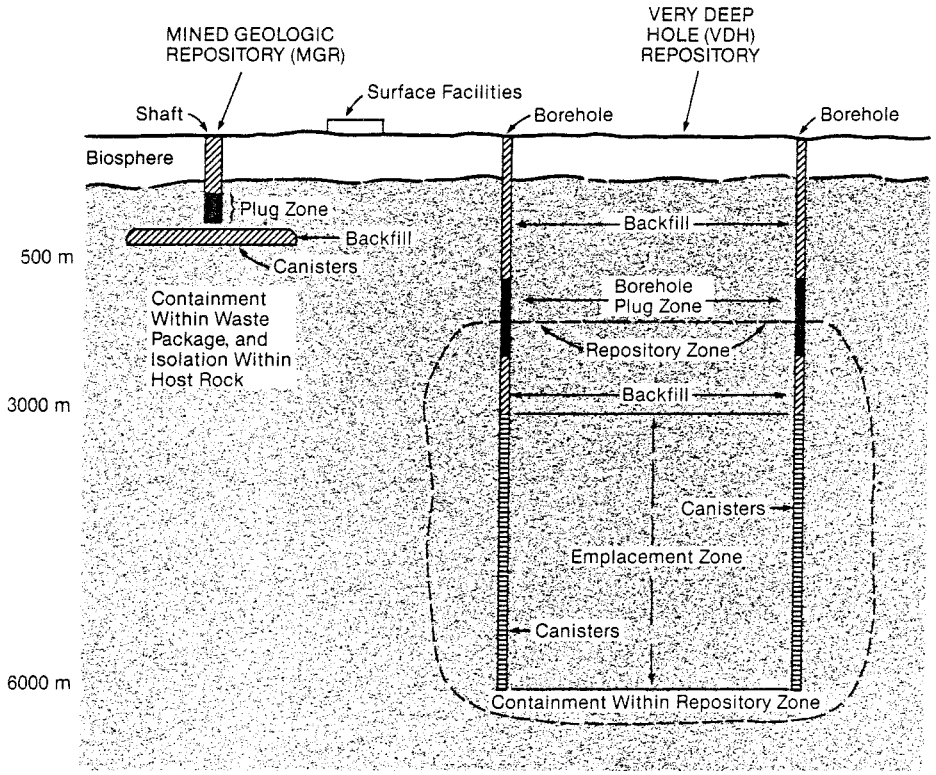


Figure 11-4. Schematic comparison of MGR and VDH concepts. (From ONWI-226)

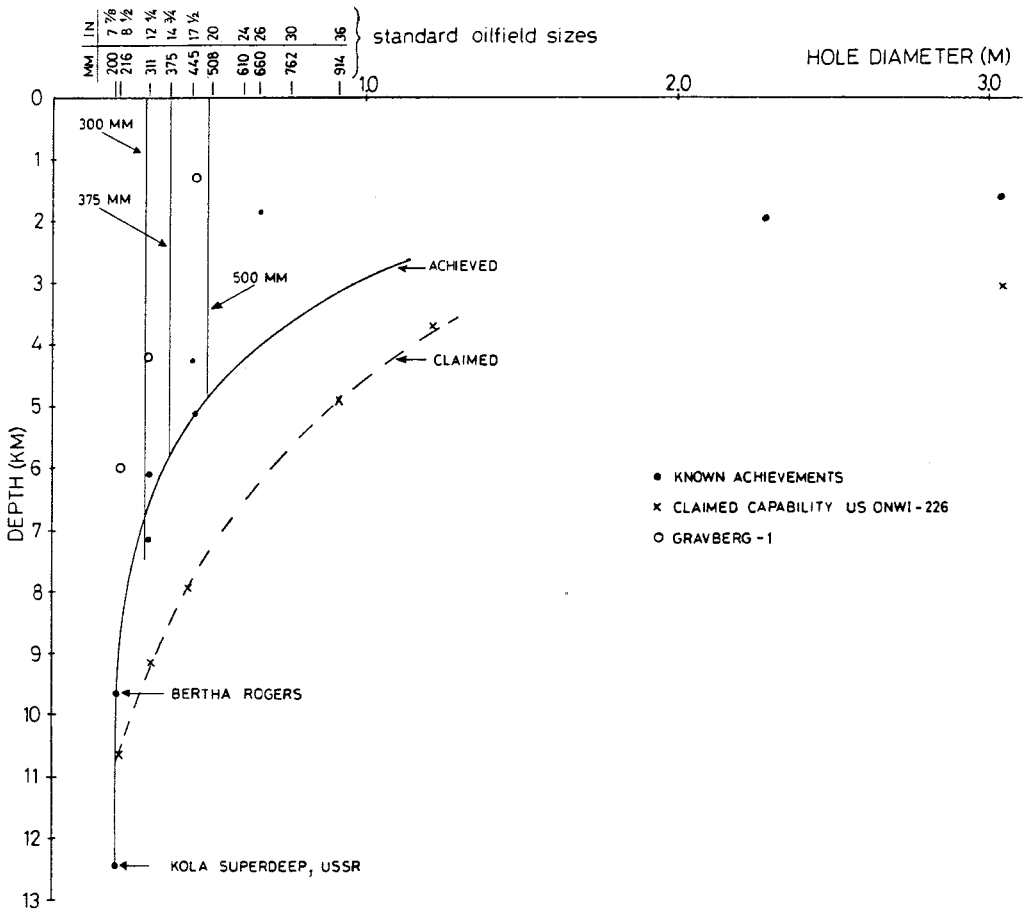


Figure 11-5. Achieved and claimed hole diameters versus depth.

tion which is involved in the Swedish deep gas drilling at Gravberg near Siljan. The first stage in a feasibility study and assessment of the economic potential of storage of nuclear waste in very deep boreholes ended with the conclusion that disposal of spent fuel in deep boreholes may be feasible and economic using today's technology. Due to the limitations of usable diameter in deep holes, see Figure 11-5, the amount of spent fuel being equivalent of 7 800 ton uranium requires more than 30 deposition holes to 5 km depth. However, considerable engineering and development work will be needed and a second stage "Outline design and quality assurance review" was started late 1987. The experiences that were gained in conjunction with drilling in Gravberg hole, the state of the art of hydrogeological and geotechnical investigations and geoscientific results from other boreholes as well, will be used with the objective to formulate the basis for the isolating qualities of bedrock surrounding very deep holes.

12 WASTE FORMS

12.1 SPENT FUEL

The main activities on waste form studies have been concentrated on spent fuel. All SKB efforts oriented towards vitrified high level waste were during 1987 performed within the JSS Project, see Chapter 20. The JSS Project was terminated by December 31, 1987. After that date, all activities will be concentrated on spent fuel.

The close contacts with other groups in the world performing similar studies have been continued. This year the annual workshop on spent fuel, the seventh one in the ongoing series, was held in Canada and arranged by Atomic Energy of Canada Ltd.

12.1.1 PWR Fuel Characterization Studies

The corrosion tests of PWR fuel which started in 1986 have continued throughout 1987. In parallel with these corrosion tests, the source material for the studies has been characterized to define the fuel rod and fuel parameters necessary to evaluate the results obtained during the corrosion tests. The first part of this characterization programme has included visual inspection of the oxide layer on the fuel rod, axial γ-scanning, profilometry, determination of fission gas release, ceramographic examinations, α- and β-autoradiography and micro γ-scanning of fuel cross sections /12-1/.

Figure 12-1 shows the axial γ-scan of the rod, using Cs-137 as monitoring nuclide. The curve thus represents the axial burnup distribution, which is shown to be uniform over a large part of the rod, although with minima at spacer positions.

An autoradiograph of a fuel pellet cross section is shown in Figure 12-2. As can be seen, there is an increased concentration of α-emitters near the periphery of the fuel pellet. This is due to the formation of plutonium through capture of epithermal neutrons. At high burnup, as plutonium participates in the fission processes, there will be increased concentrations of fission products at the periphery as is illustrated by a radial γ-scan of Cs-137 in Figure 12-3.

12.1.2 Analysis Programme

Previously, the analysis programme for the leach solutions comprised (a) uranium analysis (neutron activation and laser induced fluorescence), (b) Sr-90, (c) γ-emitting fission products, and (d) α-emitting nuclides. This programme has during 1987 been supplemented with Tc-99 analysis (radiometric and ICP). The routines for the analysis of α-emitting nuclides have also been improved. This has resulted in both lower detection limits and improved reproducibility for plutonium.

12.1.3 Fission Product Inclusions

The knowledge of the types and quantities of fission products segregated at grain boundaries or as separate phases are limited. During 1987, particular interest was paid to the well-known 4d-metal (Tc-Mo-Ru-Rh-Pd) inclusions. Figure 12-4 shows such a metallic inclusion in a BWR fuel that has been subjected to a controlled

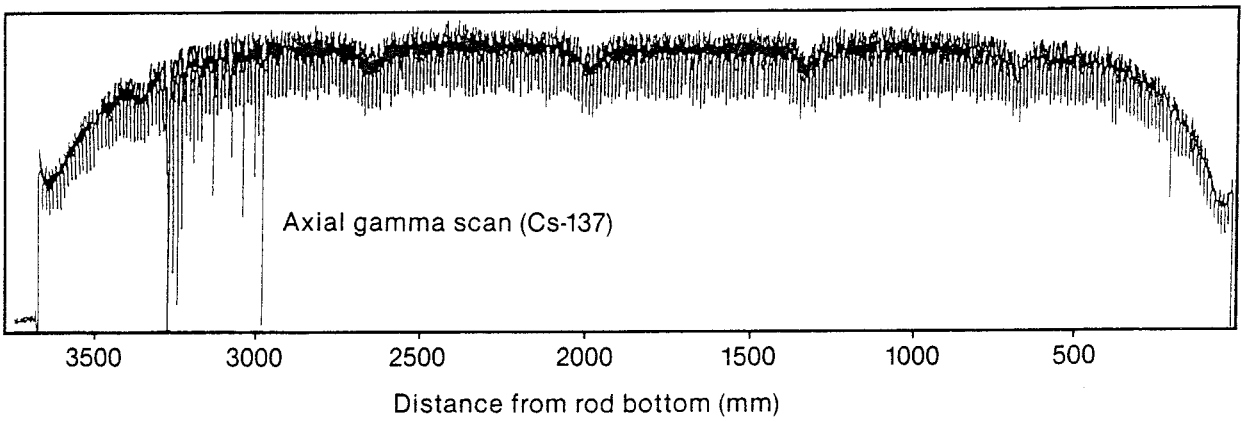


Figure 12-1. Axial γ-scan (Cs-137) of PWR rod number 03688 from Ringhals 2, assembly D07. The individual pellets can be distinguished as dips in the gamma intensity.

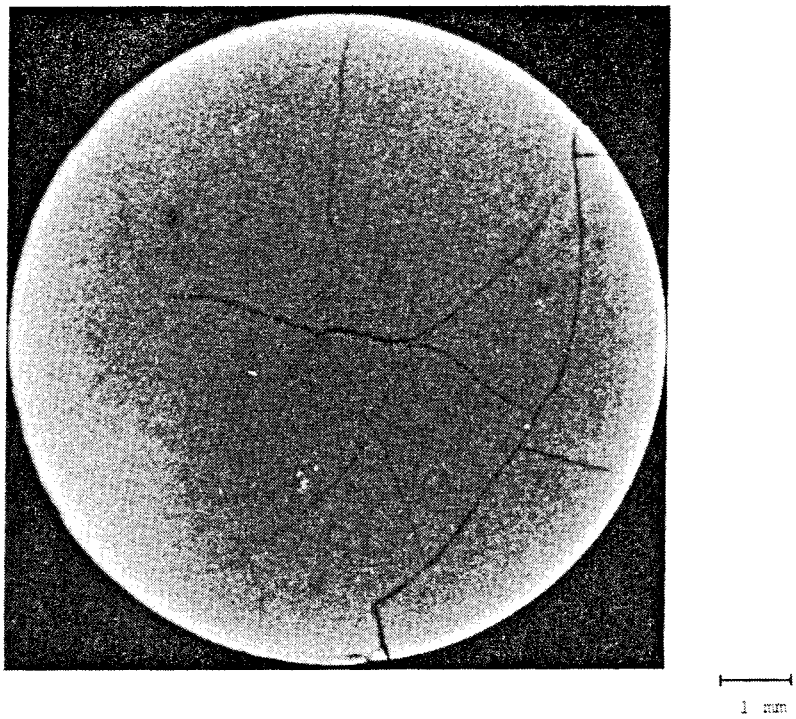


Figure 12-2. Alpha-autoradiograph of a fuel pellet showing the increased concentration of α-emitters near the periphery of the fuel pellet.

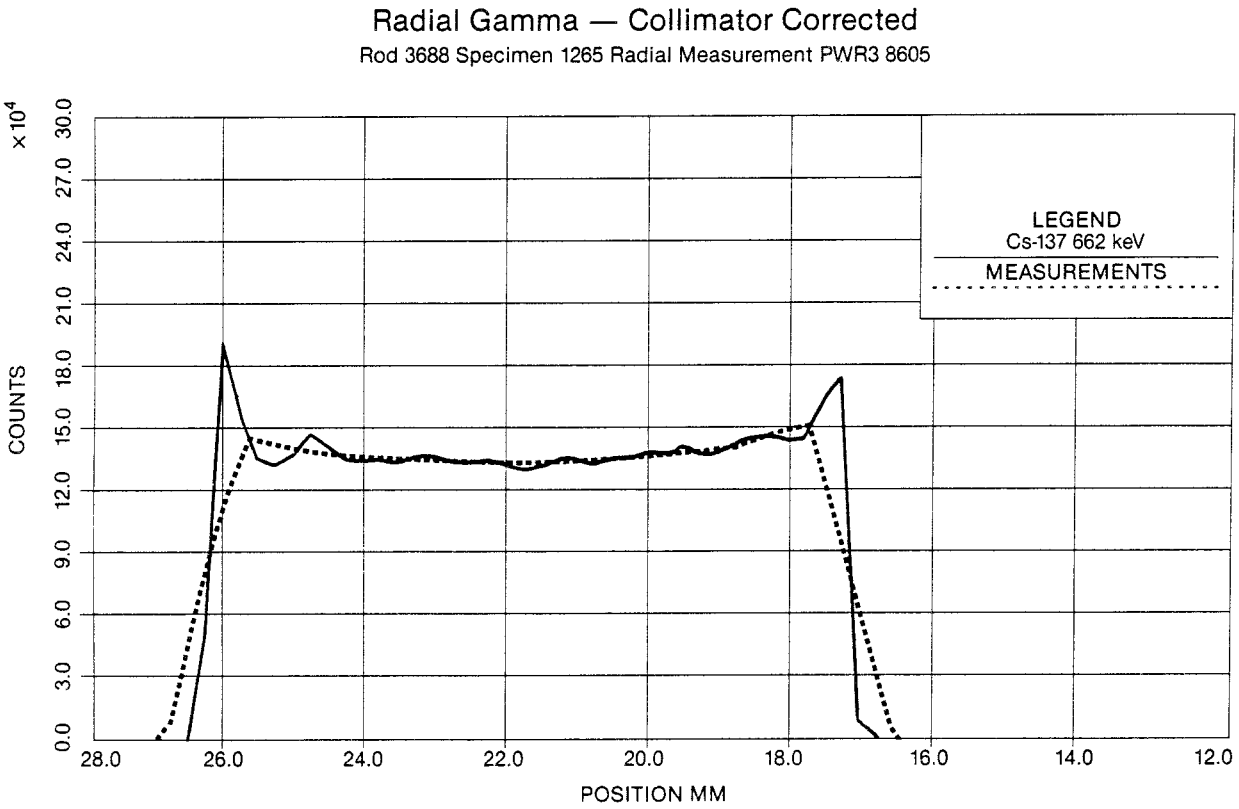


Figure 12-3. Radial Cs 137 γ-scan of a fuel pellet.

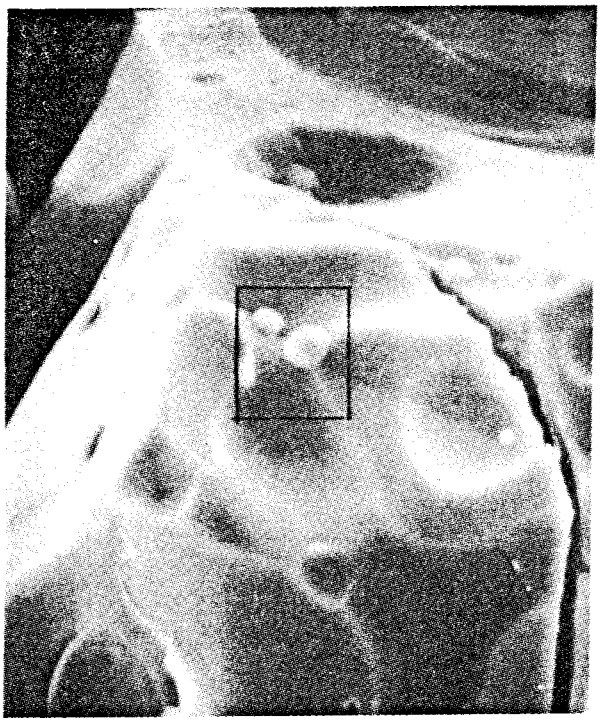


Figure 12-4. Scanning electron micrograph of BWR fuel showing spherical inclusions of noble metal fission products (squared area).

power increase. This phase separation is also observed in LWR fuel from normal operation conditions, but those inclusions are generally smaller. The present study aims at a better understanding of the inventories of such 4d-metal inclusions and the kinetics of possible release of radionuclides from these inclusions. Results so far show that for both BWR and PWR fuel the 4d-metal inclusions consistently correspond to about 0.5% by weight of the total fuel, or to nearly 50% of the total inventory of 4d-metals.

12.1.4 Spent Fuel Corrosion Studies

During 1987, PWR experiments with contact times in synthetic groundwater of 82 and 172 days were evaluated /12-2/. The third contact period was set to over one year and will not be completed and evaluated until 1988. The results so far show that for both uranium and plutonium release under oxidizing conditions there is no difference between PWR and BWR fuel. Also for strontium, the PWR results confirmed the previous findings for BWR fuel, see Figure 12-5.

In the PWR fuel experimental series, in addition to experiments performed under oxidizing conditions, experiments were carried out where the fuel was contacted with synthetic groundwater reduced under more realis-

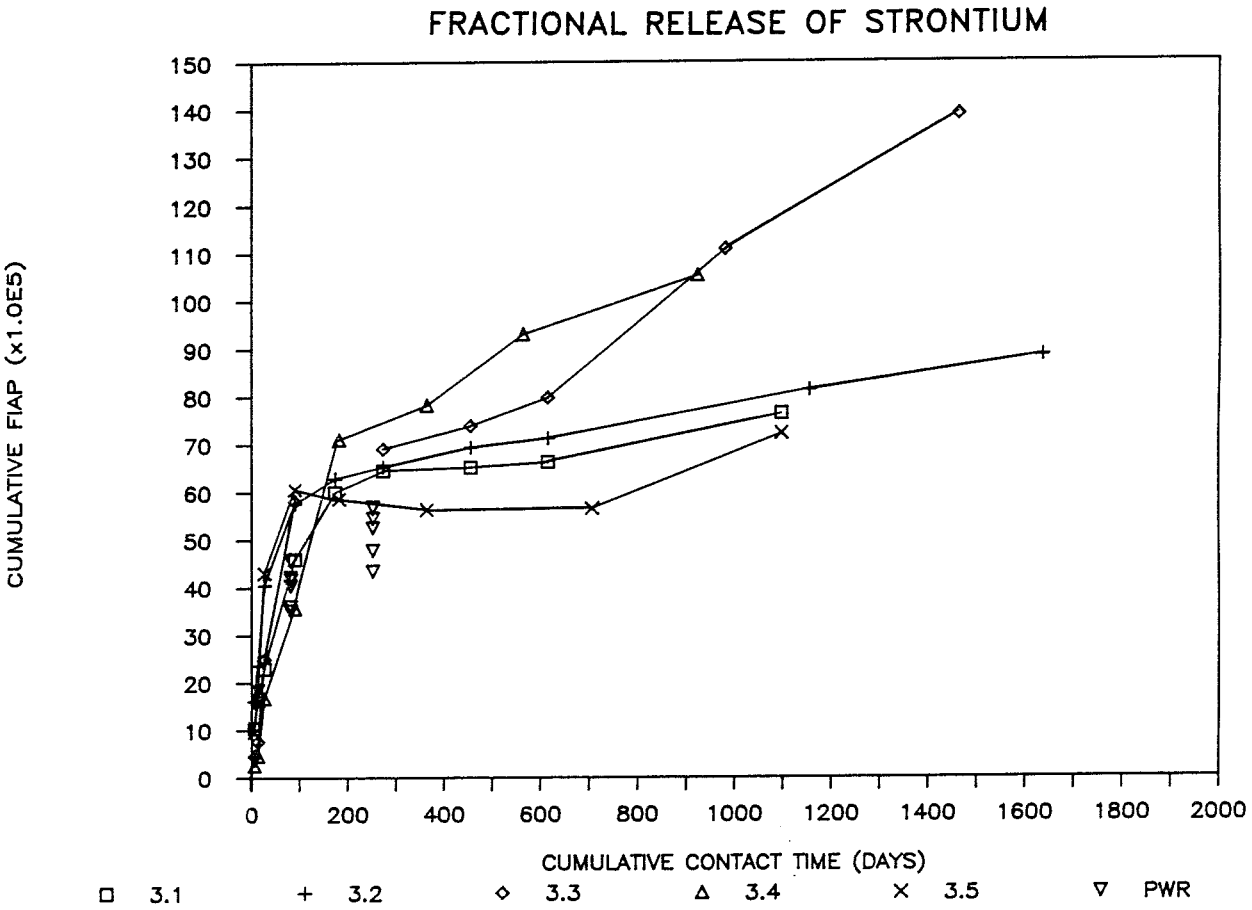


Figure 12-5. Release fraction (fraction of inventory in the aqueous phase, FIAP) of strontium for the BWR and PWR series (oxidizing conditions) plotted versus cumulative contact time. Symbols 3.1 to 3.5 denotes different BWR leach series.

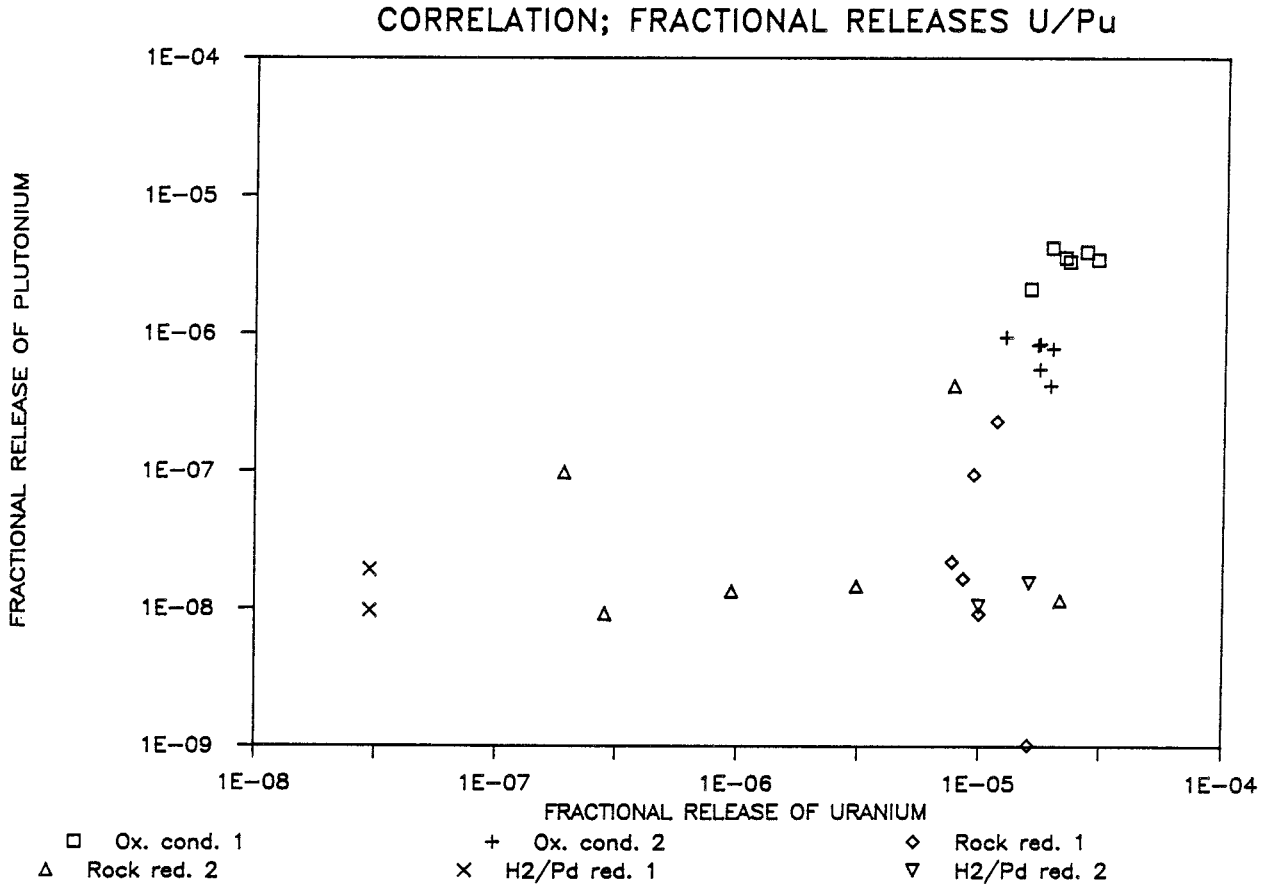


Figure 12-6. Correlation between the fractional releases of plutonium and uranium for the PWR series.

tic conditions. In these experiments, the synthetic groundwater was reduced by circulating it over granite rock cores from deep bore-holes. However, due to the complexity of the system a negative Eh was probably not achieved even though the oxygen concentration in the system was low.

Experiments were also carried out where reducing conditions were imposed by means of hydrogen gas in the presence of a palladium catalyst. This method is capable of producing an Eh down to -300 mV.

For the experiments using rock-core reduced groundwater, only a minor decrease in uranium concentrations was obtained in the first (82 days) contact period, while the second (172 days) contact gave much lower values. In contrast, low plutonium concentrations were obtained in both contact periods.

This difference between uranium and plutonium behaviour is shown particularly clearly in the results from the experiments in H_2/Pd reduced groundwater, where after the first contact period, the uranium concentrations were below the detection limit (1.5 ppb), while, probably due to leakage, relatively high values were obtained after the second. In spite of this, plutonium concentrations in these experiments were at the same level.

In the experiments under oxidizing conditions the plutonium to uranium ratios were less than the ratio in the fuel. From the results from the experiments when U dissolution or solubility is repressed under reducing conditions, it is seen that the plutonium to uranium ratio decreases abruptly with small changes in U concentration. To illustrate this, the fractional releases for plutonium for the complete PWR experimental series are plotted against the corresponding values for uranium in Figure 12-6. The reason for this drop in plutonium concentration is at present not fully understood. However, it should be noted that at the lowest value of Eh (-300 mV using H_2/Pd) congruency between the plutonium and uranium releases is displayed.

12.1.5 Release Mechanisms

The experimental programme has so far been performed on three different fuel types, BWR 42 MWd/kgU, BWR 0.5 MWd/kgU, and PWR 43 MWd/kgU, using deionized water, synthetic groundwater, dilute bentonite water, and different redox conditions. A comparison between data obtained from different fuel types and different experimental conditions can be used to elucidate the release mechanisms for the radionuclides /12-3/.

The data obtained so far seem to indicate that most of the analysed fission products are selectively released, most probably from fuel cracks, fissures and grain boundaries.

Under oxidizing conditions, the release of plutonium is most probably controlled by the solubility of a precipitated solid phase, such as amorphous $Pu(OH)_4$ and

under reducing conditions, all fuel types appear to have congruent releases of plutonium and uranium, indicating that the release is controlled by the UO_2 matrix dissolution rate.

Experiments where high burnup (42 MWd/kgU) BWR fuel has been corroded in dilute bentonite suspensions have been evaluated /12-4/. These experiments are to be considered as preliminary studies to gain experience before more complex integrated tests with irradiated fuel and repository components are initiated. An additional objective was to study whether or not the presence of a sorbing solid phase would increase the dissolution of spent fuel.

The results of this preliminary study were:

(1) In the dilute bentonite suspension, sorption of uranium is inhibited by carbonate complexing and no significantly increased corrosion of the UO_2 matrix was found.

(2) The concentrations of plutonium and cationic fission products in the aqueous phase is lowered considerably, up to three orders of magnitude in the case of plutonium.

12.2 MODELLING

The work on developing a model for spent UO_2 fuel dissolution has continued during 1987. The research activities can be divided into two areas: (1) Experimental studies of the kinetics of $UO_2(s)$ dissolution under reducing conditions. (2) Mathematical modelling of the dissolution of UO_2 fuel.

The experimental programme in order to establish the mechanisms for $UO_2(s)$ dissolution in groundwater under reducing conditionsis nearly finished. The first stage of the study has already been reported /12-5/. It was found that the dependence of the dissolution rate on pH suggested dissolution reaction via the formation of a surface complex with OH^- ions.

Initially, the uranium concentrations in solution increases to a value about one order of magnitude higher that the thermodynamically calculated solubility. These higher concentrations were found to be compatible with a somewhat oxidized primary phase. The observed steady state concentrations at pH 9 and 12 were found to agree well with the predicted equilibrium solubility of UO_2 under reducing conditions. The development of the uranium concentrations versus time is shown in Figure 12-7.

The second stage of the experimental programme, the kinetics of $UO_2(s)$ dissolution in the presence of HCO_3^- /$CO_2(g)$ is still in progress.

