SKB

# TECHNICAL REPORT

86-31

## SKB ANNUAL REPORT 1986

### Including Summaries of Technical Reports Issued during 1986

Stockholm, May 1987

**SVENSK KÄRNBRÄNSLEHANTERING AB**
*SWEDISH NUCLEAR FUEL AND WASTE MANAGEMENT CO*

BOX 5864 S-102 48 STOCKHOLM
TEL 08-665 28 00 TELEX 13108-SKB

# SKB ANNUAL REPORT 1986

## Including Summaries of Technical Reports Issued during 1986

Stockholm, May 1987

# FOREWORD

The Annual Report of SKB's activities during 1986 cover the planning, building and operational activities as well as our research and development works.

During 1986 the central interim storage facility for spent nuclear fuel - CLAB - was inaugurated and taken into full operation. The long interim storage in CLAB constitutes a fundamental part in the Swedish once-through system for final disposal of longlived wastes. With CLAB and the repository for final disposal of low- and intermediate level waste - SFR - under construction, Sweden will have a well integrated system for handling of all radioactive residues in the country for long time ahead.

SKB also, during 1986, submitted a long-term programme for the final handling and disposal of nuclear waste to the National Board for Spent Nuclear Fuel. This programme is required by the Swedish Act on Nuclear Activities and will be the basis for SKB future R&D-work.

International cooperation and exchange of informaton in all fields of the back-end of the nuclear fuel cycle is important and of great value for SKB's work. We hope that this annual report will be of interest and enhance the international information exchange.

Stockholm in May 1987
Swedish Nuclear Fuel and
Waste Management Co

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 1986.

Lectures and publications during 1986 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 1986.

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 1986 in total 360 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 a final repository for low- and medium level waste – SFR – is being built. The repository is situated in crystalline rock under the Baltic Sea. During 1986 construction and installation work have been going on and when handling machines and auxiliary systems have been installed, the repository will be commissioned and ready to receive waste in the beginning of 1988.

SKB is in charge of a comprehensive research and development program on geological disposal of nuclear waste. The budget for 1986 was about 70 MSEK.

According to the act on nuclear activities (SFS 1984:3) SKB submitted a comprehensive program for the research and development to the authority (SKN) on September 29, 1986. The program gives a general account of all measures that are needed until the final disposal of the wastes has been completed.

Some of the main areas for 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 45 billion which is less than 10% of the value of the electricity being produced.

Consulting services from SKB and associated expert groups are now available on a commercial basis. They are coordinated and marketed through SwedPower, which has the same main owners as SKB.

# CONTENTS


Page

**PART I OVERVIEW OF SKB ACTIVITIES** 9

1 General Background
2 Nuclear Fuel Supply
3 Interim Storage of Spent Fuel, CLAB
4 Transportation System
5 Final Repository for Reactor Waste, SFR
6 Research and Development
7 System Planning and Cost Calculations
8 Consulting Services
9 Information and Public Affairs

**References Part I**

**PART II RESEARCH AND DEVELOPMENT DURING 1986** 37

10 R&D Programme 1986
11 Repository Designs
12 Waste Forms
13 Canister Materials
14 Buffer and Backfill
15 Geoscience
16 The Biosphere
17 Chemistry
18 Safety Assessment
19 The Stripa Project
20 JSS Project
21 Natural Analogue Studies
22 Documentation

**References Part II**

**PART III APPENDICES** 89

Appendix 1 SKB Organization
2 Lectures and Publications 1986
3 List of SKB Annual Reports 1977-85
4 List of SKB Technical Reports 1986
5 Authors of SKB Technical Reports 1986 in Alphabetical Order

**PART IV SUMMARIES OF TECHNICAL REPORTS ISSUED DURING 1986** 107

# SKB ANNUAL REPORT 1986
# Part I

## Overview of SKB Activities

# CONTENTS OF PART I


| | | Page |
|---|---|---|
| **1** | **GENERAL BACKGROUND** | 13 |
| 1.1 | The Swedish Nuclear Power Program | 13 |
| 1.2 | Legal and Organizational Framework | 13 |
| 1.3 | The Swedish Nuclear Waste Management System | 14 |
| **2** | **NUCLEAR FUEL SUPPLY** | 17 |
| 2.1 | Natural Uranium | 17 |
| 2.1.1 | The Swedish Situation | 17 |
| 2.1.2 | The International Situation | 17 |
| 2.2 | Conversion | 17 |
| 2.3 | Enrichment | 17 |
| 2.3.1 | Supply to Sweden | 17 |
| 2.3.2 | Market | 18 |
| 2.4 | Fabrication of Fuel Assemblies | 18 |
| 2.5 | Nuclear Fuel Stockpile | 18 |
| 2.6 | Costs | 18 |
| **3** | **INTERIM STORAGE OF SPENT FUEL, CLAB** | 19 |
| 3.1 | General | 19 |
| 3.2 | Operation Experiences | 19 |
| **4** | **TRANSPORTATION SYSTEM** | 21 |
| 4.1 | General | 21 |
| 4.2 | Operation Experience | 21 |
| **5** | **FINAL REPOSITORY FOR REACTOR WASTE, SFR** | 23 |
| 5.1 | General | 23 |
| 5.2 | Design, Construction and Costs | 23 |
| 5.3 | Safety Assessment | 25 |
| 5.3.1 | Final Safety Report | 25 |
| 5.3.2 | Research Program | 25 |
| 5.4 | Some Data about SFR | 26 |
| **6** | **RESEARCH AND DEVELOPMENT** | 27 |
| 6.1 | General | 27 |
| 6.2 | Summary of Research Activities during 1986 | 27 |
| 6.2.1 | Engineered Barriers and Repository Design | 27 |
| 6.2.2 | Geoscience | 28 |
| 6.2.3 | Biosphere | 28 |
| 6.2.4 | Chemistry | 28 |
| 6.2.5 | Safety Assessment | 28 |
| 6.3 | International Cooperation | 29 |

| | | |
|---|---|---|
| **7** | **SYSTEM PLANNING AND COST CALCULATIONS** | 31 |
| 7.1 | System Planning Activities | 31 |
| 7.2 | Reprocessing | 31 |
| 7.3 | Cost Calculations | 31 |
| 7.3.1 | Plan -86 | 31 |
| 7.3.2 | Waste Management Fee | 32 |
| 7.4 | Decommissioning | 32 |
| **8** | **CONSULTING SERVICES** | 33 |
| **9** | **INFORMATION AND PUBLIC AFFAIRS** | 35 |
| 9.1 | General | 35 |
| 9.2 | SKB Information Activities | 35 |
| | **REFERENCES PART I** | 36 |

# 1 GENERAL BACKGROUND

## 1.1 THE SWEDISH NUCLEAR POWER PROGRAM

Swedens nuclear power program 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 50% of the total Swedish electric power produced in 1986.

Swedish reactors

| Reactor | | Power $MW_e$ | Commercial operation | Energy availability in 1986 % |
|---|---|---|---|---|
| Oskarshamn 1 | BWR | 440 | 1972 | 83 |
| Oskarshamn 2 | BWR | 595 | 1974 | 88 |
| Oskarshamn 3 | BWR | 1050 | 1985 | 92 |
| Barsebäck 1 | BWR | 595 | 1975 | 90 |
| Barsebäck 2 | BWR | 595 | 1977 | 85 |
| Ringhals 1 | BWR | 750 | 1976 | 79 |
| Ringhals 2 | PWR | 800 | 1975 | 57 |
| Ringhals 3 | PWR | 915 | 1981 | 79 |
| Ringhals 4 | PWR | 915 | 1983 | 77 |
| Forsmark 1 | BWR | 972 | 1980 | 93 |
| Forsmark 2 | BWR | 972 | 1981 | 93 |
| Forsmark 3 | BWR | 1050 | 1985 | 89 |

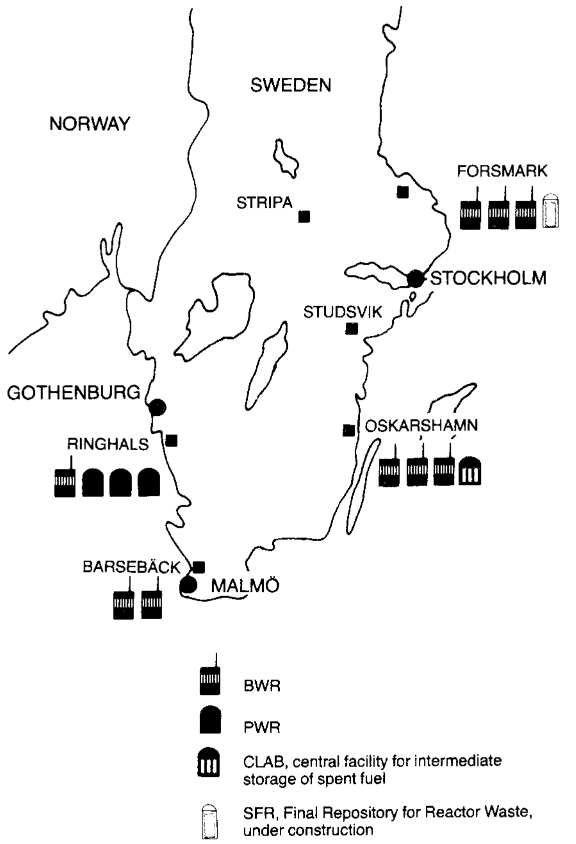



*Figure 1-1. The Swedish nuclear power program.*

## 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.

SKB is also in charge of the comprehensive research program in the waste field which the utilities are responsible for according to the law. Finally SKB handles matters pertaining to prospecting, 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 staff of SKB is about 45 persons. The organization is presented in Appendix 1. The bulk of the work is made by contractors.

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

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

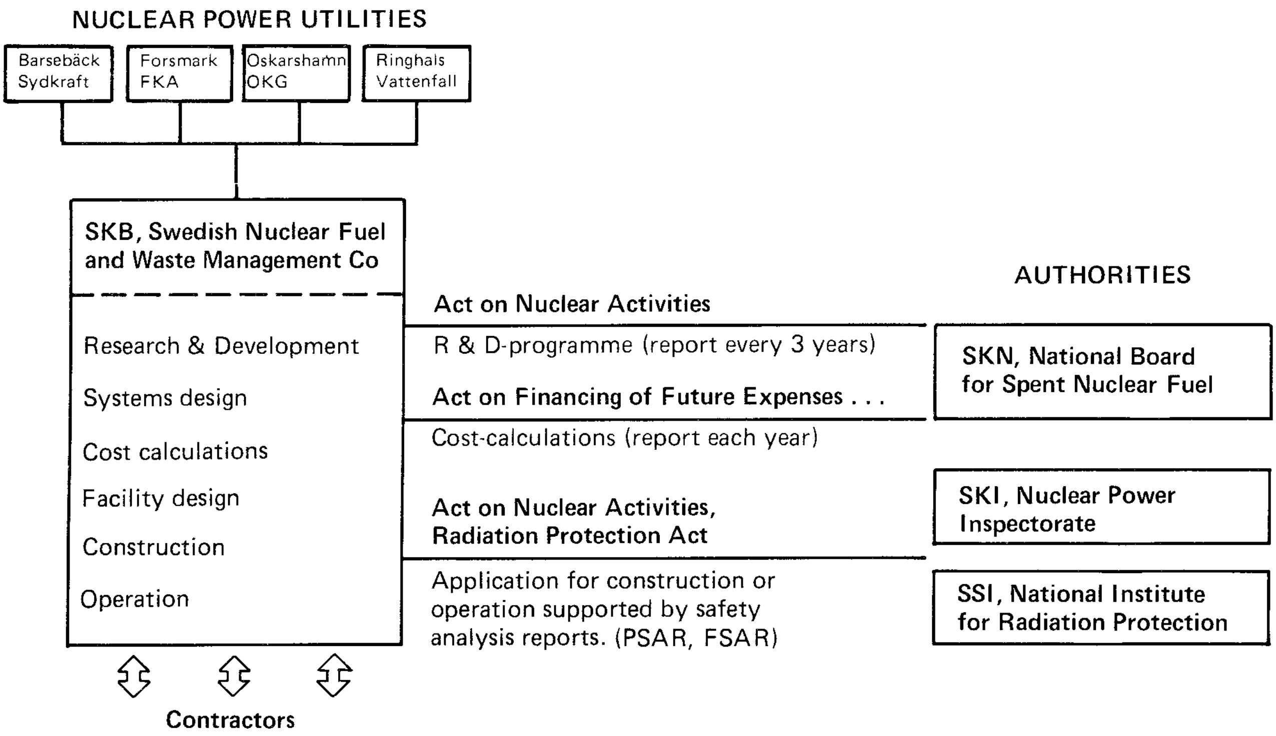



*Figure 1-2. Legal framework for activities of SKB.*

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 Institute for Radiation Protection (SSI). 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 fee has been set to 0.019 SEK per kWh for the years 1984-1986.

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 research intended to supplement the SKB-program. In order to coordinate the research programs carried out by the authorities a special "Consultative Committee for Nuclear Waste Management" (KASAM) was founded in 1985. The council shall report to the government annually on the state of the art in the nuclear waste field. The first report of KASAM was issued in December 1986 /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 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.

For low- and medium level reactor waste a central final repository, SFR, is under construction and is

**Table 1–1. Waste categories**

| WASTE CATEGORY | ORIGIN | WASTE FORM | PROPERTIES | QUANTITY |
|---|---|---|---|---|
| 1 Spent fuel | Operation of nuclear reactors | Fuel rods encapsulated in copper 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. | Solified in concrete or bitumen. Compacted waste | Low- to medium-level. Shortlived | 100 000 $m^3$ |
| 5 Decommissioning waste | From dismantling of nuclear facilities | Untreated for the most part | Low- to medium-level. Shortlived | 115 000 $m^3$ |

planned to be operative in 1988. SFR may later on be extended to accommodate also 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 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.

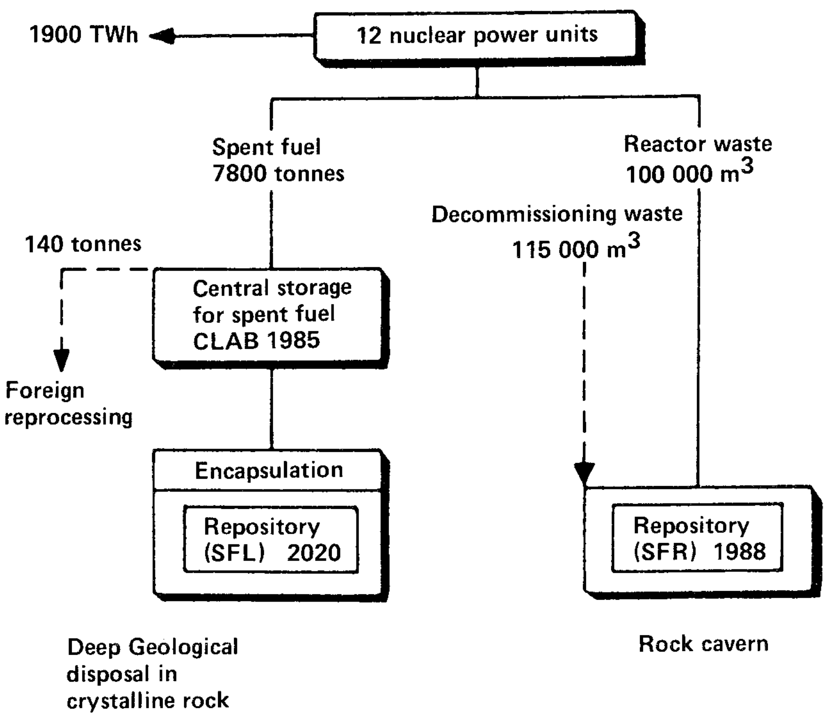



*Figure 1-3. Main system for management of radioactive waste in Sweden.*

# 2 NUCLEAR FUEL SUPPLY

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

## 2.1 NATURAL URANIUM

### 2.1.1 The Swedish Situation

The Swedish nuclear power program 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 1986 up to 1995 is 13 050 tonnes. At the end of 1986, 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 1986, some spot quantities were purchased.

Natural uranium is delivered to Sweden mainly from Canada and Australia, but also from Niger, Gabon 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.

### 2.1.2 The International Situation

**Demand and supply 1986**

The consumption of uranium in the world (except centrally planned economies) is estimated to 41 000 tonnes, while the production is estimated to 37 000 tonnes. The low production does not present a problem, as there are about 120 000 tonnes in stocks.

**Market-prices**

Figure 2-1 shows the price situation for uranium during the last years. Spot prices were low in 1986.

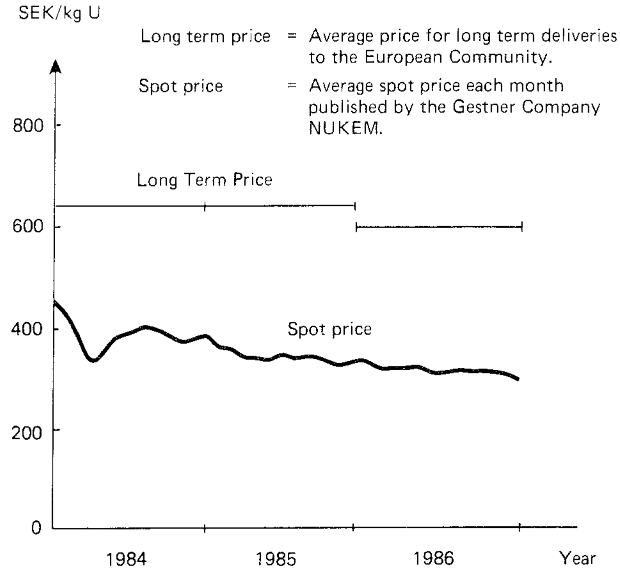



*Figure 2-1. Long term and spot prices for uranium.*

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.

## 2.2 CONVERSION

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

The world conversion capacity is around 52 000 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

### 2.3.1 Supply to Sweden

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 1986-1990, 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. This situation gives a reliable supply with deliveries from four different companies.

### 2.3.2 Market

The total enrichment capacity now available in the world, around 34 million SWUs per year, is higher than the demand for separative work, which can be estimated to 24 million SWUs in 1986.

The present capacity will probably be sufficient up to the mid 1990-ies.

## 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 from ASEA-ATOM, but also orders from the US, the Federal Republic of Germany and France.

Fabrication of fuel assemblies both for BWRs and for PWRs as well as BWR channels, BWR control blades and other components are made in Sweden at the ASEA-ATOM plant in Västerås.

Fuel fabrication at ASEA-ATOM 1986 was around 165 tonnes for BWRs and 25 tonnes for PWRs. Of this volume about 40 tonnes were exported to Finland, Federal Republic of Germany, Switzerland and USA.

The new 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. More than half of the ASEA-ATOM BWR fuel deliveries in 1986 were of this design. The SVEA fuel design gives a more even burnup, and thus a better possibility to utilize the energy from the inner fuel rods. Actually SVEA produces 8-10% more energy than a conventional fuel assembly from a given amount of natural uranium and of enrichment.

In 1986 a new type of SVEA-fuel called SVEA-100 was introduced and six fuel assemblies of this type were loaded in two swedish BWRs. The SVEA-100 fuel, where the fuel rods are thinner and divided i 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 zirkaloy 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 1986 were as shown in Table 2-1 (the production of nuclear electricity was 67 TWh in 1986):

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

| | SEK/kWh | Million SEK in 1986 |
|---|---|---|
| Natural uranium | 0.011 | 740 |
| Conversion | 0.001 | 70 |
| Isotope enrichment | 0.012 | 800 |
| Fuel fabrication | 0.006 | 400 |
| Strategic stockpile | 0.001 | 70 |
| Total front end | 0.031 | 2 080 |

# 3 INTERIM STORAGE OF SPENT FUEL, CLAB

## 3.1 GENERAL

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

The facility consists of five underground storage pools for in total 3 000 tonnes of uranium. The reception, auxiliary and office buildings are located on ground level. The facility is designed to receive at least 300 tonnes uranium per year which corresponds to the handling of about 100 transport flasks and some 10 - 20 flasks containing reactor core components.

Main suppliers contracted by SKB in realizing the CLAB facility has been ASEA-ATOM (AA), Sweden, Societé Genérale pour les Techniques Nouvelles (SGN), France and a Swedish building consortium consisting of SKANSKA, Aktiebolaget Vägförbättringar (ABV) and Widmark och Platzer (WP).

The operation of the facility has been entrusted to OKG AB, who is one of the SKB shareholders.

## 3.2 OPERATION 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 operation license valid as from 1985-12-20.

During the year 1986 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 end of 1986 in total 360 tonnes of uranium have been received corresponding to 1850 BWR and 84 PWR assemblies. In addition 18 core components flasks have been received. The performance of the plant has been excellent and the received amount of spent fuel has been according to the plans for 1986.

The cooling down system for the transport flasks, which contains cleaning filters for collection of crud and activation products from the cladding surfaces of the fuel assemblies, have been modified in order to increase their efficiency. The cooling down system is now after the modification operating according to its original design capacity. The mounting of the cooling skirt is shown in Figure 3-1.

Based on experiences it was found necessary to increase the number of operator display terminals in the central control room. This improvement has been carried out to ensure a sufficient scope of information to the operating personnel, which is of vital importance for operation of the facility, since there is no conventional instrumentation in the central control room.

The radiological working environment has been followed with special care during this first year of normal operation. The total occupational dose during 1986 was 65.8 mSv which is approximately 25% of what was expected according to the final safety report. With the 75 persons in radiological work this corresponds to an average of 0.88 mSv/individual and year. Only 49 of the 75 workers received measurable doses during the year.

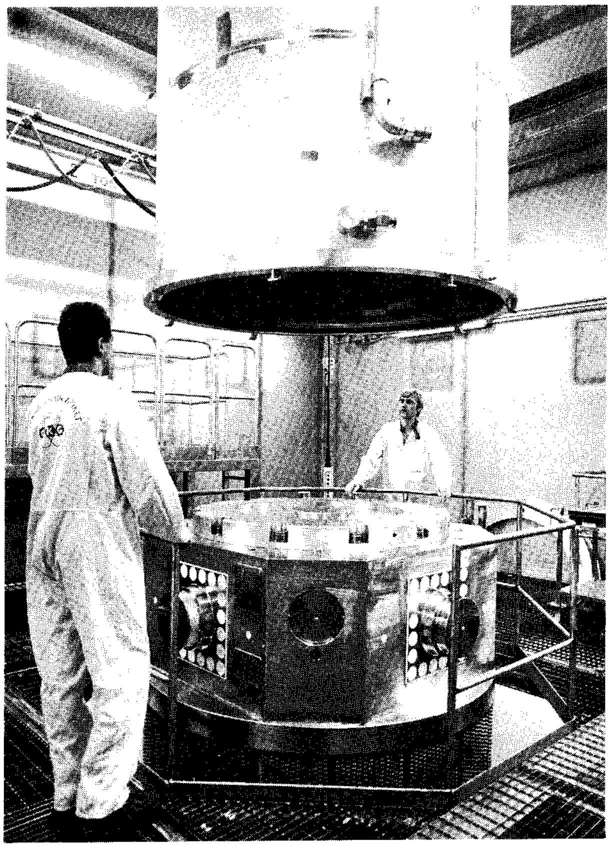


*Figure 3-1. Mounting of the cooling skirt on a transport flask in CLAB.*

# 4 TRANSPORTATION SYSTEM

## 4.1 GENERAL

The sea transportation system consists of a specially designed ro-ro/lo-lo ship. M/S Sigyn, 10 transport flasks for spent fuel, 2 flasks for core components and 3 terminal vehicles. It is actually being expanded by 25 special transport containers to be used for transportation of reactor wastes to the final repository for reactor waste, SFR. These containers will be delivered during 1987 and the first transport to SFR is planned for late 1987.