The mathematical modelling is still in its initial phase. During 1987, the thermodynamical data base for uranium (VI) has been updated and validated by comparing experimental solubilities for U(VI) solid phases with calculated uranium concentrations using the EQ3RN code.

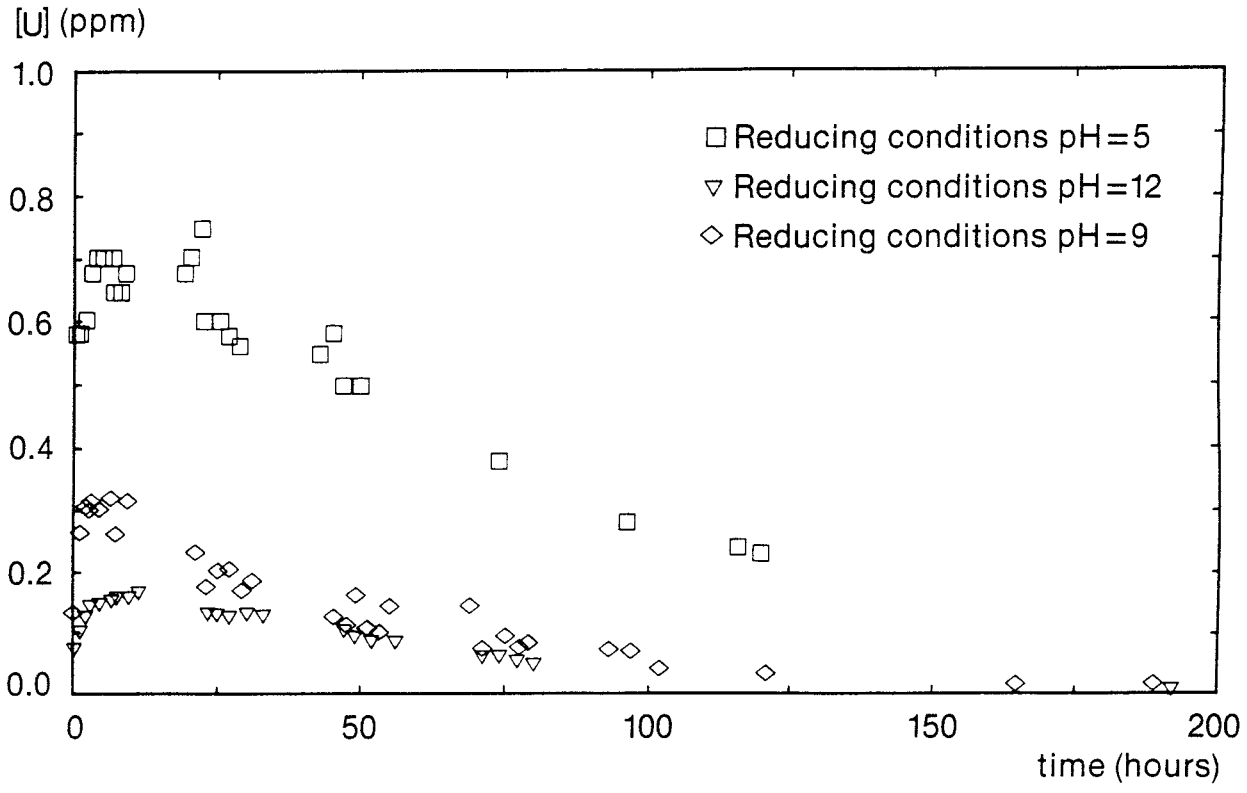


Figure 12-7. Dissolution kinetics of UO_2 under reducing conditions. Development of solution concentrations of uranium versus time for different pH values.

13 CANISTER MATERIALS

During 1987, the studies of canister materials have been concentrated on two candidate materials, copper and carbon steel.

13.1 COPPER

The investigations on copper during 1987 include continued evaluation of pitting corrosion under reducing conditions and studies of creep in copper at low temperature. For pitting studies, preliminary studies were started to determine if the technique and equipment was capable of generating and monitoring pits under controlled conditions.

Phase one of the experimental studies of creep in copper has been finished. This phase has included studies of uniaxial creep in oxygen free copper as well as in welded material. Tests have also been performed on welded thin-walled tubes under over-pressure. The data will be reported in early 1988 and the subsequent phases of the programme will be based on the presented findings.

As a result of the review of the SKB research programme 1986, SKN suggested that SKB undertook a study aiming at determining whether or not copper was thermodynamically stable in oxygen-free pure water. The reason for doubting this well established fact was a Short Communication by Hultquist in Corrosion Science where it was claimed that copper, in pure water under reducing conditions, corroded with hydrogen evolution /13-1/. In a study performed for SKB, as expected, no hydrogen evolution could be demonstrated /13-2/. An independent study performed by Sulzer Brothers Ltd. /13-3/ in Switzerland also concluded that no hydrogen was detected although the detection system used was capable of detecting hydrogen evolution at a level three orders of magnitude lower than those reported by Hultquist.

The analysis and evolution of the cannon, a 24-pounder, salvaged from the man-of-war KRONAN in 1985 has continued during 1987 and a final report of the investigation has been prepared /13-4/.

The cannon was buried vertically with its muzzle downwards into an illite and montmorillonite rich clay. The dominant corrosion products found on the cannon were cuprite (Cu_2O) and malachite ($Cu_2CO_3(OH)_2$). The amount of copper found in the corrosion products corresponded to 200 mg/cm^2 on the average. The amount leached into the surrounding clay was negligible (4 mg/cm^2). However, it was found that the predominant source of the copper in the corrosion products must be the slag product CuO, which was present as inclusions in the bronze matrix. This slag product had most probably been transformed to the corrosion products found by redox processes where Fe^{2+} and organic matter are the major electron donors. The bronze matrix exhibited very little corrosion and a conservative estimate for the maximum corrosion of copper was <10 mm in 100 000 years.

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, U.K.. During 1987 the Phase I of this project has been nearly finalized and the prototype equipment for gun column and power supply are well advanced in the design and manufacture. A special building for housing this equipment is currently under construction.

13.2 CARBON STEEL

The study of pitting corrosion on carbon steel which started at Harwell Laboratories, UK, in 1986 has continued.

Much of the effort during this period has been devoted to the development of an improved statistical method for analysing pit growth data to take account of the difference in area of laboratory specimens and full sized waste containers /13-5/. Statistical analysis of data from pit growth experiments with large area (460 cm^2) plates of BS 4360 steel have indicated that the depth distributions correlate most closely with a limited distribution function. This contrasts with previous data with small specimens (8 cm^2) of carbon 20 steel which gave a better correlation with an unlimited exponential distribution function.This difference may arise because the larger specimens give a more accurate sample of the pit depth distribution, particularly the "tail-off" at high pit depths which is crucial in determining the overall shape of the distribution. This correlation of the pit depth data with a limited distribution implies that previous statistical analyses to estimate the maximum pit depths in full size containers, which were made using unlimited distribution functions, will be pessimistic /13-6/.

An evaluation of the maximum feasible pitting period based on estimating the period during which the oxygen diffusion flux is sufficient to stabilize a passive film on carbon steel containers has indicated that this is of the order of 125 years rather than the full 1000 year container life. The estimate is sensitive to the value of the leakage current assumed to flow through the passive film, and therefore work is planned to measure this accurately in relevant granitic environments.

14 BUFFER AND BACKFILL

14.1 CLAY CHARACTERIZATION

Clays with sufficient high content of smectites are of special interest as buffer material as well as backfill and sealing materials. Their favourable performance as components in the engineered barriers are related to the swelling ability, the low hydraulic conductivity and the mechanics during creep, thermal effects, tectonics etc.

The clay minerals and the microstructure in water saturated conditions may be altered due to changes in the environment such as temperature. The data from SKB research on bentonites and other clays were used and a number of well defined dense clays, which resemble possible alteration products of highly compacted montmorillonite-rich sodium-bentonite in repository environment, have been identified. They were physically tested as regards hydraulic conductivity, swelling pressure and rheological properties, /14-1/. Some important general conclusions are:

- While none of the natural clays came close to Mx-80, the KBS-3 reference clay, with respect to low hydraulic conductivity they show low hydraulic conductivity when high bulk density is preserved, see Figure 14-1.
- Cementing processes may have altered ancient smectites.
- Creep properties appear to be of importance not only for the definition of their rheological properties but also for understanding of microstructural response to stresses.

A survey of Swedish buffer material candidates was made and updated in 1987. Quantitative X-ray diffraction analyses were made according to Reynolds, /14-2/. The applied method yields quantitative estimates with an accuracy of ± 10%.

In cooperation with CEA, studies of French clay was continued during 1987. One heater test in Stripa was ended by excavation April 22 after 6 months with a temperature at the clay/heater casing in the range of 170—180 °C. Another heater test is still running. Studies on hydrothermal generated microstructural changes in laboratory tests are also in progress. The French clay is a natural calcium smectite which has been characterized by physical and rheological testing as well, see Section 14.2.

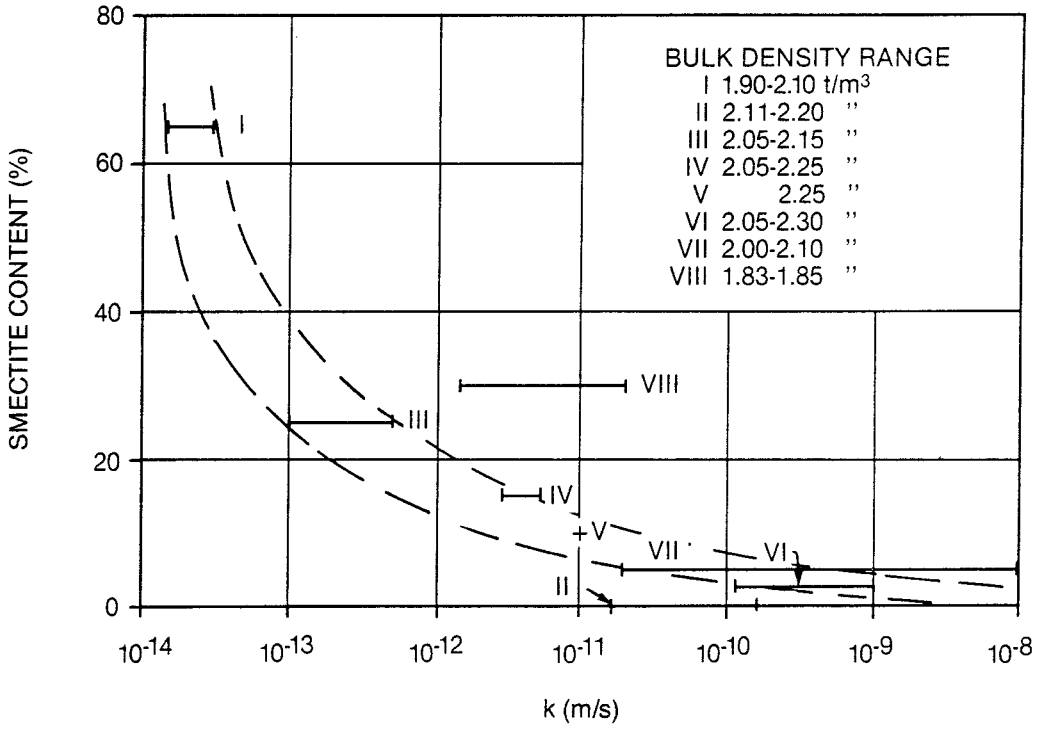


Figure 14-1. Hydraulic conductivity versus smectite content of eight clays. This content is expressed in percent of the total mineral mass. The band width is taken to represent the average spread in hydraulic conductivity of the smectitic clays with a bulk density (ϱ_m) of at least 2.0 t/m³. $I = M \times 80$.

14.2 CLAY RHEOLOGY

In the SKB research program a study on the rheology of a French smectite rich clay is included, see Section 14.1. The rheological properties of this clay have been examined in laboratory tests systematically. Triaxial tests at different densities and temperatures, rate of strain and shear tests including creep have been performed. The hydraulic conductivity, rate of water uptake, swelling ability and swelling pressure were measured as well.

The hydraulic conductivity and the measured rheological properties indicate that calcium smectite with high density ($\varrho_m \geqq 2.0$ t/m³) is very similar to sodium bentonite. Higher temperature involves increased shear strength, /14-3/.

14.3 MODELLING BUFFER PERFORMANCE

Proper design of clay barriers in repository design requires accurate mathematical modelling of water percolation, diffusion of corroding agents and radionuclides escaping from nuclear waste canisters as well as the mechanical interaction between canister, clay and rock due to gravity, thermomechanics and tectonics.

While routine laboratory tests yield average values of the hydraulic conductivity, the actual rate of flow is not revealed. Microstructure analyses of natural clays have demonstrated that there are variations in pore size and that a few wide pores may be responsible for the great majority of the permeability. A model for hydraulic and gas conductivity is derived for smectite clays which are formed from powdered sodium bentonite, /14-4/.

The model is applied to three different bulk densities for theoretical explanations of laboratory derived physical and physico/chemical properties. It is shown that realistic data are achieved for the hydraulic and gas conductivities as well as for the ratio of the anion and cation diffusion capacities. The model forms a basis for further development.

An inventory of FEM and BEM calculation programs was made and some test calculations with the code ABAQUS were made as well. Data from earlier model tests with simulated copper canister in highly compacted bentonite were used for comparisons with the calculations. More data, also from the test which simulates canister settlements, will be used in the future.

14.4 SEALING OF FRACTURED ROCK

In the Stripa Project phase 3, activities on fracture sealing are included, see Chapter 19.

The sealing efficiency of smectite gels, are depending on their ability to resist erosion by flowing groundwater. A study with light-microscope technique was investigating the processes piping and channel erosion, /14-5/.

An important conclusion was that spontaneous disintegration and loss of smectite aggregates of clay from grouted fractures will not take place even in very electrolyte-poor water at rest, see Figure 14-2. A water flow rate in the interval of 10^{-4} — 10^{-3} m/s will be required to cause substantial loss. As to the critical pressure for initiation of piping, additional experimental work is required before the validity of the physical model can be judged.

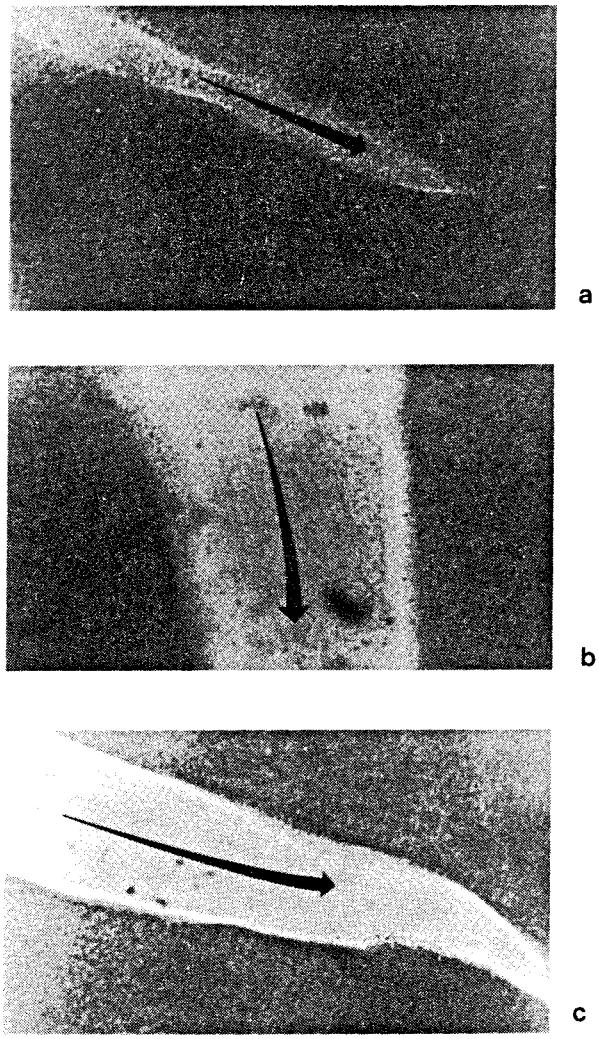


Figure 14-2. Flow test with SWY-1 Na Montmorillonite gel, W = 100% destilled water.

a) Formation of 50 μm main channel in the homogeneous clay gel.

b) Erosion of the clay gel and transport of 10—20 μm aggregates in a boundary zone (E) at a water flow rate of 10^{-4} m/s.

c) 10—50 μm aggregates are torn off and transported at a water flow rate of 10^{-3} m/s.

15 GEOSCIENCE

15.1 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 1986 /15-1/.

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 and Ävrö,
- the study on postglacial fault movements at Lansjärv,
- the study-site investigations.

The activities for the Hard Rock Laboratory — HRL — have been executed in accordance with the planning. The regional geology, geohydrology and groundwater chemistry have been documented in a series of reports. A total evaluation of the regional investigations will be reported during spring 1988. Pumptests have been performed in three areas of potential interest for siting of the laboratory and for locating a reference area not to be influenced by the laboratory. Drilling of a few cored holes to a planned depth of 1000 m begun late 1987.

Phase 2 of the fracture zone study at Finnsjön is finished. A total evaluation of the phase — detailed characterization of the fracture zone — will be reported during 1988. An outline of the tracer tests in Phase 3 of the project has been presented. The tests will be preceded by predictive modelling. Tracer tests included in the project will be applied in the modelling work of the international INTRAVAL-project, see Chapter 17.

The study of postglacial fault movements in the Lansjärv area has continued as planned. Drilling through the zone with expected postglacial movements started autumn 1987. A final evaluation of the Lansjärv study is planned to be reported early 1989.

Analyses of the Klipperås study-site have proceeded with statistical treatment of the borehole data. A regional groundwater model has been defined. Assumptions with respect to boundary conditions for a site model have been tested.

The safety analysis of the SFR-facility, see Chapter 5, that was reported to the Swedish authorities during the year has contributed to increased understanding of which factors influence the safety of a nuclear facility. It is expected that the knowledge gained will influence the future geoscience programme.

15.2 SWEDISH HARD ROCK LABORATORY — HRL

15.2.1 Overview

The primary objectives of the laboratory are to:

- Demonstrate that the site dependent factors that control the safety of a final repository are understood and can be quantified or delimited.
- Validate the models and assumptions included in the safety analyses.
- Develop methods for construction and quality assurance of a final repository for spent fuel.

The activities can be grouped in three separate phases.

The current phase – Pre-investigation – aims to site the laboratory, describe the natural conditions in the bedrock and to predict the changes that will occur during construction of the laboratory.

Phase 2 — Construction — is planned to start autumn 1990. A tunnel will be blasted to about 500 m below surface. The predictions from the previous phase will be checked and discrepancies explained.

The experience gained from the Pre-investigation and Construction Phase will later be used to characterize at least two sites in Sweden before the final selection of a site for a repository.

The third phase of the laboratory activities — Operation — is planned to commence 1993 and may last up to 50—60 years.

For the period to 1993 it is expected that the following objectivities will be reached:

- A suitable site for the laboratory.
- A detailed description of the natural conditions around the site.
- A detailed prediction of the disturbances caused by construction.
- Explanation of small discrepancies between measured and predicted responses.
- A relevant and practical methodology for detailed characterization of a rock mass, to be used for detailed investigation on two sites in Sweden.
- Construction Phase completed.
- Relevant activities planned for the Operation Phase of the project.

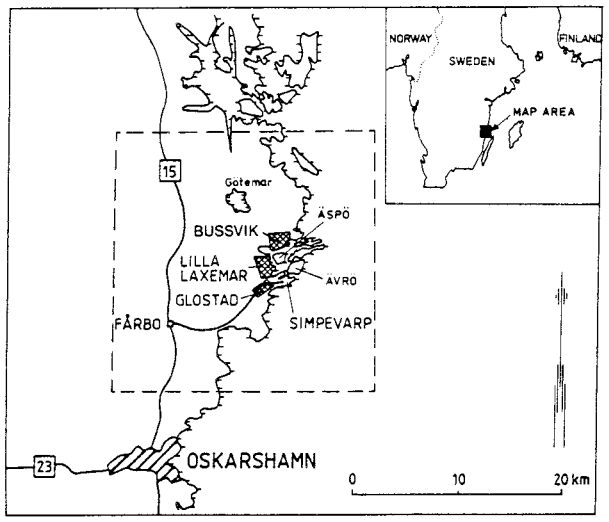


Figure 15-1. Five areas have been investigated in detail during 1987. The purpose was the siting of the laboratory and siting of a suitable reference area.

Present investigations are aimed at siting the laboratory at the Oskarshamn nuclear power plant close to the CLAB-facility, see Figure 15-1.

15.2.2 Pre-investigation Phase

The phase has been divided into three separate stages. The first stage is the Siting Stage. The second is the Site Characterization Stage and the third is the Prediction Stage.

The Siting Stage started 1986. The stage includes all data gathered up to start of diamond drilling. A final evaluation will be reported spring 1988.

The Site Characterization Stage is divided into two parts. The evaluation of the Siting Stage with additional information from three diamond drilled holes that is included in the first part of the second stage will be the foundation for the siting of the laboratory. The second part includes extensive drilling. The objective is to predict the hydraulic response from a long time pumping test. The second stage will end spring 1989.

The third stage — the Prediction Stage — comprises a comparison of measured and predicted responses from the interference test. The evaluated conceptual model will later be used for å detailed prediction of the disturbance caused when constructing the laboratory. The prediction model shall be available before construction work is started.

The current stage — the Siting Stage — was initiated autumn 1986 and a wealth of data have been gathered during 1987.

The low-altitude airborne surveys in the south-east of Sweden have been evaluated /15-2/. An interpretation of the magnetic surveys is showed in Figure 15-2.

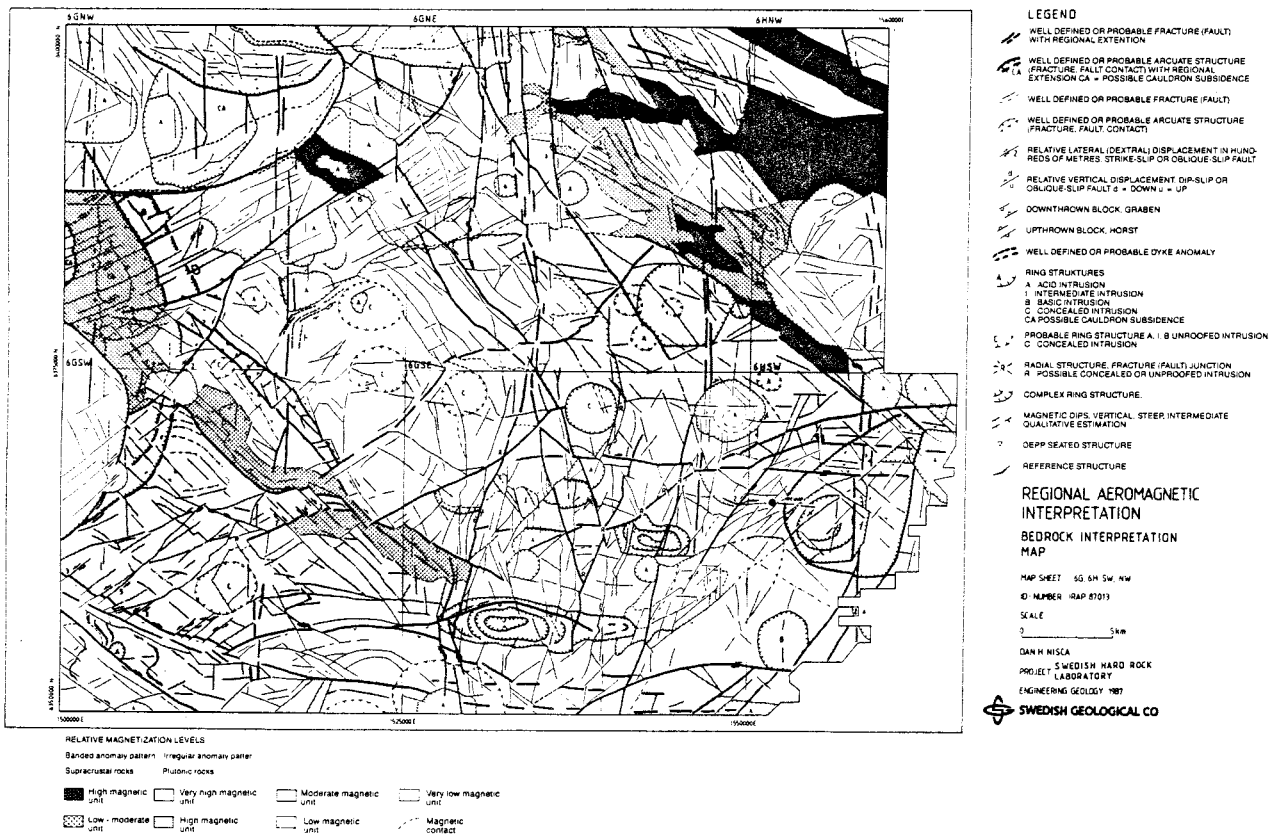


Figure 15-2. Interpretation of aeromagnetic surveys.

The area selected for interpretation is large and motivated for the purpose of a regional tectonic understanding of the area that is necessary in the later continuation of the Bedrock Stability project, see Section 15.4.3. The tectonic map shows that zones in north-south direction are most frequent. Vertical faulting is common.

Zones in east-west direction are interpreted to be older than the north-south zones. One characteristic feature in the area is the diapiric granite intrusions. The bedrock interpretation map also shows the boundaries of highly magnetic bedrock — diorite and gabbro.

The airborne surveys were supplemented by a regional gravity survey, 1220 measuring points, on average 1 point/km^2.

The total geophysical evaluation /15-3/ included the air-borne geophysical data, the gravity measurements and measurements of the petrophysical properties on 257 rock samples. The air-borne data included surveys of magnetic and electric field and gamma radiation. The electrical methods used were VLF (Very Low Frequency) in two directions and Slingram measurements. The gamma radiation instrument was calibrated against the natural isotopes of Potassium, Uranium and Thorium and against Cesium-134/137 from fallout.

The interpretation shows that the diapirs Götemar and Uthammar are plunging outwards. From the VLF-analyses it is expected that the N-S zones are the most probable water-bearing fractures.

During summer 1987 an extensive mapping of the bedrock, including description of rock and fractures was carried through /15-4, 15-5/.

The rocks of the Simpevarp area belong to the vast region of granitic intrusions extending from south-eastern Sweden towards the north and as far as south-eastern Norway. Closely related to the plutonics are extensive supracrustal extrusives. The oldest supracrustals are >1.8 Ga. The Småland granites are more than 1.7 Ga and the diapirs e.g. the Götemar granite 1.3 — 1.4 Ga. The bedrock around the Simpevarp area consists mainly of fine- to medium-grained Småland granites with dykes of greenstones. A compilation of experiences from underground construction works in the area demonstrate that grouting work often is associated with occurrence of fine-grained granitic dykes N 60-80E.

Fracture data from 122 outcrops and 17 road cuts have been gathered /15-6/. In total 13000 fractures have been mapped with respect to e.g. length, strike, dip and fracture minerals. The analyses show that fractures in NS-, N50W- and EW-direction dominate. The fracture lengths are well correlated to a log-normal distribution.

A preliminary comparison between the tectonics in the Lansjärv area, see Section 15.4.1, and the Simpevarp area has been attempted /15-7/. It demonstrates that the Lansjärv area is more ductile. The lineaments are longer and have been reactivated several times. The zones in the Simpevarp area are shorter with a more brittle behaviour.

The topography in the region has been analysed with modern techniques /15-8/. A digital elevation data base has been utilized. An orthogonal grid 50x50 m with altitude accuracy of ± 0.5 m was used to produce maps for analyses. Hill shading, residual elevation, edge texture, line texture and iso-elevation maps were the basis for regional lineament studies. Interpretation was made interactively in the computer. The topographical lineaments were as well co-interpreted with the magnetic lineaments. The correlation of the main N-S and E-W trending aeromagnetic lineaments and the topographic features is good. For the rest of the linear structures correlation is moderate. For circular structures correlation is bad. Several types of maps were used to divide the bedrock into rock blocks, see Figure 15-3, indicating potential zones of movement.

A detailed structural analysis has also been performed on the five areas depicted in Figure 15-1 /15-9, 15-10/.

Before the percussion drilling programme commenced, a regional and local compilation of hydrogeological and ground water chemistry data was reported /15-11—14/. Measured precipitation is 675 mm water column per annum /15-11/. Calculated evaporation is 490 mm and runoff between 150 to 200 mm. A total of 162 wells have been studied and analysed, /15-12/. There exists a bedrock-specific capacity. The correlation between the digital terrain model and specific capacity is scattered. Some indications show that the sectors around NE-SW more frequently are related to higher specific capacities. Geohydrological data from construction works in the area have been compiled and typical data of hydraulic conductivity specific capacity, groundwater table and water chemistry are presented /15-13/. The groundwater chemistry has also been interpreted from the survey of regional wells /15-14/. Conductivity, pH-values, calcium, magnesium, potassium, sodium, iron, manganese, alkalinity, sulfate and nitrate and others were compiled from about 300 wells in the region. Emphasis was placed on analysis of chlorides.

The primary objectives of the percussion drilling programme that was carried through on Ävrö, Äspö and Laxemar, see Figure 15-4, were to check the hydraulic connectivity in the lineaments, to provide a framework for enhanced prediction at depth and to provide data for the detailed planning of the diamond drilling programme.

Compared to all wells in the region and to the wells in the Simpevarp area /15-15/, the wells show a hydraulic conductivity in the same range as for the gabbro for the whole region. However, the variation is much higher. The total co-interpretation of geology, pump tests and ground water chemistry will be reported during 1988.