## 4.2 OPERATION EXPERIENCE

During 1986 fourteen sea-voyages, each with 4-5 transport casks, have been carried out to the CLAB facility. On-site fuel transports OKG - CLAB have been performed at five occasions with 2 - 5 flasks in each campaign.

The operation of the transport system has been successful and the radiation doses to the crew of the ship have been below detection limit. The decay heat in the transport flasks has been below 15 kW compared to the permitted 43,5 kW.

Most of the flasks have gone through the 8 - 10 cycle maintenance control at CLAB. During this, maintenance procedures from the manuel called "Green book" is followed and no significant damages or repairs have been reported. The "Green book" is a manual used by COGEMA, NTL, BNFL and SKB.

A prototype of the special transport containers (ATB), see Figure 4-1, for reactor waste to SFR has been tested onboard Sigyn, with good results.

As the weight of an ATB could be up to 120 tonnes, the cargo deck on-board Sigyn has been reinforced.

During 1988 regular transports with ATB to SFR will start and about 15 - 20 transports are foreseen.

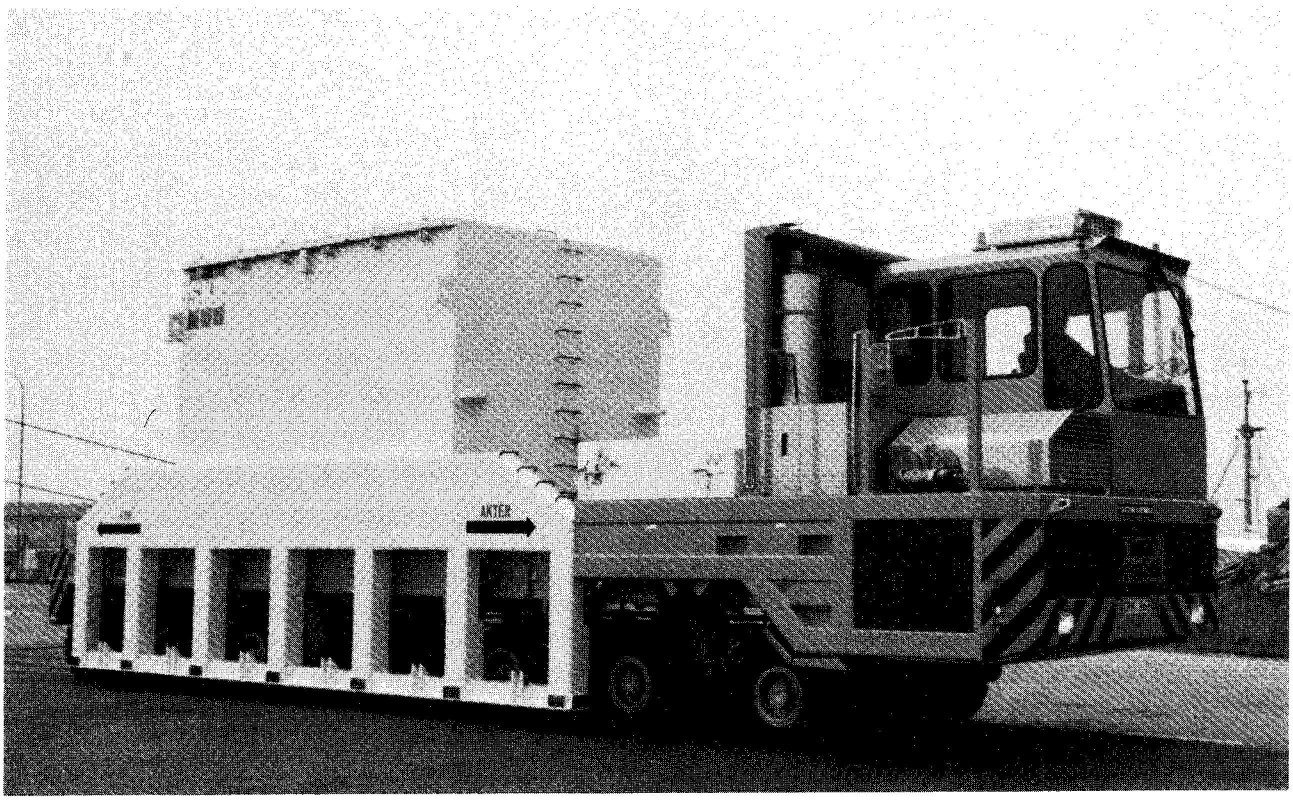



*Fig 4-1. Transport vehicle with ATB transport container for reactor waste.*

# 5 FINAL REPOSITORY FOR REACTOR WASTE, SFR

## 5.1 GENERAL

The construction of the Swedish final repository for reactor waste, SFR, has continued as planned during 1986. SFR is located under the Baltic sea, close to the Forsmark nuclear power plant. The repository is situated in crystalline rock with a minimum rock-cover of 60 m from the caverns to the sea bed. Two 1 km long access tunnels have been built from the Forsmark harbour area to the repository. The first construction phase includes four 160 m long rock caverns and one 70 m high cylindrical cavern called "the silo". In a future second phase one additional silo is planned together with one or two more rock caverns, see Figure 5-1.

Construction work started in summer 1983 and in the beginning of 1986 all the tunnels and rock caverns in the first phase were excavated. During 1986 construction and installation work have been going on in the various repository areas. After the installation of handling machines and auxiliary systems, the repository will be commissioned and ready to receive waste in the beginning of 1988. The second phase of caverns is planned to be built within 10-15 years.

The waste which will be disposed of in SFR originates from the operation of Swedens twelve 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 $m^3$.

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 needs shielding during handling and transport. Low level waste is treated in different ways and finally enclosed in standard freight containers. The total activity content is calculated to be 3 x $10^6$ GBq by year 2010. Dominating nuclides are Co-60 and Cs-137.

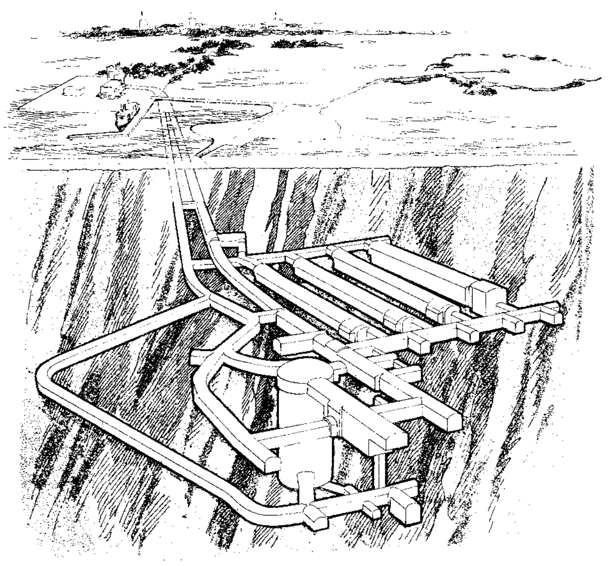


*Figure 5-1. Overview of tunnels and storage chambers in the first construction phase.*

## 5.2 DESIGN, CONSTRUCTION AND COSTS

For the design and construction of SFR, SKB has contracted Vattenfall (The Swedish State Power Board). 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.

In 1986 buildings on ground level have been constructed. A building for personnel and maintenance work, a terminal building for containers and a ventilation building at the entrance of the access tunnels, see Figure 5-2. Down in the repository concrete structures have been built in the various tunnels and caverns. Buildings for auxiliary systems and an operational building for personnel have been built in small caverns, situated at the transport tunnel, see Figure 5-3.

The installation of auxiliary systems as ventilation, drainage and electrical supply started during 1986. The permanent system for electrical supply was commissioned and the installation of ventilation equipment was completed in the ventilation buildings and the transport tunnel. Some small overhead cranes were installed and commissioned in the auxiliary buildings.

In the repository areas most of the construction work is concentrated to the silo and the cavern for intermediate level waste, BMA. The work has proceeded as planned in the BMA repository, where concrete walls are constructed. After this work a machine for remote handling of waste packages will be installed. In the silo repository, difficulties occurred with the slipforming of the concrete silo. The work started as planned but had to be stopped, because the internal walls got stuck in the slipform. After some improvements of the equipment, the slipforming of the silo was carried out successfully in the beginning of 1987.

The commissioning of SFR will take place as planned in spite of the delay of the construction work in the silo repository. The repository will then be ready to receive the first waste in the beginning of 1988.

Until the end of 1986 the accumulated cost for the project is around 475 MSEK. The total cost for this first phase is calculated to 740 MSEK.

*Figure 5-2. SFR – Overview of buildings on ground level.*

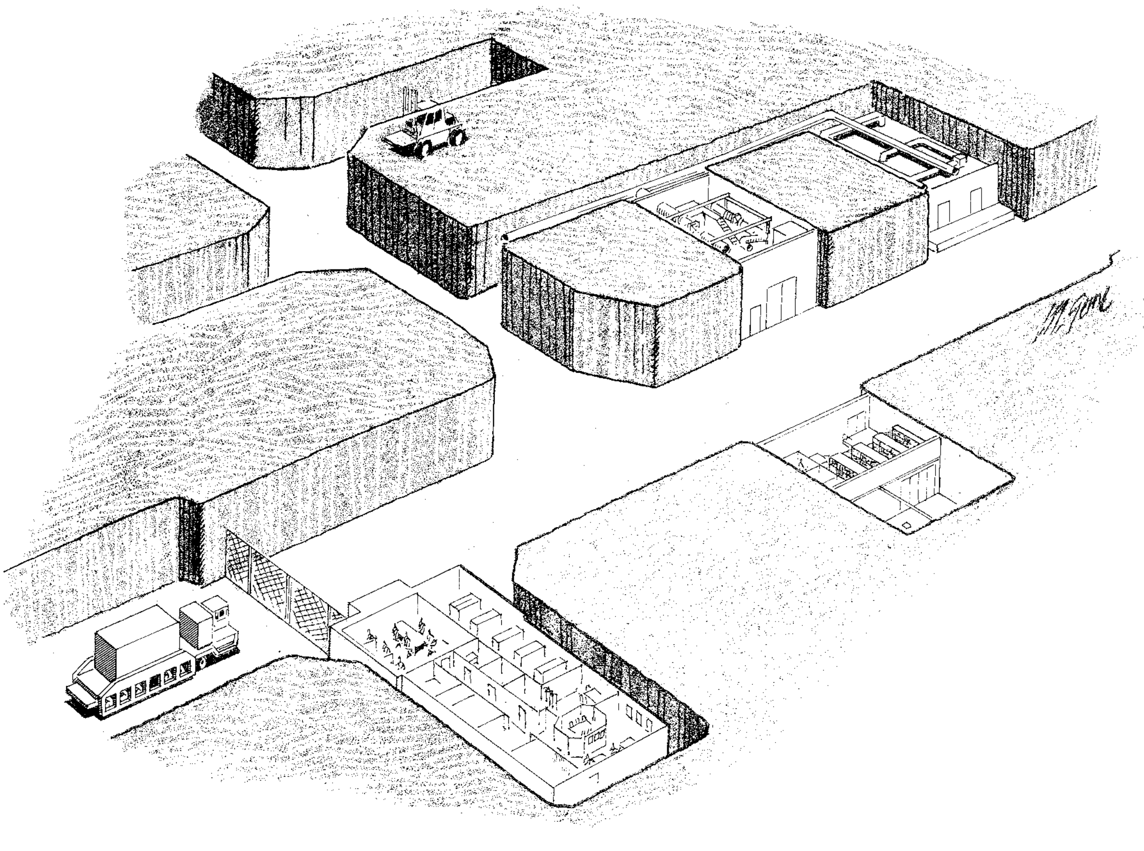


*Figure 5-3. Central part of underground facilities with the operational building and three small buildings for auxiliary systems and maintenance work.*

## 5.3 SAFETY ASSESSMENT

Depending on the origin and activity content, the waste will be disposed of in either a rock cavern or in a concrete silo. The latter is surrounded by a clay barrier and contains most of the radioactivity.

The natural and engineered barriers together with the low groundwater flow in the repository area ensures a very slow release rate of substances from the waste. A preliminary safety report, used as a base for the license for construction of SFR, indicated a conservatively calculated dose for the post operational period of $3\times10^{-6}$Sv/year for the most exposed individual.

A Final Safety Report (FSR) is now under preparation. The application for a license to operate the repository will be based on this FSR.

### 5.3.1 Final Safety Report

The contents of The Final Safety Report, FSR, consists of:

- a detailed description of the design and operation,
- analysis of the environmental impact during operation and after final sealing.

In parallel to the preparation of the FSR, a programme for characterization of the various waste packages is carried out. In general, every waste package has to be licensed for disposal before it is deposited in SFR.

The safety analyses are mainly concerning the post-closure period. Since the excavation work now is finished, it is possible to use more accurate and less conservative data in the calculations.

### 5.3.2 Research Program

Before and during the excavation work a lot of data have been collected and used for description of the geological and hydrogeological situation in the repository area.

The transport mechanism for radionuclides leaving the repository, is by the groundwater flow in the bedrock. Calculation of the groundwater flow has been performed by using available information compiled and conceptualized into descriptive models. The data constitute the results from drillings, mapping of tunnels and cores, testing in and between boreholes and groundwater inflow and head measurements at the site.

The investigations are summarized in a description of an about 85 km² large Regional model. In this model the major fracture zones are considered together with the fracture zones close to the repository area. In a local area of about 1.7 km², see Figure 5-4, a more detailed model of the hydraulic units has been compiled into a local model, see Figure 5-5. In total 22 boreholes have been monitored (68 sealed off sections) during different lengths of time. The effect of skin-zones around tunnels and grouting of permeable zones has been taken into account as the numerical model is calibrated against measured inflow rate of groundwater into the repository.

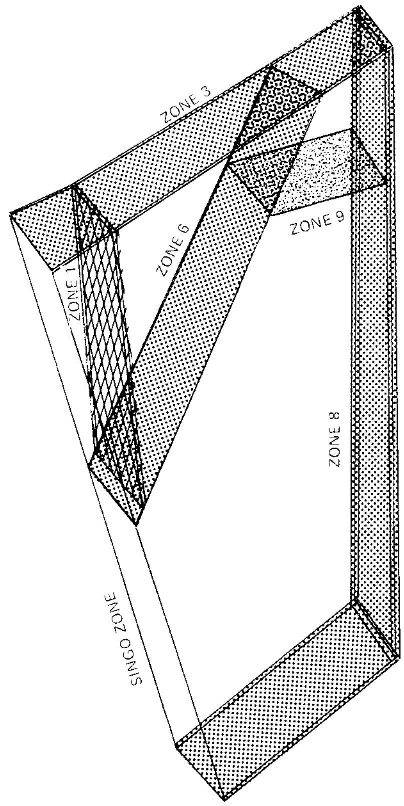



*Figure 5-4. Geometry of the Fracture zones included in the Local Model for calculation of the hydraulic regime in SFR.*

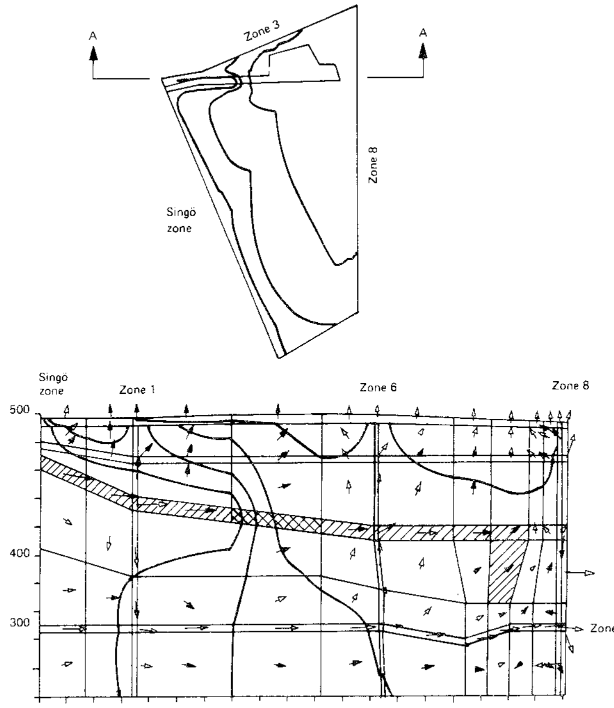



*Figure 5-5. Hydraulic head on a horizontal (top) and vertical (bottom) cross-section (A-A) through the Local Model.*

The accuracy of the numerical results has also been checked by a comparison of calculated and measured potentials in boreholes, see Figure 5-6.

In addition to the above mentioned investigations, tests have been carried out on the material used for the engineered barriers in the repository.

The chemical environment in the repository and its impact on the migration of radionuclides have been investigated. Experiments/studies on processes which could possibly affect the barriers have been performed.

## 5.4 SOME DATA ABOUT SFR

**Table 5-1. SFR-data**

| | |
|---|---|
| *First construction phase* 1983–1988 | |
| Excavated rock volume | 430 000 $m^3$ |
| Concrete structures | 22 000 $m^3$ |
| Steel structures | 600 tonnes |
| Buildings on ground level | 28 000 $m^3$ |
| Buildings in rock caverns | 22 000 $m^3$ |
| Waste storage volume | 60 000 $m^3$ |
| *Second construction phase planned* 1995–1998 | |
| Excavated rock volume | 120–170 000 $m^3$ |
| Waste storage volume | 20–30 000 $m^3$ |
| *Operational phase* 1988–2013 | |
| Operating personnel | 20–25 persons |
| Reception of waste | 5–6 000 $m^3$/year |
| Electrical power supply | 4 500 kVA |
| Ventilation system | 65–70 $m^3$/h |
| Groundwater drainage | 30–40 $m^3$/h |

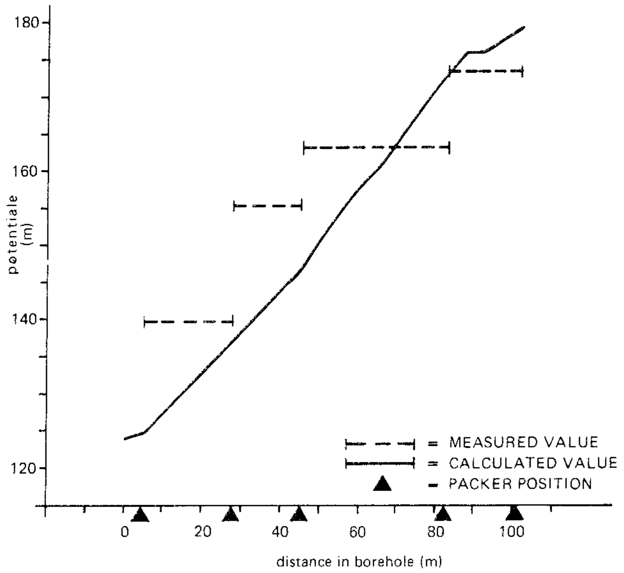



*Figure 5-6. Calculated and measured potentials along a borehole.*

# 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 as of May 1987 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. The 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. A condensed summary of the programme is included as chapter 10 in part II of this annual report.

The R&D-work during 1986 was partly dominated by the planning of the R&D-programme-86. A number of other significant activities were, however, pursued. These are briefly highlighted below and more comprehensively summarized in chapters 11 through 22 of part II.

## 6.2 SUMMARY OF RESEARCH ACTIVITIES DURING 1986

The main research activities during 1986 are part of a programme based on experiences from the KBS-3 study and the comments received in the review of that report. In addition some studies related to alternative concepts to KBS-3 have been going on.

### 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 early 1988. The work through 1986 was mainly concentrated on analysis of repository long term performance and on analysis of costs. Two different sizes of repository design were considered - capacities 1500 and 3750 tonne of U spent fuel respectively.

A preliminary study of the feasibility of disposal of spent fuel in very deep (several km) boreholes in crystalline rock was initiated in the end of 1986.

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 1986 was mainly devoted to three areas - leach studies of PWR fuel with 41 MWd/kg burnup, studies of the effects of gamma-radiolysis on fresh $UO_2$-fuel and development of models describing spent fuel dissolution. The early results from PWR fuel leaching (82 and 172 days contact time) are in good agreement with previous results from BWR-fuel. The modelling work was started during 1986 and will be a rather long term effort.

An important project started during 1986 was aiming at the development of out-of-vacuum equipment for electron beam welding. The project is sponsored by several countries in Europe under the umbrella of the EUREKA-agreement. Management and execution is by the Welding Institute in UK. SKB is participating with a limited contribution. The results could be of significant importance for the technology to seal thick metallic canisters for spent fuel.

Studies of local corrosion of copper and carbon steel have continued and started respectively. The carbon steel studies are made at Harwell in UK and are mainly directed towards statistical analysis of pit growth data.

The research on buffer and backfill material have continued with the main emphasize on bentonite 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. A survey of candidate buffer materials in Sweden has been made.

Tests concerning settlement of canisters and the shear effects on canisters from rock movements were initiated during 1986. The borehole, shaft and tunnel sealing tests in the Stripa mine were finalized as part of phase 2 in the Stripa Project. The results have fully confirmed the technique applied using dense smectite clay.

### 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 by low-altitude airborne geophysical measurements over a 800 km$^2$ area around the site.

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. The fracture zone studies have been extended to include a zone on Ävrö close to the Oskarshamn nuclear power plant and also mapping and measurements in several tunnels and underground facilities in Sweden. The fracture zone project is currently planned to be completed in 1989.

A major project on bedrock stability has been defined and studies have started of postglacial movements along a fault at Lansjärv in Northern Sweden. The project includes various geophysical and seismological measurements as well as structural analysis and rock mechanics modelling. Some drilling through the fault zone with postglacial movements is also planned.

The investigations at the Klipperås study-site have been completed and most of the analysis and reporting is also complete. Downhole radar measurements were for the first time extensively used on a study-site. Results of these will be published early 1987. In R&D-programme 1986 it was concluded that future site investigations should be concentrated on gneissic and granitic rocks and no further investigations be made on basic rocks (gabbro and similar). No new study-sites are planned to be investigated in the forthcoming three-year period. Efforts will be concentrated on supplementary measurements on previously studied sites. In 1986 rock stress measurements were made in a borehole at the Gideå site.