The diamond drilling programme commenced late 1987. KAS02 and KAS03 are planned for a depth of 1000 m, diameter 56 mm. KLX01 is planned to a depth of 700 m, diameter 76 mm.

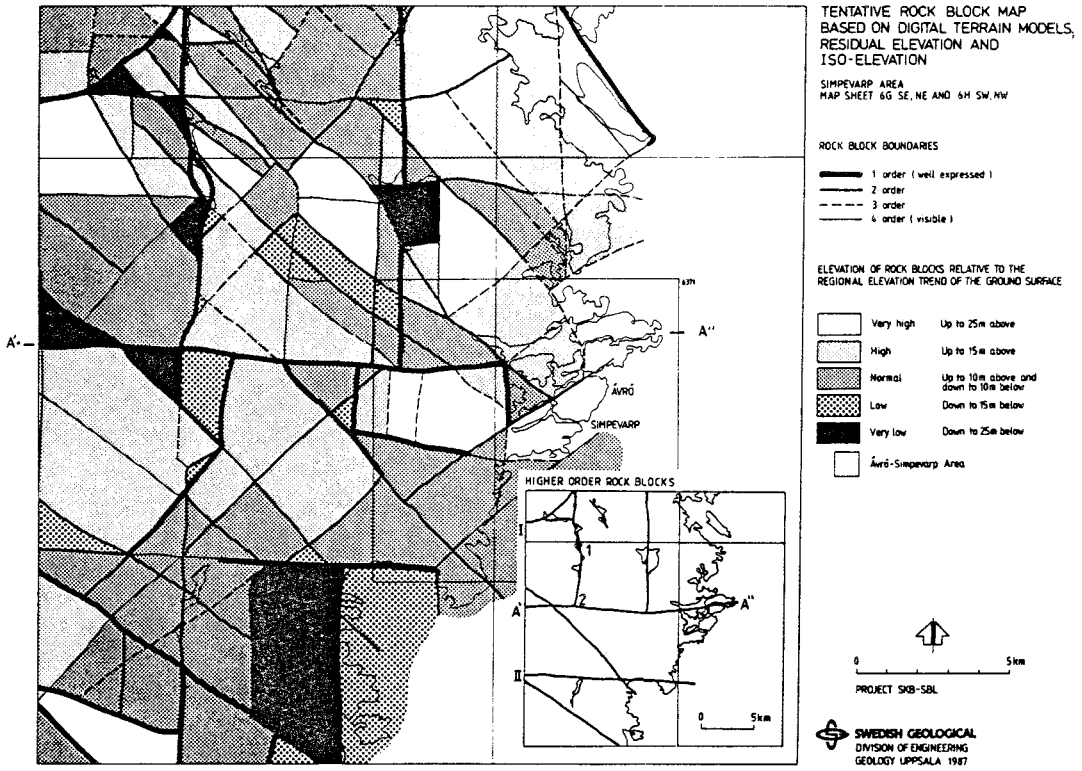


Figure 15-3. Tentative rock block map based on digital terrain models, residual elevation and iso-elevation.

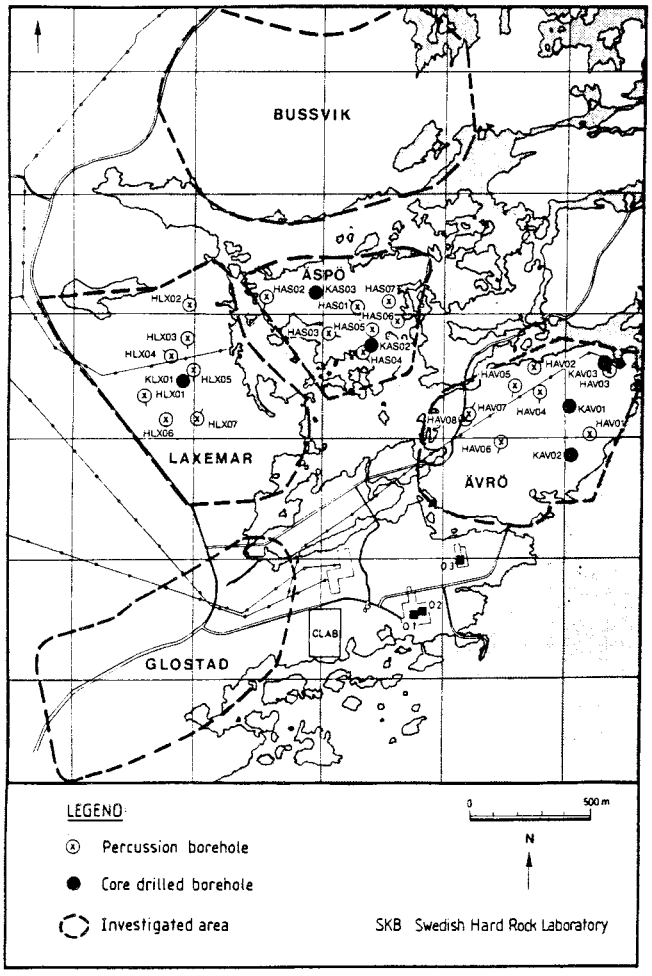


Figure 15-4. Location of target areas and exploratory drilling holes. The holes KAV01, KAV02 and KAV03 are from an ongoing fracture zone study, see Section 15.3.4.

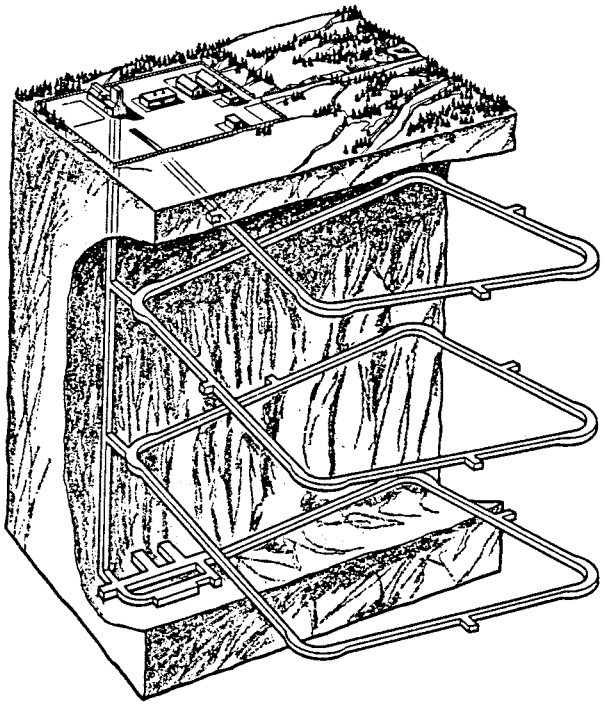


Figure 15-5. Sketch showing an access layout considered.

15.2.3 Construction Phase

Planning for the construction phase is in progress. An evaluation of the alternative access possibilities to 500 m with respect to data acquisition, modelling, cost and operation of the laboratory showed that the tunnel alternative was preferential to shaft sinking.

A preliminary, generic model of the draw-down for the shaft and the tunnel alternative considered, see Figure 15-5, has been executed /15-16/. The model utilized the Analytical Element Method. The shaft layout gives almost the same radius of influence as the spiral layout when comparing a draw-down of 1 m.

15.2.4 Operation Phase

An outline of activities during the Operation Phase is in progress. A very preliminary compilation of potential experiments will be scrutinized during 1988. It is planned that the outline of the activities during the first part of the Operation Phase will be presented in the R&D programme 1989.

15.3 GROUNDWATER MOVEMENTS IN THE ROCK

15.3.1 Overview

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

The relative importance of the parameters that describe flow in the bedrock can be assessed in performance assessments and safety analyses. The research has thus earlier benefited from the KBS-3 study /15-17/ which initiated the present studies of fracture zones, see e.g. Section 15.3.2. The Final Safety Report for the SFR-facility, see Chapter 5, is also expected to influence the current priorities of potential projects.

One of the factors that has great importance for assessment of radionuclide transport of non-sorbing 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 contrasts for the groundwater flow has been illuminated by the experiences from SFR, from actual groundwater flow measurements in boreholes at the Finnsjön study-site and analyses in generic models. It has been demonstrated that there often exists an interface between fresh and saline water at depth and that the flow is almost stagnant below the interface.

The conceptualization of the groundwater flow distribution is important for the overall assessment of radionuclide transport, both non-sorbing and sorbing. The hypothesis that groundwater flow occurs in essentially independent channels or pathways needs thorough studies. Studies of flow distribution in tunnels have supplemented borehole data during the year. A project using radar measurements in conjunction with injection of saline water has started in order to study the potential of using the technique for characterization of the flow distribution.

The assessment of the SFR-facility clearly demonstrates that there is a need for closer analyses of the so called skin zone in the vicinity of openings in the rock. It is anticipated that the ongoing studies in Stripa, Phase 3 and URL, see Section 15.5, will make substantial contributions.

15.3.2 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 /15-18/. The second phase — detailed characterization of the fracture zone — was completed late 1987. A total evaluation of the geological, geohydrological and chemical work included in the second phase will be presented during 1988. The third phase comprises essentially a series of tracer experiments. All tests are preceded by predictive modelling. The last phase is planned to be finalized during 1989.

The Finnsjön test area is depicted in Figure 15-6 and 15-7.

The subhorizontal Zone 2 was formed more than 1.6—1.7 Ga ago as a some hundred metres wide ductile shear zone at a depth of about 10 km. The zone has later

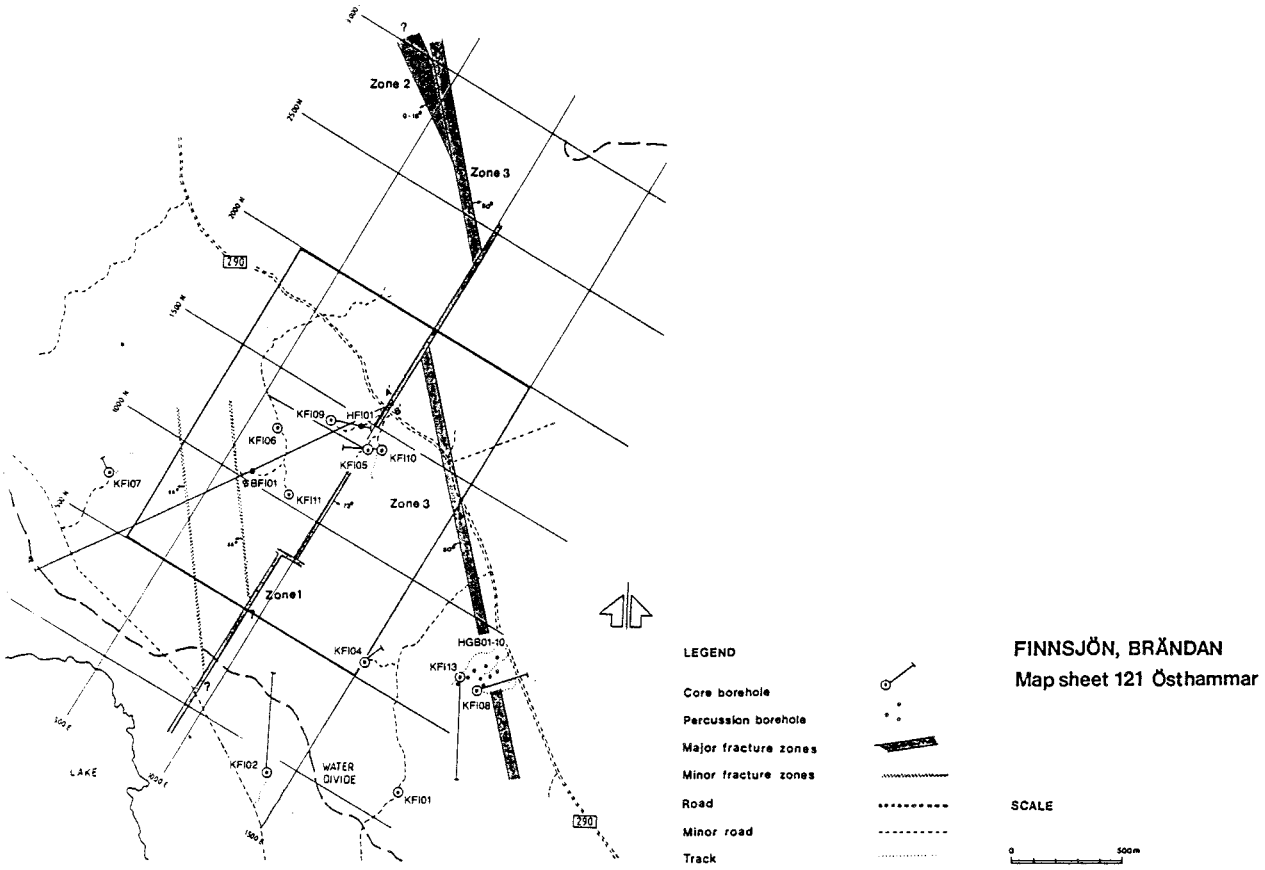


Figure 15-6. Map of the Finnsjön area showing borehole locations and major vertical fracture zones. The study is focused on the subhorizontal Zone 2, see Figure 15-7.

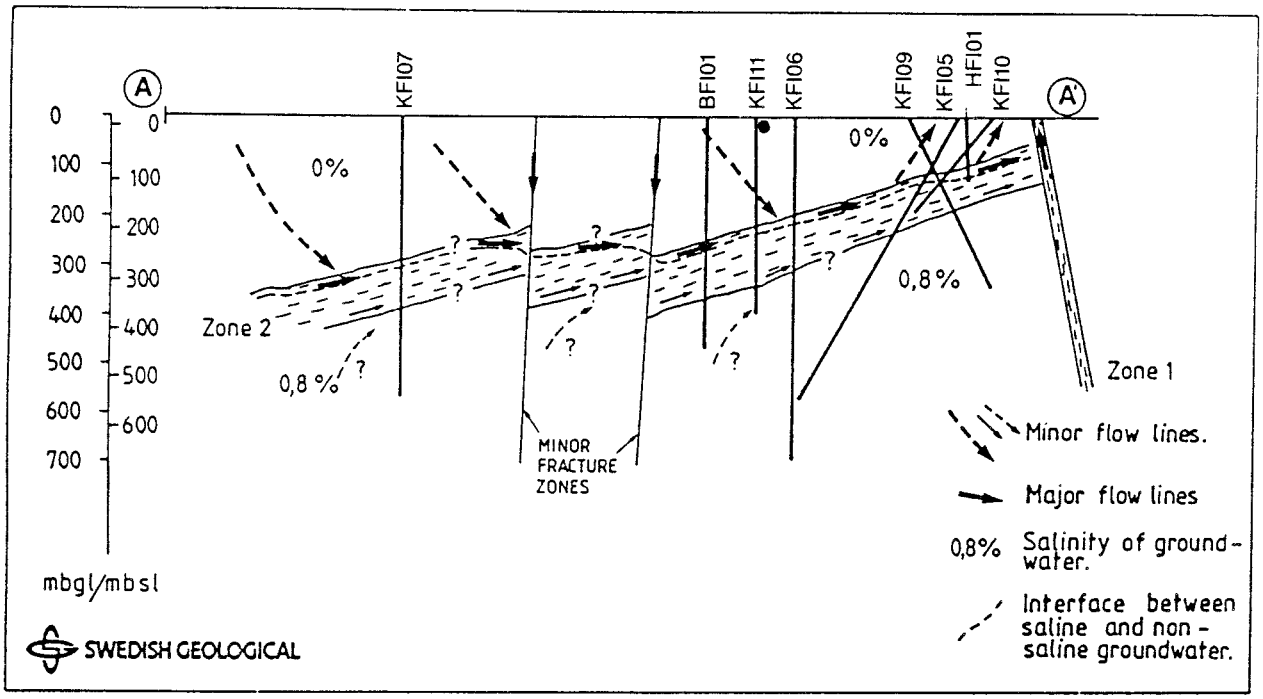


Figure 15-7. Transverse geohydrological section showing a tentative model of groundwater flow during undisturbed conditions. The location of the profile is shown in Figure 15-6.

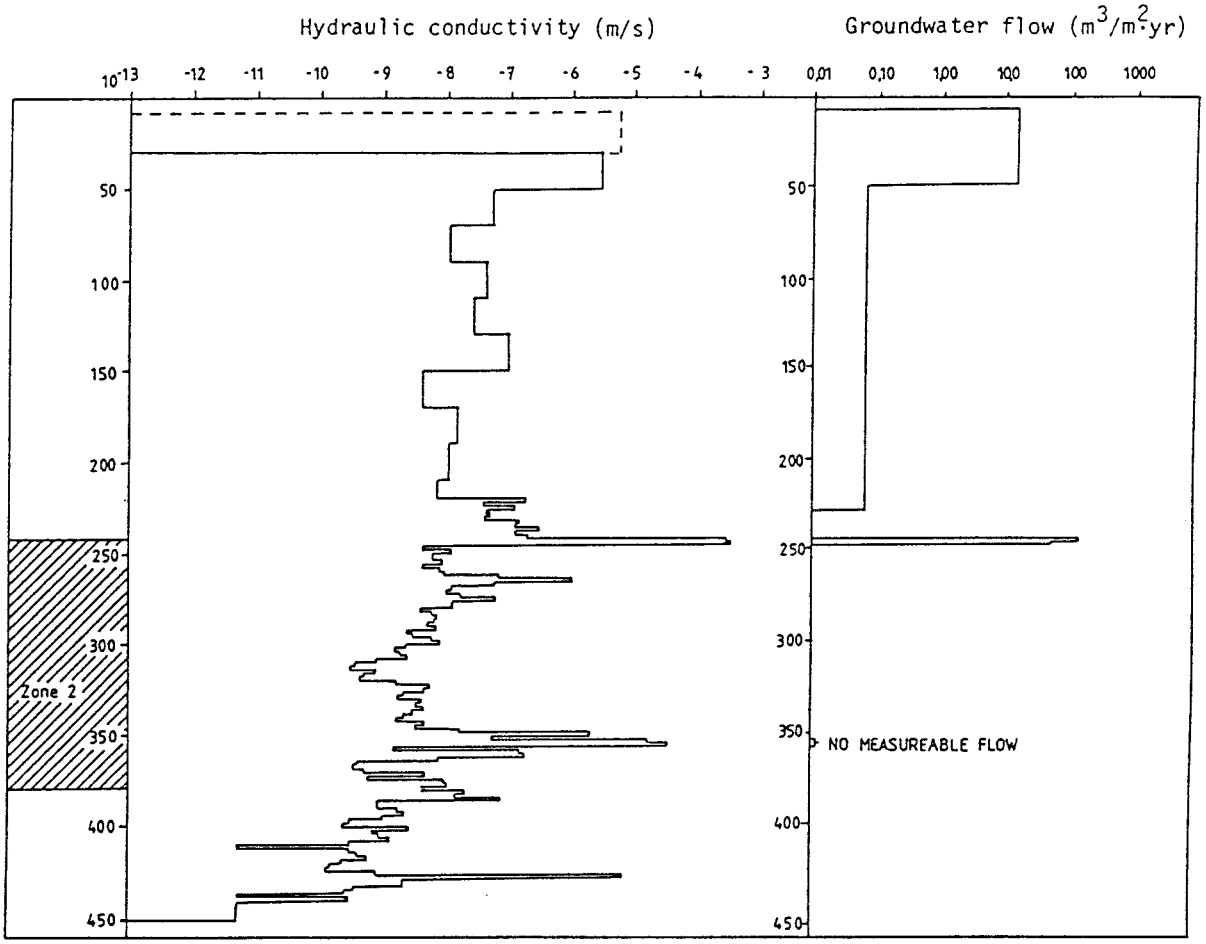


Figure 15-8 . Measurements of hydraulic conductivity and groundwater flow in borehole BFI01.

been reactivated several times. A study of fracture minerals shows that the hydraulic pathways have changed during geological time. The pathways seem to have been more and more confined to narrow fractured sections of Zone 2. The present water flow along the zone occurs predominantly in the upper part of the zone. The conclusion is substantiated by the flow measurements that has been performed using the dilution probe, see /15-19/ for description of equipment. The measurements, see Figure 15-8, show that no flow was measured below the saline interface, thus confirming that the interface can constitute a hydraulic barrier against descending non-saline water. Zone 2 acts as a boundary between two main groundwater regimes. The groundwater in the upper part of the bedrock in the western part of the Finnsjön site is drained by Zone 2. Within the zone the groundwater flows eastwards and is discharged to Zone 1 and to the areas east of the site.

The influence of salinity on groundwater flow has as well been studied in a preliminary report for the HRL /15-20/. A coastal regime with small density contrast has been modelled with varied assumptions. In one model, a horizontal layer with increased conductivity was simulated, see Figure 15-9. It is clearly demonstrated that the zone acts as a "low resistancelink" between recharge and discharge areas and that the zone acts as a hydraulic barrier.

A major work at Finnsjön during 1987 has been the groundwater sampling.

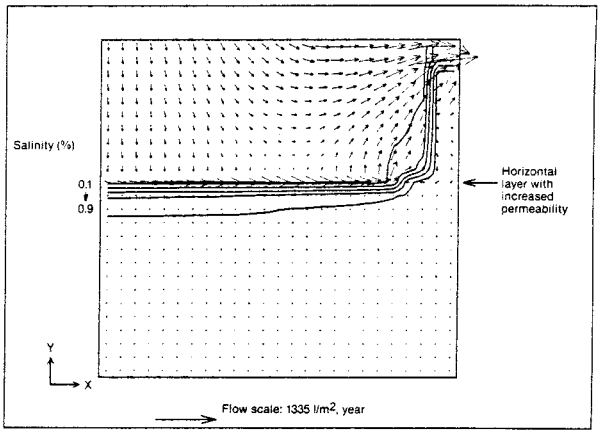


Figure 15-9. Flow distribution for a horisontal conductive layer 300 m below surface. Salinity of 1% is initially specified as a vertical boundary.

A vertical hole BFI01 was drilled down to a total depth of 460 m with booster aided percussion drilling technique. The borehole was drilled primarily for groundwater chemical characterization. Water collection was carried out by alternately drilling and sampling in a stepwise procedure. Of special interest was the subhorizontal fracture zone (Zone 2) which is known to present a structural boundary between saline and non-saline groundwater. Prior to drilling the upper part of Zone 2 was calculated to beat a depth of about 240 m below ground surface, and the thickness calculated to 85 m. The drillsteps one to six and the sampling sections are illustrated in Figure 15-10.

The location of water conducting zones was possible by continuous recording of the drill technical parameters, drill cuttings, borehole water yields and the electrical conductivity of the water.

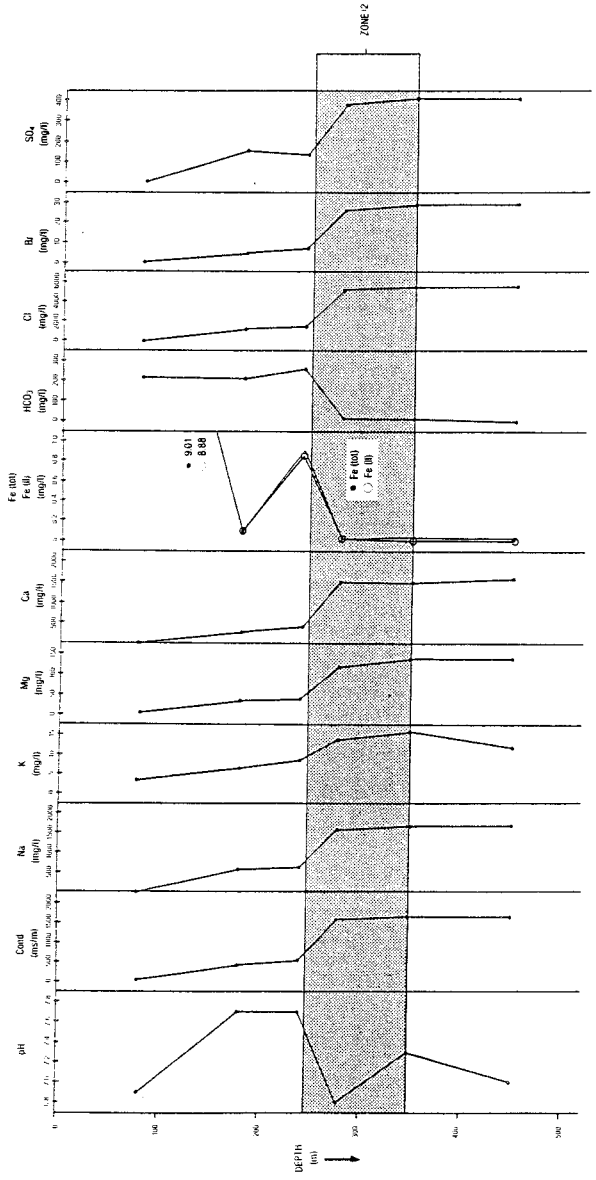


Figure 15-10. Variation of pH, conductivity and selected ions with depth (borehole BFI01).

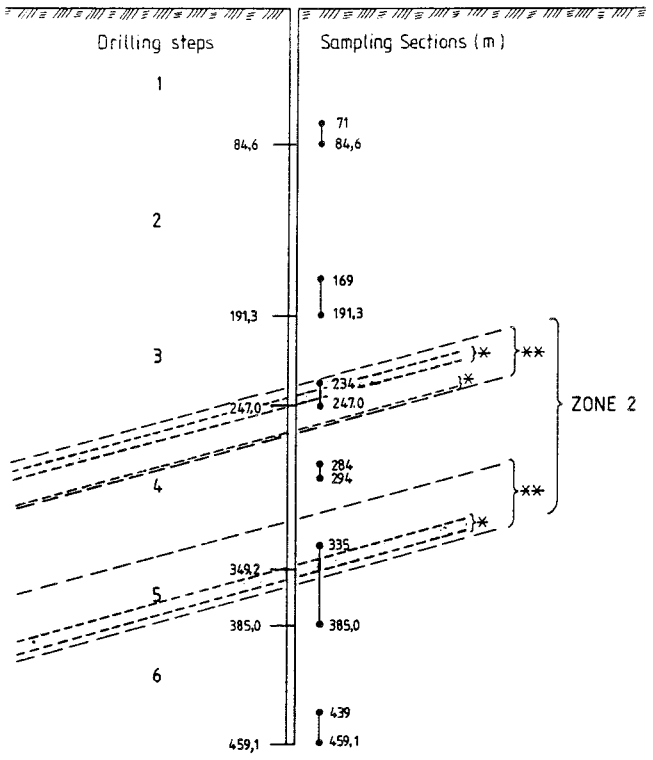


Figure 15-11. Drill steps (1-6) and sampled groundwater sections (vertical bars) for borehole BFI01.
**Fractured zones determined from drill cuttings, every fifth metre.*
***Fractured zones determined by hydraulic testing in 2 m sections, geophysical logging, tubewave and borehole radar measurements subsequent to the hydrochemical water sampling.*

There is a sharp increase in salinity of the groundwater from the upper part of Zone 2 and downwards, see Figure 15-11.

The sub-horizontal Zone 2 and the adjoining steeply dipping zone 1 have effectively trapped groundwater of a high saline character at a level which is only about 100-300 m from the bedrock surface. Zone 2 represents a zone of hydraulic mixing and the waters above and below represent extremes of composition. This local pattern can probably be extended in the Finnsjön area. It has been suggested, based on these and similar results that saline water exists throughout the bedrock and that its depth of occurrence is highly dependent on dip and sub-aerial extent of large-scale conductive zones /15-21/.

The techniques of borehole radar and tubewave measurements were tested in BFI01. The borehole will be further utilized for the tracer tests in Finnsjön.

The drilling of borehole BFI01 and hydrochemical testing have shown the advantage of using air flushed percussion drilled holes for sampling down to depths of

100—200 m, as compared to conventional water-cooled drilling where large amounts of drilling water normally are lost in the upper more conductive part of the rock. The hydrochemical parameters obtained have increased the understanding of near surface groundwater composition and the role of subvertical fracture zones for preserving old saline water signature after land uplift, see also Chapter 17. The experiences gained have been utilized in the hydrochemical studies of the Simpevarp area preceding the rock laboratory construction.

The Finnsjön site has as well been used as a test facility for methods and equipments.

Shallow reflection seismic investigation of fracture zones in the area has been attempted /15-22/. The zone 2 did not appear in the measurements. The steeply dipping Zone 1 is, however, apparent. Reflections from depths below 400 m are seen, but as a broad band of coherent energy in the same window 0.5-1.0 s, corresponding to a depth of approximately 1500—3000 m. The results can be interpreted to coincide with ideas outlined earlier /15-23/, namely that there exists a seismic discontinuity surface at about 1500 m depth.

The siting of a repository is truly three-dimensional. It has been advocated that there is a potential benefit to locate a repository below 1500 m with respect to the seismic discontinuity surface. Very Deep Drilling both in the Kola peninsula and in Sweden — the exploration hole for deep earth gas at Gravberg — however, clearly demonstrates that fracture zones can occur on all depths. It is thus important to locate a repository at a convenient distance from both vertical and horizontal zones. The KBS-3 study /15-17/ shows that a safe repository can be constructed at a depth of about 500 m. The depth must, however, be chosen dependent upon the local conditions.

Phase 3 of the fracture zone study comprises primarily a set of tracer tests. All experiments will be preceded by predictive modelling. The first, preliminary tracer test is performed in conjunction with an interference test. The second test is a radially converging tracer test with undisturbed injection. The distance between pumping and injection hole is about 150 m. The third test is a dipole test over a distance of 150 m. The last tracer test will use the natural gradient over a distance of 500 m. Mainly non-sorbing tracers will be utilized even. It is as well planned to attempt weakly sorbing tracers. The third phase is in progress and will be an example in the international INTRAVAL-project.

15.3.3 Fracture Zone Studies at Ävrö

The study at Ävrö is intended to be included at a later stage in the investigations for the HRL. The results, so far /15-24/ show that a major fracture zone is encountered between 418 and 578 m in borehole KAV01. The hydraulic conductivity varies between 1.4×10^{-6} to 3×10^{-5} m/s.

The zone dips 40° towards the horizontal, and is interpreted to strike NS. However, other alternatives of orientation are possible.

15.3.4 Studies in Connection to Construction Works

A careful mapping of water leakages in a drilled tunnel, diameter 4.5 m /15-25/ over a length of 4500 m has been performed in order to expand the data base for flow distribution and obtain estimates of e.g. channel frequency. One of the conclusions from the study is that a quarter of the inflow to the tunnel emanates from the bedrock in between the tectonic zones. Most of the leakage appear as channels but leakage also occurs as "curtains".

An evaluation of the predictivity for geophysical methods as a tool in construction work is reported /15-26/. Extensive geological and geophysical methods were used in the planning of the 80 km long Bolmen tunnel. During construction supplementary geophysical measurements were made. Continuous geo-mapping during and after construction together with data on grouting has been utilized in order to evaluate the predictive capacity of common geophysical methods as airborne electro-magnetic surveys, groundlevel VLF and Slingram, resistivity measurements and seismic refraction surveys. It was possible to indicate about 80% of zones of weakness more than 50 m wide in the tunnel. The VLF and Slingram methods indicated 75 and 85% respectively of all zones of weakness more than 50 m wide. Resistivity methods were successfully used to locate clay filled and water-bearing zones. About 75% of the length of tunnel over which resistivity values below 500 ohm were measured, required shotcrete support and pre-grouting. Using refraction seismics about 60% of zones more than 50 m wide were indicated by refraction seismic velocities of 4400 m/s or less. The corresponding value for narrower zones — 10 to 50 m wide — was about 65%.

A test for the predictive capacity of radar measurements is in progress, /15-27/. A drilled tunnel 7.6 km, diameter 3.5 m, situated in central Stockholm and presently under construction was selected. An interpretation of the radar measurements has been arrived at along a stretch of the tunnel without access to any other geological, geophysical or hydrological data, except a topographic map of the site. A second interpretation has later been presented with access to core mapping, geophysical logging and hydraulic borehole measurement data. A comparison with the actual conditions encountered in the tunnel is in progress.

15.3.5 Flow Distribution in a Fracture Zone

The basic principle behind the investigation of flow distribution in a fracture zone with borehole radar is the following:

First a reference radar measurement is made which gives information about the location and extent of fracture zones, rock type boundaries and other geological discontinuities.

The second step is to inject a saline tracer into a suitable fracture zone. The introduction of salt into the

groundwater will increase the attenuation of radar waves which can be registered through a repeated radar measurement. A difference in radar response between the measurement made prior to injection indicates that saline tracer is present somewhere along the ray path. With a sufficient number of radar measurements the location of the saline tracer in the rock can be found.

The investigation is carried out at the Crosshole Site in the Stripa Mine. Here, seven boreholes intersect the fracture zone in which the saline tracer will be injected. Single hole reflection and tomography measurements are made between different combinations of these boreholes. The number of combinations is so large that a three dimensional picture of the groundwater flow paths within this fracture zone will be obtained. The experiment is also combined with a more conventional migration experiment where the salt concentration will be measured as a function of time in all other boreholes except the one used for the injection.

The reference measurement with radar was made during 1987 and the saline injection, migration experiment and the repeated radar measurement will be made during 1988.

15.3.6 Developments in Modelling

Stochastic models have been applied to solute transports in fractured rock /15-28/. Four different field tracer tests in Sweden and Canada have been reexamined. The results show that the variance of the natural logarithm of the aperture is found to be in the range of 3 to 6 and the correlation scales for logaperture in the range 0.2 to 1.2 meters.

Generic studies of two-dimensional networks have been carried through to enhance the understanding of the channelling concept, /15-29/. About one hundred different statistically equivalent channels were generated. The aperture distribution along the channels were used to determine the total channel volume, the hydraulic conductivity, the flowrate and the residence time for a given gradient. One of the conclusions is that simulations of breakthrough curves for tracers in single fracture flow experiments indicate that when few channels participate and the dispersion in the individual channels is small, the breakthrough curve is expected not to be entirely smooth but to contain distinct plateaus.

A joint project between OWTD, US DoE and SKB on well test statistics is still in progress.

The SKB activities within the HYDROCOIN project has been reported with respect to Level 1 and Level 2 /15-30, 15-31/. Work on Level 3-sensitivity and uncertainty analyses are in progress. Nine conceptual models for the Fjällveden study-site are compared with respect to head distribution, flow field, flow rates, particle trajectories and recharge. The effect of anisotropic hydraulic properties, the effect of hydraulic contrast in the bedrock and the effect of variation of depth-dependency for the hydraulic conductivity are examined. Implementation of adjoint sensitivity technique will be finished during 1988.

Analyses of gas migration was a part of the final safety report for the SFR-facility. Calculations have been executed with two conceptual models — a continuum model /15-32/ and a discontinuum model — fractured rock /15-33/. In the latter report it is concluded that the initial hydrostatic pressure is exceeded only during a few minutes in the initial stage and that the flow problem is governed by the high permeability fractures.

15.4 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 movements can decisively alter the geohydrological situation around a final repository.

The objectives are to:

- quantify or set limits on the consequences of earthquakes, glaciation and land uplifts of importance in analyzing the safety of a final repository for spent nuclear fuel,
- process, evaluate and increase knowledge concerning the geodynamic processes in the Baltic Shield.

Major efforts in the project are directed to the Lansjärv study and to computer modelling of large scale rock masses to study effects of e.g. glaciation, ice sheet advance, deglaciation, ice sheet retreat and melt-down.

15.4.1 The Lansjärv Study

The Lansjärv fault scarp is supposed to be postglacial e.g. younger than 10 000 years.

A study is outlined to:

- obtain a geological-geophysical basis for an optional location of detailed studies with deformation measurements, drill holes and excavations. Of special importance is to indicate where new fracturing has occurred in the bedrock,
- obtain an understanding within a broader regional context for where movements and earthquakes occur today.

The major conclusions regarding the tectonics are e.g.:

- three regional fault systems were identified, two steep NW and N trending and a third NNE trending with gentle ESE dips,
- the steep fault systems have strike-slip generated deformation patterns both in the Precambrian structures and in the morphology,
- the post-glacial Lansjärv fault is part of this fault-pattern and represent movements mainly on a reactivated, gently dipping zone.

The tectonic interpretation map have utilized digital image-processing techniques for the combined interpretation of magnetic, elevation relief and gravity. The results are documented in a set of maps to be published during 1988 together with the report.

So far, no new post-glacial fracturing of the bedrock has been identified.

A diamond drilled hole through the zone of post-glacial movements is under way. Results from the hole have been delayed due to drilling problems, but measurements of hydraulic conductivity, primary stresses and groundwater sampling are expected to be reported during 1988 together with preliminary analyses of the fracture minerals in the core.

The mobile network for detecting seismic activity has registered a few events. Interpretation is under way. The permanent seismic network started operation during the autumn and events registered will be reported during 1988.

It is anticipated that the Lansjärv study will be concluded during 1989 and that the study later can be used for a comparative analysis of the tectonics in the South East of Sweden where no post-glacial scarps have been identified and where seismic activity is very uncommon.

15.4.2 Computer Modelling of the Rock Mass

As a basis for the planned modelling the existing knowledge on crustal stresses for Western Europe and North America is reviewed /15-34/. The data is used for a stress model of the Fennoscandia suggesting ridge push at the Mid Atlantic Ridge as a major stress generating mechanism for the maximum horizontal stress. Generic two-dimensional modelling is under way using an explicite finite difference technique to study the potential influence of glaciers on the rock mass at depth.

One part of the modelling project is aimed at validation of the numerical codes used. The Colorado School of Mines block tests have been used for checking the performance of the codes. The results are promising and the comparison of numerical results with stress measurements, shear displacement, shear stiffness, conducting aperture and with measurements of displacement vectorin general show a good agreement.

15.4.3 Studies in Southern Sweden

A compilation of geological data, published — and to some extent not earlier published — has been reported, /15-35/. The report will be used as a basis for further studies of tectonics and bedrock stability. The maps will as well serve as a basis for the permanent seismic network that is in operation in the South East of Sweden. No major event was registered within the network during October 1986 — March 1987. Seven other events in southern Sweden were detected and an interpretation of these is presented /15-36/.

15.4.4 Miscellaneous

Two reports concerning the aftershock sequence of the Skövde $M_L = 4.5$ earthquake have been produced, /15-36, 15-37/. The former report presents an interpretation of the aftershock sequence mainly based on the measurements received from the FOA-network used primarily for verification of nuclear explosions. An analysis of the main event is included. One conclusion is that the static stress drop is above 30 MPa for the Skövde main event.

The latter report presents results from the SKB mobile seismic network. It monitored the most comprehensive Swedish earthquake series that has ever been investigated in great detail with deployed field seismometers. Four of the field-recorded aftershocks have been recorded with by a sufficient number of stations to be individually located. Assuming 30 km as a good estimate of the main shock the located aftershocks are distributed approximately along a plane trending N30 °E. No aftershock is more than 10 km from the main shock.

15.5 URL — CHARACTERIZATION OF THE 240 LEVEL

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 1990. SKB regularly attach staff or designated representatives to follow and participate in the work, Present assignment is aiming at rock stress predictions /15-38/. A cooperative effort for a reevaluation of the so called Room 209 Excavation Response Experiment is under way.

15.6 STUDY-SITE INVESTIGATIONS

15.6.1 Klipperås

The radar measurements from the Klipperås study-site are reported /15-39/. Most radar reflecting structures are oriented in EW and have a vertical or subvertical dip. Greenstone constitutes a large part of these reflectors. A majority of the interpreted radar reflectors intersecting the borehole are coupled to low resistivity measured in the geophysical logging.

A thorough statistical analysis of all borehole data employing multivariate analysis is initiated. Special emphasis is directed to prediction of hydraulic conductivity and conducting fracture frequency.

The possibility to employ the borehole data for discrete network modelling is under way.

Groundwater modelling of the Klipperås study-site started during the year. The regional modelling exercise has so far been focused on the effect of heterogeneity on the boundary conditions for a subregional model. The preliminary calculations of the regional domain show that hydrostatic boundary conditions can be justified. Calculations for a three dimensional subregional model have been executed. These will be studied further as there is a general interest to increase the understanding

of what impact the boundary conditions have on the overall calculations.

15.6.2 Reconnaissance

Site selection activities have mainly included compilation of earlier reconnaissance works. This updated database is going to be the base for selecting possible sites.

A general plan for the screening and selection of sites is in progress and will be presented during 1988.

15.7 DEVELOPMENT OF INSTRUMENTS AND METHODS

During 1987 the main effort in the field of instruments has been concentrated more on refining and modification of already existing equipment than on development of new types. Some of the development work has been initiated in connection with the planning of the pre-investigations for the Hard Rock Laboratory where a number of new field testing methods will be used.

15.7.1 Drilling Techniques

The drilling programme for SKB site investigations comprises percussion drilled boreholes of 115 mm (sometimes 165 mm) diameter normally down to 100—150 m and diamond-drilled cored boreholes of 56 mm diameter down to greater depth, 500—1000 m. In some cases also a deeper percussion hole is drilled with a high-effective booster compressor machine.

The small 56 mm diamond-drilled boreholes have in combination with specially designed borehole instruments been successfully used for the collection of geoscientific data for the characterization of geological formations.

A new step in order to optimize the data collection from the relatively cheap 56 mm boreholes has been taken in the development of the telescope borehole technique. The uppermost 100 m of the borehole are drilled with a greater diameter, 155 mm. During the following drilling operation from 100 m to total depth a temporary casing is installed and air lift pumping is conducted in the outer annulus, see Figure 15-12. In this way a drawdown of several tenths of meters will be created and the contamination of drilling fluid into the rock formation is reduced or eliminated.

The increased diameter in the upper part of the borehole makes other tests possible in the small boreholes such as pumping test and multilevel installations for combined water sampling and water table recordings, which will be used in the characterization stage of the Hard Rock Laboratory project.

15.7.2 Multipacker Borehole Installations

For piezometric measurements in 56 mm boreholes a packer system for maximum five recording levels previously has been used. A new packer system is now constructed which enables sealing of up to ten borehole sections in order to measure pressure levels as well as to perform water sampling. The packers which are flexibly separated, are inflated by water pressure via tubings from an air-over-water pressure regulating system at the surface. A 1 m long sealing rubber element is fixed around a steel mandrel and there are ten pressure tubings for individual connection of pressure lines from each separated interval up to the surface, see Figure 15-13.

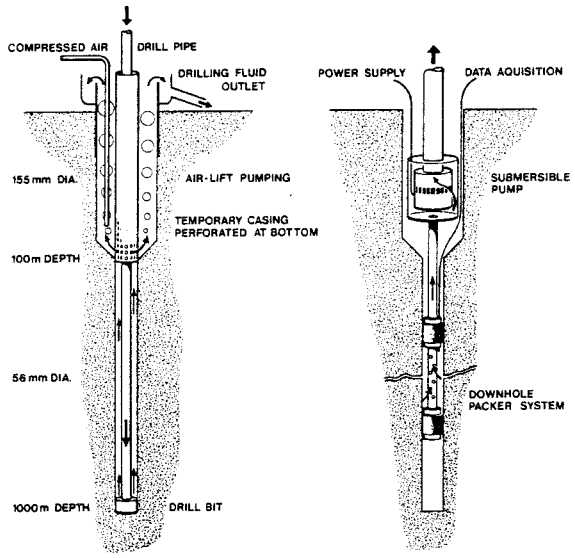


Figure 15-12. Drilling of telescope borehole and principle overview of test arrangement for pumping test from a packed-off section.

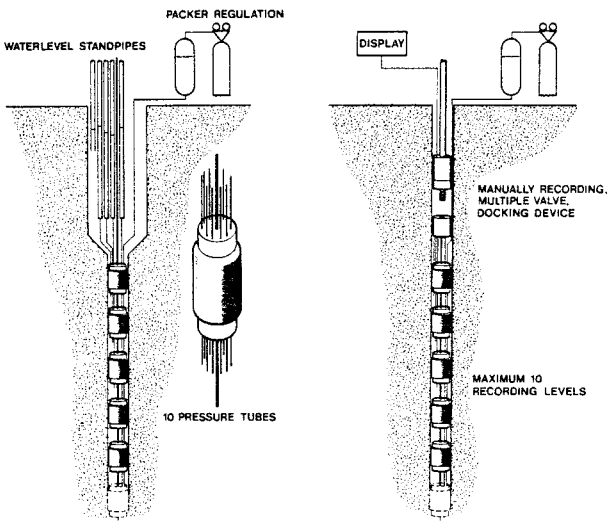


Figure 15-13. Inflatable packer with 10 pressure tubings and multipacker borehole installations in standard and telescope boreholes. Manually operated recording equipment.

In the telescope boreholes, as described in Section 15.7.1, the pressure lines are widened to plastic standpipes for water level recording and water sampling. For use in the normal 56 mm boreholes the pressure lines are connected with a downhole multiple valve and docking device. To this device different kinds of manually operated equipment, such as a pressure transducer or water sampler, can be connected. The system will be used for longterm monitoring of piezometric pressures and groundwater chemistry.

15.7.3 Hydraulic Equipments

The improved version of the piezometric pressure recording system, Piezomac II, is now in operation. To the data collection and control unit both standard analogue pressure transducers and the special multipressure probe can be connected from one or several boreholes. The multipressure probe connects five measuring sections in a 56 mm borehole to the same transducer via a new multiport valve made by ceramics.

In connection with the improvement work on the hydraulic equipments; Umbilical Hose system, Pipe String system and Piezomac II, the data handling has been systematized in a software network system. Measured data from all hydraulic equipments are processed in a similar way in order to produce suitable types of data sheets.

15.7.4 Borehole Radar

The borehole radar has been successfully used during the year, not only in SKB-projects but also for similar purposes in Switzerland, Canada and Japan.

The field equipment has been improved, i.e. the old ABC-computer has been replaced by an IBM-compatible computer — Compaq Portable II.

The interpretation techniques, analyzing methods as well as computer softwares are continuously refined. Since tomographic analysis has been a useful way of interpretating crosshole data, efforts have been laid on more effective processing of reflexion data. Implementation of a Fourier transform has been made for improved filtering of radar data. A first step is taken towards data migration in order to present real pictures of the geometry of the radar-reflectors. Separate studies of the radar method are described in Sections 15.3.4 and 15.3.5.

15.7.5 Others

The construction of a second mobile field laboratory for collecting and chemical analysis of groundwater is completed. To compare with the first laboratory some new techniques have been adopted, such as digital data transmission between downhole probe and surface equipment.

A new version of an equipment for rock stress measurement with the method of hydraulic fracturing is under construction. The equipment, mounted on a truck, will make such measurements possible in 56 mm boreholes down to 1000 m depth. Packer system with pressure transducer during the fracturing phase and borehole camera with compass during orientation phase are lowered down the hole with an umbilical hose.

16 THE BIOSPHERE

16.1 GENERAL

Since 1985 the main thrust in the biosphere studies of the SKB has been to evaluate the uncertainty in the biosphere. A main cause for this uncertainty in the capacity of the biosphere to transfer radionuclides from groundwater to man is the continuing evolutionary changes of the ecosystems. These changes are fast compared to the release durations anticipated in most repository concepts. This means that a release of radionuclides from a repository can encounter many different biosphere recipients with corresponding changes in the amounts that will be transferred to man. A focus of these studies has been the investigation of the natural ageing of lakes or estuaries that via eutrophication or land rise are turned into agricultural land. Another study is looking at the changes in the characteristics of the sediments of a lake caused by a local inflow of deep groundwater to the bottom.

For some radionuclides there is felt that the data on their environmental behaviour is not very satisfactory. For one of these, carbon-14, a study was initiated in 1987 to critically look at all factors of importance to the source term, distribution to the various types of repositories, chemical behaviour in the repositories, the geosphere and the biosphere and the transfer to man.

The collection of data from two Swedish sites on the behavior of the Chernobyl fallout in the soil and the near surface groundwater is continuing.

16.2 THE NATURAL AGEING OF LAKE ECOSYSTEMS

Natural changes in the ecosystem of two lake/estuary systems in Sweden have been investigated since 1984. Due to the land rise in the region and the sedimentation in the lakes, areas have successively changed from brackish bays of the Baltic Sea to semi-enclosed estuaries, freshwater lakes and agricultural areas. All these stages in the natural development have their own characteristics with regard to how radionuclides are distributed, diluted and reconcentrated in the ecosystem.

In order to evaluate how a possible release of radionuclides from a repository could be transferred to man under the various development stages, the dynamics of the lake system has been studied by measurement of water flow, suspended matter, macroconstituents of the water, pH, conductivity, sedimentation rate, trace metals etc. The sediments and the soil in the agricultural areas have been investigated with regard to pore water chemistry, redox conditions and trace metal partitioning between the solid and liquid phases. Sediment cores have been doped with tracers repositioned and analyzed after one and two years.

Most of the data has now been collected and are under evaluation. Due to the diversion of manpower and funds caused by the investigations of the Chernobyl fallout, this final part of the study is delayed and will be reported in 1988.

The reports published today are:

SKB TR 84-17
P O Agnedal et al.; The dynamics of lake, bog and bay — Consequences of exposure to man related to final storage of spent nuclear fuel.

SKB TR 86-29
S Evans; Quantitative estimates of sedimentation rates and sediment growth in Swedish lakes.

SKB TR 86-30
B Sundblad; Recipient evolution — transport and distribution of elements in the lake Sibbo — Trobbofjärden area.

SKB TR 87-30
K Andersson; Water composition in the Lake Sibbofjärden — Lake Trobbofjärden area.

In a final report, due in 1988, the results will be evaluated from the modelling point of view and concentration factor for nuclides important for the repository safety will be compared for the various evolutionary phases.

16.3 THE EFFECT OF GROUNDWATER INFLOW ON SEDIMENTS

All the release pathways of radionuclides to man assume that the deep groundwater will reach the biosphere either in a well or in a groundwater outflow area. The outflow areas are often at low points on the ground and frequently in the lakes or streams. Should a substantial groundwater outflow occur in a lake it is probable that it will have an effect on the sedimentation rate of the local area, on the chemical composition of the sediments and on its biological activity. All these factors are important parameters for the transfer of radionuclides to man.

In order to elucidate what differences there are between sediments in stagnant areas and in inflow areas

an investigation was started in 1987. During this year an inventory was made to find suitable places for the main study. Two lakes have been identified as suitable for the study, Hillesjön and Långhalsen. Samples will be collected of sediments and water in the inflow area as well as a reference area. An effort will be made to get in situ measurements of redox potentials.

The study is planned to be reported early in 1989.

16.4 CARBON-14

As a consequence of the fact that carbon-14 were among the dominating nuclides when the doses where calculated for the inland scenario of the SFR, see Section 5.3.1, a critical compilation and reevaluation of the data base for that nuclide has been initiated. It is believed that substantial and unnecessary conservatism has been introduced into the calculations. An example on the biosphere side is the assumption that the carbon released from the repository will have concentration factors in the fish corresponding to carbon in edible organic matter. The most probable situation is that either the carbon is present as carbonate in the repository, then it will precipitate as $CaCO_3$, or it is present as short chained hydrocarbons like methane. In this case it might be quickly transported to the biosphere but have low concentration factors in food chain via fish.

16.5 THE CHERNOBYL FALLOUT

During 1986 and 1987 an extensive sampling has been made of the fallout from Chernobyl in two areas previously investigated by SKB in Sweden. The aim is to study the initial deposition and its subsequent redistribution in soils, biota and the shallow groundwater.

A compilation of the results from the sampling is published in /16-1/. The possibilities for using the material for validation of nuclide migration models in the biosphere and in the shallow groundwater seems to be good. SKB intends to continue the sampling and initiate an evaluation effort at a suitable time.

17 CHEMISTRY

The chemistry programme has been divided into four major parts:

- Geochemistry, including the chemistry of the groundwater and fracture minerals in the geosphere and the disturbed near-field.
- Radionuclide chemistry, i.e. the chemistry of the relevant radionuclides in the near-field and the geosphere.
- Chemical transport in the near-field and the geosphere of radionuclides and inactive species (gas, corrodants, radiolysis products etc).
- Validation of transport models by means of laboratory tests, in-situ tests and study of natural analogues.

Table 17-1. Qualitative comparison of drilling and sampling methods and potential sources of contamination.

Contamination source \ Method	Air-flush Booster Drilling	Water-flush Rotary Drilling	Step-wise Sampling	Normal Sampling
Drilling water	+	–		
Open-hole Effect			+	–
Drilling Debris	–	+		
Dissolved Oxygen	–*	+		
Borehole water	+	–	+	–

* below the threshold depth, estimated to 200—300 metres.

17.1 GEOCHEMISTRY

17.1.1 Groundwater Analyses

Water sampling in connection with percussion drilling have been tested as a technique to completely avoid contamination of groundwater with flushing water /17-1/. This is otherwise a frequent disturbance of the groundwater chemistry when normal core drilling is performed.

A borehole of 460 m was drilled at Finnsjön with air-flushed percussion drilling technique. The study was a part of the fracture zone project, see Section 15.3.2. Groundwater samples were obtained in a stepwise drilling/sampling procedure. A subhorizontal conductive zone located between 240 and 360 m was penetrated during the operation. The results have shown that air-flush drilling in this particular case was most effective down to about 250 m. After this depth a considerable air pressure is needed to clear the hole from rock debris and water. The qualitative conclusions on drilling and sampling techniques are summarized in Table 17-1. Groundwater sampling in percussion drilled holes is recommended as a superior method down to depths of about 100-200 m.

The chemical composition of the groundwater is presented in Table 17-2. The sharp increase in groundwater salinity over the subhorizontal zone is evident. This salinity increase is mainly composed of sodium, calcium and chloride ions. Carbonate ion concentration is on the other hand lower at depth, see Table 17-2. Based mainly on the high chloride content in combination with the low oxygen-18 isotope content it has been suggested that the saline water is a mixture of glacial melt water and bedrock saline waters of Yolidia—Littorina origin, introduced some 2500—8 000 years ago /17-1, 17-2/. The zone has evidently acted as a hydraulic trap, preserving the saline water in and beneath it.

The techniques and results of groundwater chemistry investigations within the SKB research and development program from 1983 to 1987 have been summarized

Table 17-2. Summary of selected groundwater chemical parameters from each sampled level in borehole BFI01, Finnsjön.

Sample	Depth below surface (m)	Tritium (TU)	^{14}C (corr ^{13}C) (years)	^{18}O (‰ vs SMOW)	^{2}H (‰ vs SMOW)	pH	Eh (mV)	Cond. (ms/m)	Na^+ (mg/l)	Ca^{2+} (mg/l)	Fe (II) (mg/l)	Fe(Total) (mg/l)	HCO^-_3 (mg/l)	O_2 (mg/l)	Cl^- (mg/l)	Br^- (mg/l)	I^- (mg/l)
BFi1	71—85	36±3	1430	-12.0	-88.2	6.9	+40	54	23	26	8.88	9.01	220	0	61	0.3	0.002
BFi1	169—191	5±2	9160	-11.8	-85.2	7.7	-320	415	610	270	0.50	0.51	210	0	1320	4.5	0.020
BFi1	234—247	<3	8090	-11.7	-85.7	7.7	-270	531	650	420	0.87	0.90	260	0	1500	7.0	0.035
BFi1	284—294	—	8780	-11.5	-89.0	6.8	+400	1570	1600	1520	0.009	0.022	59	—	5220	26.0	0.070
BFi1	335—385	<3	13710	-11.8	-86.9	7.3	+340	1650	1700	1500	0.009	0.29	59	5	5500	29.0	0.120
BFi1	439—459	<3	8640	-11.8	-88.7	7.0	+400	1660	1700	1600	0.005	0.016	48	4	5500	29.0	0.120

in the technical report /17-4/. A doctoral thesis has also been presented by Peter Wikberg at the Royal Institute of Technology based on these results /17-3/. The conclusions were centered on the development of deep groundwater redox conditions and supported by laboratory experiments simulating natural conditions.

The results and experience gained have been further used for groundwater investigations within the Swedish Hard Rock Laboratory project, see Chapter 15, the Lansjärv study, see Chapter 15, and the Poços de Caldas project, see Chapter 21.

17.1.2 Geochemical Evaluations

The results of the groundwater analyses at Klipperås have been evaluated together with results from fracture mineral analyses and hydrogeological investigations /17-5/. Geochemical modelling have been used to explain the watercomposition. Two kinds of groundwater compositions have been distinguished; near-surface water and what is referred to as intermediate water. The intermediate type contains slightly enhanced contents of sodium and chloride and reduced amounts of calcium and carbonate. No deep saline water have been found except for the slight increase in chloride content in the intermediate water. The geochemical modelling of the representative groundwater compositions showed that the waters are nearly saturated with calcite and other carbonate minerals, that both ferric iron and aluminum ions appear to be saturated with their hydroxides and that the uranium concentration levels are regulated by either the precipitation of amorphous uranium dioxide or saturation with some secondary uranium mineral. Calculated uranium saturation indices for some feasible minerals and a sensitivity analyses of these values are presented in Table 17-3. The geochemical code EQ3NR, installed at the SKB VAX computer, has been used for these calculations.

Measurements of Eh and pH were performed with the down hole probe. Geochemical calculations of Eh shows that redox conditions are controlled by minerals in the rock /17-3, 17-4, 17-5, 17-6/. Earlier investigations of Eh used an equipment, consisting of a flow-through cell with Eh, and pH electrodes, placed on the ground surface. It was at that time impossible to prevent contamination by small amounts of oxygen which caused an oxidation of part of the sulphide. Therefore the Eh values were controlled by the sulphur-hydrogen sulphide system. As oxygen contamination is no longer present, neither ferric iron species nor polysulphide has been formed in the sampled groundwaters, and as expected the experimental Eh values are much lower than the calculated sulphur-sulphide values /17-4/. An example of the stability in the Eh-readings with the new equipment is presented in Table 17-4.

Extensive geochemical calculations have also been performed on the earlier hydrochemical measurements at the Finnsjön study site. The geochemical codes WATEQ3 and EQ3NR have been used to explain the water composition in relation to minerals /17-7/.

Uncertainties in the early pH measurements (1979-1982) were confirmed by computer simulations with the geochemical reaction path code EQ6 which showed that exchange of carbon dioxide between sample and atmosphere probably had occurred prior to pH-measurements. Calculations with EQ6 were also performed to simulate the effect of mixing of groundwaters of different salinity in the sub-horizontal Zone 2 in Finnsjön. It was clearly shown that calcite oversaturation may be obtained that way, see Figure 17-1.

Table 17-3. Sensitivity analysis for uranium saturation indices calculated by varying each of the parameters Eh, pH and total uranium individually. Results from EQ3NR calculations on a sample from borehole KKL01, at 398 m vertical depth. Uranium concentrations are given in mg/l.