### 6.2.3 Biosphere

The characterization of the Klipperås site with regard to natural radioactive substances in shallow ground waters, soil and biota was supplemented in 1986. The studies of the natural ageing process of a lake was continued and the main part of phase two was completed. A third phase aiming to modelling of the longterm behaviour of radionuclides in a lake ecosystem was initiated.

The accident of the Chernobyl reactor no. 4 caused a major release of radionuclides into the atmosphere, which then partly was deposited through fallout in Sweden. Two of the SKB study-sites (Finnsjön and Gideå) are located close to the areas with relatively high fallout. A sampling programme was started in the summer 1986 and will continue in order to evaluate the possibilities for using the data to validate models for radionuclide transport in the biosphere and in 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.

The measurement and analysis of groundwaters and of fracture minerals and isotopes at the Klipperås study-site show very interesting, high quality and consistent results. They confirm the general picture of the geochemical conditions at depth in granitic rocks, which was used in e.g. the KBS-3-study.

Humic and fulvic acids may have an impact on the radionuclide transport in ground waters. Such acids are collected from deep ground waters and isolated and purified for complexation experiments. The experiments are made by a working group at the University of Linköping in cooperation with a group at CEA in France.

### 6.2.5 Safety Assessment

A special working group for integrated performance analysis (SFG = samfunktionsgruppen) was formed within the R&D-division. The major tasks for the group are - establish a basis for comparison of various alternatives with regard to safety; follow ongoing studies of alternatives and give advice on how to analyse performance and safety; compare various alternatives for design and safety and give input to culling and prioritization; review the status of knowledge in critical areas for repository safety and suggest supplements or changes to R&D-programme. The main work of the group has so far been related to the ongoing WP-Cave-study.

The development of the probabilistic performance assessment computer model called PROPER continued throughout the year. SKB participated in a benchmark study organized by the OECD/NEA Probabilistic Systems Assessment Code User Group. The study involved 10 organizations in 7 countries.

## 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 and CEA in France. A similar agreement with Euratom has been concluded in 1986. Information exchange without formal agreements has been made with organizations in the Federal Republic of Germany, Belgium, United Kingdom, Japan, Finland and Spain.

During 1986 Swedish specialists and consultants to SKB have worked for longer or shorter periods of time at research organizations in France (CEA, Fontenay aux Roses) and USA (Battelle Memorial Institute). In a similar way foreign experts have been working at Swedish research institutions within the framework of the SKB Research programme.

Several important actions were taken on international projects during 1986. The multinational OECD/NEA Stripa Project managed by SKB reached agreement to continue with a new five year Phase 3 - programme. 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. For 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.

Phase 2 of the Stripa project has essentially been completed and most of the reports from that work will be published in 1987. A few experiments will not be finished until mid-1987. The results of phase 2 have been very valuable. In particular the development of borehole radar and cross hole seismic measurements have been very successful. The same holds for the borehole, shaft and tunnel sealing experiments, which fully have demonstrated the ability and applicability of bentonite for these purposes.

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.

The Japanese-Swiss-Swedish project, JSS, for studies of highly radioactive waste glass has been expanded with a phase V which will be the final one. The project is sponsored by CRIEPI in Japan, NAGRA in Switzerland and SKB. Experiments are made at Studsvik in Sweden and at EIR, Würenlingen in Switzerland. A major modelling effort is made at the Hahn-Meitner-Institute in Berlin (West). The work throughout 1986 has proceeded according to plans. The modelling work so far has been rather successful.

A new international project was started in 1986 - The Poços de Caldas project. Participants are SKB, NAGRA in Switzerland, UKDOE in Great Britain and CNEN, Nuclebras and Rio de Janeiro University in Brazil. 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 DoE in USA has expressed its intent to join the project. 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.

SKB is participating in the international HYDROCOIN-project which is coordinated by a secretariat set up by the Swedish Nuclear Power Inspectorate and OECD/NEA. SKB has also taken part in the planning of a follow-on project called INTRAVAL which is planned to start in 1987.

# 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 Facilities. As some of the steps will not be implemented until 30 years from now, changes in the systems are very probable.

A systematic approach to the study of alternative disposal concepts has been presented in the R&D-programme. The technical and economical impact on the waste management system of the different concepts are studied in parallel with the safety aspects.

During 1986 an evaluation of the WP-Cave-concept has been started by SKB. It continues the work done in a preproject sponsored by SKN. The purpose is to evaluate the WP-Cave concept from a technical/economical point of view as well as from a safety point of view. Further information on the WP-Cave concept is given in Chapter 11.2.

## 7.2 REPROCESSING

For the Swedish situation it is considered that the once-through strategy without reprocessing of the spent fuel is the most rational and cost-effective. The work on transferring the Swedish reprocessing contracts with COGEMA to other customers have therefore continued in 1986.

One step in this direction was the agreement concluded in 1985 between SKB and four utilities in the Federal Republic of Germany to exchange fuel. In June 1986 the Swedish Government approved the exchange, which meant that 57 tonnes of Swedish spent fuel stored at La Hague were taken over by the German utilities before reprocessing. In exchange SKB will receive 24 tonnes of Mixed Oxide (MOX) fuel for interim storage in CLAB and subsequent final storage. The transports from Germany to Sweden will start in 1987.

## 7.3 COST CALCULATIONS

### 7.3.1 Plan -86

According to Swedish law all costs for the management of radioactive waste, including the decommissioning of the nuclear power plants, have to be born by the owners of these plants. The costs are covered by a fee determined annually by the government.

The basis for the fee is a cost calculation of all the activities for the back-end of the nuclear fuel cycle, which is carried out by SKB each year /7-1/. The cost calculation is based on the scenario for the back-end activities described in Chapter 1.3. The cost calculations include the costs for construction, operation and decommissioning of all necessary facilities and equipment. These are:

- Transport system.
- Interim storage for spent fuel, CLAB.
- Encapsulation station.
- Disposal facility for spent fuel and other long-lived wastes.
- Disposal facility for reactor operation wastes and decommissioning wastes, SFR.

Also included are the costs for R&D and for the decommissioning and dismantling of the nuclear power plants, as well as the costs to be paid to COGEMA in accordance with the remaining reprocessing contracts. In the cost calculations it is, however, assumed that no Swedish fuel will be reprocessed under these contracts.

The estimated future costs, at the price level of January 1986 are about SEK 39 billion. Up to and including 1986 already SEK 5.3 billion have been spent. This figure includes costs for CLAB, SFR and the transportation system as well as for reprocessing services and the R&D-program. The total cost for the back-end of the nuclear fuel cycle in Sweden is thus about SEK 45 billion. The value of the corresponding electricity produced at the nuclear power plants is about SEK 500 billion.

Many of the costs will be incurred fairly far in the future. The total expenditures will be spread out over a period of more than 70 years. Figure 7-1 gives a rough account of the distribution of costs in time.

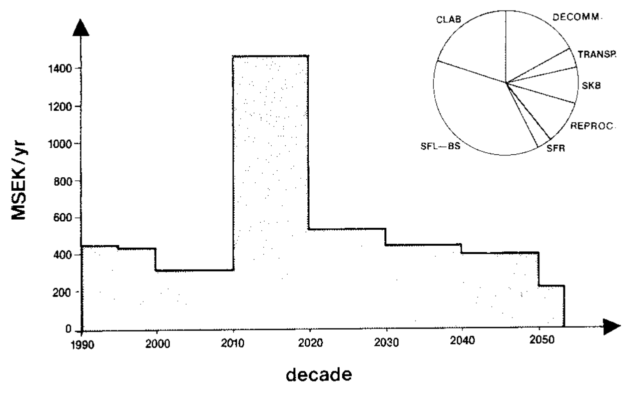



*Figure 7-1. Approximate distribution in time of future waste management costs for Sweden's nuclear power program.*

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 % |

The cost calculations are based on a preliminary design of the different facilities. In this work the experiences gained from the construction of the CLAB and SFR facilities are very valuable as background for the cost data.

### 7.3.2 Waste Management Fee

Based on the cost calculations the government has decided that the fee for 1987 should be SEK 0.019 per kWh on an average which corresponds to a total cost for the Swedish nuclear utilities of SEK 1.3 billion/year. The fee is paid into funds, one for each utility, 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

The costs for the decommissioning and dismantling of the nuclear power plants make up a substantial part (about 20%) of the total back-end costs. In 1985 SKB together with the utilities initiated a study of the technology and costs for decommissioning /7-2/. The study has been performed in close cooperation with personnel from the nuclear power plants.

The result of the study shows that, from the viewpoint of radiological safety, a nuclear power plant can be dismantled immediately after it has been shut down and the fuel has been removed, which is estimated to take about one year. Most of the equipment that will be used in decommissioning is already available and is used routinely in maintenance and rebuilding work at the nuclear power plants. Special equipment need only be developed for dismantlement of the reactor vessel and for demolishing of heavy concrete structures.

The dismantling of a nuclear power plant can be accomplished in about five years, with an average labour force of about 200 persons.

The cost of decommissioning a boiling water reactor (BWR) of the size of Ringhals 1 has been estimated to be about MSEK 540 in January 1986 prices, and for a pressurized water reactor (PWR, Ringhals 2) about MSEK 460. The costs for the other Swedish nuclear power plants lie in the range of MSEK 410-760.

These are the direct costs for the decommissioning work, to which must be added the costs of transportation and disposal of the decommissioning waste, about 100 000 $m^3$. These costs have been estimated to be about MSEK 600 for the 12 Swedish reactors.

SKB is presently not doing any technical R&D-work on decommissioning. The development of special methods and equipment will only be started a few years before the nuclear power plants are taken out of operation. 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. However, consulting services are not a business of SKB. Therefore, such services from SKB and Associated Groups are marketed and coordinated in the name of SKB's sister company SwedPower, SwP.

SwedPower, which has the same main shareholders as SKB, renders world-wide services based on the entire Swedish power technology. SwP is 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 SwP as the contracting party.

For each assignment, a project team of selected individuals is formed and a project leader is appointed. The advantage of appointing specialists from the client's staff to the project groups is considered, see Figure 8-1.

During 1986 a contract was signed with Battelle Memorial Institute, USA, regarding assistance in the studies for a final repository for high level wastes in crystalline rock. A similar project was also carried out within the site characterization program in Finland.

A feasibility study regarding a wet interim storage facility was carried out for Korea Nuclear Fuel Company and negotiations for further work are in progress.

A one-year study regarding a total nuclear back end strategy was initiated for the national utility Taiwan Power Company.

During 1986, SwedPower/SKB was also engaged for radar measurements at the Grimsel Rock Laboratory in Switzerland and for stress measurements at the Underground Research Laboratory in Canada.

Finally, a cooperation was established with the Spanish national waste management organization, ENRESA, regarding future assistance in nuclear back-end studies.

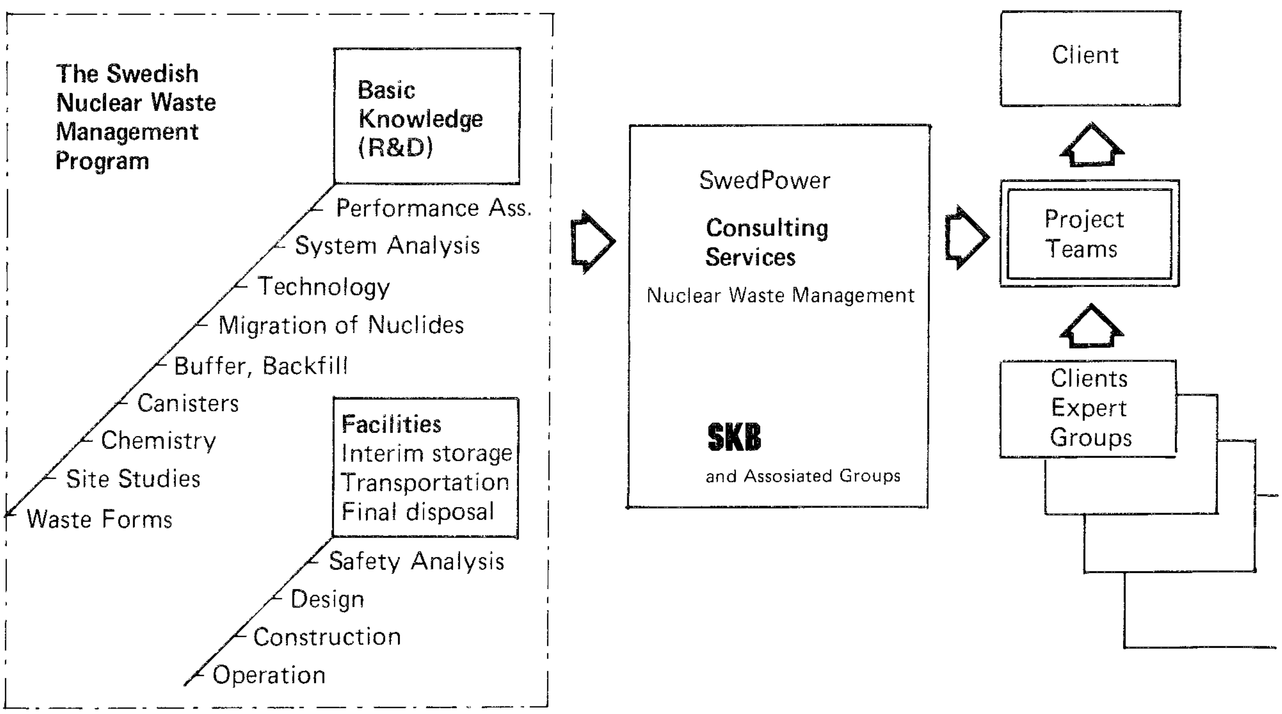



*Figure 8-1. Business areas and organization of SwedPower consulting services.*

# 9 INFORMATION AND PUBLIC AFFAIRS

## 9.1 GENERAL

Information to the public concerning facilities and the safety of the systems is a very important part of the waste management program. In order to achieve acceptance of the site for a final repository at the end of the 1990's extensive information will have to be furnished both locally and on a national level.

After the Chernobyl accident in April, 1986 it was noted that the debate in Sweden turned away from the waste management questions towards nuclear power plant safety issues. However, there have already been signs that the debate gradually will focus anew on waste management issues.

The implementation of the waste management system will not be possible unless it is accepted by the general public.

## 9.2 SKB INFORMATION ACTIVITIES

SKB has already since it started the R&D-program on waste disposal in 1977 informed the public on its activities. The aim, based on the awareness that the public is entitled to open and clear information about the handling and disposal of nuclear waste, has been to give a clear and unbiased description of the main issues.

In order to broaden the general information about SKB activities and their relation to the Swedish nuclear power program a Department of Public Affairs and Media Relations was established within SKB in 1985. During 1986 public opinion was polled in three different parts of Sweden. With the help of external consultants a careful analysis was made of the communication measures necessary to improve the common knowledge of waste management issues.

Two main news events was generated by SKB during 1986:

- The CLAB facility was inaugurated at April 29 with the participation of hundreds of distinguished guests. The press coverage was extensive, when viewed in relation to the fact that the Chernobyl accident was revealed on the day before.
- In September two simultaneous press conferences were held at different places in Sweden to present the first SKB three-year R&D-program as required by the 1984 Act on Nuclear Activities. Great interest was shown by the press at this occasion.

During the year there has also been a number of interviews and programmes on Swedish radio and television with the participation of experts from SKB, as well as an extensive press coverage of different SKB research work done locally.

More than 50 groups of foreign specialists and politicians was received at the SKB facilities CLAB, SFR and Stripa. Swedish politicians, local schools as well as the general public have of course also been frequent visitors to these facilities.

Information material, such as brochures and video films, is being produced on a continuous basis. The items currently available in English are listed below.

An in-house magazine, SKB-nytt (SKB News), began publication during 1986 with the aim to reach not only the employees but also the wide selection of scientists, researchers and consultants working for SKB.

SKB has appeared during the year at a number of exhibitions, e.g. in Geneva at the meeting organised by FORATOM and ENS (European Nuclear Society).

**BROCHURES**
- SKB - Activities
- SFR - Final Repository for Reactor Waste
- CLAB - Central Interim Storage Facility for Spent Nuclear Fuel
- M/S Sigyn
- Stripa - A Deep Underground Research Facility
- Data on Nuclear Power and Waste

**VIDEO CASSETTES AND FILMS**
- Progress of the Stripa Project
- A Final Repository at Forsmark
- CLAB in Action
- Looking Deep into the Rock
- Nuclear Fuel and Waste (produced during 1986)

# REFERENCES PART I


## CHAPTER 1

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

**1-2 KUNSKAPSLÄGET PÅ KÄRNAVFALLS-OMRÅDET 1986**
KASAM, December 1986 (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**
Volumes I-IV
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.

## CHAPTER 7

**7-1 PLAN 86**
– Costs for management of the radioactive waste from nuclear power production, SKB TR 86-12, June 1986.

**7-2 Technology and costs for decommissioning the Swedish nuclear power plants,**
SKB TR 86-18, May 1986.

# SKB ANNUAL REPORT 1986
# Part II

# Research and Development During 1986

# CONTENTS OF PART II


| | | Page |
|---|---|---|
| **10** | **R&D programme 1986** | 41 |
| 10.1 | Guidelines | 41 |
| 10.2 | Overview of Planned Research and Development | 42 |
| 10.3 | Studies of Alternatives | 43 |
| 10.4 | Spent Fuel Studies | 43 |
| 10.5 | Geoscience Studies | 43 |
| 10.6 | Study-site Investigations | 44 |
| 10.7 | Underground Research Laboratory | 44 |
| 10.8 | Chemistry | 45 |
| 10.9 | Natural Analogues | 45 |
| 10.10 | Site-selection | 45 |
| 10.11 | Review of the R&D-Programme-86 | 45 |
| 10.12 | Execution of the Programme | 46 |
| **11** | **REPOSITORY DESIGNS** | 47 |
| 11.1 | General | 47 |
| 11.2 | WP-Cave | 47 |
| 11.2.1 | Design | 47 |
| 11.2.2 | Repository Performance | 48 |
| 11.2.3 | Cost Analysis | 49 |
| 11.3 | Deep Boreholes | 49 |
| **12** | **WASTE FORMS** | 51 |
| 12.1 | Spent Fuel | 51 |
| 12.1.1 | PWR Fuel Leaching Studies | 51 |
| 12.1.2 | Radiolysis Studies | 51 |
| 12.2 | Modelling | 52 |
| **13** | **CANISTER MATERIALS** | 53 |
| 13.1 | Copper | 53 |
| 13.2 | Carbon Steel | 54 |
| **14** | **BUFFER AND BACKFILL** | 55 |
| 14.1 | Overview | 55 |
| 14.2 | Physical State of Smectite-adsorbed Water | 55 |
| 14.3 | Settlement of Canisters | 56 |
| 14.4 | Model Shear Test of Canisters with Smectite Clay Envelopes | 56 |
| 14.5 | Clay Characterization and Possible Alteration Phenomena | 57 |
| **15** | **GEOSCIENCE** | 59 |
| 15.1 | Overview | 59 |
| 15.2 | Underground Research Laboratory | 59 |
| 15.3 | Fracture Zone Studies | 59 |
| 15.4 | Development of Methods and Instruments | 60 |
| 15.5 | Developments in Computer Modelling | 61 |
| 15.6 | Bedrock Stability | 61 |
| 15.7 | Study-site Investigations | 61 |
| **16** | **THE BIOSPHERE** | 63 |
| 16.1 | Biosphere Characterization and Natural Radioactivity | 63 |
| 16.2 | Natural Ageing in Lake Ecosystems | 63 |
| 16.3 | The Chernobyl Fallout | 63 |

**17 CHEMISTRY** 65

17.1 Geochemistry 65
17.1.1 Groundwater Analyses 65
17.1.2 Fracture Minerals and Isotopes 66
17.1.3 Near-field Conditions 67
17.2 Radionuclide Chemistry 67
17.2.1 Solubility and Speciation 67
17.2.2 Colloides, Organic Complexes and Microbes 67
17.2.3 Sorption and Diffusion 67
17.2.4 Radiolysis 68
17.2.5 Concrete 68
17.3 Chemical Transport 68
17.4 Validation of Transport Models 68
17.4.1 Laboratory Experiments 68
17.4.2 In-situ Tests 68

**18 SAFETY ASSESSMENT** 71

18.1 General 71
18.2 Probabilistic Systems Analysis 71

**19 THE STRIPA PROJECT** 73

19.1 Introduction 73
19.2 The Program for Phase 3 of the Stripa Project 73
19.3 Results of Phase 2 74
19.3.1 Crosshole Techniques for the Detection and Characterization of Fracture Zones 74
19.3.2 Three-Dimensional Migration Experiment 75
19.3.3 Borehole, Shaft and Tunnel Sealing Test 76

**20 JSS-PROJECT** 79

**21 NATURAL ANALOGUE STUDIES** 81

21.1 The Poços de Caldas Project 81

**22 DOCUMENTATION** 83

22.1 Technical Reports 83
22.2 SKB Data Base System 83

**REFERENCES PART II** 85

# 10 R&D PROGRAMME 1986

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 the radioactive wastes from nuclear plants in a safe way.

The nuclear utilities have instructed 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 beginning in 1986. The first such comprehensive programme was submitted by SKB to SKN on September 29, 1986 /10-1/. The programme gives a general account of all measures that are needed until the final disposal of the wastes has been completed. For the period 1987-1992 a more detailed programme is given. This is in accordance with the requirements in the law. The programme is supplemented by two background reports /10-2, 10-3/. The following sections give a condensed summary of the R&D-programme-86.

## 10.1 GUIDELINES

The goal of radioactive waste management in Sweden is to dispose of all radioactive wastes generated at the Swedish nuclear power plants in a safe manner.

The following general guidelines apply to the waste management system:

- The radioactive waste shall be disposed of in Sweden.
- The spent nuclear fuel shall be temporarily stored and finally disposed of without reprocessing.
- Technical systems and facilities shall fulfil high standards of safety and radiation protection and satisfy the requirements of the Swedish authorities.
- The systems for waste management shall be designed so that requirements on the control of fissionable material can be fulfilled.
- In all essential respects, the waste problem shall be solved by the generation that utilizes electricity production from the nuclear power stations.
- A decision on the design of the final repository for spent nuclear fuel shall not be taken until around the year 2000 so that it can be based on a broad body of knowledge.
- The necessary technical solutions shall be arrived at within the country, at the same time as available foreign knowledge shall be gathered.
- The conduct of the work shall be guided by the regulatory authorities' continuous review and assessment and the directives issued by them.
- The activities shall be conducted openly and with good public insight.

From the Swedish nuclear power plants there will be three main types of waste – spent nuclear fuel, reactor wastes and decommissioning wastes. A simplified scheme for the necessary components of a complete waste management system for these types of wastes is shown in Figure 10-1. Major parts of this system have already been taken into operation or are under construction. This is the case for the transportation system, the interim fuel storage – CLAB – and the repository for reactor wastes – SFR. For these parts of the system the R&D-phase is already past. The programme is therefore mainly directed towards handling and disposal of spent fuel.