Calculation	Uraninite UO_2(cr)	UO_2(am)	U_3O_8	U_4O_9	Schoepite $UO_3 \cdot 2H_2O$	Uranophane[a]	Coffinite[b]
original [c]	+ 4.41	− 0.54	− 11.56	+ 7.81	− 9.38	+ 32.51	+ 4.45
Eh = -357 mV	+ 4.41	− 0.54	− 16.85	+ 5.17	− 12.03	+ 27.24	+ 4.45
Eh = -225 mV	+ 4.40	− 0.55	− 6.29	+ 10.42	− 6.74	+ 37.78	+ 4.44
pH = 9.2	+ 3.69	− 1.26	− 9.72	+ 6.93	− 8.10	+ 36.92	+ 3.67
pH = 7.2	+ 4.65	− 0.30	− 14.84	+ 6.77	− 11.14	+ 27.02	+ 4.70
$(U)_T = 3.2 \cdot 10^{-3}$	+ 5.01	+ 0.06	− 9.75	+ 10.22	− 8.78	+ 33.72	+ 5.05
$(U)_T = 0.5 \cdot 10^{-3}$	− 12.58	− 17.52	− 62.50	− 60.12	− 26.36	− 1.45	− 12.53

Notes a: Uranophane: $Ca(UO_2)_2(SiO_3)_2(OH)_2(c)$
b: Coffinite: $USiO_4(c)$
c: Eh = 300 mV, pH = 8.2, $(U)_T = 1.73 \cdot 10^{-3}$ mg/l

Table 17-4. **Eh measurements from a section of borehole KKL01 in Klipperås at a vertical depth of 398 m. The Eh values are given in mV and the measurements started after more than one week of stabilization.**

Date	Time	Downhole probe Carbon	Platinum	Gold	Surface flow-through cell Carbon	Platinum	Gold
85-06-28							
	00:25	-309	-193	-220	-317	-315	-226
	09:21	-311	-195	-223	-318	-316	-230
	16:21	-308	-189	-217	-318	-317	-232
85-06-29							
	00:21	-305	-192	-227	-318	-316	-231
	08:21	-304	-197	-265	-319	-318	-236
	16:21	-301	-209	-277	-319	-319	-239
85-06-30							
	00:21	-304	-230	-288	-318	-318	-291
	08:21	-306	-273	-295	-320	-319	-295
	16:21	-308	-284	-300	-320	-321	-297
85-07-01							
	00:21	-310	-292	-304	-319	-319	-295
	08:21	-305	-288	-299	-320	-320	-296
	16:21	-311	-299	-308	-319	-319	-297
85-07-02							
	00:21	-312	-300	-309	-320	-321	-293
	08:21	-309	-303	-312	-320	-321	-297
	16:21	-311	-311	-316	-320	-320	-302

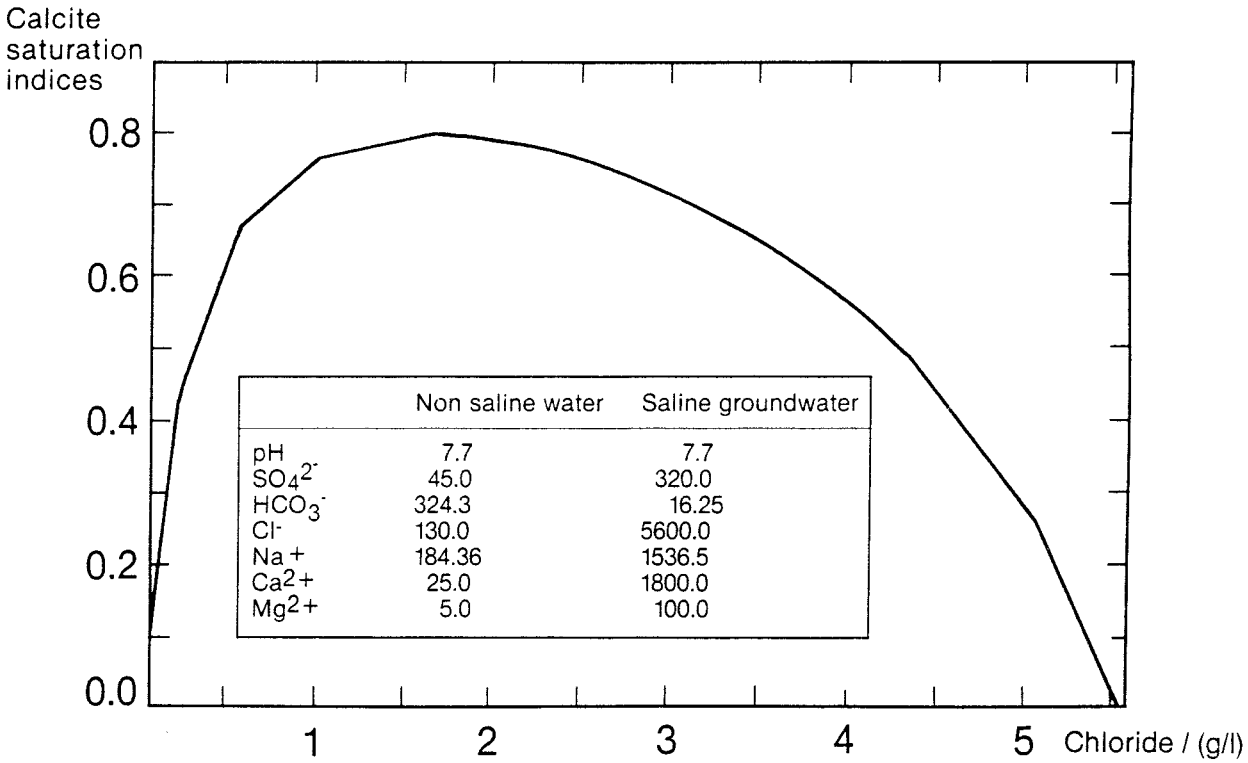


Figure 17-1. Results of an EQ6 simulation showing the effect of mixing two groundwaters. The chemical composition of the two waters used as end-members are presented. The saline water is similar to that from KFI05, 384 m and the non-saline is similar to that from KFI04, 247 m.

17.1.3 Near-field Conditions

Geochemical model calculations on near-field conditions have been performed at the University of Strasbourg. Three systems have been considered; bentonite clay/groundwater, bentonite clay/copper/copper minerals/groundwater and the effect of acid and bases on bentonite clay. Calculations of the stability fields of smectites and illites as a function of temperature and chemical composition of the clay particles have been presented in a technical report /17-8/.

17.2 RADIONUCLIDE CHEMISTRY

17.2.1 Solubility and Speciation

Experimental work on the determination of thermodynamic constants for solubility, inorganic complex formation and redox properties of actinides in groundwater has been performed. Most work has been done on uranium and thorium/17-7/.

A study of co-precipitation of lanthanides and actinides with uranium and the implication of this phenomena on the release and transport of radionuclides in the near-field has been presented in a technical report /17-10/. Thorium, lanthanum and barium were chosen as model substances together with the major component uranium, see Table 17-5. Co-precipitation of radionuclides is also expected to occur at the formation of calcite and iron oxyhydroxides. This is treated in a separate part of the report.

SKB is supporting the participation of Swedish experts in the development of a chemical database for important radionuclides at OECD/NEA. The participation occurs in working groups on uranium, plutonium and radium. SKB is also participating in the CEC organized study CHEMVAL on the validation of geochemical codes used for evaluation of radionuclide release and transport.

Table 17-5. Relative composition of the aqueous phase and an experimental precipitate after aging. The results indicate a congruent co-precipitation of La(III) and Ba(II) and an enrichment of Th(IV) in the solid.

Metal ion	% in solution	% in solid
U(IV)	98.0	97.5
Th(IV)	1.0	1.7
La(III)	0.5	0.4
Ba(II)	0.5	0.4

17.2.2 Colloides, Organic Complexes and Microbes

The content of inorganic colloidal particles in groundwater samples have been analyzed in order to assess the potential effect of radionuclides transported as pseudo-colloids i.e. adsorbed on mobile particles. Groundwater samples from Stripa, Kamlunge and Svartboberget were analyzed. Most of the samples had particle contents below 0.1 mg/l. The highest value obtained was 0.4 mg/l. Undisturbed groundwater is expected to have much lower colloid concentration /17-11/.

Hollow fibre filtering technique has been applied to saline groundwater from Forsmark. This very sensitive technique for measuring trace elements carried by inorganic particles or organic macromolecular complexes were unable to detect any colloidal fraction in this case. Consequently these groundwaters are very low in colloidal species. The hollow fibre filtering was carried out in the field laboratory in direct connection with the sampling.

The formation and stability of inorganic colloids in groundwater have been studied as a part of a redox experiment in Fjällveden /17-4, 17-11/. Oxygen was pumped into a water conducting section at 468 m in the borehole KFJ02. This caused, as expected, a marked increase in particles containing iron and sulphur, see Figure 17-2. Even the content of silica containing par-

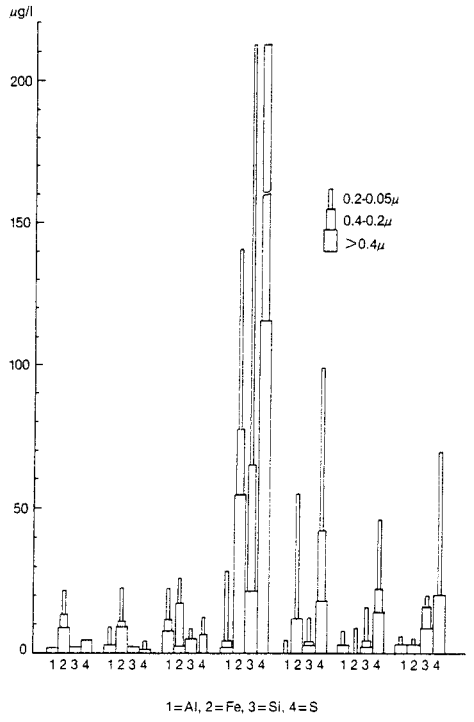


Figure 17-2. The concentration and size distribution of particulate material filtered off the groundwater in a redox relaxation experiment in KFJ02, 468 m level. The first three groups correspond to undisturbed conditions. The large group represent particle content 2 weeks after oxygenation. Only 10% of original water is left. The following three groups are obtained 1, 5 and 7 days after onset of pumping.

ticles increased. However, a few days of pumping restored the original conditions with the exception of sulphur particles which were still more than normal after one week of pumping. The probable explanation is that iron hydroxide particles are lost to the fracture walls and consequently not transported over large distances.

Humic and fulvic acids collected in natural groundwaters are being studied. The material is being concentrated, purified, analyzed and used in experiments on radionuclide retention.

The effect of complex formation between natural organic materials — humic and fulvic acids — and radionuclides have also been studied in cooperation between a group at the University of Linköping and the French organization CEA /17-12, 17-13, 17-14/.

SKB is supporting the participation of a Swedish expert in the international working group COCO, managed by CEC. The task of the group is to assess the importance of colloides and organic complexes for the transport of radionuclides. Interlaboratory comparisons are an important part of this work.

Microbes in groundwater have been analyzed. The in-situ gas sampling equipment have been used to obtain relevant samples. The presence of bacteria in deep groundwaters have thereby been confirmed though the content is low. Microbes in the geosphere are also being analyzed as a part of the Poços de Caldas project, see Chapter 21.

17.2.3 Sorption and Diffusion

Investigations of diffusion of radionuclides into the connected micropore system of granitic rock and through bentonite clay has continued /17-15, 17-16/.

Surface complexation theory is being tested as a mean of modelling radionuclide sorption and diffusion on mineral surfaces.

An experimental study of sorption of sodium-22, strontium-85, cesium-134 and europium-152 on fracture surface material has been completed /17-17/. Sorption on crushed material from the fractures; fracture filling minerals and granite, were compared to measurements on intact fracture surfaces. The experiments were performed in order to obtain complementary information for the laboratory validation tests of radionuclide transport through overcored fissures.

17.2.4 Radiolysis

Alfa-radiolysis of groundwater and water in bentonite clay have been investigated /17-18/. Experiments and theoretical calculations have been performed and compared. It has been possible to measure the production of hydrogen peroxide due to alpha-radiolysis of simulated groundwater. The influence of groundwater components such as chloride, carbonate and ferrous iron ions have been investigated, see Figure 17-3.

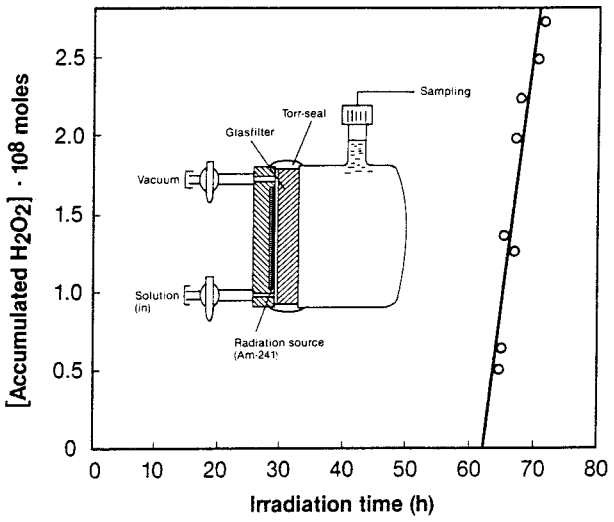


Figure 17-3. Measured H_2O_2 production inralpha-irradiated synthetic groundwater.

17.2.5 Concrete

Radionuclide chemistry in concrete and the consequences on near-field chemistry of using concrete is being studied at the Chalmers University in Gothenburg. This work has temporarily been directed to the safety assessment of the SFR facility and the WP-cave concept, see Chapter 11 and Chapter 18. A continued and increasing general interest in this area is foreseen.

17.3 CHEMICAL TRANSPORT

The distribution of groundwater flow in fractured crystalline rock is a very important prerequisite for the advective transport of dissolved radionuclides /17-19/, see also Chapter 15. A model for the flow of water restricted to channels in a single fissure has been presented /17-20/.

Transport modelling has been temporarily concentrated on the safety assessment of the SFR-facility and the WP-cave concept /17-21, 17-22/.

Advanced models which couples transport with geochemical reactions have been tested and applied. An important application is the calculation of chemical interaction between bentonite and concrete with the code CHEMTRN which has been developed at Lawrence Berkeley Laboratories in USA /17-23/.

Coupled models, transport-geochemistry are also being developed in order to simulate the movement of a redox front /17-24/. These models are being validated by application to the redox front observed in the uranium mine in Poços de Caldas. The investigation of the uranium mine is part of the Poços de Caldas Project, see Chapter 21.

17.4 VALIDATION OF TRANSPORT MODELS

17.4.1 Laboratory Experiments

Natural open fractures in granitic rock have been overcored and brought into the laboratory. These overcored fractures have been used continuously for a number of years for experiments with water flow in fractures and radio nuclide migration. Data from these experiments are being offered as a test case in the international INTRAVAL study managed by SKI. Transport models will thereby be validated by independent working groups.

A laboratory setup with rock pieces and groundwater is used to simulate natural reducing conditions /17-4/. This is also being used for experiments to validate uranium reduction and co-precipitation.

17.4.2 In-situ Tests

In-situ tests with non-sorbing tracers have been performed in the Stripa mine as a part of the international OECD-NEA project, see Chapter 19. In these "3-dimensional migration experiment" a number of non-sorbing tracers have been injected at 9 different locations and recovered at the roof and walls of a drift underneath the injection points. The distances between injection points and drift ranged from 10 to 50 m.

A small scale migration experiment has also been performed in Stripa in a set of 9 vertical, 20 m deep boreholes. The migration distances are in the range 1—2 m. One phase has been reported /17-25/. These experiments have now been completed and are being evaluated. This experiment is entirely sponsored by SKB.

The SKB sponsored experiments in Stripa to validate the existence of an interconnected pore system which started in 1982 has now been finished. Two tests have been reported /17-26, 17-27/. The last test which went on for 3.5 years is being evaluated.

A test to use radar to follow saline water in conducting fractures between boreholes have been initiated in Stripa. In-situ tracer test in or in connection with large conductive zones has been initiated in Finnsjön. The new series of Finnsjön in-situ tracer test in the subhorizontal fracture zone (Zone 2) has been offered as a test case to the INTRAVAL study, see Figure 17-4. The international working groups have also been offered the opportunity to make independent predictive modelling before the results become available.

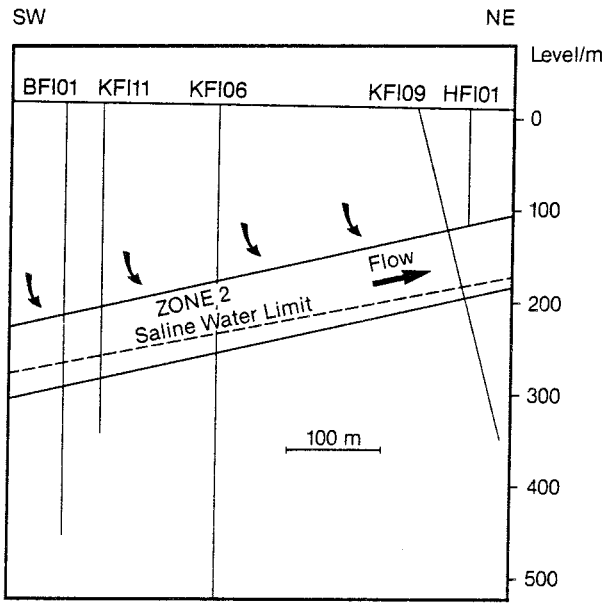


Figure 17-4. The subhorizontal fracture zone (Zone 2) in Finnsjön to be used for in-situ tracer tests.

18 SAFETY ASSESSMENT

18.1 GENERAL

The safety assessment activities within SKB have been related to five areas during 1987.

- Participation in the development of the Final Safety Analysis Report for the repository for low and intermediate level waste, SFR, see Chapter 5.
- Discussions and advice through the SFG (the integrated performance group) in selections of assessment sequence, scenarios and levels of conservatism for the evaluation of the performance capacity of alternative repository designs.
- Development of standard scenarios for post closure safety assessment of high level waste repositories.
- Studies of carbon-14.
- Development of the PROPER Code Package.

With regard to the investigation of alternative repository concepts, the activities on the WP-cave and disposal in Very Deep Holes have been discussed in Chapter 11. A comparison of these alternatives with the reference concept of KBS-3 will be made during 1988.

A compilation of scenarios that have been evaluated during earlier Swedish safety assessments was started during 1987. The work is adjusted in time and scope to the international scenario evaluations made within OECD/NEA. The intention in SKB is to screen the availability of models and data for relevant scenarios and test systematic approaches to scenario identification.

While working with the SFR safety assessments it was found that carbon-14 was often among the dominating nuclides. It is felt by many safety assessors that — in a repository environment dominated by concrete — this is to a large extent an effect of extensive safety margins on data for:

- how much of the carbon in the repository will not be precipitated as $CaCO_3$, and the sorption characteristics of this fraction, and
- the possible concentration factors of this non precipitated and non sorbing fraction in the biosphere.

A critical reevaluation of this data was started in 1987.

18.2 THE PROPER CODE PACKAGE

The PROPER code package is designed to assist the analyst in performing uncertainty and sensitivity analysis in model calculations. The PROPER Monitor is a computer program to be used by other programs: it links a number of submodels selected from a library at run time and carries out an analysis on the desired outputs. Postprocessing codes belonging to the system can be used to treat the results statistically or graphically. A summary description can be found in /18-1/.

The work during 1987 has been concentrated on moving the PROPER Monitor from a conceptual stage to a tested, verified and reliable product, on the further development of the postprocessing software, and on creating a numerically sound basis for the further development of submodels dealing with the hydrology, the near field and the far field.

Testing and verification of the existing version of the Monitor has been carried out on different levels:

a) INDEPENDENT TESTING where two programmers not previously involved in the development of the Monitor were assigned to push the software as far as they could using the available documentation,

b) FEATURE or HIGH-LEVEL TESTING and VERIFICATION including features identified as crucial, such as the generation of random numbers and random variates, sampling precision measurement, the transfer of time series between submodels, the collection of crude statistics for postprocessing etc,

c) LOW-LEVEL TESTING where all routines associated with the internal data base that is automatically created during a simulation for storage of time series and time series information were put on test; a program (TESTMON) was designed especially for this purpose,

d) INTERCOMPARISON TESTING in the international PSAC User Group Level Zero Intercomparison under the auspices of the OECD/NEA /18-2/.

A few points that did not match the specifications were detected. They are presently being corrected and the PROPER Monitor Version 1.0 is planned to be released some time during the spring of 1988.

A new and improved method for measuring the sampling precision in real time has been developed for use in the Monitor Version 2 planned to appear in early 1989.

A new postprocessing code (POSTREG) to be used for sensitivity analyses was developed in 1987. It is based on the features of partial correlation and stepwise regression analysis. The prototype version is retained for later inclusion in a "super postprocessor" combining the features of the present POSTREG, POSTMON and GPLOT and adding to their capabilities.

The hydrology code FSCF ("Flow of Slightly Compressible Fluids"), /18-1/, was finally adapted to the PROPER package and a first test was carried out.

A new numerical method for solving linear partial equations was tried in the development of a new far field submodel taking chain decay into account. Problems with that procedure has delayed the completion of the submodel.

19 THE STRIPA PROJECT

19.1 INTRODUCTION

When the KBS work began in 1976—77, an underground research laboratory was established in the disused iron ore mine at Stripa, 15 km north of Lindesberg. The purpose was to study the natural geological barrier and to determine different properties of proposed engineered barriers in a representative environment (granitic crystalline bedrock).

Stripa aroused international interest at an early stage by providing a unique opportunity to start field tests in good granitic rock at a depth of 350—400 m relatively quickly. Swedish-American cooperation was initiated in 1977 in the form of the Swedish-American Cooperative Programme (SAC), sponsored by SKB and the US DoE.

The aim of this cooperation was to develop technology for measuring certain properties of the Stripa granite, e.g. thermomechanical, geophysical and geochemical properties. The results of this programme have been published in a large number of reports.

The high international class of the Swedish-American research and the great interest on the part of the OECD member countries in continued research resulted in an expanded international cooperation in the Stripa Project. It was started in May 1980 as an autonomous OECD/NEA project with SKB as the coordinating party. Phase 1 was carried out during the period 1980—1985, followed by Phase 2, which commenced in 1983 and was concluded in 1987.

Phase 3 of the program started as of September 1, 1986 and will be carried out during the period 1986—1991. Seven countries, Canada, Finland, Japan, Sweden, Switzerland, United Kingdom and USA, are participating in Phase 3.

19.2 PHASE 3 OF THE STRIPA PROJECT

Phase 3 of the Stripa Project is a direct continuation and is based on the work carried out within Phases 1 and 2, but new research activities will also enter in. An undisturbed granitic rock volume (approx 125 m x 125 m x 50 m) will be investigated. A schematic illustration of the test area is shown in Figure 19-1. A mathematical

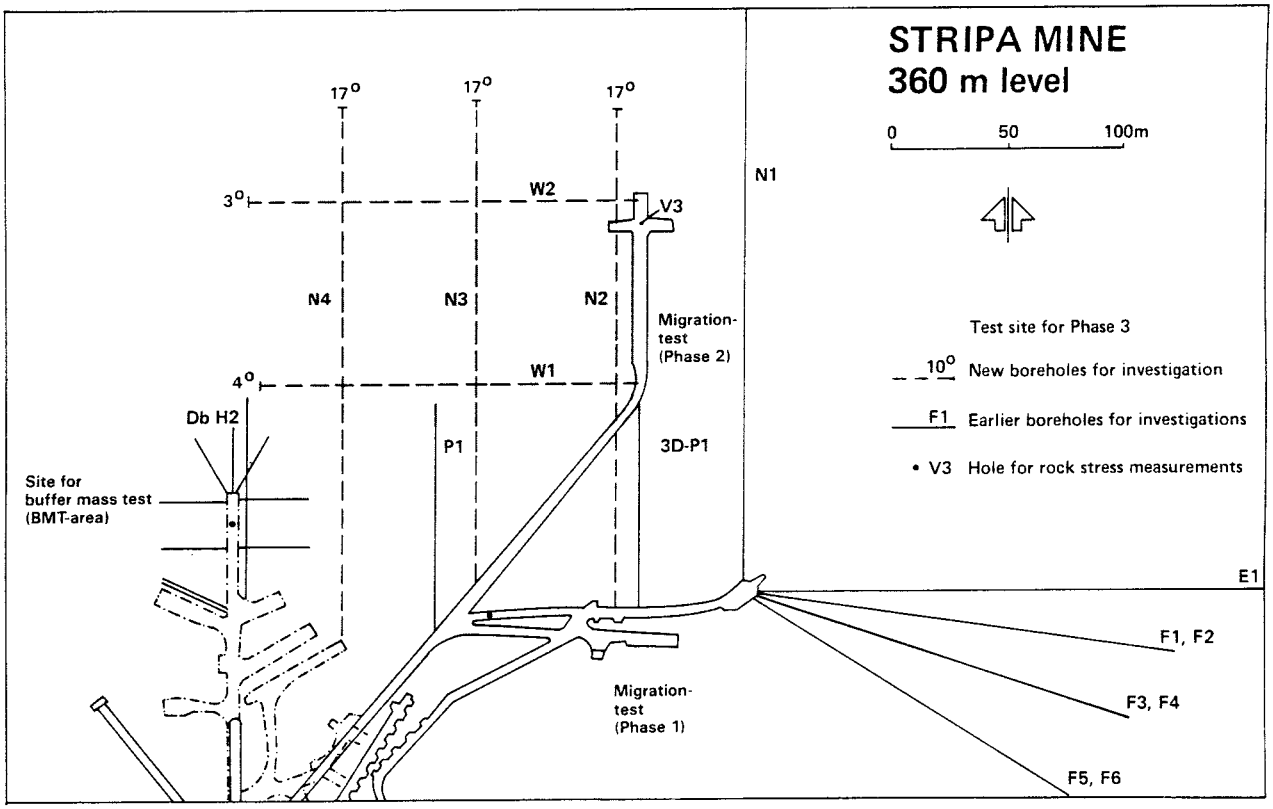


Figure 19-1. Schematic illustration showing the test site for the investigations of Phase 3.

model for groundwater flow will be developed and compared with values measured in the field. Previously obtained results show that models that treat the rock as a porous medium cannot describe in detail the conditions prevailing in a fractured granitic rock volume of the size in question. The mathematical model to be tested is based on a combined deterministic and statistical description of the groundwater flow in a discrete fracture pattern in three dimensions.

The investigations at Stripa have shown that it is not realistic to describe a fracture as an aperture of constant width between two plane-parallel surfaces. Instead, it appears as if the water runs through randomly oriented channels in the fracture. The prevailing hypothesis today when it comes to channelling is that water in one channel mixes with water from other channels in an irregular pattern and that there exist zones with stagnant or nearly stagnant water where diffusion is the dominant transport mechanism. Phase 3 includes a continuation of the tracer tests from Phase 2 for the purpose of investigating the water flow in fractures in greater detail and thereby shedding more light on the phenomenon of channelling. These tests will be concluded with a large-scale tracer test in the aforementioned undisturbed rock volume. The results of these investigations will also be compared with calculated values.

The development of advanced measurement methods and instruments for rock investigations will continue during Phase 3. The work pertains to a high-resolution and direction-sensing borehole radar and improved technology for high-resolution seismics in boreholes.

A new research field in Phase 3 is technology for measuring the hydraulic length and width of fractures. These measurements are intended to complement the fracture mapping that is being carried out in connection with the excavation of a tunnel through the test site. This information is important for the modelling of the flow of water in the rock and the optimization of the technical design.

Of importance for the technical design of the final repository is also the use of sealant materials to limit or prevent the migration of radionuclides from the repository. Phase 3 includes an extensive research effort. Among other things, the properties of different materials for injection grouting of rock will be studied. A large-scale grouting test will probably be carried out. Of particular importance is long-term stability in the expected environment around a final repository.

19.3 RESULTS OF PHASE 3

Research has been conducted within the following three main areas:

- Site Characterization and Validation,
- Improvement of Site Assessment Methods and Concepts,
- Groundwater Flow Path Sealing.

The results obtained are presented in quarterly, internal and technical reports.

Some initial findings made during 1987 are presented below. For more detailed presentation of the work within Phase 3 during 1987, see the Annual Report of the Stripa Project.

19.3.1 Site Characterization and Validation

Most of the activities within the Site Characterization and Validation program have during 1987 been carried out using the six boreholes N2, N3, N4, W1, W2 and V3 indicated on Figure 19-1. Prior to the drilling and logging of the six boreholes a system for head monitoring has been set up in the Stripa Mine to follow changes in hydraulic head caused by drilling and experimental activities at the new site. The head has been monitored using 26 measuring points surrounding the Phase 3 site. Measurements have been taken in intervals from one to six hours.

Single hole geophysical logging

To achieve comprehensive knowledge of the physical conditions in the rock mass in the vicinity of the boreholes the following geophysical borehole methods have been used: borehole deviation, natural gamma ray, neutron-neutron, sonic, single point resistance, normal resistivity, temperature, borehole fluid resistivity (salinity), and televiewer.

The porosity of the bedrock has been calculated using the resistivity measurements. In borehole N4 both a thermal and an epithermal neutron measurement have been performed, showing both methods to be influenced mostly by the water content in the fractures. These methods are accordingly very good "water indicators".

Borehole radar and crosshole seismics

The borehole radar investigation program has comprised single hole reflection measurements with centre frequencies of 22, 45 and 60 MHz. The frequencies 22 and 45 MHz have been used in the boreholes N2, N3, N4, W1 and W2. Reflection measurements with the centre frequency 60 MHz were made in V3 prior to and after the rock stress measurements (hydrofracturing) in that hole. Crosshole tomographic measurements have also been made between the boreholes W1-W2, N2-N3, N3-N4 and N2-N4. Crosshole reflection measurements have also been made between the same boreholes. The reflection measurements were made with the transmitter fixed at three positions in each borehole while the receiver was moved in 1 m increments in the other borehole. All crosshole sections were measured with the centre frequencies 22 and 60 MHz, except N2-N4 which was measured only with the lower frequency. The entire measurement program has totalled over 20 000 rays.

The radar range obtained in the single hole reflection measurements was approximately 100 m for the lower frequency (22 MHz) and about 60 m for the centre frequency 45 MHz. In the crosshole measurements trans-

mitter-receiver separations from 60 to 200 m have been used.