The research is aimed at obtaining the necessary information base for a site-specific siting application for a final repository for spent nuclear fuel around the year 2000. Until then a system optimization must be carried out so that a system adapted to a given site can be specified.

The research and development work shall be conducted with the intention to protect the environment from the harmful effects of radioactive waste with due regard to:

- economy,
- comprehensiveness,
- flexibility,
- relevance to the dominating problems and the need for a broad acceptance in society, both among specialists and government authorities and among the general public.

The requirement on comprehensiveness in the research means that various alternatives shall be studied and evaluated. Flexibility should therefore be retained for as long as possible. Effective R&D requires defined goals and delineated frames. It is therefore important to select and focus the research work in

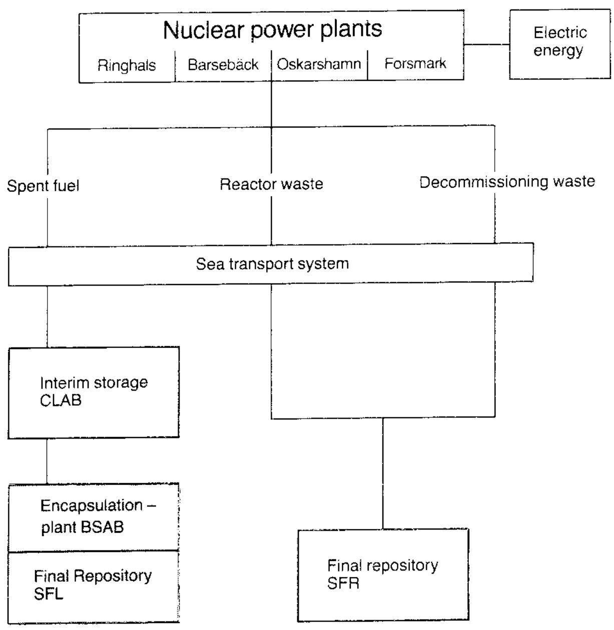



*Figure 10-1. The Swedish Waste Management System.*

such a manner that priority is given to the most interesting and realistic alternatives. The research must be continuously related to those phenomena that are of relevance to the function and safety of the final repository.

Up to 1984, the main goal of SKB's research was to demonstrate that a safe final disposal of spent nuclear fuel can be effected in Sweden. Efforts were concentrated on a specific method. This is described in the KBS-3 Report /10-1/. The safety account in KBS-3 is based on a number of pessimistically chosen premises. Credit is not taken for inadequately understood conditions and factors if they act in a favourable direction. Methods and data have consistently been selected to provide an estimated upper limit for the impact of the final repository on the biosphere. The safety analysis in KBS-3 therefore contains considerable margins of safety that were not possible to quantify at the time. One important goal of the continued R&D work is to gain better knowledge of the actual margins of safety. Improved knowledge in this respect provides a better basis for an optimization of the final disposal method and allows greater freedom in the choice of a repository site.

## 10.2 OVERVIEW OF PLANNED RESEARCH AND DEVELOPMENT

The safety of a final repository is based on a system of barriers that prevent or limit the dispersal of radioactive materials from the final repository. Some of the barriers are natural (geological) and some are engineered (canister, buffer, waste matrix). The research concerns the properties and performance of these barriers with the aim of arriving at an optimized choice of barrier system and repository site. Figure 10-2 shows an outline of a timetable for the measures needed before start of construction of a final repository for spent fuel.

Up to the mid-1990s, goal-oriented research is being conducted on alternative designs of the barrier system and on the fundamental phenomena of importance for safety, optimization and choice of system and site. At the same time, the necessary development of analysis models is being pursued.

In parallel with this, the general area characterization that has been going on since the end of the 1970s will be completed. In the early 1990s, a couple of sites will be selected for detailed investigations. For all the

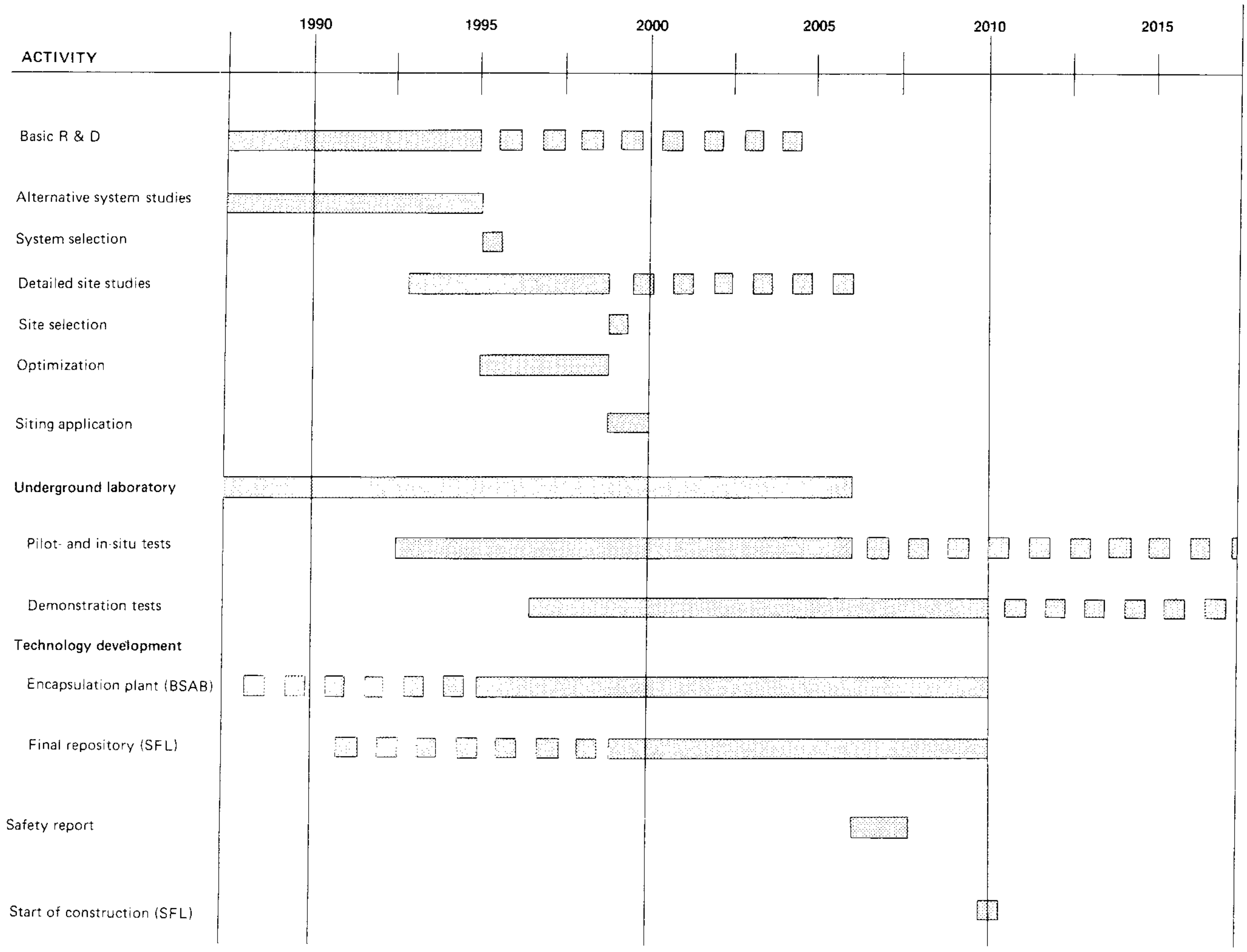



*Figure 10-2. Overall timetable for measures up to the start of construction of the final repository and the treatment plant.*

sites that could be candidates for a siting application in the year 2000 these investigations should not be begun later than 1993.

In the mid-1990s, the studies of barrier systems will be summarized and one or possibly two main alternatives will be chosen as a basis for a site-specific optimization of the final repository system. The optimization will be carried out until 1998, when work will begin on a siting application. The application will be submitted in the year 2000.

To sum up, the choice of system is planned for the mid-1990s and the choice of site for 1998.

For the period 2000-2010, the emphasis is foreseen to lie on technology development and demonstration of the function of the chosen system. Pilot tests and long-term in-situ tests should be begun in good time before the year 2000 in order to provide support for a siting application. These tests should be conducted in the underground research laboratory that is presented in section 10.7. Larger-scale and integrated demonstration trials will probably be conducted at a later stage either in the underground research laboratory or on the selected repository site. The design of these trials is dependent on the development of the technology. Certain demonstrations and in-situ tests are also foreseen during the construction phase.

Research and development within fundamental fields of importance for safety and long-term function will continue even after the mid-1990s. But their scope is expected to decrease and the emphasis to shift towards phenomena of special importance for the system(s) chosen as the main alternative(s).

The results of continued detailed observations on the selected site, of tests in the underground research laboratory, of supplementary basic research, of demonstration trials and of ongoing technology development will be summarized in a safety report that will be reviewed by the authorities prior to the start of construction.

## 10.3 STUDIES OF ALTERNATIVES

An important part of the programme for the next few years is to evaluate different alternative designs of the repository system.

The barriers can be varied in different ways by choice of material and design. Similarly, adaptation of the barriers to the site can be accomplished in several ways for the different basic disposal alternatives. If the fact that such factors as repository depth, rock types etc can vary is also taken into consideration, a very large number of possible variants are obtained. A narrowing-down of the studied alternatives must be made continuously in order to obtain a manageable basis for an optimal design of the final repository.

During 1986-87, SKB is conducting a performance and cost analysis of the WP-Cave, which is one example of an alternative departing from KBS-3. Other interesting alternatives are horizontal emplacement of the canisters in full-face driven tunnels (studied by NAGRA in Switzerland); disposal in very deep holes drilled from the surface and plugged at the top; disposal in long tunnels at great depth in the rock beneath the Baltic Sea etc.

Within the framework of a specific base alternative different materials and designs can be selected for the canister and the buffer. A review of different possibilities will be made.

## 10.4 SPENT FUEL STUDIES

The waste form - spent fuel - is given in the main alternatives being studied. Studies of spent nuclear fuel in a final repository environment are therefore a very important part of the research programme. The emphasis lies on experimental studies of the interaction between fuel, groundwater and substances that may be dissolved in the groundwater. This work has been going on for many years and will continue for a considerable time. The research aims at clarifying the chemical-physical processes that govern the dissolution of radionuclides from the fuel. Besides the experimental work, considerable work is therefore also being done on developing theoretical models. The goal is to have a model that can describe the process of fuel dissolution and be used in an optimization of the barrier system by the mid-1990s. The studies of spent fuel are being conducted in close contact with similar projects in other countries, mainly Canada and the USA. Other major nuclear power countries have reprocessing of the spent fuel as their main alternative and are consequently concentrating their research on vitrified high-level waste from reprocessing.

## 10.5 GEOSCIENCE STUDIES

Research and development in the geoscientific field is being concentrated on the following areas, which are of central importance for design, safety analysis and site selection:

- Groundwater movements in the rock.
- Stability of the rock.
- Study-site investigations.
- Radionuclide transport in the rock.

In connection with the work in these areas there is a continued effort to further develop methods and techniques for geoscientific measurements and investigations. Groundwater movements are and will be studied in several projects such as:

- the third phase of the international Stripa-Project 1986-1991,
- field studies of fracture zones at Finnsjön and Ävrö,
- studies of fractures, fracture zones and water inflow in some tunneling projects in Sweden,
- measurements and observations at SFR,
- supplementary investigations at study-sites previously studied by SKB.

In addition to these field studies an extensive development of mathematical models to describe groundwater movements is also included in the work. Several different methods will be tested in order to achieve increased accuracy in the safety analyses.The bedrock stability is investigated in a recently started study of a postglacial movement near Lansjärv in northern Sweden. This project includes field studies of seismology, rock mechanics etc. Further, consequences of earthquakes, glaciation etc will be evaluated.

## 10.6 STUDY-SITE INVESTIGATIONS

Geological investigations on different scales have so far been carried out on a total of 14 sites. Relatively extensive investigations have been carried out on eight study-sites. Limited surface investigations, and in some cases also limited drillings, have been carried out on an additional six sites. On the basis of these investigations and other preliminary studies and reconnaissances, it can be concluded that there are good possibilities of finding sites in Sweden that possess the geological characteristics required for the construction of a safe final repository.

The bedrock on the study-sites where more extensive investigations have been carried out consists of gneissic or granitic rock types. The data currently available on these types of rock are judged at present to be sufficient to permit a comparison between different sites and an assessment of existing variations. There is, however, reason to supplement the data by special in-depth investigations on one or more of the already investigated study-sites. The scope of these supplementary investigations will be defined in a special study being carried out during 1986-87. Further investigations of additional sites in gneiss/granite using the present-day standard programme cannot be expected to make more than a marginal contribution to the existing state of knowledge.

Among the other rock types in Sweden besides gneiss and granite that have been discussed as alternatives for hosting a final repository, the one which has aroused the greatest interest is gabbro. The advantages of gabbro are its geohydrological and geochemical properties. A disadvantage could be its poorer thermal conductivity. However, the investigations that have been carried out to date in gabbro are not sufficient to determine whether gabbro could be a favourable alternative.

Further studies are required in order to fully evaluate basic rock types such as gabbro. Drillings on a gabbro site were commenced in the autumn of 1985 at Kolsjön in Uppland County, in part for the purpose of meeting the requirements of the Nuclear Activities Act on comprehensiveness in this geological respect as well. However, the investigations had to be terminated due to local protests.

In connection with the evaluation of previous results and experience on which this research programme has been based, the question of gabbro investigations was also considered. Investigations already completed and general experience of gabbro show that it would probably be relatively difficult to find sufficiently large homogeneous formations among the relatively sparsely occurring gabbro massifs, in comparison with gneiss or granite. On the other hand, as has previously been noted, there are many places in Sweden with gneiss/granite where a final repository is fully possible. The benefit of any further investigations of gabbro is deemed marginal and further investigations of this rock type are not a prerequisite for the implementation of the final disposal scheme.

The conclusion is that it is best to concentrate further geological studies on gneiss and granite. These rock types are sufficiently good and are the most likely candidates for hosting a final repository.

## 10.7 UNDERGROUND RESEARCH LABORATORY

The planned R&D work shall be of high quality, have a balanced scope and be carried out effectively. These demands have been evaluated based on the experience that has been gained from the study-site investigations, from the Stripa project, from the SFR project and otherwise from the geohydrological studies in particular. An evaluation of facts, demands and appraisals clearly points towards the need for more detailed and comprehensive investigations. The site where these are performed should possess the necessary geological characteristics and be undisturbed. In order to meet these and other needs, an underground research laboratory is planned. The purpose of this laboratory is to:

- Provide a base for development and testing of the detailed investigation methods that are to be used in detailed site investigations in the 1990s.
- Study in detail the groundwater flow within a larger region (than in Stripa) and how this flow is affected by shaft sinking or tunnelling.
- Serve as a site for geoscientific investigations and experiments.
- Permit tests of nuclide transport (with the groundwater) to be carried out within well-characterized and representative regions.
- Provide a site for pilot tests with certain system components or certain equipment.
- Provide a site for in-situ tests for studies (over a relatively long period of time) of the cofunction of parts of a repository system.
- Provide a site for large-scale demonstrations.
- Provide a site for the testing of civil engineering methods or construction technology for a final repository.
- Serve as a well-characterized reference site for studies of different repository alternatives.

Some of these purposes will already be fulfilled during the preliminary investigation and construction phase. The data obtained at that stage will provide a basis for validation and refinement of mathematical models for eg groundwater flow. They also permit validation and improvement of the preliminary investigation methods used. Other purposes will not be fulfilled until the laboratory stands completed.

The underground rock laboratory should be available when Stripa phase 3 is concluded, ie at the beginning of the 1990s. This means that the preparatory work should start immediately. The activities at the laboratory will probably extend over a period of at least 15 years. Experience from other underground facilities especially Stripa, URL in Canada and SFR will be taken into account in planning, preliminary investigations and design work.

An underground research laboratory should be situated on a site with suitable geology and where an existing infrastructure and some services are available. To begin with, the suitability of one of the nuclear power sites, especially Simpevarp at the Oskarshamn power plant, will be explored.

Investigations for and establishment of a research laboratory are planned to take place in phases. The first phase, which is planned to begin in early 1987, includes preliminary studies and investigations from the surface. The purpose is to get an idea of the possibilities offered by the geology for the establishment of an underground research laboratory. The information needed to locate a shaft or an entrance tunnel will also be gathered. After evaluation, detailed investigations will be conducted from the surface and in boreholes, followed by shaft sinking (or tunnelling). The final phase includes establishment of the research laboratory and investigations from drifts (tunnels) as they are extended. The final phase is scheduled to start 1993. Additional investigations and planning are required before the exact time can be determined.

The detailed investigation technique that will later be used on the candidate sites for the final repository will be developed and tested during construction and operation of the underground research laboratory.

## 10.8 CHEMISTRY

Transport of radioactive substances from the waste to the biosphere via the groundwater is the most important transport mechanism. The chemical parameters that control this process are therefore as important for safety as the groundwater movements. The chemical parameters are also of crucial importance for possible corrosion of canister material. Further chemistry studies are therefore an important part of the R&D work. The chemistry has a bearing on all parts of the barrier system, both engineered and natural barriers and their function.

In order to study how radioactive substances are transported with the groundwater, various tests are being conducted with tracer substances. The tests provide fundamental information on water flows in fractures and on chemical interaction between dissolved substances and fracture or rock minerals. Such tests have been conducted and are being conducted within the Stripa project. Further tests are planned both in phase 3 of the Stripa project and within the framework of the fracture zone investigations. In a later phase, tracer tests will be performed at the underground research laboratory.

## 10.9 NATURAL ANALOGUES

The tests that are being conducted in the field and in the laboratory can, for natural reasons, only be performed on a relatively short time scale and the results can therefore not be used to validate models for radionuclide transport on the longer time scale that is relevant for a final repository. In order to obtain data that are more representative of this longer time scale, so-called "natural analogues" are being studied. These include the transport of naturally occurring radioactive materials. SKB is participating together with NAGRA in Switzerland and the Department of the Environment in Great Britain (UKDOE) in a study of a uranium mineralization and a thorium mineralization (with very high contents of uranium and thorium, respectively) at Poços de Caldas in Brazil. This project started in 1986 and is planned to extend over a three-year period. Further studies of similar natural analogues are underway or planned.

## 10.10 SITE-SELECTION

Before a site is chosen for the final repository, more detailed investigations are required than those that have thus far been carried out on the study-sites. Only on the basis of such investigations can the necessary information be obtained for the site-related optimization of the final repository and the preparation of a siting application.

Detailed investigations should be carried out on two sites during the 1990s. The investigations should cover a period of at least five years and be completed by no later than 1998 to provide a basis for the final choice of a site for the final repository. The investigations at this site will then continue for an additional number of years.

Before a site is chosen for detailed investigation, a general geological survey equivalent to a study-site investigation should be carried out. This means that investigations on any new sites are planned to take place no later than during the period 1990-1992.

The basis for the selection of sites for detailed investigations will be the study-site investigations that have been conducted during the past ten years and the further inventories and reconnaissances that SKB will have done up to that stage. The latter will be completed during the period 1986-1989. If conditions prove suitable, the site for the rock laboratory may be one of the sites chosen for detailed investigations. The experience gained from the establishment of the research laboratory will be of great importance in the choice of sites for detailed investigations.

## 10.11 REVIEW OF THE R&D-PROGRAMME-86

The research and development programme is reviewed by the National Board for Spent Nuclear Fuel (SKN) who shall report its findings and recommendations to the Swedish government before June 1 1987.

SKN has sent the programme for review to a large number of authorities, institutes, universities and interest groups in Sweden as well as to several organizations abroad. Thus the programme is reviewed by panels set up by NEA and by IAEA. Other foreign reviewers are TAC in Canada, VTT in Finland, CEA in France, NRPB in UK, NIREX in UK and BGS in UK among others. In conjunction with its report to the government SKN must also suggest an adequate procedure for taking the necessary decisions with respect to selection of sites for detailed characterization and finally of repository site. This request was put forward by the government in a special directive issued in December 1985.

## 10.12 EXECUTION OF THE PROGRAMME

The programme will be executed under the leadership of SKB, who is responsible for planning, initiation and coordination of the work. The R&D work will mainly be carried out under contracts to research institutions at universities and institutes of technology, to industry, consultants or other Swedish and Foreign groups with the necessary competence. SKB will be responsible for continuous documentation and compilation of the results and for their application.

The planning of large projects, as well as results and their application, will be discussed in reference groups including outside specialists. The results will be continuously reported in SKB Technical Reports, in scientific journals and at international conferences and seminars. In this way, a review and assessment of the scientific quality of the work will be obtained.

Safety, performance, feasibility and development potential will be continuously analyzed for the various alternative system designs in an integrated performance group consisting of persons from both SKB and engaged consultants.

The work in reference and integrated performance groups, and the review and assessment of the results of the R&D work, will provide a basis for a continuous steering of the research direction. A gradual reallocation of priorities between different studied alternatives is foreseen on the basis of the results obtained in this fashion.

The cost of executing the programme is estimated to be a total of about SEK 600 million during the six-year period 1987-1992, of which about SEK 175 million is the expected cost of the underground rock laboratory.

The R&D work is being financed from the funds that are built up through a special fee levied on nuclear power production. The funds are administered by the National Board for Spent Nuclear Fuel, which also disburses money to SKB.

# 11 REPOSITORY DESIGNS

## 11.1 GENERAL

The main purpose for the investigations of engineered barriers after the acceptance of the KBS-3 report in 1984 has been to evaluate what possible alternatives there are to the disposal concepts presented in KBS3. In the background report on Alternative Disposal Methods /11-1/ a number of possible repository designs/concepts have been discussed. Of these alternatives only the WP-Cave has been subject to major investigations during 1986.

The WP-Cave concept was originally developed by the Boliden WPContech AB, and had been investigated by the National Board for Spent Nuclear Fuel (SKN) during the period 1982–1985 /11-2/. Early in 1986 the concept was adopted for evaluation by SKB. The programme comprises evaluations of the performance, the potential safety and the economy of the concept and possible variants of it. The intention is to have the potentials of the WP-Cave evaluated during 1988.

In December 1986 a conceptual study of another alternative disposal method was initiated – the very deep borehole disposal concept.

The intention is to bring up the knowledge of the various alternatives to a level where the repository designs can be compared with regard to technical feasibility, potential safety and economy.

## 11.2 WP-CAVE

### 11.2.1 Design

The main features of the WP-Cave design are:

- A central, compact storage space for the spent fuel.
- A wide, low-permeable bentonite slot surrounding the central part at a distance.
- An outer structure of drifts and drillholes short-circuiting the groundwater gradients over the repository.

The structure is egg-shaped as seen in Figure 11-1. The design is developed for construction in crystalline rock. The depth can be chosen on the basis of site-specific data on rock structure, virgin stresses and hydrogeology.

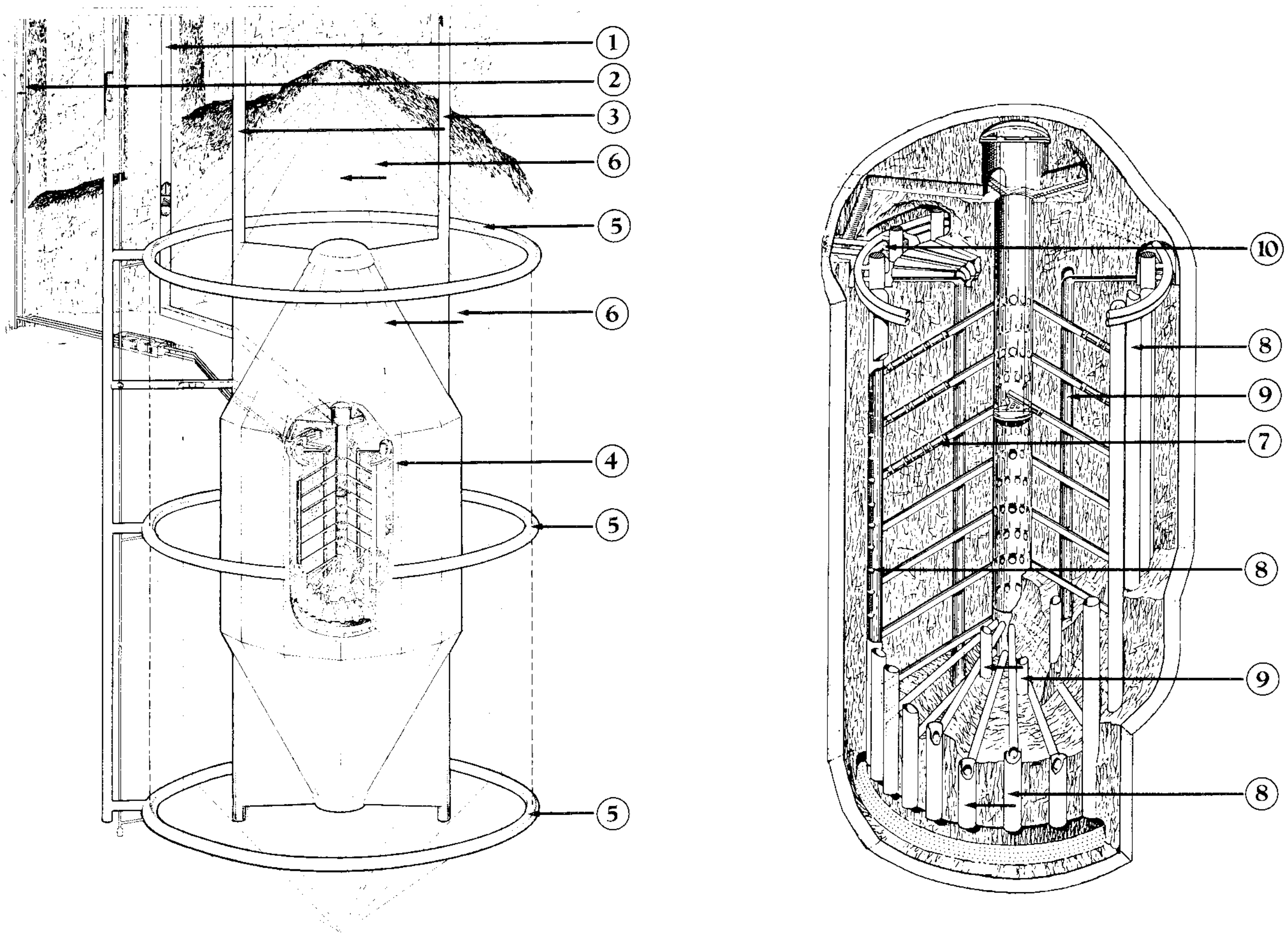



*Figure 11-1. Artist's view of a WP-Cave structure with the capacity of about 1500 tonnes of U. The dimensions of the bentonite-quartz barrier are 300 m in height and 130 m in width.*

Different sizes of the structure are studied. The one shown in Figure 11-1 has a storage capacity of about 1500 tonnes of U. The dimensions of the bentonite-sand slot are 300 m in height and 130 m in diametre.

The storage space consists of one central shaft from which the entrances of the radial, sloping canister channels are reached. A canister channel is connected to one outer shaft and one inner shaft, forming a loop for air circulation. The canister is positioned centrally in the channel with a gap for the air to pass around.

Outside the disposal area at about 20 m distance a slot is excavated and filled with a mixture of bentonite and sand.

The technique for this excavation and refilling operation is outlined in accordance with the mining method "Cut-and-Fill", /11-3/. The function of the bentonite layer is to constitute a barrier against water flow between the waste in the center and the groundwater outside.

Two variants are investigated, one alternative is a structure with a bentonite-sand slot totally surrounding the storage space, the other alternative has no slot around the bottom, see Figure 11-2.

Outside the bentonite-barrier a structure of horizontal, annular drifts and vertical drillholes is made. This structure has been named "Hydraulic Cage". It will provide preferential pathways for the groundwater around the repository, thus eliminating the hydraulic gradient over the storage area.

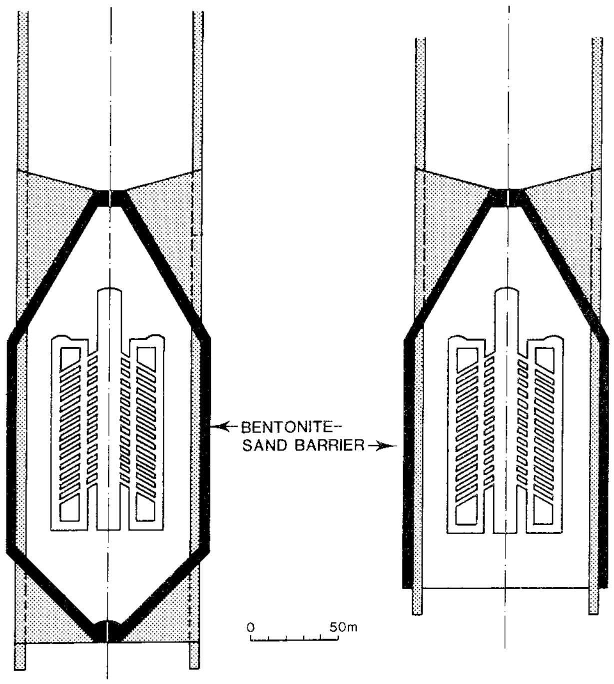



*Figure 11-2. Two alternative designs of the bentonite-sand slot. Left hand side alternative with totally surrounding slot. Right hand alternative with open bottom.*

## 11.2.2 Repository Performance

The preliminary performance analysis is focused on the behavior and properties of different parts of WP-Cave during four different time periods:

- Construction.
- Deposition of the spent fuel and active air cooling of drained repository.
- Sealing, water filling and storage up to the time of canisters failure.
- The long-term storage period.

The construction of a WP-Cave is excepted to take five years.

The dry cooling period is presumed to last for about 100 years if 40 years old spent fuel is disposed.

The sealing can be carried out in several ways. One alternative is to seal-off all entrances and allow the groundwater to enter through the bentonite-sand slot by natural flow. A second alternative is to flood the cave as part of the sealing operation.

The canisters are made of iron with an assumed service life of a few hundred years. This assumption is chosen as the WP-Cave study specially considers the possibilities of using low-carbon steel as canister material.

**The Cooling Period**

The compact storing of the spent fuel will require additional cooling to limit the maximum temperatures at the bentonite barrier. The cooling is maintained by circulating air heat exchanged with surface air directly or via an underground intermediate heat exchange plant.

During this period the hydraulic cage has the function of a drainage system. It collects infiltrating water which is pumped to surface.

**Post Closure Storage**

After sealing the repository, the function of both the hydraulic cage and the bentonite barrier is to reduce the transport of radionuclides from the waste to the flowing groundwater. The bentonite reduce the hydraulic conductivity and the hydraulic cage reduce the hydraulic gradients.

The possibilities for achieving these functions will be investigated.

After sealing the temperature will increase in the inner rock mass resulting in an expansion of the rock into the bentonite-sand slot. The maximum temperature at the wall of the outer shafts has been estimated to be 140°C /11-2/ and 80°C in the rock closest to the slot. The displacement of the bentonite-sand slot is estimated to be about 100 mm. In the same temperature wave the rock mass outside the slot will also expand into the slot. This displacement is estimated to be about 40 mm, making a total compression of the slot with 140 mm. The high stresses induced in the inner rock mass and in the wall of the outer rock means that the rock mass will develop a fissured structure.

After the temperatures have peaked the displacement is recovered. Then the bentonite-sand will expand due to the swelling abilities of the material. The question, however, is how reversible this process will be. The swelling pressure of the bentonite will not totally stand up to the weight of the inner rock mass. Most probably the slot can not recover its total, initial width. Part of the rock mass shrinkage is converted into open fissures.

The heat increase will also induce a thermal gradient on the ground water flow. The magnitude and importance of this gradient with respect to the structure of the outer rock mass will be studied.

Once the water gets into contact with the fuel, dissolution starts in a rate dependent on e g pH, Eh, temperature and water quality. After the canisters are penetrated, dissolved nuclides can migrate out to the bentonite-sand barrier. The rock mass to be passed will be able to sorb some of the leaching nuclides.

### 11.2.3 Cost Analysis

The cost of the WP-Cave concept will be evaluated. Preliminary result identifies four major items with significant impact on total costs:

- Capacity of one WP-Cave.
- Width of the bentonite-sand slot.
- Selection of the bentonite material.
- Selection of the sand material.

Figure 11-3 shows the differences of costs dependent on the choice of design parameters. The cost figures of the diagram are relative figures where 100% stands for the cost of the basic alternative WP-Cave 1500 (1500 tonnes of U) with 5 m wide slot refilled with Wyoming bentonite and Bornholm quartz sand. As seen there is a 20% difference between a size of WP-Cave containing 1500 tonnes of U and a size contraining 3750 tonnes of U.

A somewhat larger difference is obtained if a less expensive refilling materials are chosen. A difference of about 50% is found between the basic alternative and the larger WP-Cave with less wide bentonite-sand slot refilled with less expensive bentonite and sand.

## 11.3 VERY DEEP BOREHOLES

Late 1986 a preliminary study of the feasibility of disposal of high level waste in very deep (several kilometers) boreholes in crystalline rock was defined. The preliminary study is intended to be followed by a conceptual design, a review of possibilities for quality assurance and an evaluation on safety potentials and costs.

| Size | WP-Cave 1500 | | | | WP-Cave 3750 | | | |
|---|---|---|---|---|---|---|---|---|
| Slot width m | 5 | 3 | 5 | 3 | 5 | 3 | 5 | 3 |
| Bentonite | Wyom | Wyom | Ital | Ital | Wyom | Wyom | Ital | Ital |
| Sand | Quartz | Quartz | Cr rock | Cr rock | Quartz | Quartz | Cr rock | Cr rock |

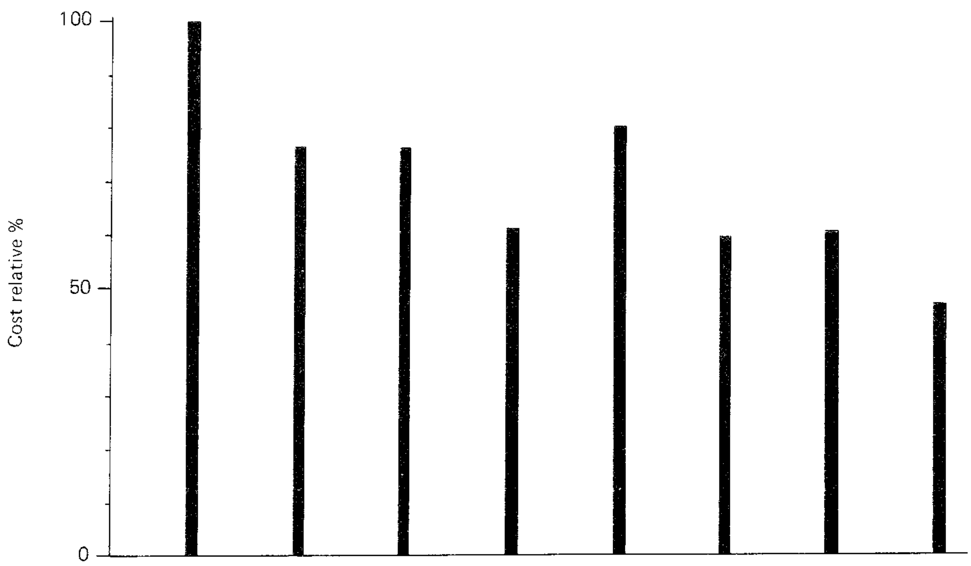



*Figure 11-3. Comparison of design parameter choice on total costs for underground parts of final repository with WP-Cave-design for spent fuel.*

# 12 WASTE FORMS

## 12.1 SPENT FUEL

As for 1985, the main activities on wasteforms have also for 1986 been 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 sixth one in the ongoing series, was held in USA and arranged by Lawrence Livermore National Laboratory.

The SKB experimental program to study the corrosion of spent fuel is now in its sixth year. The experiments, which are performed in Studsvik Energiteknik's Hot Cell Laboratory, have so far been mainly applied to fuel specimens from a high burnup BWR fuel rod (42 MWd/kg U), although experiments have also been performed on low burnup fuel (ca 0.5 MWd/kg U). Results from these experiments have been published earlier. Concurrently with continued experiments on the BWR fuel, extending the integrated contact times, experiments have also been in progress since early 1986 on a PWR fuel rod of about the same burnup (41 MWd/kg U) and a gas release from fuel to the cladding gap during operation of about 1%.

### 12.1.1 PWR Fuel Leaching Studies

To date experiments with leachant contact times of 82 and 172 days have been completed and evaluated. The results obtained for oxidizing conditions are in good agreement with what has been previously found in the BWR studies. The uranium concentrations in solution for the BWR and PWR series are shown in Figure 12-1. As can be seen, there is no difference in uranium leaching behaviour for the two source materials, confirming the previously reported solubility limited release with an equilibrium uranium concentration in solution of about 1 ppm /12-1/.

Similarly, the plutonium concentration found in the BWR fuel leach studies is well reproduced in the present PWR study, see Figure 12-2, with initially higher concentrations at shorter contact times, followed by a progressive decrease in concentration as the contact times are prolonged. However, it remains to be demonstrated that the same long-term equilibrium concentration of about 0.2 ppb will be attained also in the PWR fuel leach series.

The PWR investigations also included experiments performed under reducing conditions. Two techniques were employed to achieve low redox potentials. In one series, crushed granite from deep boreholes was used as reductant and in a second series, $H_2$-gas in the presence of a palladium catalyst was used. However, the method of using crushed rock gave somewhat ambigueous results, indicating that further development work will be needed before the method can be readily applied in a hot cell environment. Using $H_2$/Pd as reductant, significant decreases in concentrations of leached species were obtained. However, this method has the disadvantage that the

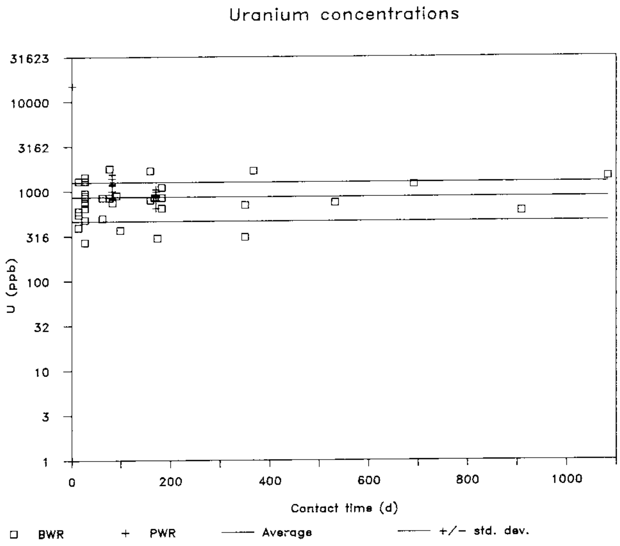



*Figure 12-1. Uranium concentrations versus contact time for BWR- and PWR-fuel leaching.*

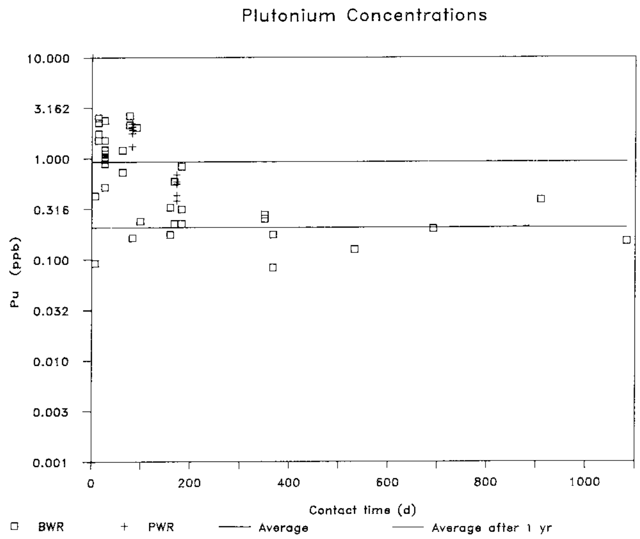



*Figure 12-2. Plutonium concentrations versus contact time for BWR- and PWR-fuel leaching.*

leachant is saturated with hydrogen, which may in an unrealistic way prevent possible surface oxidation of the fuel matrix by alpha radiolysis of the solution. Nevertheless, results obtained so far indicate that under reducing conditions the release of matrix bound radionuclides (e.g. plutonium) is, under the experimental conditions, controlled by the uranium release and solubility only and as the dissolution of the $UO_2$ matrix stops, the release of plutonium is also inhibited even though plutonium has not yet reached its solubility limit.

### 12.1.2 Radiolysis Studies

During 1986, experimental studies of the effects of radicals produced by gamma radiolysis on the corrosion/dissolution of $UO_2$ fuel has been performed. To date, only preliminary results are available and the research program is planned to continue also throughout 1987. After this period decision will be taken on a possible continuation of the program based on the obtained results. A status report is scheduled to be issued by the end of 1987.

## 12.2 MODELLING

During 1986, an effort to develop a model for the spent fuel dissolution has been started. As a first step, the solubility of amorphous $UO_2(s)$ has been measured over a wide pH range /12-2/. The crystalline $UO_2(s)$ of the fuel matrix will constitute the innermost barrier in the repository. However, partial solubilization of $UO_2(s)$ under oxidizing conditions and a later reprecipitation when reducing conditions are restored is a conceivable scenario. Under these circumstances, the solubility of the amorphous $UO_2(s)$ may well be an important parameter. In this first study a rather high solubility ($[U(IV)] = 10^{-4.4}$M) was measured in the pH range 6 to 10.5 under reducing conditions.

# 13 CANISTER MATERIALS

During 1986, the studies of canister materials have been concentrated on two candidate materials, copper and carbon steel.

## 13.1 COPPER

As for 1985, additional studies based on the KBS-3 reviews have continued. These investigations include evaluation of pitting corrosion on copper under reducing conditions and studies of creep in copper at low temperatures. For pitting studies, the first phase including development and testing of experimental techniques and equipment are now finished and preliminary results are expected to be available by the end of 1987.

The first series of experimental studies, including uniaxial creep in unwelded copper are practically finished and studies of uniaxial creep in welded material as well as creeptesting of copper tubes under internal overpressure are underway. The investigations of uniaxial creep in unwelded copper will during 1987 be supplemented with studies of creep at lower stress levels (10-100 MPa).

In addition to these studies, SKB has decided to participate in a EUREKA project aiming at developing out-of-vacuum equipment for electron beam welding of heavy constructions. This project is managed by the Welding Institute and sponsored by several European countries. During 1986, the first phase of the project was started and construction and building of the necessary equipment are under way.

The studies of hot isostatic pressing of copper has during 1986 had a lower priority, and has mainly been concentrated on the influence of the production techniques and qualities of the copper powder on the quality of the final product. These studies are still continued and are expected to be finalized in 1988.

Marine archaeology has offered a possibility for study corrosion in the interface between a copper rich cannon and glacial clay for more than 300 years. In 1980, the man of war KRONAN was found near Öland at 26 m depth in the Baltic, where it sank June 1, 1676, in a battle between the Swedish and the united Danish/Dutch fleet.

In 1985 a bronze cannon was salvaged, see Figure 13-1. The cannon was almost completely buried in a vertical position in a clay consisting of illite, montmorillonite and kaolinite.

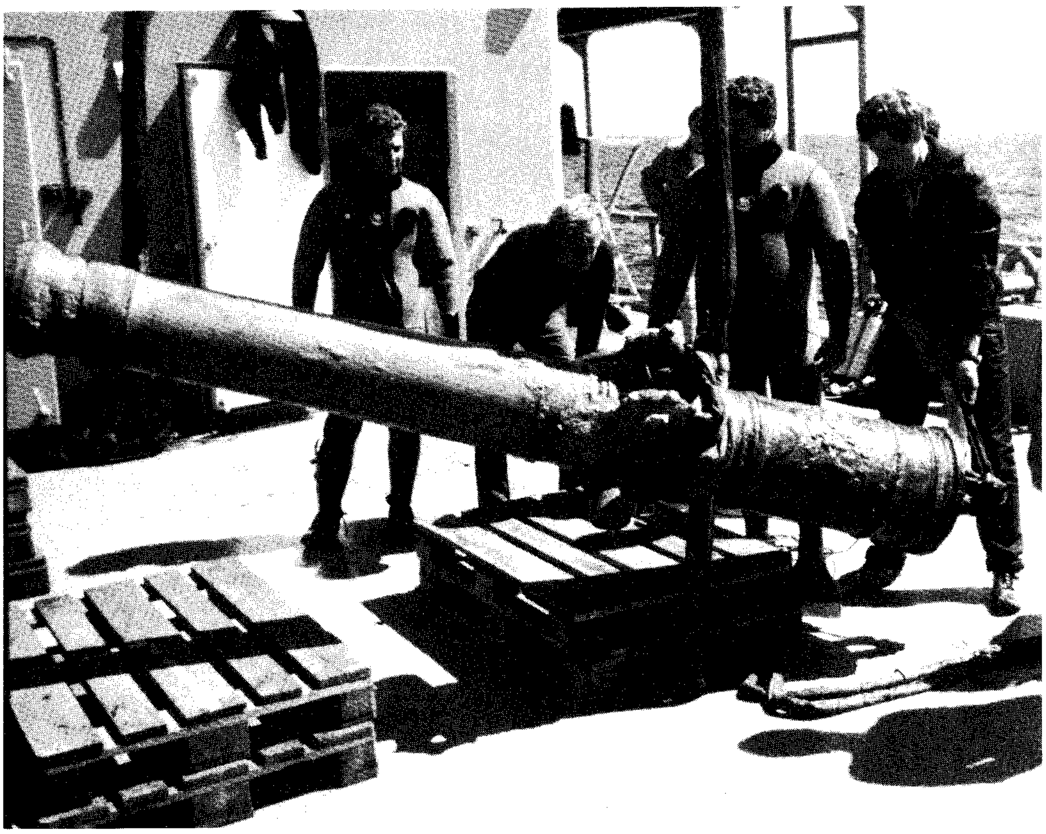


*Figure 13-1. Salvage of the bronze cannon from KRONAN, June 1985.*

Microsond analysis of the bronze indicate a bronze composition of Cu, 96%, Sn 3%, Zn and Fe together <0,5%. The metal matrix contains inclusions of tenorite. The Cu-concentration in the bronze shows a clear trend for lower values near the surface, see Figure 13-2. Cu was traced in the surrounding clay to a distance of about 4 cm from the cannon, see Figure 13-3.