An integrated analysis has been performed of the radar results obtained from the three different measurement modes. From the processed radar data geometric information about the location and extent of major features has been extracted. The geometry of the boreholes has forced radar data to be collected in two different planes, i.e. the N2-N3-N4 and the W1-W2 plane located above the other plane. The borehole geometry has given a better definition of the major features in the planes of investigation compared to other locations within the site.

The radar model of the site includes three major features (fracture zones) and four minor zones. The location of these features in the N2-N3-N4 and the W1-W2 planes are displayed in Figures 19-2 and 19-3 respectively. The zones RA, RB and RH are considered as major zones while RC, RD, RK and RL are of smaller magnitude. The zones can also be grouped according to their orientation. The zones with a northeasterly strike (N35—40 °E) and a dip of approximately 35 ° to the south are RA, RB, RC and RD. Zones RK and RL are almost perpendicular to this set and have a strike of N55 °W and a dip of 65 °N. The zone RH strikes N5 °W and dips steeply (≈60 °) to the East.

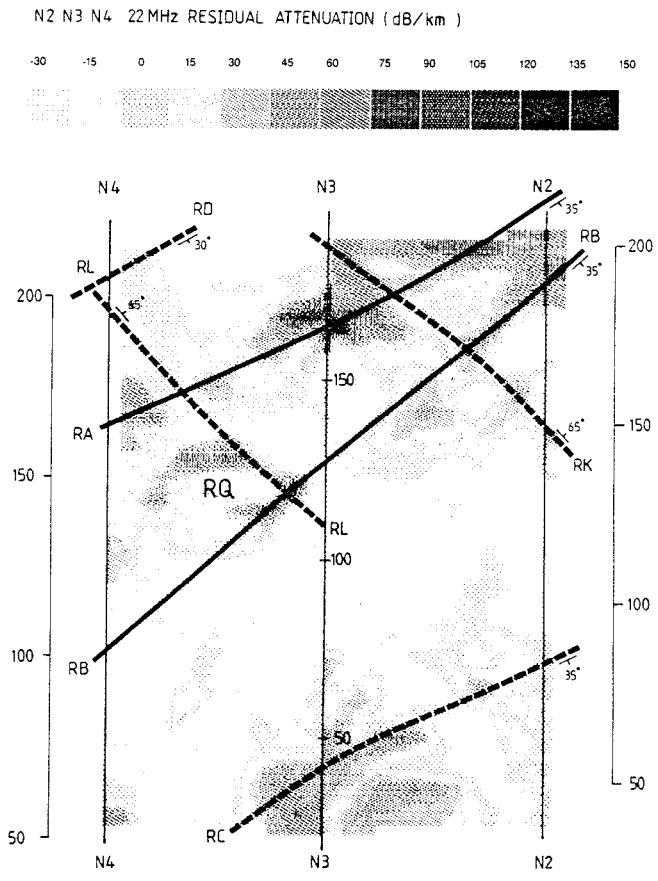


Figure 19-2. The radar model of the test site includes three major features (fracture zones) and four minor zones. The figure shows the location of these features as seen in the N2-N3-N4 plane.

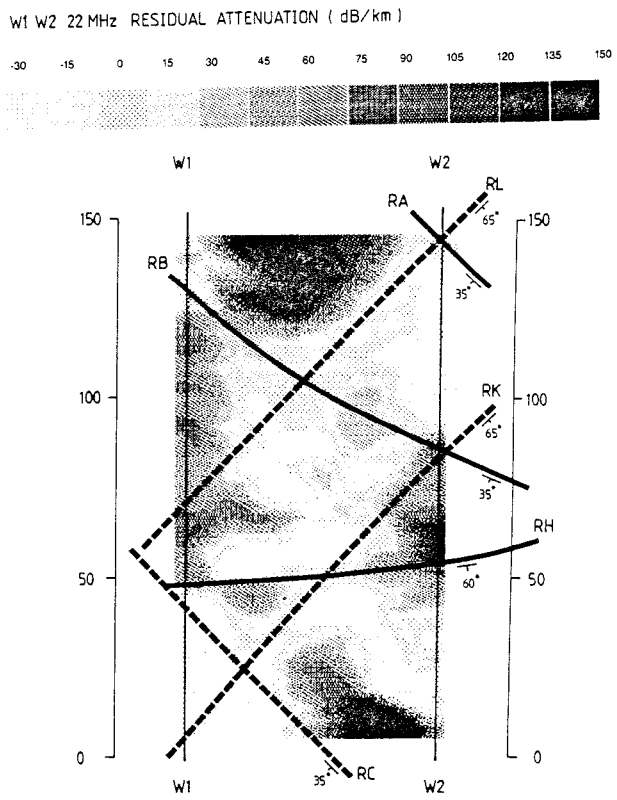


Figure 19-3. The radar model of the test site includes three major features (fracture zones) and four minor zones. The figure shows the location of these features as seen in the W1-W2 plane.

The zones, as they are seen from the tomograms, consist of a number of patches of increased attenuation and slowness following lines in the planes between the boreholes. Increased slowness and/or attenuation corresponds to increased porosity, fracturing, and/or alteration of the Stripa granite. The results indicate that the zones are not homogeneous but rather that they are highly irregular containing parts where their contrast to the background rock is quite small. The zones appear to be approximately planar at least at the scale of the site. If the geometry of the zones are studied at a smaller scale the planar nature of the zones might be less obvious. At a smaller scale the patchiness becomes dominating and the zones can appear quite irregular.

Seismic crosshole and reflection measurements have also been performed at the Site Characterization and Validation Site (SCV-site). Three sections were measured, one between the boreholes W1 and W2, one between N2 and N3 and one between N3 and N4. The results of these measurements will be compared with the borehole radar measurements.

Geochemical investigations

The chemical composition of the groundwater sampled in the conductive parts of the drillholes N2, N3, N4, W1

and W2 is used to locate different flow paths in the investigated rock mass. Based on the composition it is also possible to judge whether the groundwaters are recently mixed due to e.g. short-circuiting of different flow paths through the boreholes.

Hydraulic investigations

The aim of the hydraulic investigations which form part of the Site Characterization and Validation (SCV) Project is to provide data for input to the groundwater flow model of the "virgin site". Since it is envisaged that the eventual model will be some form of deterministic/probabilistic (network) hybrid the hydraulic data is to gain some corroboration in places (by virtue of measured heads) of the rightness of the geophysics-based geometric model of the site.

The novel aspect of the SCV Project is the attempt to apply probabilistic network models to a site characterization. The aspect of probabilism means a large data set is desirable especially concerning those features which most affect the flow properties of the whole rock mass. In a fractured crystalline rock the fractures are obviously the paths for water flow. In the SCV Project much effort is going into mapping of fractures and the assignment of those fractures and their characteristics to different fracture sets. Hence the hydraulic programme was geared to measuring the hydraulic properties and heads of the fractures. Thus although this was designed as a reconnaissance programme it was necessary to devise a programme of testing which would measure as many individual fractures as possible. Given the number of fractures in the rock mass and their frequency it is clearly impossible (in a reasonable period) to measure the hydraulic properties of every single fracture. In order to overcome this problem, it was decided to concentrate on the most important fractures. This resulted in the adoption of the approach known as "focused testing". The idea of the "focused testing" is to concentrate the effort involved in the testing so that the most conductive fractures are measured in most detail.

19.3.2 Improvement of Site Assessment Methods and Concepts

Development of High Resolution and Directional Radar

The borehole radar developed during phase 2 has a demonstrated the ability to detect fracture zones in different geological environments. Radar measurements can also with considerable accuracy determine the angle of intersection between a fracture plane and a borehole. The antenna is, however, axially symmetric with respect to the borehole and this makes it physically impossible to determine completely the orientation of a reflector. Such information has rather been obtained by combining results from several boreholes during the analyses of radar data.

It would be very valuable to obtain the missing angle (the azimuth) directly during measurements in a single borehole. Radar measurements could then be performed efficiently at sites where only one borehole is available. Furthermore the identification of individual fracture zones would be simplified if all the necessary data were available in the original radar picture.

A first test of the radar system took place in Stripa where a number of calibration measurements were performed. The analysis showed that the measured signal can be separated into directional and dipole components in the way predicted by theory and error is quite small.

Improvement of Techniques for High Resolution Borehole Seismics

The tasks for the year 1987 were:

- the construction and testing of a prototype coherent seismic source,
- development of algorithms and programs for processing the waveform information, and
- the construction of a field acquisition/processing workstation for quick result interpretation on site.

The construction of the prototype source and of the field workstation were completed during 1987 as planned. The work on the software has proceeded so far with good results.

Fracture Network Modelling

Phase 3 of the Stripa Project aims to develop and demonstrate tools for the assessment of sites for repositories to contain radioactive waste. The Project has therefore funded the further development of the Harwell three-dimensional network code, named NAPSAC. In Stage 4 of the present phase of the project, the code will be involved in predicting flow into the validation drift of the Site Characterization and Validation program.

During 1987 the NAPSAC code has been progressively enhanced so that it can now calculate flow through a few thousand rather than a few dozen fractures. Such calculations call for very efficient numerical algorithms and a computer with very large memory. In the summer Harwell took delivery of a CRAY2 computer. Parts of the NAPSAC code had then to be revised to make best use of this resource and to cope with the different operating system. The innermost parts of the code have now been written in CRAY2 Assembler Language, and are executed at over 300 million floating-point operations per second. Calculations with networks of several thousand fractures require only a few minutes.

The block chosen for the Phase 3 experiments apparently contains several million fractures, although few seem to carry significant flow. Hence a feasible network simulation of the entire block must ignore fissures with aperture less than a certain size. If the limit is set so that the Phase 3 block would contain no more than a few thousand transmissive fractures, then preliminary calculations suggest that the truncated network will carry about 80% of the predicted flow through a network comprising all observed fissures.

The excavation of the validation drift is likely to lower the hydraulic head over the surface of the Phase 3 block. Changes at this surface can be calculated by means of an equivalent porous medium model of the vicinity of the mine. The model being prepared for this purpose is consistent with local and regional finite-element models developed to investigate flow in the area surrounding the Stripa site.

The conceptual model in preparation will seek to locate major fracture zones within the Phase 3 block. If the hydraulic impact of these zones can be established, they may provide natural boundaries for detailed modelling within a more restricted part of the block.

Drainage into the validation drift may be markedly influenced by the damaged zone created during excavation. We are reviewing how to account for changes in aperture due to stress relaxation at the drift surface.

Channelling Experiment

Model calculations show that channelling may have a strong detrimental effect on radionuclide transport because fast channels may carry some of the mass of the nuclides considerably faster than the average flow would and may give this portion less time to decay. Channelling further aggravates the retardation of sorbing nuclides because less surface area for sorption is available in a channel within a fracture than if the whole fracture surface area is exposed to the flowing water.

The objectives are:

— To study channelling properties within single fractures.
— To study interconnection and mixing between channels within a single fracture.

The channelling properties of interest are:

1. Frequency of channels.
2. Widths of channels.
3. Distances between channels.
4. Fracture transmissivity variations in the fracture. plane
5. Interconnection of channels within a fracture.
6. Mixing between channels.
7. Fracture aperture.
8. Dispersion.

Properties 1—4 will be studied in the single hole experiment, where up to 10 holes in different fractures will be investigated. This experiment will give the properties close to the measuring hole.

The interconnection and mixing between channels, fracture aperture and dispersion will be studied in one selected fracture, which previously has been investigated with a single hole test. A second measuring hole will be drilled at 1 to 2 m distance. Pressure pulse tests as well as tracer injections will be utilized in the double hole experiment.

The experiment started early this year and will continue until mid 1989. During 1987 the major part of the equipment was put together and tested in the laboratory. Some problems occurred with leakage due to defect solenoid valves. The first single hole test is planned to be performed in March 1988. The experiment is within the time schedule.

Estimation of Fracture Length an Aperture from Single Fracture Well Tests

The objectives of the experiments are to obtain information on the length and interconnection of fractures from wall tests performed in the Phase 3 block. The tests are run using constant pressure methods while recording the transient flow rate. Additional tests are being performed to assess the effects on non-linear flow on well-test response curves.

The project's activities in 1987 have been (1) to further develop solutions for constant-pressure well tests including leakage effects and a greater range of flow geometries and (2) to work with the British Geological Survey in performing constant pressure tests for determining boundary effects.

19.3.3 Groundwater Flow Path Sealing

The object of the rock sealing project, in its first phase, is to identify suitable grouting materials and techniques to bring them into narrow fractures. A literature survey and state-of-the-art review of the function and longevity of grouts have been made, which indicated that smectite-based and cementitious grout materials are the most promising ones. Two major candidates have been investigated with respect to all major properties that control their groutability and longevity.

An earlier tested grouting technique based on superposition of static injection pressure and vibrations has been further developed.

The matter of longevity of the candidate grouts has been investigated but needs more attention. However, a preliminary estimate is that the chemical stability may be extremely long-lasting, i.e. tens or hundreds of thousand years depending on the temperature and percolation rates. Thus, it is felt that there is a very good basis for continuing the Stripa sealing project.

Among the most important findings is the one that soft Na montmorillonite clay gels may be much less sensitive to illitization than dense clay of the same type and that 130—150 °C may be a critical temperature for the transformation to beidellite, which is a necessary prerequisite for conversion to illite. As to the cements, it seems as if salt water and low permeation would imply lifetimes exceeding tens or hundreds of thousand years.

A most important observation is that cement has a self-healing ability on mechanical fracturing and heating. This is due to a preserved hydration potential even at relatively high water contents.

The most essential goal of the Rock Sealing Project, i.e. to develop a technique to bring in grout into fractures with a "hydraulic" aperture of about 100 m, has

been reached. Actually, it has been demonstrated that clay and cement grouts of considerable density penetrate fractures with an aperture of down to 10—20 μm by applying the "Dynamic Injection Technique". The distribution of grouts in fractures can be reasonably well predicted on the basis of Lugeon testing and fracture mapping, applying a flow model that has been developed in the course of the project. This theory requires application of suitable flow parameters that depend on the grout density, the applied frequency, and the geometry of the system (fracture aperture, borehole diameter). Parameter values can be deduced from viscometer tests with special respect to the influence of vibrations.

The very promising laboratory and initial field tests strongly suggest continuation of the project. A Pilot Field Test has been planned to take place in early 1988, comprising Lugeon tests for hydraulic characterization of the test rock area and for prediction of the grout penetration. The test will have the form of grouting four 1.5 m holes, two 7 m long ones and two 40 m long holes for checking the sealing effect and the agreement between predicted and actual distributions of the grouts in fractures, that intersect the holes. The location of the grouts in the fractures will be documented through comprehensive excavation of the rock mass. Both cement and clay will be used.

20 JSS-PROJECT

The SKB studies of high level waste glass durability is performed entirely within the JSS-Project. (A joint project between SKB, NAGRA in Switzerland and CRIEPI in Japan.) The JSS-Project has been subdivided into five phases, where the bulk of the experimental data were collected in phases I to III and phases IV and V dealt more specifically with modelling of the interactions in the system glass/bentonite/water/steel corrosion products. In phase V, a glass, MW, developed for the vitrification of Magnox wastes by BNFL at Sellafield was also included in the programme.

The final reports of phase IV were issued during 1987 /20-1, 20-2/. During 1987 also the experimental part of phase V was finalized, although the final reports of the JSS Project will be issued in 1988.

In phase IV, an effort was made to interpret the experimental results in terms of a first order dissolution/onprecipitation reaction with the activity of orthosilicic acid in solution controlling the rate of reaction. A computer programme, GLASSOL, was developed, based on the dissolution/precipitation mechanism, to simulate the glass water reaction, and an acceptable agreement between observations and the model was achieved. It was found that after silica saturation had been achieved in the solution, the glass corrosion rate dropped considerably. However, in phase IV it was not possible to derive this long-term corrosion rate with sufficient accuracy. Experimental work in phase V was concentrated on the completion of these long-term corrosion data and simulations thereof by using high surface area to solution volume ratios.

Apart from the above mentioned complementary experimental studies, Phase V of the project was concentrated on the final evaluation of the Cogéma glass data base obtained in the project in terms of glass long-term performance.

It was found that at silica saturation, the glass corrosion continues with a low all long-term rate. At 90 °C, this rate was about 1000 times lower than the initial corrosion rate. However, the effect of temperature on the long-term rate could not be measured since the rates at lower temperature were to small to be determined within the precision of the experimental data.

The presence of bentonite was found to slightly increase the initial corrosion rate. However, the long-term rate was unaffected by the presence of bentonite.

The normalized release of actinides into solution was always less than 1% of that of soluble elements. The soluble fraction of plutonium reached a constant value of about 10^{-9} mol/dm^3 independent of the type of experiment. However, the release of actinides into solution was governed to a significant extent by colloid formation. This colloid formation did not seem to be affected by the presence of bentonite.

20.1 MODELLING OF LONG-TERM PERFORMANCE

The GLASSOL code was used to evaluate the long-term performance of the Cogéma glass during a time period of up to 100 000 years /20-3/. With the help of data and detailed alteration phase analyses derived from observations on million year old basaltic glasses /20-4/, the model was validated in as far as to justify a constant long-term rate. This type of rate was considered as an upper limit for the alteration of the Cogéma glass.

There are some uncertainties in the experimentally measured parameters. In order to illustrate the sensitivity of the calculated results to the variation in parameter values, a set calculations have been performed for which the parameter and the bounding assumptions have been varied. The result for a constant repository temperature of 90 °C are illustrated in Figure 20-1:

Case (a) is based on the initial rate of reaction only and therefore describes a hypothetical case. The values calculated in Case (a) values will not be exceeded even with an infinite volume or flow rate of groundwater. The actual release will be much less than these extrapolated values.

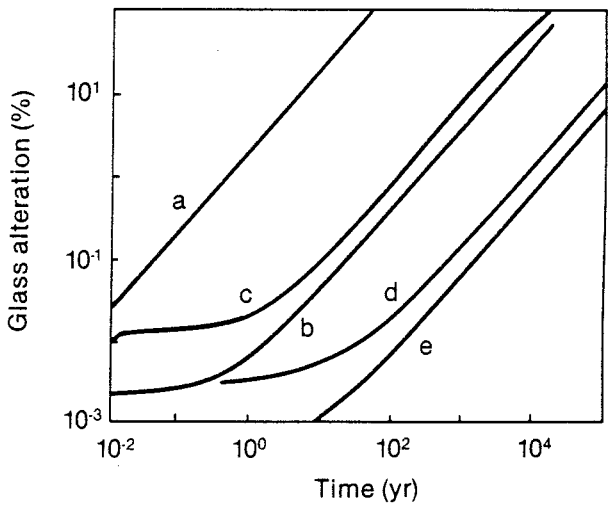


Figure 20-1. Calculations with varied parameter values for a constant repository temperature of 90 °C.

Case (b) is the reference case and is considered to be the most likely case. It is based on the experimental data, i.e., an initial reaction rate of 1.5 g/(m²d) and a long term rate of $2.5 \cdot 10^{-3}$ g/(m²d) and a log K for silica saturation of -2.94. The life time of a Cogéma glass block is found to be 10 000 years minimum.

Case (c) is calculated to account for uncertainty in the experimental data. The initial reaction rate constant is not modified because its value is known accurately enough, and it has only a limited effect on the long-term predictions. The silica concentration is allowed to approach the saturation value for amorphous silica which is about 5 times higher than the silica saturation constant for the glass surface. A long-term rate is used which is two times higher than the rate from the experimentally determined rate. The comparison of the curves (b) and (c) shows that experimental uncertainty does not significantly affect the calculated minimum life time of the glass block of about 10 000 years.

Cases (d) and (e) are calculated for glass/water reactions which stop after reaching silica saturation with respect to the glass surface. These cases are calculated as a bounding condition, to account for the possibility that the long-term rate may decrease with time. In case (d) the reaction rate is governed only by the groundwater flow rate and by the solubility limit of silica with respect to the glass surface. Case (e) describes the release when a 1 m backfill barrier of bentonite is present with a diffusion coefficient for silicic acid of 10^{-11} m²/s.

For the reference temperature of 90 °C, a lower release than that given by the curves (d) and (e) respectively, cannot be substantiated as long as groundwater access is permitted. This means that even when the long-term rate decreases with time, soluble elements would still be completely released from the glass within less than 1 million years.

Nevertheless, at lower temperatures the long-term rate will probably also be lower, while flow rate and diffusivity are not that much influenced by the decrease in temperature. Assuming the same temperature dependence for the long-term rate as for the initial reaction rate, the performance of the glass at a temperature of 50 °C was also calculated, see Figure 20-2. The cases (d) and (e) represent realistic cases. For the calculations a forward rate of 0.02 g/(m²d) was used. Case (b) and (d) gave identical results, because the long-term rate is expected to be lower than the transport rate of groundwater and as long as there is no near field transport barrier. In case (e) also the effect of the near field barrier is considered for the situation were the long-term rate is zero.

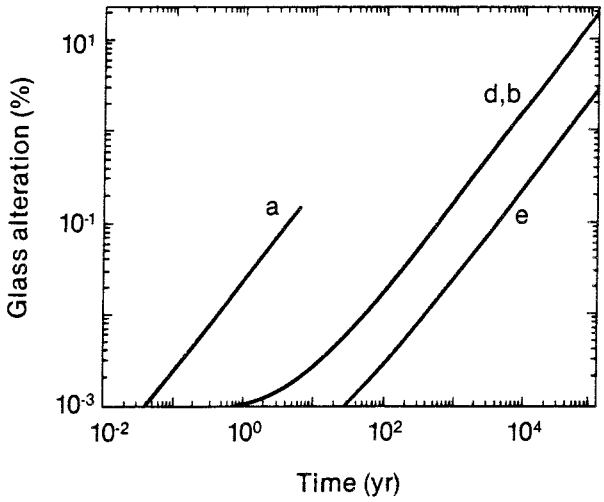


Figure 20-2. Same as Figure 20-1 but for a repository temperature of 50 °C.

21 NATURAL ANALOGUE STUDIES

21.1 THE POÇOS DE CALDAS PROJECT

Two sites in the Poços de Caldas district in Minas Gerais, Brazil are being investigated within the frame of the project; The large thorium deposit in Morro do Ferro and the Osamu Utsumi uranium mine, C-09.

Sweden (SKB), Great Britain (UK DOE), Switzerland (NAGRA), USA (US DoE) and Brazil (Rio de Janeiro University, CNEN and NUCLEBRAS) are participating in the project. The project is managed by SKB.

The natural analogue studies are divided into three subprojects:

1 To evaluate the transport and speciation of natural radionuclides and rare-earth elements in a fissure flow system in crystalline rock under both oxidizing and reducing conditions.

2 To study colloid formation and mobility in natural groundwaters and the role of colloids in radionuclide transport.

3 To study the thermal influence on the transport of natural radionuclides and rare earth elements.

The most important goals of the subprojects are as follows:

1 — Validate equilibrium models for different water-mineral systems.
— Understand the mechanisms for the dissolution and precipitation of uranium and other elements around the redox front.
— Compare retention factors from in-situ measurements with laboratory values.
— Determine the occurrence and extent of diffusion in microfractures in the rock.
— Determine the influence of microbes and microbial processes on radionuclide migration.

2 — Characterize and determine the concentration of natural colloids and organic complexes in the groundwater.
— Determine the fraction of thorium, radium and rare-earth metals that are transported in the form of colloids and organic complexes.

3 — Measure and evaluate the distribution of analogue elements across a hydrothermal contact.
— Determine the local extent of hydrothermal activity.
— Determine the nature of hydrothermal fluids and their influence on rock permeability.
— Understand the hydrothermally influenced transport mechanisms.

The introductory phase — the pilot and feasibility study — started in May 1986. In the course of the pilot study a borehole was percussion drilled with air-flushing down to 99 m in the Uranium Mine. Two feasibility study boreholes were subsequently drilled using water-flush rotary coring techniques down to depths of 126 m and 60 m respectively, see Figure 21-1. Microbiological sampling and geological logging of the core were carried out in parallel with the drilling, with subsequent sampling of the core for geochemistry mineralogy. The three boreholes were geophysically logged and hydrau-

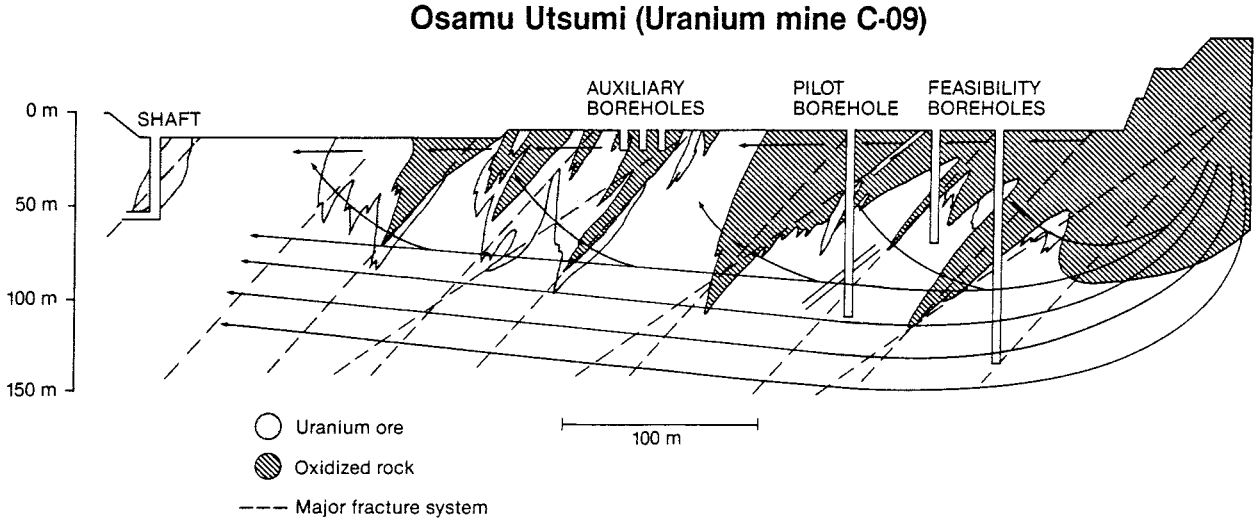


Figure 21-1. Section profile showing the relationships of the pilot and feasibility boreholes and groundwater sampling locations with the known geology, geochemistry and hydrogeology of the site.

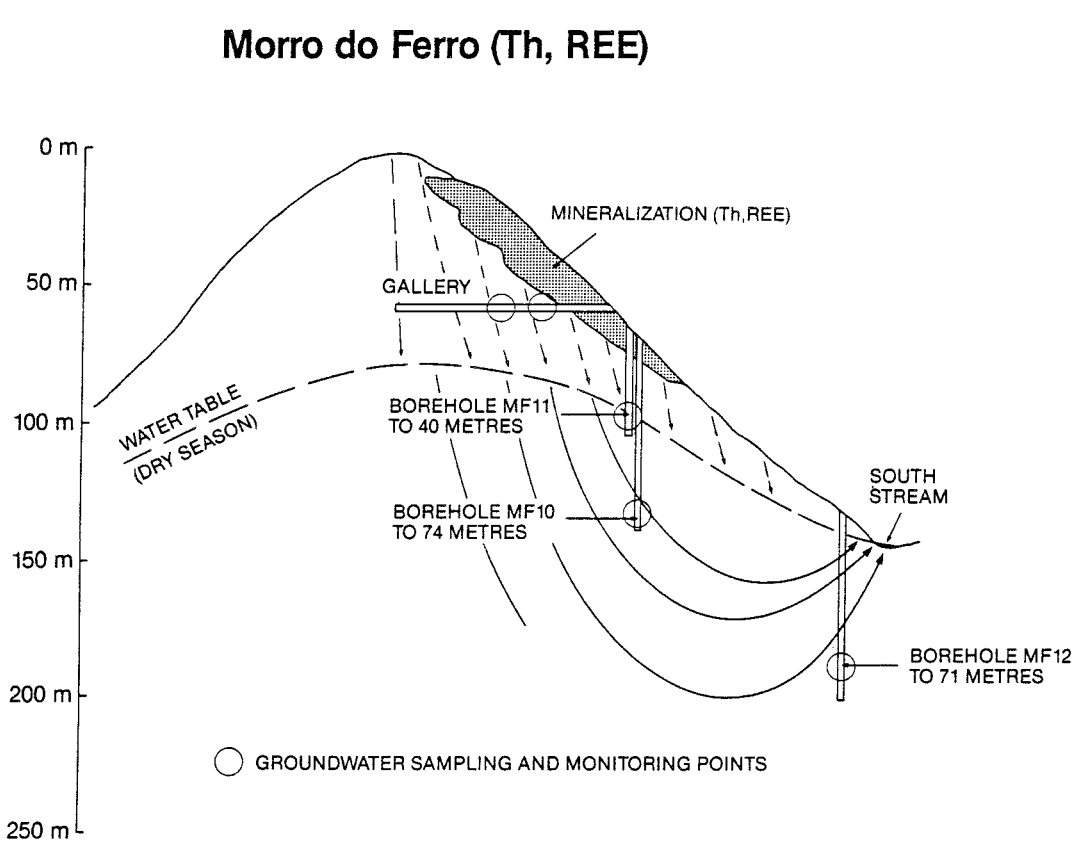


Figure 21-2. Location of groundwater sampling points and drilled boreholes MF10, 11 and 12 in relation to the thoriummineralization and the unsaturated and saturated bedrock zones.

lic tested. Groundwater sampling and monitoring were carried out.

The feasibility programme for Morro do Ferro involved drilling three boreholes, see Figure 21-2. Despite the rock instability it was possible to obtain a good core recovery and MF 10 was drilled to 74 m, MF 11 to 40 m and MF 12 to 71 m. A redox front was encountered at 35.7 m in the MF 12. Hydraulic testing and groundwater sampling were carried out.

Based on the results of the feasibility study and the major objectives of the project a program for further investigations were suggested and the Steering Committee decided to continue the project for its originally anticipated total duration of three years. US DoE decided to join the project which made it possible to include the third subproject in the overall program.

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 86 and Plan 87,
- in the series of SKB technical reports,
- in SKB working reports,
- in internal SKB reports,
- in contributions to scientific journals, symposia and conferences in different subject areas,
- 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 a data base system at SKB.

22.1 TECHNICAL REPORTS

SKB Technical Reports and many main reports, like for instance the KBS-3 report, are written in English. They are given a broad distribution to the scientific community in the nuclear waste field in order to get feedback to the program by the comments, discussions and contacts between specialists that they may give rise to. They are also used as means for the information exchange agreed upon in bilateral information exchange agreements. SKB Technical reports are filed as microfish at IAEA in Vienna and available through them.

During 1987 a guideline for formatting typescripts which are intended to be part of SKB documentation system, was produced. The guideline are available at SKB messenger.

22.2 CONTRIBUTIONS TO PUBLICATIONS, SENARS ETC

The contributions to conferences, symposia and scientific journals have been extensive during 1987, see Appendix 2.

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

One contribution can be noted in particular. After an invitation from the US-Congress, SKB President together with the Director General of the Swedish State Power Board held a briefing in January 1987 concerning the Swedish programme on nuclear waste treatment. The presentation was held in Washington D.C. to four of the US-Congress committees. Later in 1987 a delegation of senators also visited SKB and its facilities.

22.2 SKB DATA BASE SYSTEM

The data from the geological site investigations are now gathered in a common database (name: GEOTAB). This database is a so called relational database, giving the investigator the possibility to freely select and retrieve complete information of high quality. The database now contains data from 40 areas with surface data plus data from about 320 boreholes in these areas. Data are structured in 5 subject areas, about 75 methods and about 300 tables. Any one of these 300 tables can be combined with any other one. Total data volume is about 100 Mbyte. New data is continuously fed into the system with a time lag since the measurement varying between one day and some weeks, depending on which quality-assurance routines that must be applied.

The programs in GEOTAB are written in C, using the database manager MIMER and is currently running heavily 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. It should be possible to port it to any UNIX svstem with minor effort.

Stastistical and graphical presentation is currently provided on personal computers, to which GEOTAB offers nice file conversion capabilities.

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Case 4 Transient thermal convection in a saturated medium

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Part III

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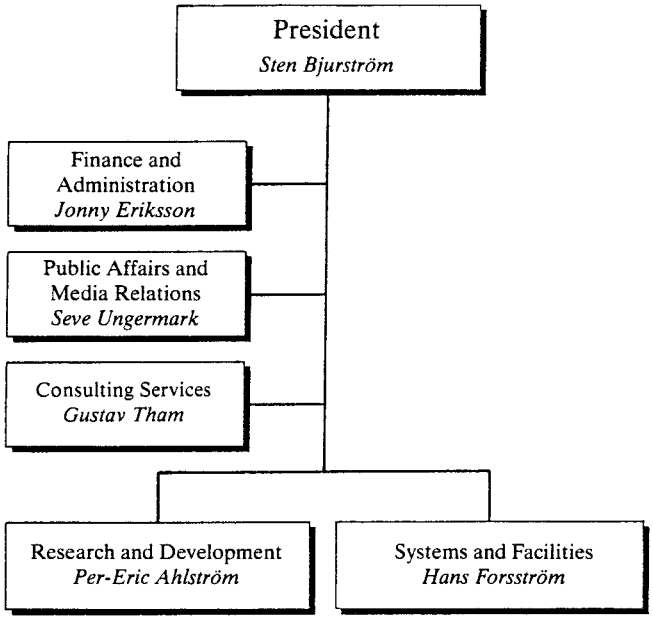
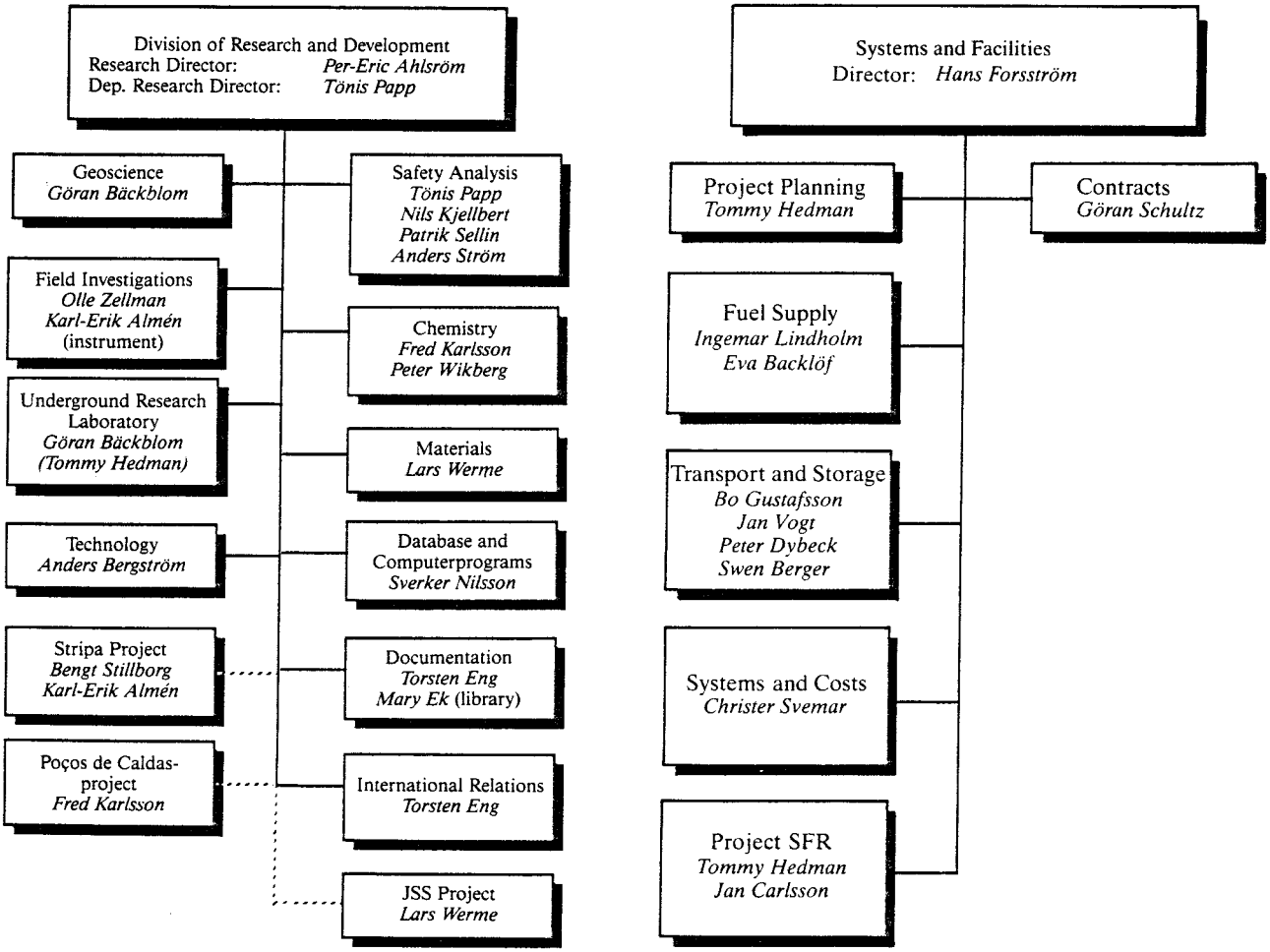
Appendix 1

ORGANIZATION CHARTS FOR SKB AND ITS DIVISIONS





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GFF, Vol 109, 1987, page 55 — 57

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February 1987

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Fuel rod/pellet characterization program part one
Roy Forsyth, Editor
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Calculations on HYDROCOIN level 1 using the GWHRT flow model
Case 1 Transient flow of water from a borehole penetrating a confined aquifer
Case 3 Satureted-unsaturated flow through a layered sequence of sedimentary rocks
Case 4 Transient thermal convection in a saturated medium
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Royal Institute of Technology, Stockholm
March 1987

TR 87-04
Calculations on HYDROCOIN level 2, case 1 using the GWHRT flow model
Thermal convection and conduction around a field heat transfer experiment
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TR 87-05
Applications of stochastic models to solute transport in fractured rocks
Lynn W Gelhar
Massachusetts Institute of Technology
January 1987

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Some properties of a channeling model of fracture flow
Y W Tsang, C F Tsang, I Neretnieks
Royal Institute of Technology, Stockholm
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Peter Wikberg, Karin Axelsen, Folke Fredlund
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Piping and erosion phenomena in soft clay gels
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Outline of models of water and gas flow through smectite clay buffers
Roland Pusch, Harald Hökmark, Lennart Börgesson
Swedish Geological Co, Lund
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TR 87-11
Modelling of crustal rock mechanics for radioactive waste storage in Fennoscandia—Problem definition
Ove Stephansson
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TR 87-12
Study of groundwater colloids and their ability to transport radionuclides
Kåre Tjus and Peter Wikberg***
* Institute for Surface Chemistry, Stockholm
** Royal Institute of Technology, Inorganic Chemistry Stockholm
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June 1987

TR 87-15
Geochemical interpretation of groundwaters from Finnsjön, Sweden
Ignasi Puigdomènich[1], Kirk Nordstrom[2]
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[2]U S Geological Survey, Menlo Park, California
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Corrosion tests on spent PWR fuel in synthetic groundwater
R S Forsyth[1] and L O Werme[2]
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[2]The Swedish Nuclear Fuel and Waste Management Co (SKB), Stockholm
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Conny Holmqvist, Rutger Wahlström
Seismological Department, Uppsala University
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Calculation of gas migration in fractured rock
Roger Thunvik[1] and Carol Braester[2]
[1]Royal Institute of Technology Stockholm, Sweden
[2]Israel Institute of Technology Haifa, Israel
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Calculation of gas migration in fractured rock — a continuum approach
Carol Braester[1] and Roger Thunvik[2]
[1]Israel Institute of Technology Haifa, Israel
[2]Royal Institute of Technology Stockholm, Sweden
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Y Tardy, J Duplay and B Fritz
Centre de Sédimentologie et de Géochimie de la Surface (CNRS)
Institut de Géologie Université Louis Pasteur (ULP)
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John Smellie[1], Nils-Åke Larsson[1], Peter ikberg[3], Ignasi Puigdomènech[4], Eva-Lena Tullborg[2]
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Radionuclide sorption on granitic drill core material
Trygve E Eriksen and Birgitta Locklund
The Royal Institute of Technology
Department of Nuclear Chemistry, Stockholm
November 1987

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Radionuclide co-precipitation
Jordi Bruno and Amaia Sandino
The Royal Institute of Technology
Department of Inorganic Chemistry, Stockholm
December 1987

TR 87-24
Geological maps and cross-sections of Southern Sweden
Karl-Axel Kornfält[1] and Kent Larsson[2]
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December 1987

TR 87-25
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Kai Palmqvist[1] and Roy Stanfors[2]
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Earthquake measurements in souther Sweden
Oct 1, 1986—Mar 31, 1987
Ragnar Slunga, Leif Nordgren
National Defence Research Establishment
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December 1987

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Radionuclide deposition and migration within the Gideå and Finnsjö study sites, Sweden
A study of the fallout after the Chernobyl accident
Erik Gustafsson[1], Mats Skålberg[2], Björn Sundblad[3], Olle Karlberg[3], Eva-Lena Tullborg[4], Thomas Ittner[2], Paul Carbol[2], Niklas Eriksson[2], Svante Lampe[3]
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Alteration of isolating properties of dense smectite clay in repository environments as exemplified by seven pre-quarternary clays
Roland Pusch, Lennart Börgesson, Mikael Erlström
Swedish Geological Co, Lund
December 1987

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Water compositions in the Lake Sibbofjärden — Lake Trobbofjärden area
Karin Andersson
Studsvik Energiteknik AB, Studsvik
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Rheological properties of a calsium smectite
Lennart Börgesson, Roland Pusch
Swedish Geological Co, Lund
December 1987

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Survey of Swedish buffer material candidates and methods for characterization
Mikael Erlström, Roland Pusch
Swedish Geological Co, Lund
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SKB ANNUAL REPORT 1987
Part IV

Summaries of Technical Reports Issued During 1987

SKB Technical Report No 87-01

RADAR MEASUREMENTS PERFORMED AT THE KLIPPERÅS STUDY SITE

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February 1987

ABSTRACT
Single hole radar measurements, with center frequencies of 22 and 60 MHz, have been performed in ten out of fourteen boreholes at the study site Klipperås. VRP (Vertical radar profiles) have also been performed in six of the ten boreholes. All fracture zones previously derived from core maps and logging data were discovered during the analysis of the radar measurements. From the large-scale pattern of the radar maps it can be deduced that most radar reflecting structures are oriented in E-W and have a vertical or subvertical dip. Greenstone constitutes a large part of these structures, which can be considered as extensive structures and do not constitute isolated fragments in the rock mass. A majority of the interpreted radar reflecting structures intersecting the borehole are coupled together with low resistivity. All greenstones and mafic dykes (dolerite and basalt) which are characterized by low resistivity give rise to radar reflections. Wider fracture zones and other units, e.g. mafic dykes (dolerite and basalt), with a very low resistivity give a strong loss in radar pulse energy. The predicted orientation of the fracture zones from earlier investigations agrees well with the orientation calculated from radar crossing angles. Different orientations of the fracture zone H1 have been analyzed. With a strike in north-south and a dip of 20° the outcrop of this fracture zone correlates well with a geophysical anomaly obtained along profiles extended outside the investigated area.

SKB Technical Report No 87-02

FUEL ROD DO7/B15 FROM RINGHALS 2 PWR: SOURCE MATERIAL FOR CORROSION/LEACH TESTS IN GROUNDWATER.

FUEL ROD/PELLET CHARACTERIZATION PROGRAM PART ONE

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March 1987

ABSTRACT
The oxide layer on fuel rod 03688 from Ringhals 2 has been examined visually by periscope. The observations indicate that the lower part of the rod has not reached transition in the oxidation process, while it is in this stage in a region 150-600 mm from the bottom and has passed transition in oxidation above 600 mm from the bottom. The oxidation close to the spacers is less than in surrounding parts of the rod.

SKB Technical Report No 87-03

CALCULATIONS ON HYDROCOIN LEVEL 1 USING THE GWHRT FLOW MODEL

Case 1 **Transient flow of water from a borehole penetrating a confined aquifer**

Case 3 **Saturated-unsaturated flow through a layered sequence of sedimentary rocks**

Case 4 **Transient thermal convection in a saturated medium**

Roger Thunvik

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March 1987

ABSTRACT

The present report presents solutions to HYDROCOIN Level 1: Case 1, 3 and 4. Case 1 deals with transient flow of water from a borehole which penetrates a confined aquifer consisting of a homogeneous, isotropic permeable medium which is underlain by a single horizontal fracture. Case 3 deals with a problem of saturated-unsaturated flow through a layered sequence of sedimentary rocks. Case 4 deals with transient thermal convection in a saturated permeable medium.

HYDROCOIN is an international cooperation project to compare different computer models used for describing groundwater flow in geological media. The purpose of the project is to improve the understanding of various strategies for modelling groundwater flow for the safety assessment of final radioactive waste repositories.

The project is structured in three levels. The object of level 1 is to examine the numerical accuracy of the computer models compared. The object of level 2 is to study the capability of computer models to describe in-situ measurements. Level 3 is concerned with sensitivity and uncertainty analysis of groundwater flow.

SKB Technical Report No 87-04

CALCULATIONS ON HYDROCOIN LEVEL 2, CASE 1 USING THE GWHRT FLOW MODEL

THERMAL CONVECTION AND CONDUCTION AROUND A FIELD HEAT TRANSFER EXPERIMENT

Roger Thunvik

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March 1987

ABSTRACT

The present report presents solutions to HYDROCOIN Level 2: Case 1, dealing with thermal convection and conduction around a field heat transfer experiment. HYDROCOIN is an international cooperation project to compare different computer models used for describing groundwater flow in geological media. The purpose of the project is to improve the understanding of various strategies for modelling groundwater flow for the safety assessment of final radioactive waste repositories.

The project is structured in three levels. The object of level 1 is to examine the numerical accuracy of the computer models compared. The object of level 2 is to study the capability of computer models to describe in-situ measurements. Level 3 is concerned with sensitivity and uncertainty analysis of groundwater flow.

SKB Technical Report No 87-05

APPLICATIONS OF STOCHASTIC MODELS TO SOLUTE TRANSPORT IN FRACTURED ROCKS

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January 1987

ABSTRACT

A stochastic theory for flow and solute transport in a single variable aperture fracture, bounded by a sorbing porous matrix into which solutes may diffuse, is developed using a perturbation approximation and spectral solution techniques which assume local statistical homogeneity. The theory predicts that the effective aperture of the fracture for mean solute displacement will be larger than the aperture required to calculate the large-scale flow resistance of the fracture. This ratio of apertures is a function of the variance of the logarithm of the apertures. The theory also predicts the macrodispersion coefficient for large-scale transport in the fracture. The resulting macrodispersivity is proportional to the variance of the logaperture and to its correlation scale. When variable surface sorption is included, it is found that the macrodispersivity is increased significantly, in some cases more than an order of magnitude. It is also shown that the effective retardation coefficient for the sorptively heterogeneous fracture is found by simply taking the arithmetic mean of the local surface sorption coefficient. Matrix diffusion is also shown to increase the fracture macrodispersivity at very large times. A reexamination of the results of four different field tracer tests in crystalline rock in Sweden and Canada shows aperture ratios and dispersivities that are consistent with the stochastic theory. The variance of the natural logarithm of the aperture is found to be in the range of 3 to 6 and the correlation scales for logaperture ranges from .2 to 1.2 meters. Detailed recommendations for additional field investigations at scales ranging from a few meters up to a kilometer are presented.

SKB Technical Report No 87-06

SOME PROPERTIES OF A CHANNELING MODEL OF FRACTURE FLOW

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December 1986

ABSTRACT

Water flow in fractures in crystalline rock has been observed to be unevenly distributed over the fracture plane. The network of channels in the plane of the fracture is formed by the connected open portions of the fracture among areas of contact of the two fracture surfaces. Measurements of the aperture density distribution within a particular laboratory sample of granite fracture have shown that the distribution is skewed with a long tailing towards the larger apertures. The measured aperture distribution had a correlation length between a fifth and a tenth of the fracture length.

In earlier studies it has been shown that two-dimensional networks may be generated based on the statistical distributions. The hydraulic properties of the generated two-dimensional networks have been studied. Under an imposed hydraulic head difference over the fracture the water flow will take place in a few preferred pathways, avoiding those areas where the fracture aperture is small. In the two-dimensional network the paths will divide and merge occasionally but a water parcel introduced at the inlet will follow one pathway and a parcel introduced at another point may follow another pathway. In this study we set out to investigate the properties of the individual pathways as to volumes, flowrates, and residence times. In addition to this the dispersion properties of the network of channels in a fracture are investigated.

The Gamma distribution and the log-normal distribution were used to describe the density distribution of the apertures within a channel. For every set of parameter values (correlation length, and the parameters of the distributions) 95 different statistically equivalent channels were generated. The aperture distribution along the channels are then used to determine the total channel volume, the hydraulic conductivity and the flowrate and residence time for a given gradient.

The volumes of the channels were found to vary little whereas the hydraulic conductivity, which is primarily determined by the smallest aperture along the channels, varies considerably. For a wide density distribution the hydraulic conductivity easily spans several orders of magnitude. The flowrate and the velocity variations are

primarily influenced by the conductivity variations and are only to a small extent influenced by the volume variations in the channel. The average specific area of the whole channel exhibits small variations.

The hydraulic and transport properties of hypothetical fractures containing several channels are investigated by randomly picking several of the generated channels, coupling them in parallel and subjecting them to the same hydraulic head difference. The flowrate and residence time distribution of the coupled channels is used to investigate the dispersion properties of the fracture. It was found that the dispersion expressed as Peclet numbers was on the order of 1 to 4 for most of the distributions used but could attain very large Peclet numbers for (unrealistically) narrow aperture distributions.

Simulations of breakthrough curves for tracers in single fracture flow experiments indicate that when few channels participate and the dispersion in the individual channels is small, the breakthrough curve is expected not to be entirely smooth but to contain distinct plateaus. This property has been noted in several experiments.

The presented model has some interesting properties for modelling flow and transport in 3-dimensional fracture networks. Such a network might be modelled as a bundle of "parallel" channels (essentially a one-dimensional model) instead of as a three-dimensional network of fractures. This simplifies the computational effort enormously.

Several assumptions in the proposed channeling model must, however, be tested further and the results of the model compared to both other more complex models and to field experiments.

SKB Technical Report No 87-07

DEEP GROUNDWATER CHEMISTRY

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June 1987

ABSTRACT

The chemical conditions of deep groundwaters in granitic rock is described. A large number of groundwater analyses have been made throughout the Swedish nuclear waste management program, directed by SKB, for studying possible high level radioactive waste repository sites. The prime objective of this report is to present the redox potential measurements and to relate them to possible chemical reactions in the groundwater/rock system. Laboratory simulations have been performed in order to understand and support the field observations.

A mobile field laboratory has been constructed and found to give results which are more reliable with respect to redox sensitive constituents than previous analyses.

A down-hole sond has been used for Eh measurements. These measurements are not disturbed by atmospheric oxygen. The results of the measurements indicate that the deep groundwater is strongly reducing. This fact is also supported by the analyses of redox sensitive elements.

SKB Technical Report No 87-08

AN APPROACH FOR EVALUATING THE GENERAL AND LOCALIZED CORROSION OF CARBON STEEL CONTAINERS FOR NUCLEAR WASTE DISPOSAL

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June 1987

ABSTRACT

The paper considers the long term corrosion of carbon steel containers for heat generating nuclear waste in a granitic repository. Under such conditions carbon steel may exhibit general, localised or passive corrosion behaviour depending on the exact composition and redox potential of the groundwater contacting the containers; localised corrosion being of most concern because it has the fastest propagation rate. It is well established, however, that such localised corrosion is only possible when the environment is sufficiently oxidising to maintain a positive potential gradient between the cathodic surface and the corrosion sites, which requires that species with oxidising potentials greater than water need to be present. This fact provides a basis for estimating the periods during which containers may be subject to localised and subsequently to general corrosion, and hence for making an overall assessment of the metal allowance required for a specified container life. A model for the diffusion transport of oxygen has been developed, and a sensitivity analysis has shown that the period of possible localised attack is strongly dependent on the passive film leakage current, the radiation dose rate and the oxygen diffusion coefficient.

SKB Technical Report No 87-09

PIPING AND EROSION PHENOMENA IN SOFT CLAY GELS

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May 1987

ABSTRACT

The present study has confirmed the conclusions from earlier investigations of piping and erosion of soft smectite gels by showing that the erodibility can be predicted by comparing the drag forces exerted by flowing water and the cohesive particle bonds in the gels.

Optical microscopy used to identify the detailed erosion mechanisms shows that discrete flakes are not eroded as assumed earlier. The minerals torn off from the gels in fact consist of stable aggregates sized 5-50 μm in the case of electrolyte-poor water and even larger units in ocean-type water. The theoretical model as well as the experiments show that erosion is initiated at a flow rate of 10^{-4} m/s in the first-mentioned type of water and that it becomes significant at 10^{-3} m/s. In salt water the gels are much more erosion-resistant.

Piping, which preceded the erosion in the tests, can take place in the form of radial expansion of natural pore passages in the gels, or by tensile failure, depending on the boundary conditions. Theoretically, the critical pressure to produce piping is about 1 kPa at a water content of 1000 % of Na montmorillonite and this appeared to be on the same order of magnitude as the experimentally determined values for the very conservative conditions that were applied. Separate tests of a clay rich in hydrous mica showed much less erodibility and higher piping resistance than of the smectite gels.

SKB Technical Report No 87-10

OUTLINE OF MODELS OF WATER AND GAS FLOW THROUGH SMECTITE CLAY BUFFERS

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Swedish Geological Co, Lund

June 1987

ABSTRACT

While routine laboratory tests yield average values of the hydraulic and gas conductivities, the actual rate and capacity of flow is not revealed. Microstructure analyses of natural clays with hydrous mica or smectite as major clay mineral have demonstrated that there are large variations in pore size, and that a few wide pores may be responsible for the great majority of the permeation. A similar behavior may be valid also for "artificially" produced smectite clays which are formed from powdered Na bentonite. A model is derived for such clays in which the powder grains are regarded as anisotropic aggregates which swell on wetting and form a network with pores that are successively filled with a clay gel that emanates from the aggregates. The density and hydraulic conductivity of the gel is a function of the pore size and distribution as well as of the porewater chemistry.

Applying the model to three "reference" clay types of different bulk density, it is shown that realistic data for the hydraulic and gas conductivities as well as for the ratio of the anion and cation diffusion capacities are arrived at. The model is therefore taken as a basis for further development.

SKB Technical Report No 87-11

MODELLING OF CRUSTAL ROCK MECHANICS FOR RADIOACTIVE WASTE STORAGE IN FENNOSCANDIA — PROBLEM DEFINITION

Ove Stephansson

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May 1987

ABSTRACT

The problem of long term stability and geodynamic processes of the Baltic Shield has been addressed in the research plan for the oncoming six years, 1987-1992, of the Swedish Nuclear Fuel and Waste Management Company. The aims of the research activities are to quantify and place limits on the effects of earthquakes, glaciation and glacial rebound. Special attention will be paid to the safety analysis of a final storage of spent nuclear fuel.

In modelling the deformation of large scale rock masses and the stability of vaults for radioactive waste disposal, we need to know the geometry and structure of the geomechanical parameters of large rock masses and the boundary conditions that we might apply to our models.

Existing knowledge on crustal stresses and their orientation for Western Europe and North America is reviewed, and data on crustal stress gradients for Fennoscandia are presented. The vertical stress is taken to be equal to the weight of the overburden and the horizontal stress gradients are in accordance with shallow stress measurements, predominantly thrust fault earthquake fault plane solutions and ridge push at the Mid Atlantic Ridge as a major stress generating mechanism for the maximum horizontal stress.

Generic, two-dimensional models are proposed for vertical and planar sections of a traverse having a direction NW-SE in Northern Fennoscandia. The vertical section comprises a three-layered model of the lithosphere from the oceanic-continental crustal boundary at the shelf of the North Sea, to the centre of uplift in the Bothnian Bay. Faults are assumed to extend down to the upper-lower crust boundary at a depth of about 20 km. The proposed traverse will include the major neotectonic structures at Lansjärv and Pärvie, respectively, and also the study site for storage of spent nuclear fuel at Kamlunge, close to the SE end of the traverse.

In modelling the influence of glaciation, deglaciation and glacial rebound on crustal rock mechanics and stability, two modelling approaches are suggested. In the first approach, the ground surface and the crustal-mantle interface has a prescribed shape in accordance

with known functions of elastic-viscous rebound for each side of the ice front and the uplift is varied according to existing knowledge about total, present and remaining uplift.

The second modelling approach uses ice as a surface load, where the boundary of the ice sheet follows the extension of the Weichselian glacial ice at the continental shelf of Northwestern Norway.

In principal three different size of models are suggested. Global models, with a length of about 100 km, will make it possible to increase our overall understanding of the change in stresses and deformations and they can provide boundary conditions for regional and near-field models. The regional models can be used for studies of the neotectonic structures and the near-field models will be used for stability analysis of the vault for final storage of spent nuclear fuel.

The last section of the report is devoted to a study of the strength of granitic rock masses. Here the rock mass discontinuity characteristics are shown to be of equal, or even greater importance in studies of crustal stability and integrity of vaults than is the case with much stronger and stiffer intact rocks. Differences in the shear strength of rock joints and faults at low and high effective normal stress are demonstrated and equations to describe these properties are presented. The stiffness of joints and faults is assumed to be independent of the block size, whereas shear stiffness is most likely to vary as a function of the length of the joint/fault and the effective normal stress. Properties of this type must be considered in the modelling of the crustal rock mechanics for any of the three models described above.

SKB Technical Report No 87-12

STUDY OF GROUNDWATER COLLOIDS AND THEIR ABILITY TO TRANSPORT RADIONUCLIDES

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March 1987

ABSTRACT

The general aim of this investigation was to test if the two photon correlation spectroscopy equipments at the Institute for Surface Chemistry could be used to measure the colloid concentration in groundwater and also to measure the surface potential (zeta potential) of these colloids.

Groundwater colloids from Stripa, Kamlunge and Svartboberget have been investigated. Well characterized pure kaolin was used as a model colloid.

The equipment for dynamic light scattering at the Institute for Surface Chemistry was found to be sensitive for detection of colloids in groundwater down to 100 μg/l. The highest amount measured in real groundwater was 400 μg/l. In KBS-3 one assumed a content of 500 μg/l, this seems to be a good assumption.

The equipment at the Institute for Surface Chemistry for measuring the zeta potential is also based on dynamic light scattering, in combination with detection of a Doppler shift in the frequency of the scattered light in an electric field (Malvern Zetasizer). This equipment is less sensitive than conventional light scattering equipment and hence it is necessary to concentrate the groundwater between 200 and 1000 times.

The method gives a distribution curve for zeta potentials (surface charges). In principle, it should be possible to detect several particle types with different charges. In practice, this is possible only for well-defined model systems, where there are large variations in the particle size and refractive indexes.

The accessible equipment was found to be useful for the estimation of the colloid content in groundwater and also for the estimation of a mean value (with distribution) of the zeta potential of the colloides.

Due to the low concentrations of colloids, a very low content of multiple valent cations can drastically change their zeta potentials, which is illustrated by model studies with kaolin and Fe^{3+}. It could be possible to estimate the size of these changes on basis of the model of James and Healy for ion adsorption on mineral surfaces.