The corrosion products, cuprite and malachite, have the same appearance all over the cannon except for the uppermost part that was situated above the bottom of the sea, see Figure 13-4. It was found that the formation of cuprite involves a transformation of tenorite and can be explained by redox processes where Cu(s), $Fe^{2+}$ and organic matter are the major electron donors. Redox measurements give a mean value of +450 mV and suggest an oxidizing environment. A second cannon was salvaged during 1986 and the study continues.

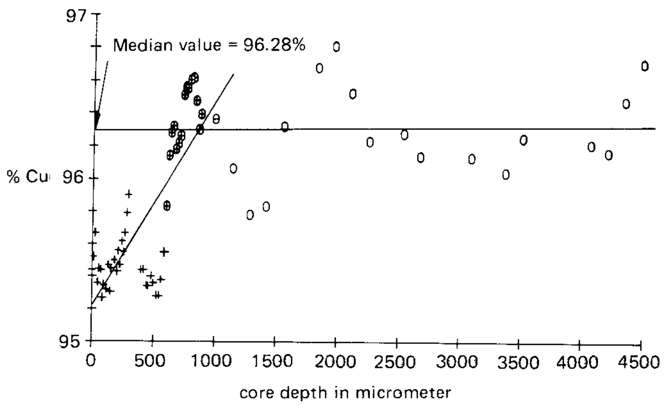



*Figure 13-2. Leaching profile of a bronze matrix.*

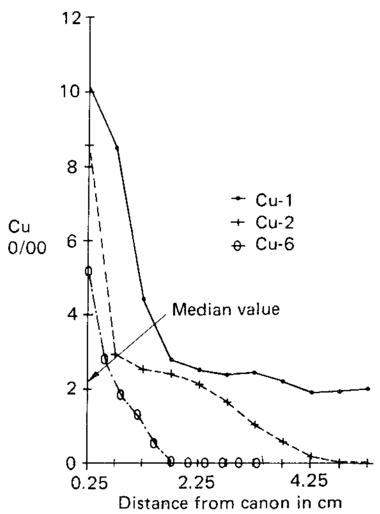



*Figure 13-3. Distribution of copper in clay.*

*Figure 13-4.*
*The bronze cannon before hoisting but after excavation of the clay at one side. The upper darker part of the cannon is situated above the bottom of the sea.*

## 13.2 CARBON STEEL

During 1986, studies of pitting corrosion on carbon steel have started at Harwell Laboratories, UK. A first approach for evaluating the general and localized corrosion of carbon steel canisters for a KBS-3 type nuclear waste repository has also been made /13-1/. The main effort in 1986 concerned statistical analysis of the pit growth data obtained earlier at Harwell Laboratories as well as new experimental results generated within the SKB program, using extreme value statistics.

# 14 BUFFER AND BACKFILL

## 14.1 OVERVIEW

The KBS-3 concept for the disposal of spent fuel implies that waste canisters will be surrounded by dense bentonite clay, see Figure 14-1. The tunnels will be backfilled with bentonite based mixtures compacted on-site. The canister envelopes will consist of close-fitting blocks of precompacted bentonite powder. After insertion in the deposition holes the blocks will absorb water from the rock, swell and fill the initial gaps between the canisters and the confining rock. Thereby the buffer mass becomes homogeneous and almost impermeable for long time, see Figure 14-1.

An alternative concept is the WP-Cave, see Chapter 11, where the isolating clay barrier may be bentonite based mixtures composed of similar material as for the tunnels in the KBS-3 concept and compacted on-site.

In the SFR, see Chapter 5, the silo envelope in the slot between rock and the concrete wall is deposited as an air dry bentonite powder in rather loose fill. After water saturation the density will be in the interval 1,6 to 1,8 t/m$^3$.

During 1986 some smectite-rich materials were tested for these applications with regards to the rheology and other properties of importance for the performance.

The physico/chemical interaction between the crystal lattice of smectite and water molecules in the buffer mass was studied and tested with regard to the

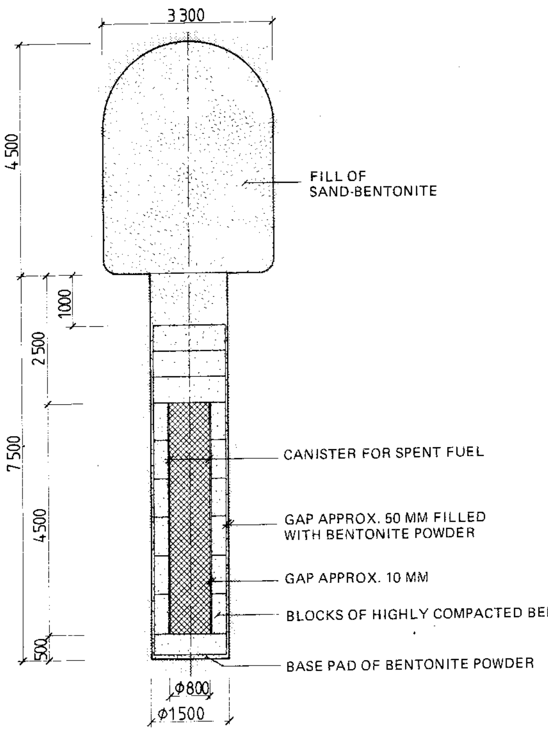



*Figure 14-1. Deposition hole with canister and buffer material and with backfill in storage tunnel.*

physical state of adsorbed water, see Section 14.2.

The rheology of the system water/smectite mineral is the basis for the analysis of the stress/deformation with time during the canister settlement and the interaction between canister, buffer and rock in the case when rock deformations induce shear as well. The settlement of canisters and the shear effects on canisters in dense smectite clay envelopes in deposition holes were tested during 1986, see Section 14.3 and 14.4. French smectite rich clays are evaluated in tests going on in the Stripa mine and in laboratories in a research program in cooperation with CEA, France.

A survey of candidate buffer materials in Sweden has been performed. Possible alteration of the isolating properties of smectite clay in the repository environment can be elucidated by natural analogues and by laboratory testing. One process is pressure dependent dissolution of minerals in quartz-type buffer materials, see Section 14.5.

The borehole, shaft and tunnel sealing test in the Stripa mine has been finalized and the sealing techniques have been fully confirmed regarding the use of dense smectite clay, see Chapter 19. The sealing of fractured rock is one task in the running study within the Stripa Project phase 3 see Chapter 19.

## 14.2 PHYSICAL STATE OF SMECTITE-ADSORBED WATER

Montmorillonite crystals are known to interact strongly with the first few hydrate layers. Since the specific surface area is very large, i e 600-800 m$^2$/g in the sodium state, a major part of the water in dense montmorillonite clay is assumed to be in a physical state that is different from that of free water. Several attempts have been made to determine the pore water density, and the values reported in the literature cover a wide range. It is essential to consider the spatial arrangement of the montmorillonite flakes since it determines the relative amount of internal and external water i.e. interlaminar water in a few molecule layers on the crystal surfaces and external water in larger pores.

A new technique was used in an experimental study with a pycnometer, see Figure 14-2, which was placed in a constant temperature water bath. The motion of the meniscus in the capillary was recorded as a compacted water saturated block of bentonite was allowed to equilibrate with surrounding water. The microstructural arrangement of the thin crystal flakes is concluded to be of great importance in the evaluation of the physical state of the porewater. In dense water-saturated clay samples a significant part of the

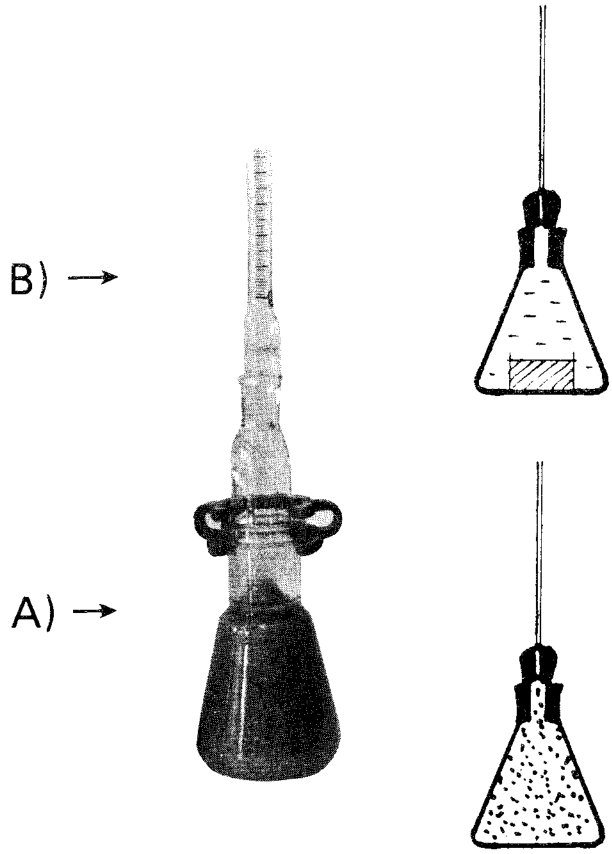



*Figure 14-2. The pycnometer/capillary device.*
*A) 60 cm³ pycnometer with expanded clay gel,*
*B) Capillary 2.2 mm inner diameter.*
*Upper right: Dense clay sample submerged*
*Lower right: Appearance after complete dispersion*

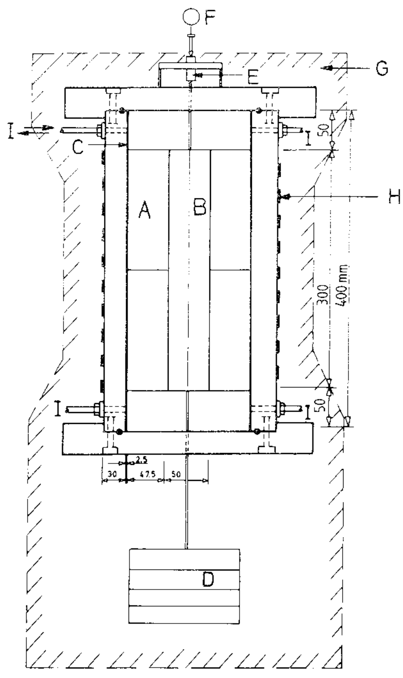



*Figure 14-3. Test device for canister settlement*
*A) Bentonite blocks,*
*B) Copper canister,*
*C) 2.5 mm filter,*
*D) 80 kg dead weight of lead,*
*E) Inductive strain gauge,*
*F) Mechanical dial gauge,*
*G) Heat insulation,*
*H) Heat coil,*
*I) Drainage tubings.*

porewater has a higher, elastic compressibility than that of free water. The tentative water structure model implies that there is a threshold shear stress that must be exceeded before significant permanent strain is developed, see Technical report 86-25 /14-1/.

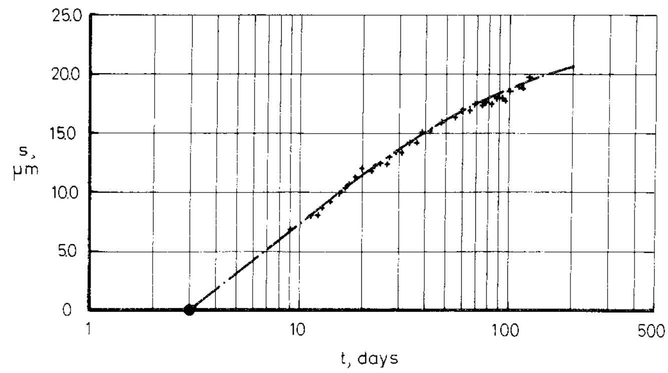



*Figure 14-4. Recorded settlement of the model canister in the second heating period (T=70°C). The plottings cover the postconsolidation stage.*

## 14.3 SETTLEMENT OF CANISTERS

A study of the long-term settlement of a model canister surrounded by water saturated Na-bentonite was conducted with a device shown in Figure 14-3 at room temperature and in steps up to 70°C, see Figures 14-4. The initial settlement rate appears to be in agreement with a settlement that is changing logarithmically with time. Some deviation from this turned up in the second heating period. This can possibly be explained by the fact that the shear stresses in the model canister test were low, see Technical report 86-23 /14-2/.

A similar test with a larger canister in a simulated deposition hole in the rock is presently prepared in the Stripa mine.

## 14.4 MODEL SHEAR TEST OF CANISTERS WITH SMECTITE CLAY ENVELOPES

Small or large rock movements caused by the thermomechanic behaviour or tectonics may induce strain and stresses in a canister with in a buffer, see Figure 14-5.

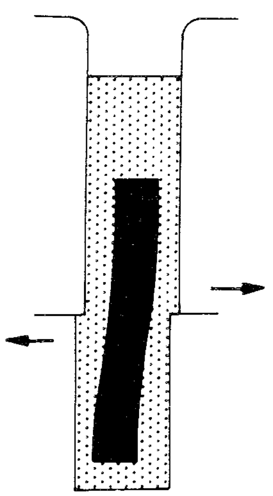


*Figure 14-5. Rock displacements generating strains and stresses in the canister.*

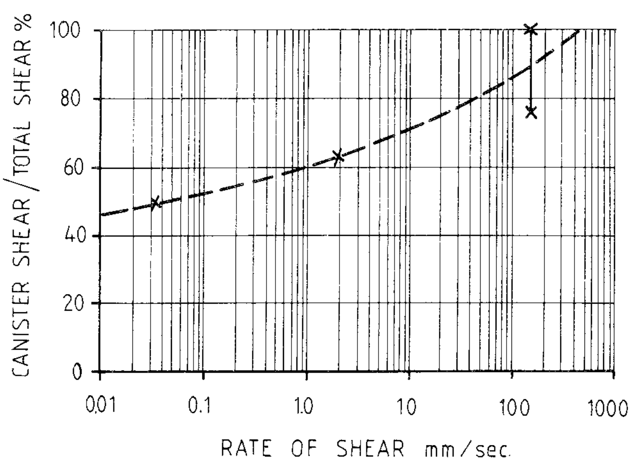



*Figure 14-7. The ratio of the canister shear deformation to the total shear deformation as a function of the rate of shear.*

Model shear tests can be used for validation of theoretical modelling. Three tests were performed with dense, water saturated sodium bentonite in a special apparatus, see Figure 14-6. The displacement of the bentonite was measured after shear test and the deformations of the canisters as well. The viscous behaviour of the system is evident in the deformations, see Figure 14-7 and Technical report 86-26 /14-3/.

Data from the model tests, running laboratory measurements of the rheology properties and future FEM-calculations will be used in the development and validation process for suitable theoretical models.

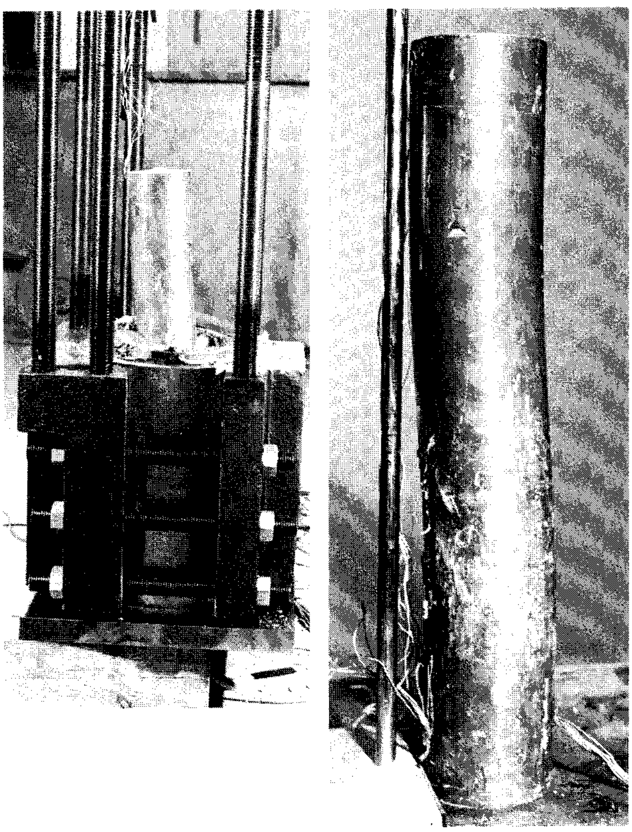


*Figure 14-6. The canister during excavation (left photo). The tilting of the canister can clearly be seen. The right photo shows the deformed canister.*

## 14.5 CLAY CHARACTERIZATION AND POSSIBLE ALTERATION PHENOMENA

Quantitative clay mineral analysis and other characterization of the clay minerals are needed for correlations of the material characteristics with properties of importance for the buffer and backfilling performance. Nature may show how physical, chemical conditions interact with the clay minerals. A survey of Swedish buffer material candidates, testings of methods of clay mineral quantification and investigations of possible alterations of minerals and isolating properties are under way and in the final reporting phase. Two samples, pure quartz sand and a sand-bentonite (10% bentonite) mixture were tested under high pressure (20 MPa) and temperature (115°C) over a period of 70 days without evidence for a pressure-caused dissolution of the silica, see Technical report 86-28 /14-4/.

# 15 GEOSCIENCE

## 15.1 OVERVIEW

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

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 such areas as:

- the planned underground research laboratory,
- the fractures zone studies at Finnsjön and Ävrö,
- the study on postglacial movements at Lansjärv,
- the study-site investigations.

Developments of methods and instruments is largely a step-by-step procedure. The Finnsjön study-site is used for pilot testing of geological, geophysical, geohydrological and geochemical methods and instruments.

Modelling forms a part of the projects. SKB participates in the international HYDROCOIN-project aiming at verification of geohydrological computer codes,validation of models and sensitivity and uncertainty analyses. The present work on the fracture zone studies at Finnsjön is devoted to in-situ tracer tests. The objective is to make an in-situ tracer test and perform predictive modelling before the actual experiment is executed.

The project on Bedrock stability has started with a study on the postglacial movements at Lansjärv. These movements are supposed to have taken place during or after the last deglaciation 8000 – 9000 years ago. The gross part of field measurements performed at the Klipperås study-site have been presented during the year. The results well agree with what can be expected in granitic rock. Modelling and evaluation is under way.

## 15.2 UNDERGROUND RESEARCH LABORATORY

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 analysis.

Much work will be devoted to establish an investigation technique and strategy for detailed characterization of geology, groundwater flow and chemistry. The validity of the adopted methodology will be assessed during the construction of the laboratory and is in essence intended to be applied when detailed investigations of two sites starts about 1993. If conditions prove suitable, the site of the underground laboratory may be one of the sites chosen for detailed investigations.

The intention is to site it in an area that will provide access to fracture zones and different rocktypes, but also access to a geological setting that is comparable to possible future repository sites. This laboratory will replace the Stripa mine in the 1990-ies.

It is expected that the planned laboratory will be a vital part of the Swedish research programme for management of nuclear waste. The laboratory will in mid 1990's be used for studies of performance interaction between the repository's engineered and natural barriers. The site will also be used for demonstration of system, technology and quality assurance.

The work started during 1986. During the year low-altitude airborne geophysical measurements around the Simpevarp area in south-east Sweden was completed.

Roughly 800 km$^2$ was surveyed from a flight altitude 30 m. Grid density was 40x200 m.

The survey comprised measurements of magnetic and electric field and the gamma radiation. The electrical methods used was VLF (Very Large Frequency) in two directions and Slingram measurements. The gamma radiation instrument is calibrated against the naturally occurring isotopes of Potassium, Uranium, Thorium and Cesium-134/Cesium-137.

These results will be interpreted during 1987 and supplemented with surface geophysics. Mapping of geology is planned to start in the spring of 1987 so that a drilling program can be initiated during 1987.

Detailed outlines of the project is expected to be finalized during 1987.

## 15.3 FRACTURE ZONE STUDIES

Groundwater flow and transport of radionuclides in existing fracture zones are of high importance in a safety assessment. The fracture zone studies give particular attention to:

- Data of importance for retention of nuclides eg. flow rate and conductive fracture frequency.
- Reliability ot investigation methods.
- Influence of fracture zones on regional groundwater movements.

Studies have been undertaken at the Finnsjön study-site, at Ävrö close to the CLAB facility and in several tunnels and underground facilities.

During 1986 earlier work at the Finnsjön study-site has been reported in detail /15-2/.

A subhorizontal zone, depth 100-300 m, is found to have a dominating influence on the groundwater flow. The zone is about 70 m wide and with a minimum lateral extent of 500 m. The hydraulic conductivity of the zone is in the order of $10^{-6}$ to $10^{-5}$ m/s with several values higher than $10^{-4}$ m/s measured over 20 m sections. Supplementary conductivity measurements with 2 m section over zone have been completed during the year.

Saline water of about 5000 mg/l of chlorine is found below the zone. The marked interface between fresh and saline water indicates that the subhorizontal zone constitutes, at least in part, a hydraulic barrier against descending non-saline groundwater. The density variations due to variation of salinity, however, is complicating the evaluations of piezometric heads.

The earlier work has been extended during the year and to some parts been aimed at development and evaluation of new methodology.

An additional cored hole has been drilled and logged. Uranine was used as a tracer in the drilling fluid and it was possible to obtain quite a satisfactory break-through curve of this water at a percussion-drilled hole 440 m away. First arrival occurred after 37 days under a gradient of about 0.4 %. Pressure responses were obtained in the surrounding holes during drilling. Simple measures such as following the tracer-marked drilling fluid and measuring pressure responses during drilling seem to be efficient methods to establish the dip and strike of fracture zones and the hydraulic connectivity between the test holes.

New methodology for groundwater chemistry has been tested. A large diameter percussion hole, diameter 165 mm, was drilled to a depth of 460 m through the zone. The objective was to obtain groundwater samples that have not been contaminated by drilling fluid. Samples were collected on several depths and analysed. The preliminary evaluation show that many components can be sampled under more undisturbed conditions than before. The percussion technique however unfortunately causes oxidation of the groundwater close to the hole which is a clear disadvantage when sampling components sensitive to the redoxpotential. Analysis of drilling debris show that a big part of the debris is left in the hole.