SKB Technical Report No 87-13

SHALLOW REFLECTION SEISMIC INVESTIGATION OF FRACTURE ZONES IN THE FINNSJÖ AREA METHOD EVALUATION

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Jonas Lindgren

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June 1987

ABSTRACT
In the Finnsjö area a reflection seismic profile has been shot. Under the profile the crystalline bedrock lies close to the surface (seldom more than 2 m), and the seismic velocities are high. There are known fracture zones in the area. A larger, sub horizontal fracture zone (zone 2) turned out to be difficult to detect, while a steeply dipping zone (Brändan zone) seems to be more reflective. It has not been possible to present a stacked section that enhances zone 2 so it can be followed along the profile. A reason can be that it simply is not a very reflective zone.

SKB Technical Report No 87-14

COMBINED INTERPRETATION OF GEOPHYSICAL, GEOLOGICAL, HYDROLOGICAL AND RADAR INVESTIGATIONS IN THE BOREHOLES St1 AND St2 AT THE SALTSJÖTUNNEL

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June 1987

ABSTRACT
Radar measurements have been used to produce a model of the geological structures along a section of the Saltsjötunnel. The model was arrived at without access to any other geological, geophysical or hydrological data except a topographic map of the site. The radar model has then been compared to results from core mapping, geophysical logging and hydraulic borehole measurements. All available data have been put together to check the validity of the radar model and then to revise it in order to obtain an improved model of the site.

The model produced by the radar results have in general been in agreement with the result of the other borehole investigations. The combined interpretation reveals two sets: the first set is adjoined with lithological variations in the bedrock striking roughly N-S with a more or less vertical dip. The second subhorizontal set which constitute the most prominent fracture zones is striking NW with a dip 35 ° towards NE. The combined interpretation resulted in a model comprising three dominating subhorizontal zones. The three subhorizontal zones are interpreted to be the most dominating fracture zones within the investigated area.

SKB Technical Report No 87-15

GEOCHEMICAL INTERPRETATION OF GROUNDWATERS FROM FINNSJÖN, SWEDEN

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2 **U S Geological Survey, Menlo Park, California**

August 1987

ABSTRACT

Chemical and isotopic analyses of groundwaters taken from boreholes at the Finnsjön study site have been evaluated. The predominant rock type consists of granodiorite, and within the crystalline rock matrix, both the fracture network and its coating minerals have a large effect on the aqueous geochemistry of the site.

The tritium content of the samples has a positive correlation with total iron and organic carbon, and a negative correlation with Cl^-, Mn^{2+} and NH_4^+. The very presence of this isotope in the waters is a strong indication that mixing of very young waters with older, deep waters has probably taken place during sampling.

The disagreement between the field and laboratory pH-values collected during 1979-1982 introduces a serious difficulty in the interpretation of that data.

Nevertheless, computer calculations with aqueous speciation models (WATEQ3 and EQ3NR) give a picture of the water-rock interactions. The mineral saturation indices of calcite, strontianite, rhodochrosite, and siderite show that the concentration levels of Ca^{2+}, Sr^{2+}, Mn^{2+} and Fe^{2+} are probably fixed by the aqueous carbonate system and its minerals. However, unreasonably high saturation indices of calcite (up to +1.7) confirm the uncertainties in the pH-values. Computer simulations with the EQ6 code show that $CO_2(g)$ outgassing/ingassing might have contributed errors in the pH measurements during the sampling procedure. EQ6 simulations also show that mixing of waters from different aquifers might have induced transient over-or undersaturation of carbonate minerals.

Equilibrium between groundwaters and fluorite and barite appear to fix the concentrations of F^- and Ba^{2+} respectively.

Some of the sampled groundwaters reach relatively high salinities (chloride levels of 6 g l^{-1}). The origin of the saline components is still uncertain. There are some similarities between the ionic ratios of Finnsjön waters and Stripa groundwaters. Specially, the saline waters sampled at borehole Fi8 (which intercepts the Gåvastbo fault) have as high Ca/Mg and Br/Cl ratios as Stripa waters, and the lowest sulfate concentrations, indicating a greater degree of mineral-water interactions and lower redox potential than the rest of the samples.

SKB Technical Report No 87-16

CORROSION TESTS ON SPENT PWR FUEL IN SYNTHETIC GROUNDWATER

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Stockholm, September 1987

ABSTRACT

Short fuel/clad segments from a high burnup PWR fuel rod have been exposed to simulated groundwater under both oxidizing and reducing conditions. Two methods of establishing reducing conditions were employed: by using H_2 gas in the presence of Pd catalyst, and by circulating the groundwater over rock-cores from a deep borehole.

The results from the first two contact periods of 82 and 172 days are in good agreement with those obtained previously on a high burnup BWR fuel rod. In particular, it was found that under oxidizing conditions, uranium saturates at about the 1 mg/l level, and plutonium at about the 1 μg/l level.

Under reducing conditions, these solubilities decreased by about two orders of magnitude.

SKB Technical Report No 87-17

THE JULY-SEPTEMBER 1986 SKÖVDE AFTERSHOCK SEQUENCE

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August 1987

ABSTRACT
On July 14, 1986, one of the strongest earthquakes in Sweden during this century, M_L = 4.5, occurred near Skövde. A mobile network with analog and digital stations was rapidly deployed in the epicentral area. A comprehensive sequence of earthquakes was recorded, with three different temporal patterns of successively decreasing energy release. Besides a large shock, M_L = 3.4, less than one hour after the main shock, 20 aftershocks took place during nearly two months of field operation, 12 of them in the first 10 days. Four aftershocks could be independently located: the focal depth was approximately 30 km and the location of each epicentre was less than 10 km from that of the main shock. The magnitudes vary from -0.7 to 2.8. The main shock and aftershocks seem to be distributed along a plane trending N3 °W. The location of the foci in the lower crust is unusual for Baltic Shield earthquakes.

SKB Technical Report No 87-18

CALCULATION OF GAS MIGRATION IN FRACTURED ROCK

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Stockholm, September 1987

ABSTRACT
Medium and low level radioactive waste repository caverns are planned to be located in fractured hard rock formations at a depth of about 50 metres below the sea level. Chemical reactions in the stored waste will result in gas (hydrogen) production in a saturated water environment. Under such conditions the gas will displace the water from the fractures and migrate towards the surface and finally be released through the sea bottom. The lateral gas movement is considered negligible and the computations were performed under the assumption of vertical flow. Calculations are presented for rock properties characteristic to the Forsmark area. The rock permeability was determined by flow tests in vertical boreholes. It is assumed that the permeability distribution obtained from these boreholes is representative also for the permeability distribution along the repository cavern. Calculations were worked out for two different types of boundary conditions, one in which a constant gas flow rate equivalent to a gas production of 33000 kg/year was assumed and the other in which a constant gas cushion of 0.5 metres was assumed. For the permeability distribution considered, the breakthrough at the sea bottom occurred within one hour. The gas-water displacement took place mainly through the fractures of high permeability and practically no flow took place in the fractures of low permeability. A gas cushion was formed during a very short period. The gas breakthrough at the sea bottom results in a sudden drop in pressure and backflow in the low permeability classes of fractures.

SKB Technical Report No 87-19

CALCULATION OF GAS MIGRATION IN FRACTURED ROCK — A CONTINUUM APPROACH

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Stockholm, September 1987

ABSTRACT

A study of gas migration from low level radioactive repositories in which the fractured rock mass was conceptualized as a continuum, was carried out by the aid of a computer program based on a finite difference numerical method of solution to the equations of flow. The displacement is considered to be governed by the equations of simultaneous two-phase flow, gas and water. Without having the possibility of practical determination of the parameters of the continuum equivalent such as capillary pressure and relative permeabilities of the fractured rock, these functions were assumed. The calculations are intended to correspond to the prevailing in the Forsmark low level repository area where radioactive waste repository caverns are planned to be located at a depth of about 50 metres below the sea level. Chemical reactions in the stored waste will result in gas (hydrogen) production in a saturated water environment. Under such conditions the gas will displace the water from the rock and migrate towards the surface and finally be released through the sea bottom. Calculations were worked out for a constant gas flow rate equivalent to a gas production of 20000 normal cubic metres per year. The investigated flow domain was a vertical cross-section passing through the repository. The results show that in the empty cavern the gas formed in the cavern moves almost instantaneously upward and accumulates below the roof of the cavern. The gas penetrates the rock and displaces the water after a gas cushion of 0.4 m, corresponding to the assumed entry capillary pressure value, is formed below the roof of the cavern. In the cavern, the gas-water interface is horizontal. The gas advance is faster in the centre of the repository than at the edges. The displacement is limited to the near region to the repository. The breakthrough time at the sea bottom is about 0.6 days. The results are different from those obtained in the previous studies in which the rock was conceptualized as a discrete system of fractures in which the flow process is dominated by the largest fractures and as a consequence the breakthrough time is smaller.

SKB Technical Report No 87-20

STABILITY FIELDS OF SMECTITES AND ILLITES AS A FUNCTION OF TEMPERATURE AND CHEMICAL COMPOSITION

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ABSTRACT

Besides arguments which suggest that clay minerals are metastable phases at the surface of the Earth, there are also indications that the chemical compositions of smectites and illites somewhat reflect the temperatures at which they form and the different chemical environments in which they may approximately equilibrate. Thus the thermodynamic properties of clay minerals must be further explored.

Almost all the standard XRD-determined pure clay phases, in fact, appear to be mixtures of particles of highly dispersed chemical compositions. Furthermore, within an apparent monomineralic population of particles, chemical variables are intercorrelated in such a way that correlations clearly reflect the temperatures at which these populations are supposed to have been formed. The (Fe^{3+}) VI-content in octahedral position is positively correlated with the tetrahedral charge (glauconites) at low temperature and with the octahedral charge (celadonite) at high temperature. The (Al^{3+}) VI-content is negatively correlated with the tetrahedral charge at low temperatures (montmorillonite) and positively correlated to the tetrahedral charge (illite) at higher temperatures. The (Mg^{2+}) VI-content is negatively correlated with the tetrahedral charge (stevensite) at low temperature, while it is positive!y correlated to the tetrahedral charge at high temperature (saponite).

A thermodynamic ideal solid solution analogue is proposed which accounts for such correlations. The solid solution is considered, at a particle scale, as an ideal mixture of individual layers, weakly bent each to the next. Each layer presents the chemical composition of a given end member, so that the proportions of the different end members change from one particle to another. Because the solid solution theory requires that several ideal solid solutions cannot be in equilibrium in the same environment, one must consider that each particle and its surrounding solutions forms an independent microsystem.

Considering one particle of a given chemical composition, the multipole solid solution theory allows to calculate the weighted contributions of each end member into the ideal clay solid solution along with the chemical composition of the aqueous solutions in equilibrium with the considered particle in its independent microenvironment.

This model is able to predict the nature of the chemical correlations which are expected, at a given temperature, within a given population. This model is also applied to the prediction of the temperature required for the conversion of smectite into illite during the burial diagenesis.

SKB Technical Report No 87-21

HYDROCHEMICAL INVESTIGATIONS IN CRYSTALLINE BEDROCK IN RELATION TO EXISTING HYDRAULIC CONDITIONS: KLIPPERÅS TEST-SITE, SMÅLAND, SOUTHERN SWEDEN

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ABSTRACT

From a total of 14 cored boreholes drilled at the Klipperås test-site area, three were selected for hydrochemical characterization; boreholes Kl 1, Kl 2 and Kl 9. From these holes, 7 conductive borehole sections were isolated and sampled, one each from Kl 1 and Kl 9, and the remaining 5 from Kl 2. The location and extension of the conductive fracture zones were greatly facilitated by borehole tubewave (borehole Kl 2) and radar (boreholes Kl 1, Kl 2 and Kl 9) techniques.

Of these 7 borehole sections sampled, the water budget calculations predicted that four should result in representative groundwaters, one possible representative groundwater, and two unrepresentative groundwaters. Groundwaters which are here considered representative are defined as those which show no evidence of mixing with other water sources, whether from drilling water, younger, nearsurface water, or other deeper groundwaters. Taking into consideration the groundwater chemistry and available isotopic data, it was possible to support the water budget calculations for 3 of the 4 representative sections; inadequate pumping time to remove all the residual drilling water was the most obvious reason for the unacceptance of the remaining section. What all 3 representative levels have in common is a positive head deviation and moderate hydraulic conductivities between 7 x 10^{-10} to 9 x 10^{-8} m/s. Those horizons, characterised by high conductivity but negative head, may eventually yield a representative sample, but only after considerably longer pumping intervals than the periods usually employed for sampling purposes.

Plugging of borehole Kl 2 to minimise open-hole effects during the time-lag between drilling and sampling, which in this case amounted to 3-6 months, was considered worthwhile for some of the sampled sections, especially those of moderate conductivity (and low negative head) characteristics. Plugging of all zones, and especially high-conductive zones, has to be carried out rapidly in order to be in any way effective.

Two groundwater types are indicated: groundwaters of nearsurface origin, and of intermediate origin. No deep saline varieties were encountered. In comparison with the near-surface waters, the intermediate type contains slightly enhanced contents of Na, Cl, Br and F, and reduced amounts of Ca and HCO_3; slightly higher pH is also suggested. The overall reducing nature of the groundwaters is indicated by the consistently negative redox potential values (-360 to -270 mV) and supported by most of the analysed total iron being in the ferrous state. Geochemical modelling of the representative groundwaters showed that: a) the groundwaters are nearly saturated with respect to calcite and other carbonate minerals, b) both Fe^{3+} and Al^{3+} ions appear to be saturated with their hydroxides ($Fe(OH)_3$ (amorph.) and gibbsite respectively), and c) the uranium concentration levels for some samples are regulated by the precipitation of UO_2 (amorph) whilst others indicate saturation with some secondary uranium mineral (possibly uranophane). These findings are to some extent supported by mineralogical studies of the sampled fracture zones.

The absence of any marked redox trends, together with the relatively little chemical variation in the groundwaters. bearing in mind that sampling has been systematically conducted to considerable depths, underlines the caution necessary when sampling is mainly carried out within highly active, relatively isolated hydraulic fracture systems, which traverse through the bedrock. Much of the sampled water has undoubtedly originated at substantially higher levels than those depths actually sampled, and their presence at greater depths is due to downward hydraulic gradients along active fracture zones, many of which have been shown through drilling to be mainly sub-vertical in orientation through the bedrock.

SKB Technical Report No 87-22

RADIONUCLIDE SORPTION ON GRANITIC DRILL CORE MATERIAL

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Stockholm, November 1987

ABSTRACT

Distribution ratios (K_d) were determined for ^{85}Sr, ^{134}Cs and ^{152}Eu on crushed granite and fissure coating/filling material from Stripa mines. Measurements were also carried out on intact fissure surfaces. The experimental data for ^{85}Sr and ^{134}Cs on crushed material can be accommodated by a sorption model based on the assumption that the crushed material consists of porous spheres with outer and inner surfaces available for sorption. In the case of ^{152}Eu only sorption on the outer surfaces of the crushed material was observed. The absence of sorption on inner surfaces is most probably due to high depletion of the more strongly sorbed ^{152}Eu in the water phase and very low diffusivity of ^{152}Eu in the sorbed state.

SKB Technical Report No 87-23

RADIONUCLIDE CO-PRECIPITATION

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Stockholm, December 1987

ABSTRACT

The thermodynamic and kinetic behaviour of the minor components of the spent fuel matrix has been theoretically and experimentally investigated. Two different situations have been studied: Part I, the near field scenario, where the release and migration of the minor components is dependent on the solubility behaviour of $UO_2(s)$; Part II, the far field, where the solubility and transport of the radionuclides is related to the major geochemical processes occurring.

SKB Technical Report No 87-24

GEOLOGICAL MAPS AND CROSS-SECTIONS OF SOUTHERN SWEDEN

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December 1987

ABSTRACT

The Geological Survey of Sweden (SGU) and Softrock Consulting, Genarp have compiled the present geological maps and crossections of southern Sweden — including the surrounding offshore areas — by order of the Swedish Nuclear Fuel and Waste Management Co (SKB) and South Sweden Power Supply (SK).

The purpose of this compilation was to produce a basis for forming a judgement of the stability of the bedrock of southern Sweden.

The maps and cross-sections are based on both published and unpublished material.

The present report is meant to give complementary information to the maps and cross-sections (numbered from 1 to 44). Copies of these are available at the Geological Survey in Lund.

At the end of this report reduced scale versions of the maps and cross-sections are added (Pl. 1-44).

Kent Larsson has prepared the part of the work dealing with the sedimentary rocks, and the crystalline rocks have been treated by Karl-Axel Kornfält.

SKB Technical Report No 87-25

THE BOLMEN TUNNEL PROJECT.

EVALUATION OF GEOPHYSICAL SITE INVESTIGATION METHODS

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December 1987

ABSTRACT

In conjunction with planning of the 80-km long Bolmen tunnel, extensive geophysical and geological investigations were performed during the years 1967 to 1972. During the course of tunnel construction supplementary geophysical measurements were also made along numerous stretches.

Continuous geo-mapping of the whole tunnel was carried out in close conjunction with the blasting work. In this work, special attention was paid during penetration of zones of weak rock. The combination of geophysical and geological pre-investigations and careful documentation of the tunnel provides a unique opportunity to compare the predictions based on different geophysical methods of measurement with the actual conditions encountered in the bedrock.

This report presents a summary of all the geophysical measurements along and adjacent to the tunnel and an evaluation of the ability of the various methods to permit prediction of rock mass parameters of significance to stability and water bearing ability. The evaluation was performed for the Swedish Nuclear Fuel and Waste Management Co. and shows that, using airborne electro-magnetic surveys, it was possible to indicate about 80% of all the zones of weakness more than 50 m wide in the tunnel. Airborne magnetic surveys located about 90% of all dolerite dykes more than 10 m wide.

Ground-level VLF and Slingram methods of electromagnetic measurement indicated 75% and 85% respectively of all zones of weakness more than 50 m wide. Resistivity methods were successfully used to locate clay filled and waterbearing fracture zones. About 75% of the length of tunnel over which resistivity values below 500 ohm m were measured required shotcrete support and pre-grouting.

Of 141 wide zones of weakness (more than 50 m wide) in the Bolmen tunnel about 60% were indicated by refraction seismic velocities of 4400 m/s or less. The corresponding result for narrower fracture zones (10 to 50 m wide) was about 65%.

SKB Technical Report No 87-26

THE KYMMEN POWER STATION

TBM tunnel

HYDROGEOLOGICAL MAPPING AND ANALYSIS

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December 1987

ABSTRACT

The aim of the project is to make a detailed investigation of the geological conditions and the different kinds of leakages along a tunnel belonging to the Kymmen power station in the province of Värmland, Sweden.

The studies are carried out in a TBM tunnel, which due to particularly mild treatment of the bedrock during the driving process, affords unique opportunities for detailed studies of groundwater leakages.

The mapping, covers a tunnel length of 4500 m. In the drawings of the geological mapping all the continuous fissures and fissures with leakage irrespective of their length or continuity are shown. A table accompanying each section covered by the drawings indicates the character of the surface of the fissure (raw, plane, smooth, winding etc), the contents of filled fissures and any variations in the widths of fissures.

Zones in which the bedrock is more or less mechanically crushed and intersected by close fissures are marked with special screen designations in the drawings. One of the appended tables gives the extent and the type of crushing. Between varying degrees of crushing and types of mechanical crushing, 5 types of tectonic zones are distinguished for differentiation.

In the same way, based on the extent and type of alterations, 5 types of clay-alterations are distinguished. In mapping visible leakage, 5 classes have been distinguished according to size.

In addition to mapping the location of leakage from channels which end at a point from which droplets can escape (point leakage), there are accompanying tables which indicate damp and dry sections of tunnel separately. The tables also often give detailed information about aquiferous fissures.

SKB Technical Report No 87-27

EARTHQUAKE MEASUREMENTS IN SOUTHERN SWEDEN

Oct 1, 1986 - Mar 31, 1987

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December 1987

ABSTRACT

A network of four stations covering southeastern Sweden has been operated for the period Oct 1 1986 — Mar 31 1987. The project is financed by SKB. During the period no earthquakes within the four station network were detected. Seven other earthquakes in southern Sweden were detected and they have been analysed by use of data from all seismic stations operated by FOA. Three of these events were aftershocks to the strong Skoevde event, 860714, M_L = 4.5. This made it necessary to include the Skoevde main event together with a couple of earlier aftershocks in the analysis presented in this report. Thus the present study gives 10 new earthquake mechanisms. Three of these events are in the range M_L = 3.5-4.5. Of the earlier about 170 earthquake mechanisms available for southern Sweden the largest is M_L = 3.2. The earthquakes of the present study thus give significant new information about Swedish seismic activity. The results are:

— the focal depths of the larger events of the lake Vaenern area are about 27 km, this is deeper than the most common earthquake depths 7-18 km, actually all but one of the earthquakes in this report are deeper than 18 km
— the horizontal stresses relaxed by the new earthquakes agree with previous studies, WNW-ESE compression
— the static stress drops are high for the larger events, above 30 MPa (300 bar) for the M_L = 4.5 event
— the Skoevde main shock fault is striking ENE, this is different from the N-S striking fault shown to be sliding during the lake Vaenern event 810213, M_L = 3.2
— the aftershocks to the Skoevde events migrate upwards with a rate of about 10 km per year
— the large events seem to occur in small gaps within the microseismicity of the previous 5 years
— the faulting mechanisms are primarily strike-slip at rather vertical faults.

SKB Technical Report No 87-28

RADIONUCLIDE DEPOSITION AND MIGRATION WITHIN THE GIDEÅ AND FINNSJÖN STUDY SITES, SWEDEN.

A STUDY OF THE FALLOUT AFTER THE CHERNOBYL ACCIDENT

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ABSTRACT

Radionuclides originating from the Chernobyl accident in April 1986 were deposited over large areas of Sweden. The distribution and migration of the radionuclides during the first months after deposition were measured in a comprehensive survey within twostudy sites, Gideå in Ångermanland county and Finnsjön in Uppland county. The sites are previously investigated in the SKB site characterization programme and well defined regarding geology and hydrology.

The survey was concentrated to a small sub-area in each study site, 0.9 km² in Gideå and 0.7 km² in Finnsjön. The measurements performed will, together with environmental conditions, primarily constitute the basis for budget calculations of radionuclide redistribution within the studied areas. The aim is to utilize the results in radioecological and geohydrological migration modelling in the time perspective of several years.

Sampling and measurements in situ were carried out on five occasions from June 1986 to February 1987. A total of 374 samples of soil, rock, vegetation, water and sediment were taken at 85 sampling sites and analysed by gamma spectrometry and autoradiography. Soil profile samples were characterized regarding; texture, geological classification, organic matter, pH and trace element composition. Measurements in situ of the ground surface deposition were performed at 46 sites by gamma spectrometry and along 65 lines at 32 sites by exposure rate measurements.

Radionuclides analysed are; Mn-54, Co-60, Sr-90, Zr-95, Nb-95, Mo-99, Ru-103, Ru-106, Ag-110 m, Sb-125, I-131, Cs-134, Cs-136, Cs-137, Ba-140, La-140, Ce-141 and Ce-144. The Cs-137 surface activity gave a range of 30-100 kBq/m² in Gideå and 20-40 kBq/m² in Finnsjön.

Radionuclide migration is observed in soil profiles, groundwater and rock fissures. An active transport by surface water is also evident from sediment samples. Radionuclides have been absorbed in different types of vegetation. In October 1986 five months after the deposition on the ground surface, radionuclides were found at 20 cm depth in soil profiles. A faster and different manner of migration for Sb-125, Ru-106 and Co-60 compared to cesium is also observed. Nine month after the deposition Ru-106 is found in fairly deep groundwaters sampled in artesian drill holes. In a shallow well was, beside Ru-106, also Ag-110 m, Cs-134 and Cs-137 found five months after the deposition.

SKB Technical Report No 87-29

ALTERATION OF ISOLATING PROPERTIES OF DENSE SMECTITE CLAY IN REPOSITORY ENVIRONMENT AS EXEMPLIFIED BY SEVEN PRE-QUARTERNARY CLAYS

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December 1987

ABSTRACT

Seven pre-Quaternary clays with a smectite content ranging between zero and about 25% were taken as possible reaction products resulting from chemical alteration of dense sodium bentonite. They were characterized with respect to the mineral composition and microstructural constitution and tested with reference to their hydraulic conductivity, swelling ability and creep properties.

It was found that since they were all less permeable than a typical large granitic rock mass they would serve as flow barriers in a repository. Thus, even rather extreme chemical attack is not expected to eliminate the most important barrier function of Na bentonite in re-

pository environment. However, slight mechanical disturbance of a heterogeneously altered smectite clay buffer or seal, may be critical. Thus, the investigated, less smectitic clays experienced a rather dramatic increase in hydraulic conductivity on expansion and remolding. This is explained by the inability of a microstructurally discontinuous smectite component — particularly in the Ca-form — to swell and fill voids. The minimum content of Na smectite to preserve the self-healing capacity is estimated at 15-25%.

Slight or moderate cementation was indicated by two of the clays by the creep tests. At a smectite content of 15-25% it is probable that self-healing will take place after a mechanically induced breakage of the cementing bonds.

The tests gave a good basis for future development of rational, routine tests as well as for a relevant characterization of buffer material candidates.

SKB Technical Report No 87-30

WATER COMPOSITIONS IN THE LAKE SIBBOFJÄRDEN — LAKE TROBBOFJÄRDEN AREA

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August 1987

ABSTRACT

The recipient evolution project aims at achieving an understanding of the processes occurring within a lake and its sediments during the life-time of the lake in order to permit predictions of long-term behaviour of radionuclides released into lake sediments.

An experimental program concerning field investigations in the drainage areas of Lake Sibbofjärden and Lake Trobbofjärden has been performed. This report covers the chemical analyses of surface and sediment pore waters as well as a study of trace radionuclide sorption in sediments.

Chemical data for surface water and sediments from several different types of lakes and streams have been collected.

The chemical composition of the sediment pore water seems to be strongly related to the lake water composition in the upper layers, while changes, mainly in the ionic strength are occurring with increasing depth.

The next phase of this project will be focused on the development of a mathematical model, describing the time dependent processes of importance to the turnover of radionuclides during the various phases of the evolution of a lake.

Processes of chemical nature of large importance here are e.g. sorption of radionuclides on suspended material in the water. and migration and fixation in the sediment.

The chemical analyses described in this report give a data-base for use in connection with the modelling.

Data on average water composition at various stages of the lake evolution (pH, ionic strength, saturation state, contents of complex formers like phosfate, sulfate, fluoride, and organic compounds) give data for estimating the potential sorption on suspended matter.

The migration and fixation in sediments is governed by pore water data like pH, Eh, ionic strength, content of complex formers, and physico-chemical properties like water content and organic content of the solid phase.

The study of sorption in sediment cores, coupled with an ongoing in-situ study of diffusion of radionuclides in sediments provide sorption and transport data for a validation of the model.

SKB Technical Report No 87-31

RHEOLOGICAL PROPERTIES OF A CALCIUM SMECTITE

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December 1987

ABSTRACT

The rheological and mechanical properties of a Ca-smectite have been investigated by different laboratory tests. By these tests the permeability, the water uptake properties, the swelling properties, the swelling pressure, the stress-strain properties, the strength and the creep properties have been determined. The influence of density, temperature, time and stress level have been considered.

Mathematical models of the measured properties and behavior of the clay have been suggested so that calculations involving mechanical and rheological scenarios can be made.

The behavior of the clay have been discussed with reference to the microstructure and comparisons between the investigated Ca-smectite and a Na-smectite (Mx-80) have been made.

One main conclusion is that the difference between the properties and behavior of Ca-smectite and Na-smectite is small at densities $\varrho_m < 2.0$ t/m³. At densities $\varrho_m < 2.0$ t/m³ the difference is increasing with decreasing density.

SKB Technical Report No 87-32

SURVEY OF SWEDISH BUFFER MATERIAL. CANDIDATES AND METHODS OF CLAY MINERAL CHARACTERIZATION

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Swedish Geological Co, Lund

December 1986

ABSTRACT

The major criteria for natural clayey materials to qualify as candidate buffer materials are concluded to be a high content of 2:1 clay minerals — smectite, hydromica — and accessibility of very large quantities of fairly homogeneous raw material. Only four major source materials appear to fulfil these requirements, namely the Vallåkra, Kågeröd and Fyledalen clays, as well as the Quaternary moraine clay from the Lund-Landskrona area. The three first-mentioned materials represent the Mesozoic formations in Scania. The Vallåkra clay has smectites and kaolinite as major clay minerals. The beds have a very large extension and offer possibilities of finding substantial quantities of very smectite-rich portions. This is the case at Margreteberg but in this area iron compounds appear to coat the smectite aggregates and prevent them from expanding spontaneously. Attempts have been made to remove this cementing substance and there is good hope to find an effective industrial process of low cost.

The Kågeröd clay has evolved as a major candidate because the clay fraction, which forms 20-30% of the bulk material, is almost exclusively composed of smectites. The extension of the beds is enormous and a further, detailed prospection is recommended in order to find areas which are particularly rich in clay.

The Fyledalen clay has a high clay content with kaolinite and hydromica as major minerals. The conclusion is that this is the most easily accessible large and rich source of hydromica in Sweden.

In addition to these major, relatively pure materials, weakly smectitic moraine clays should also be considered as potential candidates since their granular composition make them ideal for backfilling purposes.

One of the major questions in characterizing clays for use as buffer materials is to make reliable quantitative determinations of the clay mineral content. A major goal of the present study was to identify the most accurate method that is used internationally, and Reynolds' technique was focussed on early in the project. It has turned out that his method is very accurate when using a small quantity of pyrofyllite as reference substance, and a refined version of the method is therefore suggested as an SKB standard in future prospecting and characterization of buffer materials.