It has been considered appropriate to extend the fracture zone study further. A fracture zone earlier detected in the site investigation program at Ävrö, close to the CLAB-facility, was chosen for a detailed investigation. The procedures developed at Finnsjön have been adopted and proved to be satisfactory. The geometrical extension of the zone and its conductivity has been evaluated. The aim is to integrate the characterization with the investigations for the underground research laboratory.

Certain studies have been made of fracture zones in tunnels and underground facilities in Sweden, both existing /15-3/ and those under construction. A very detailed mapping of inflow of water to a fullface bored tunnel was completed. About 4 km of the tunnel was mapped. Evaluation will enhance the development of conceptual models for groundwater flow.

## 15.4 DEVELOPMENT OF METHODS AND INSTRUMENTS

The state-of-the-art of the Swedish geochemical and geophysical instrument equipments used in the SKB research programme has been summarized in a SKB Technical Report /15-4/.

Developments in methods and instruments during the year can be summarized as:

**Hydraulic testing**

A technical report dealing with methods for hydraulic testing in crystalline rock has been compiled /15-5/. A total of eight single hole methods have been tested in field. A comprehensive evaluation of the methods applicability in crystalline rock has been conducted. The injection test method under a constant head, followed by a fall-off period, was selected as a standard method for site investigations.

A joint project between Office of Waste Technology Development, USDoE and SKB on well test statistics proceeds. The objective is to provide guidelines for well-test programs. Data from the Swedish study--sites are used in the evaluation efforts.

**Improvement of hydraulic testing equipment**

The umbilical hose equipment for hydraulic injection tests in boreholes down to 1000 m depth has been improved regarding the data acquisition system /15-4/. A microprocessor has been mounted in the downhole probe, to allow digital signal communication for data collection and test valve operation. In order to present the measured data in graphs for the different evaluations techniques earlier described a new plotting program has been developed.

**Dilution probe**

The dilution probe has been used in a number of measurements for calculation of natural groundwater flow. The lower measuring limit in fractured crystalline rock is in the order of $10^{-11}$ m/s. In a formation with the hydraulic conductivity of $10^{-8}$ m/s and a gradient of 0,01% the required test period is 30-50 days. Lower groundwater flow will increase the measuring period. The equipment is so far working in 110 mm boreholes.

**Borehole radar**

Radar measurements has been conducted as a part of several projects. At the Klipperås study-site a total of 7850 m of single hole radar measurements were performed. The method has also been used in the fracture zone projects at Finnsjön and Ävrö.

A specially designed test of the radar method has been initiated. In two cored holes drilled as two sides of a regular triangle single hole reflection as well as cross-hole measurements has been performed. A prediction model will be presented without knowledge from any other data. The model will be supplemented with results from logging of cores, geophysics and hydraulics. The predictions will later be controlled against mappings from a fullface bored tunnel that is under construction.

About 70 m of the tunnel will be thoroughly analysed.

The radar is under continuous development. In addition to the normal 22 MHz frequency an 60 MHz antenna has been developed to give a better resolution close to the borehole wall. The equipment has also been improved regarding signal transmission with optical cables and interpretation techniques. The development of directional antennas which may determine the direction to the reflection plane has been initiated and will continue in the Stripa Project, phase 3.

**Tube wave**

The tube wave method has been tested in the fracture zone project in Finnsjön. The measurements are conducted similar to a VSP (Vertical Seismic Profile) measurement with hydrophones lowered into the borehole to measure the response of a detonation at the surface. When the seismic P-wave reach an open fracture penetrated by a borehole, the compression will generate a tubewave. The tube wave propagates along the borehole wall and analysis of the hydrophone response provide an estimate of the location of water-bearing fractures. The method is supposed to be effective for the detection of fracture zones and further evaluation and comparison with detailed tests will show the sensitively to smaller fractures.

**Water and gas sampling**

A second field laboratory for analysis of ground water is under construction.

The construction of a gas sampling system has been finished /15-4/. The specially designed water sampler is collecting the water at the test section. The pressurized groundwater including all dissolved gases is confined in the sampling cylinder and transported to the gas laboratory where a quantitative analysis of a number of gases is made.

## 15.5 DEVELOPMENTS IN COMPUTER MODELLING

SKB participate in the international HYDROCOIN-project with the GWHRT-HYPAC-model, /15-6, 15-7/. The work on Level 1, code verification and Level 2, validation is completed and final reporting is under way. The performance of the code was convincing. One verification case has been reported, /15-8/. Resent work in the HYDROCOIN-project is directed to Level 3, sensitivity and uncertainty analyses. The study-site Fjällveden is one of the cases chosen for such analyses. Within this context adjoint sensitivity analysis is implemented in the GWHRT-code.

Transient, unsaturated 3D flow has been implemented as well. The code will be applied to model the draw-down that occurred during construction of the Underground Research Laboratory in Canada, /15-9/.

A study of the confidence in solutions of flow through stochastically generated hard rock formations has been attempted. The conclusions of the study is that stochastically generated formation properties may lead to non-conservative results.

A major geohydrological work has been accomplished during construction of the SFR-facility, see Part 1, Chapter 5. Developments in modelling have been directed to gas migration studies.

## 15.6 BEDROCK STABILITY

The project on bedrock stability is continued with an in-depth study of the postglacial movements in Lansjärv.

Compilation of geology and geophysics within an area of 200x150 km is under way. The goal is a detailed planning of the field programme for 1987. Some supplementary ground geophysical measurements were completed in order to check the dip of some major faults around the Lansjärv area.

A preliminary structural analysis of the postglacial faults in northern Sweden /15-10/ has been presented. It is suggested that < 1 km thick thrust flakes extruded along the NNE trending fault by oblique transpression along pre-existing steep ESE dipping megashears. The postglacial kinematics inferred from the structures suggest a sudden relief during glacial unloading of plate tectonics forces from horizontal NW or WNW compression accumulated during glacial loading.

Crustal rock mechanics modelling will be used to assess the influence of ice loading and unloading and tectonic forces on a repository. This modelling forms a part of the Lansjärv study and will be an aid in interpreting tectonic movement in the area. The first phase of the modelling is code verification and necessary idealization of the problem to be studied. This idealization will be based on existing material on the geodynamics of the Baltic Shield.

The planning for seismic networks in northern and southeastern Sweden is completed. The networks will start running during 1987.

A mobile seismic network has been used for aftershock surveys of the $M_L$ = 4.1 earthquake close to Skövde in July 14 1986. Evaluation is initiated to interpret if any of the 9 aftershocks occurred close to the surface. Some effort has also been directed to follow the microseismic events due to hydraulic fracturing in a geothermal Hot Dry Rock project in Fjällbacka managed by Chalmers Institute of Technology.

## 15.7 STUDY-SITE INVESTIGATIONS

**Klipperås**

The investigations performed at the study-site Klipperås, located in the south-eastern part of Sweden, have been reported in a number of reports /15-11–15-16/. The radar measurements will be reported 1987.

The investigation area is about 5 km$^2$ and of very flat topography. The geological characterization of the rock volume is mainly based on surface geophysics and extensive borehole investigations due to the fact that very few outcrops exist. In total 14 deep cored boreholes, of which the deepest is 960 m, and 14 percussion boreholes have been drilled.

The dominating rock type is a grey-red medium grained and massive granite. Greenstone and porphyric dykes are normally oriented in E-W with vertical or subvertical dip. The youngest rock comprise mafic dykes in N or NE direction.

Within the area 13 fracture zones has been located. They are oriented in two main directions N and NE with vertical dip, some of them associated with dykes. One subhorizontal zone is detected at about 750 m depth. The radar interpretation is in agreement with earlier evaluations on the directions of the fracture zones, greenstones and mafic dykes.

Hydraulic testing and groundwater table monitoring has been conducted in 7 and 21 boreholes respectively. The hydraulic injection tests gave values of the hydraulic conductivity similar to other investigations on granitic rock. The mean value for the rock mass at 500 m depth is $4.10^{-10}$ m/s. The pressure variation over the area is very low (less than 5 m) reflecting the flat topography.

The chemical composition of the deep groundwater has been analyzed showing low redox potential and results similar to other areas. Fissure fillings from the core samples has also been analysed. Calcite dislocation and precipitation of Fe-oxhydroxide in the uppermost part of the bedrock and also in some fracture zone of greater depth is indicating oxidizing conditions which are diverging from the reducing conditions in the dominated parts.

**Gideå**

Determination of the rock stress has been conducted in a borehole at the Gideå study-site /15-17/. The hydraulic fracturing method was used in 25 successful tests down to depth of 500 m. The minimum horizontal stress increases close to the theoretical vertical stress, while the maximum horizontal stress is about a magnitude 1.6 greater. The direction of the maximum horizontal stress was determined to N 67°E.

Using data from earlier investigations at the study-site Gideå and supplementary fracture measurements, a brittle tectonic model has been constructed. Hydraulic test data were classified into the main tectonic elements. These are tension fractures in N-S and E-W and conjugate shear fractures surrounding "undisturbed" rock blocks. It is suggested that the mean conductivity of the E-W tension fractures, at depths greater than 200 m, is about 30-80 times greater than those of the undeformed parts of the tectonic blocks, the N-S tension fractures and the shear zones, /15-18/.

# 16 THE BIOSPHERE

## 16.1 BIOSPHERE CHARACTERIZATION AND NATURAL RADIOACTIVITY

During 1985 the geological study-site at Klipperås was characterized with regard to radioactive substances in shallow ground waters, soil and biota, SKB TR 85-09. In certain organic soils and peat samples fairly high levels of some radionuclides were observed. As the origin of these nuclides could not be clearly explained, new samples were taken and analysed during 1986.

The results from the analyses are presented and the possible mechanisms to build up the higher concentrations are discussed in SKB TR 86-24. The leaching of U and Th from the alluvial zone of a podsolic profile and the enrichment in a nearby peatlike horizon was demonstrated. In peatbogs the reason for the high levels of U, Th and $^{137}$Cs (bombtest fallout) are more complicated. The $^{228}$Ra/$^{232}$Th disequilibrium and the presence of $^{137}$Cs are strong indications of current or recent migration, and indirectly of groundwater flows in the bog. Part of the cesium seems to have entered the bog via groundwater from below, and part of it from the surface migrating downwards. A fractionation of $^{226}$Ra and $^{228}$Ra by the plant nutrient cycle was also observed.

## 16.2 NATURAL AGEING IN LAKE ECOSYSTEMS

A study on how the natural ageing processes in a lake will influence the transfer of various radionuclides through the lake ecosystem to man, was launched in 1984. During 1985 and 1986 the second phase of the project was carried out. This phase comprised the sampling of sediments, soil, water and biota and the determination of key parameters such as water balance, sedimentation rate and transport rate of dissolved constituents.

The only task remaining in this phase is the evaluation of radionuclide diffusion in sediments. About 40 sediment cores that were doped with radionuclides ($^{99}$Tc, $^{85}$Sr, $^{125}$I, $^{134}$Cs, $^{152}$Eu, $^{232}$Th and $^{241}$Am) were analysed in 1986 a year after repositioning in the original lake sediments. Afterwards they were again repositioned and will be taken up and analysed after the icecover of the lake has melted in spring 1987.

The results of phase two have been reported in SKB TR 86-29 and SKB TR 86-30. The results of the chemical analyses will be reported in 1987 as soon as the cores have been analysed.

A third phase started late in 1986 with the aim to model the longterm behaviour of radionuclides within a lake ecosystem. Here the results from phase two will be used.

## 16.3 THE CHERNOBYL FALLOUT

In April 25 the reactor accident in Chernobyl caused a substantial release of radionuclides into the atmosphere. Some of this deposited as fallout in Sweden. Since two of SKBs geological study-sites, Gideå and Finnsjön, were quite close to areas that got the greatest fallout, see Figure 16-1, a sampling programme was initiated.

An initial compilation of the results from the sampling during summer, autumn and winter 1986 is planned to be ready in the middle of 1987. The possibilities for using the material for validation of nuclide migration models in the biosphere or in the shallow groundwaters will be evaluated and form a basis for future efforts.

The national coordination of the Swedish work connected with the Chernobyl fallout is made by the Swedish National Institute for Radiation Protection.

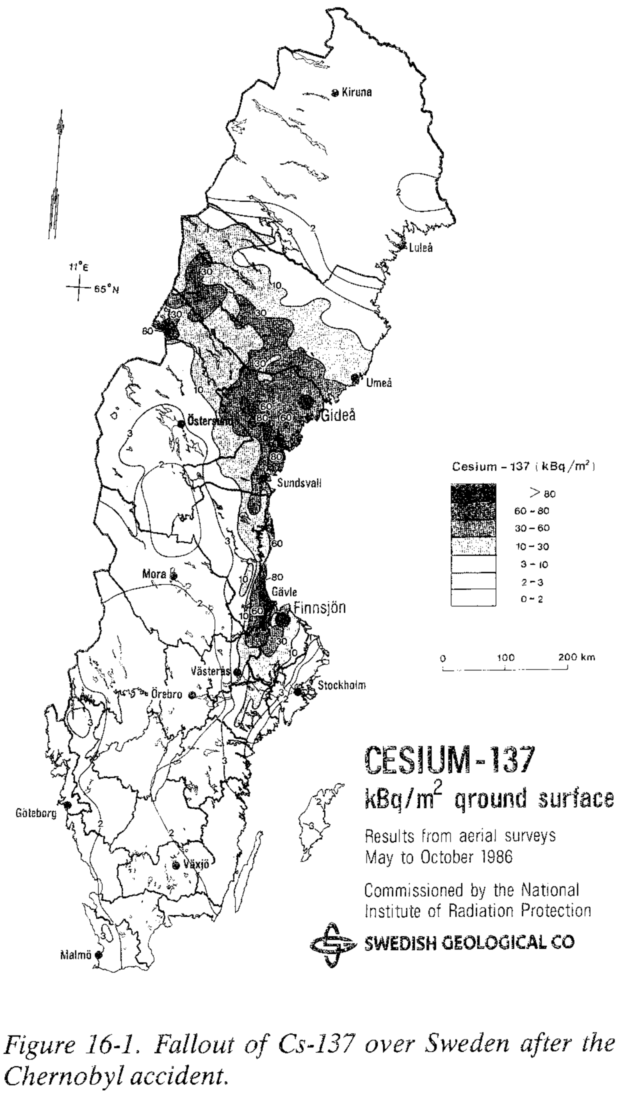



*Figure 16-1. Fallout of Cs-137 over Sweden after the Chernobyl accident.*

# 17 CHEMISTRY

The chemistry program 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.

## 17.1 GEOCHEMISTRY

### 17.1.1 Groundwater Analyses

The results of the analysis of groundwater samples from the study-site Klipperås have been compiled in the technical report SKB TR 86-17. The mobile field laboratory, taken into operation 1984, was used for the later part of those investigations. A total of seven levels in three core drilled holes were sampled. High quality samples of groundwater from between 400 to 700 m depths were obtained from the boreholes Kl 1 and Kl 9. The calculated "ages" for these samples from carbon-14 measurements are around 30 000 years. Though this value is not necessarily the correct mean transit time it does point towards very isolated conditions and excellent sample quality /17-1/.

During 1986 the mobile field laboratory, including the downhole sond for pH and Eh measurements, have been used in Finnsjön. In order to completely avoid the use of drilling water, which may be left and contaminate the water samples, a new technique was tested. A vertical hole was made by air percussion drilling and sampling was made between a sealed off section and the bottom of the hole during pauses in the drilling. Good quality groundwater samples have thereby been obtained from the upper 200 m which are otherwise difficult to sample due to the disturbance caused by the drilling water in rock of relatively high conductivity. The results are being evaluated. Gas sampling with evacuated sampling cylinders in the downhole sond was also tested.

Other groundwater analyses made with the mobile field laboratory are summarized in Table 17-1. It has been concluded from this table that four different categories of groundwater may be distinguished. They are characterized by their relative contents of the main components sodium, calcium, chloride and carbonate, see Figure 17-1. The mobile field laboratory was at the end of 1986 moved to Forsmark to be used for groundwater sampling and analyses in the underground facility SFR.

The groundwater analyses performed during the Swedish study-site investigations 1982 to 1983 have been evaluated by chemical equilibrium calculations

**Table 17-1. Chemical composition of groundwaters analysed with the mobile field laboratory. All concentrations are given in mg/l.**

| Bore-hole | Level m | $Na^+$ | $K^+$ | $Ca^{2+}$ | $Mg^{2+}$ | $HCO^-_3$ | $Cl^-$ | $F^-$ | $SO^{2-}_4$ | $HS^-$ | Fe tot | $Fe^{2+}$ | pH | Eh mV | Type |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Fj 2 | 468 | 36 | 1.4 | 27 | 3.0 | 182 | 3.7 | 0.6 | 2.0 | 0.2 | 0.65 | 0.65 | 6.9 | -220 | A |
| Fj 7 | 722 | 300 | 1.3 | 40 | 0.2 | 16 | 470 | 6.2 | 0.5 | 0.6 | 0.005 | 0.004 | 9.0 | -350 | C |
| Kl 1 | 406 | 45 | 1.0 | 14 | 2.3 | 78 | 45 | 3.8 | 1.8 | 0.1 | 0.013 | 0.012 | 8.2 | -305 | B |
| Kl 2 | 326 | 28 | 1.1 | 31 | 1.0 | 137 | 17 | 2.8 | 0.1 | 0.08 | 0.140 | 0.134 | 7.6 | -290 | B |
| | 741 | 38 | 1.6 | 16 | 2.0 | 99 | 23 | 4.4 | 0.1 | 0.24 | 0.045 | 0.039 | 8.2 | -340 | B |
| | 761 | 12 | 3.0 | 23 | 4.0 | 106 | 7 | 2.7 | 0.5 | 0.03 | 0.350 | 0.345 | 8.0 | -290 | A |
| | 860 | 65 | 1.6 | 8.3 | 1.8 | 102 | 51 | 5.3 | 1.5 | 0.12 | 0.043 | 0.041 | 8.1 | -300 | B |
| Kl 9 | 696 | 16 | 1.3 | 29 | 3.0 | 120 | 6 | 3.0 | 4.4 | 0.02 | 0.096 | 0.094 | 7.6 | -275 | A |
| Fi 9 | 94 | 410 | 6.2 | 101 | 16 | 286 | 670 | 3.0 | 100 | 0.22 | 0.590 | 0.580 | 7.5 | -245 | D |
| | 182 | 1050 | 17 | 708 | 78 | 150 | 2900 | 10 | 220 | 0.24 | 0.915 | 0.915 | 7.3 | -220 | D |
| | 360 | 1600 | 8 | 1900 | 110 | 33 | 5200 | 7.4 | 300 | 0.01 | 0.310 | 0.310 | 7.7 | ---- | D |

Fj = Fjällveden   Kl = Klipperås   Fi = Finnsjön

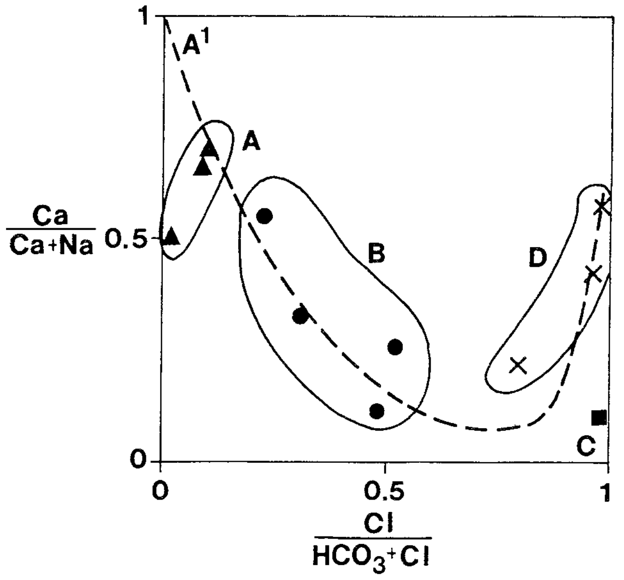



*Figure 17-1. Relative abundance of major ions in groundwater. Four types of waters may be distinguished. See also Table 17-1.*

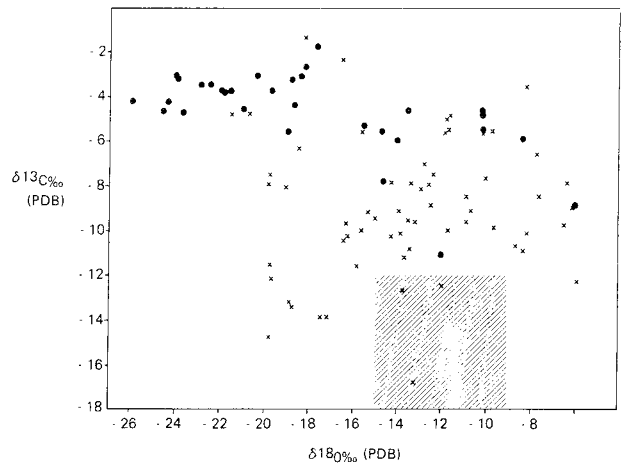



*Figure 17-2. $\delta^{13}$ versus $\delta^{18}$ for calcite samples from basite (0) and granite (X). Striped area describes the isotope interval of calcite precipitated at present temperatures from meteoric groundwaters.*

using the geochemical computer codes WATEQ3 and EQ 3NR (SKB TR 86-03). This evaluation was concentrated to the redox active species and it was concluded that not only iron compounds are of importance for the reducing character of groundwater but also dissolved sulphide and dissolved organic carbon.

### 17.1.2 Fracture Minerals and Isotopes

The fissure fillings from the Klipperås study-site have been analyzed and characterized (SKB TR 86-10). A large number of drillcores were studied. The frequencies of fracture filling calcite and iron(III)-oxhydroxide-minerals as a function of depth show that calcite have a tendency to be dissolved and iron(II)minerals to become oxidized in the upper part of the rock – roughly the upper 100 m. Signs of these changes are also found at greater depths, in fracture zones. It may be concluded that the upper 100 m is chemically a much more dynamic region as compared to deeper levels. This is due to constant fresh supply of chemically aggressive substances such as carbon dioxide from the soil and oxygen from the air. It is also due to the much higher water flow rates in this upper part of the rock. Deeper penetrations in conductive vertical fractured zones is not unreasonable or unexpected.

Active circulation of groundwater should be expected to influence the isotopic composition of fracture filling calcites in open water-conducting fractures. This is indeed indicated by a comparison between analyses of carbon-13 and oxygen-18 in fracture filling calcites in granitic and gabbroic rock, see Figure 17-2. The basic rock has preserved the hydrothermal isotopic fingerprint to a larger extent than fissures within the granitic rock. Calcite in open fissures in granitic rock has changed towards a calcite similar to one that is precipitated from a groundwater composition of today. This is probably a result of higher hydraulic conductivity in granitic rock as compared to basic rock (SKB TR 86-10).

The accelerator-masspectrometer has made it possible to analyse small samples of calcites for carbon-14. This has recently been tested on three samples from a drillcore from Taavinunnanen and one sample from a drillcore from Klipperås /17-2/, see Table 17-2.

There is a marked correlation with depth in the Taavinunnanen results and the high values in Klipperås are in accordance with independent observations of hydraulic activity there. Admittedly, these are still few examples but even so they promise a new methodology to trace water flow paths in fractured crystalline rock with calcite present as fracture mineral. The distribution of flow is vital for the safety assessment of radioactive waste disposal.

**Table 17-2. Carbon-14 in samples and fracture filling calcite.**

| Area | Depth m | $^{14}C$ pmC |
|---|---|---|
| Taavinunnanen | 92.2 | 8.9 |
| " | 191.5 - 192.0 | 1.2 |
| " | 385.7 | 0.8 |
| Klipperås | 125.1 | 73.5 |

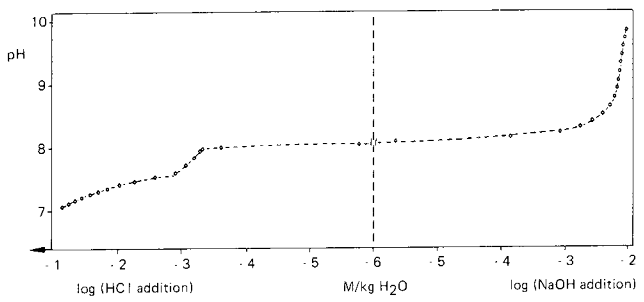



*Figure 17-3. Calculated titration curve of the bentonite Stripa water system by NaOH or HCl at 25°C. The concentration of bentonite is 10 moles per kg water.*

### 17.1.3 Near-field Conditions

Geochemical models have been used to simulate possible chemical interactions in the near field. Calculations have during 1986 been performed on the effects of strong acid or base on bentonite, see Figure 17-3, and on the possibility of reactions between copper and bentonite. This work is being conducted by specialists at the University of Strasbourg. The geochemical code DISSOL was used to simulate the titration of bentonite at 25°C. A fictitiously heating to 100°C was accomplished by the code THERMAL /17-3/.

## 17.2 RADIONUCLIDE CHEMISTRY

### 17.2.1 Solubility and Speciation

Thermodynamic constants for solubility, inorganic complex formation and redox properties of actinides in groundwater containing dissolved carbonates are being measured. Work has been concentrated to uranium and thorium /17-4 and 17-5/.

Investigations of co-precipitation of lanthanides and actinides with uranium are being continued. Simulated groundwater conditions are used for validation experiments, see Section 17.4.2.

Thermodynamic constants for uranium determined within this program have been introduced into the OECD/NEA chemical data base for important radionuclides and minerals. The work on uranium is well advanced.

The geochemical code EQ 3/6 is implemented on the SKB VAX Computer and the database is being updated.

Carbonate complexes for neptunium and plutonium have been investigated in cooperation with the French organization CEA /17-6 and 17-7/.

### 17.2.2 Colloides, Organic Complexes and Microbes

Radiocolloides in the form of pseudocolloides i.e. radionuclides absorbed on inactive particles such as clay and quartz particles have been identified as important for the safety of radioactive waste disposal (see KBS-3). A report on the transport properties of americium-pseudocolloides have been finished (SKB TR 86-02). In column experiments the major part of americium sorbed on colloidal matter is retained. Only a minor fraction was found to be mobile, especially at high flow rates.

Groundwater samples have been taken and analysed for content of inorganic colloidal particles. The results are being evaluated.

Humic and fulvic acids are being collected from deep groundwaters. A working group has been formed at the University of Linköping. Samples of organic material from groundwater are being analysed there. The Humic and fulvic acids are isolated and purified for complexation experiments, see Figure 17-4. Such experiments have been conducted in cooperation between this group and the French organization CEA /17-8/.

The interaction of iron and calcium ions with fulvic acids have been investigated at the University of New York in Buffalo and reported /17-9/.

Microbes in the geosphere are being analysed as a part of the Poços de Caldas project, see also Chapter 21.

### 17.2.3 Sorption and Diffusion

Experiments with diffusion of radionuclides into rock samples have been continued. The elements used are strontium, iodine, technetium, americium, neptunium and plutonium. The granite samples were taken from Finnsjön, Stripa and Studsvik. Notable is an observed relatively slow diffusion of anions like iodine and pertechnetate - comparable to strontium diffusion - and a fast diffusion of cesium.

Diffusion of the fission products strontium, technetium, iodine and cesium and the actinides thorium,

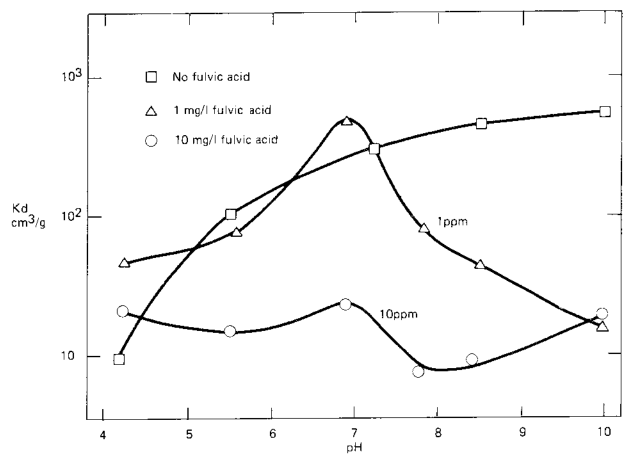



*Figure 17-4. The influence of fulvic acids from 500 m depth from study-site Fjällveden on the sorption of americium on aluminium oxide as a function of pH. The ionic strength is held at I = 0.01 with sodium per chlorate.*

protactinium, uranium, plutonium and americium in compacted bentonite have been studied and reported (SKB TR 86-14). The effect of speciation have been observed in these experiments i.e. technetium diffuses one order of magnitude slower under reducing conditions and small relatively mobile fractions of uranium, neptunium and plutonium were observed, see Table 17-3.

Experiments on the possibility of using complexation theory to explain the sorption and diffusion of radionuclides on minerals have been initiated.

**Table 17-3. Diffusivities of fission elements and actinides in bentonite clay. More than one diffusing fraction is observed for uranium, neptunium and plutonium.**

| Element | Dá m²/s | Dá m²/s |
|---|---|---|
| Cs | 2.4 $10^{-12}$ | - |
| Sr | 2.0 $10^{-11}$ | - |
| I | 1.2 to 2.6 $10^{-12}$ | - |
| Tc ox | 1.2 $10^{-12}$ | - |
| Tc red | 8.4 $10^{-14}$ | - |
| Th | ≤ 7.7 $10^{-15}$ | - |
| Pa | 6.2 $10^{-13}$ | - |
| U | 6.4 $0^{-13}$ | 3.4 $10^{-12}$ |
| Np | 3.7 $10^{-13}$ | 1.2 $10^{-11}$ |
| Pu | ≤ 1.9 $10^{-15}$ | 3.2 $10^{-12}$ |
| Am | 1.3 $10^{-14}$ | - |

### 17.2.4 Radiolysis

The production of hydrogen in alfa-irradiated compacted water saturated bentonite clay has been determined experimentally and compared with the theoretical calculations using a homogeneous reaction model for the radiolysis. A fair agreement was obtained (SKB TR 86-04). Experiments with uranium is reported in Chapter 12.

### 17.2.5 Concrete

Radionuclide chemistry in concrete and the consequences on nearfield 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. A continued and increasing general interest in this area is foreseen.

## 17.3 CHEMICAL TRANSPORT

There are indications from recent field investigations and laboratory experiments that flow in fractured crystalline rock may at least partly occur in channels. A

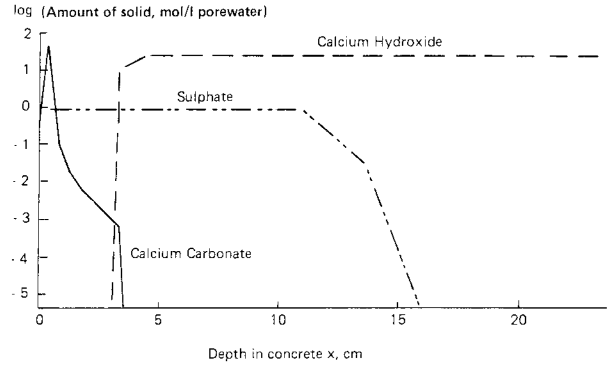



*Figure 17-5. Calculated depletion/penetration profiles in concrete after 100 years of contact with bentonite. The computations are done with the CHEMTRN code on a CRAY-1 computer.*

theoretical treatment of radionuclide transport restricted to channels - including sorption and diffusion into the open micropore system to the rock - has been reported (SKB TR 86-13).

Transport modelling has been temporarily concentrated to the safety assessment of the SFR-facility and the WP-cave concept. Notable is the modelling of potential gas transport in SFR and the chemical interaction bentonite-concrete. The last has been achieved with coupled models geochemistry-transport. The computer code CHEMTRN, developed at Lawrence Berkeley Laboratories in USA have been used for this purpose. Simpler models have also been tested. An example of the results of such a computation is given in Figure 17-5.

## 17.4 VALIDATION OF TRANSPORT MODELS

### 17.4.1 Laboratory Experiments

Open fractures in granitic rock have been identified, overcored by drilling and brought into the laboratory. The direction of the drilling is chosen so that the fracture runs parallel with the core axis. These isolated fractures are then used for laboratory experiments of water flow and radionuclide transport. Tests have been made to vary the external pressure on the stone and to simulate natural reducing groundwater conditions. The flow tests are carried out in cooperation with specialists at Lawrence Berkeley Laboratories, USA.

Natural reducing conditions have been successfully simulated in a closed laboratory system with groundwater and pieces of granitic rock. This set-up is being used for the validation of uranium reduction and coprecipitation in the near-field.

### 17.4.2 In-situ Tests

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

A small scale migration experiment is also being 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 of this test has been reported (SKB TR 85-12) and a second phase using macromolecular tracers has been initiated. This experiment is entirely sponsored by SKB.

Another series of SKB sponsored in-situ experiments in Stripa was started in 1982. The aim was to validate the existence of an inter connected micropore system in an undisturbed rock mass. All of these experiments have now been finished. Two tests have been reported (KBS TR 82-08 and 83-39). The last test which went on for about 3,5 years is being evaluated by laboratory analyses of drilled out rock samples. Penetrations of tracers 30 - 40 cm into the seemingly intact rock has been observed.

# 18 SAFETY ASSESSMENT

## 18.1 GENERAL

The future role of performance evaluations and safety assessments in the development of a repository for spent nuclear fuel in Sweden has been discussed in Chapter 6 of the R&D programme 1986 /18-1/. During the next few years the main objective will be to use the assessment methodology to evaluate available alternatives for repository or barrier design. The technical feasibility, the potential safety effect, the uncertainties in the performance predictions and the economic characteristics of the alternatives must be assessed in a way that will permit comparison between options for both site and repository system.

In order to facilitate this a special group was formed late in 1986. It is called SFG (the integrated performance group) and has the following tasks:

- Establish a basis for comparison of various alternatives with regard to scenario selection, data quality, assessment methodology, conservatism and quality assurance.
- Follow ongoing studies of alternatives and give advice on parameter spans of interest, need for details, need for quality assurance etc. that is caused by the requirement that investigated component or designs have to be able to function in the boundary requirements given by Swedish geology and possible total repository concepts that might be available.
- Compare the various alternatives for design or safety barriers as a basis for culling and priorities in the alternative studies and in the R&D effort.
- Review the status of knowledge in areas critical for repository safety and suggest complementary actions or change in priorities in the R&D effort.

A main ambition in the comparison of the alternatives will be to base the evaluations on probable scenarios and as realistic data as possible. At present the SFG has mainly been interacting with the WP-cave studies, see Chapter 11. Future priority areas are an assessment of the safety of the KBS-3 concept based on expected or most probable performance, and an evaluation of the feasibility and safety potential of a very deep drillhole disposal concept.

The development of models and appropriate data bases for the performance and safety evaluations is made mainly by those working within the research areas and is discussed in the corresponding chapters. As a tool complementing the deterministic models a probabilistic assessment model called PROPER is under development. Progress under 1986 is reported below.

## 18.2 PROBABILISTIC SYSTEMS ANALYSIS

The purpose of PROPER is to provide a tool for assessing uncertainties in the results of performance assessments by propagation of input parameter uncertainties. The numerical method used for that is Monte Carlo simulation, see Figure 18-1. Spinoffs from the methodology include provisions for making sensitivity analyses and linking assessment models selected from a library, see Figure 18-2.

Besides the library of submodels, PROPER contains a monitor/driver and a postprocessor for statistical evaluation of the results, see Figure 18-3.

The efforts made during 1986 has included the submodels as well as the monitor and the postprocessor. The status of the prototype submodel library at the end of the year is shown in Table 18-1. All of them are at a preliminary stage. The hydrology model FSCF is undergoing modifications and has not actually been tested within the system.

**Tabel 18-1. Prototype submodels in the PROPER library**

| | |
|---|---|
| BIO40 | Biosphere: revised factors from KBS-3 calc. (Ref KBS TR 86-15) |
| FAR30 | Far field transport incl. matrix diff. (no chain dec.) |
| [FSCF10 | Hydrology: 2 - D & axisymm.] 3 - D FEM) |
| HYDR81 | simulates FSCF10. |
| NEAR20 | Near field transport, stat. diff. to cracks with water flow (through clay), canister corrosion. Single canister, single nucl. |

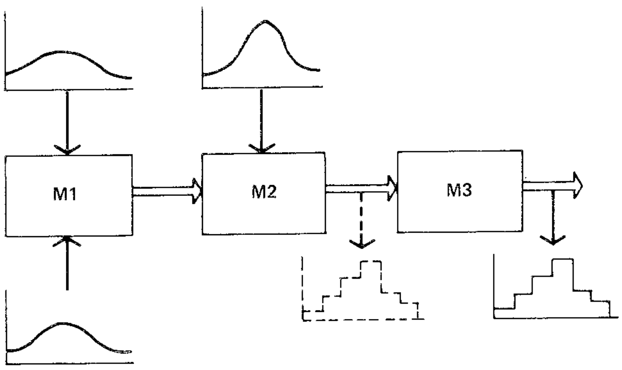



*Figure 18-1. Working procedure of the PROPER code. The inputs to a number of submodels linked together (here: M1, M2 & M3) are randomly sampled from distributions. Time series are passed between submodels. Output statistics can be obtained as histograms, etc.*

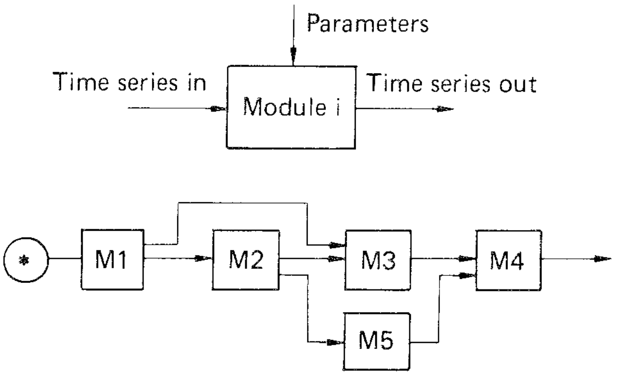



*Figure 18-2. Submodel linkage and communication in PROPER.*

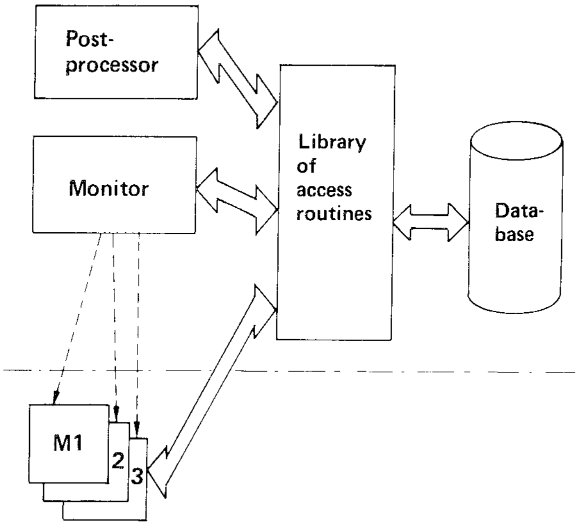



*Figure 18-3. PROPER structure. The monitor drives the computations carried out by the submodels. Results are evaluated using the postprocessor.*

SKB participates in the NEA Probabilistic Systems Assessment Code User Group. In 1986, a benchmark study was carried out involving, besides SKB, AECL and NUTP in Canada, CSK in Belgium, JRC/Ispra, TVO in Finland, UKDOE, AERE and NRPB in the UK, and BWIP in the US. The purpose was to put the monitors/drivers of the participants' codes to a test. Figures 18-4 and 18-5 show typical results from that study and specimens of the type of output that can be provided by PROPER.

Further efforts during 1986 has involved development of numerical routines for use in PROPER and testing of the sampling routines, among others. Emphasis has also been placed on the development of the PROPER documentation.

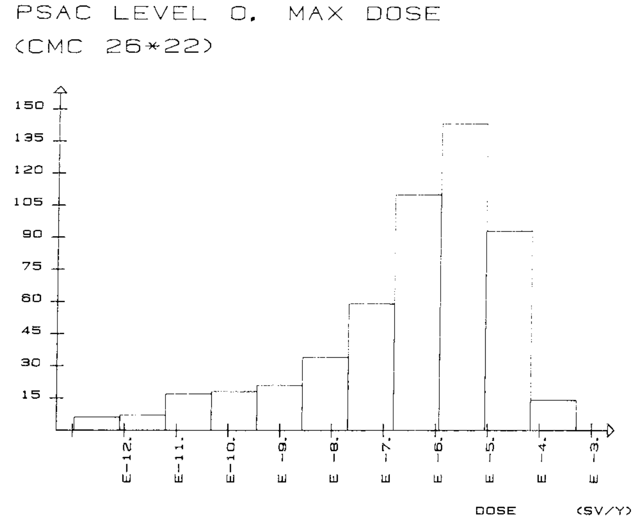



*Figure 18-4. Output histogram from the PSAC User Group Level 0 Benchmark Study.*

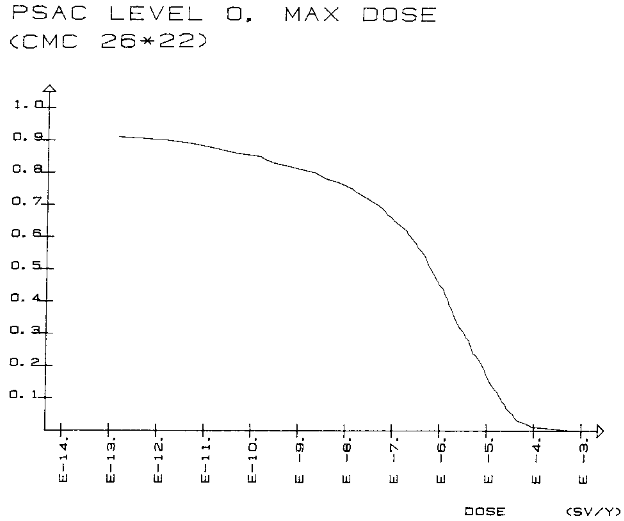



*Figure 18-5. Complementary cumulative distribution from the PSAC User Group Level 0 Benchmark Study.*

# 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 /19-1/.

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 1980-85, followed by Phase 2, which commenced in 1983 and will be concluded in 1987. The results of the Stripa Programme are being published in a Stripa series of Technical Reports. The Annual Report of 1985 /19-2/ include a complete listing of the Stripa Technical Reports.

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) have confirmed their participation in Phase 3.

## 19.2 THE PROGRAM FOR 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 be included. An undisturbed granitic rock volume (approx 125 m x 125 m x 50 m) will be investigated and Figure 19-1 gives a schematic illustration of the test area. For this rock volume a mathematical model for groundwater flow will be developed and later be compared with values measured in the field.

Previously obtained results show that models which 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 investigations at Stripa have shown that neither is it realistic to describe a fracture as an aperture of constant width between two plane-parallel surfaces. Instead, it appears

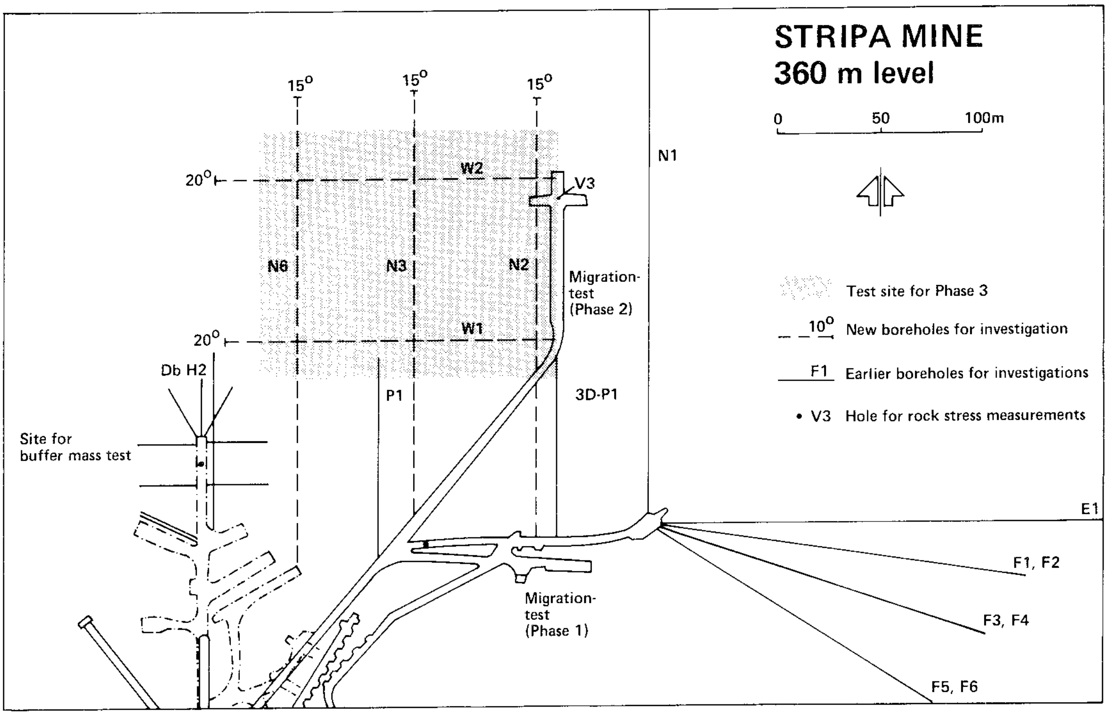



*Figure 19-1. Schematic illustration showing the test site for the investigations of Phase 3.*

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. 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.

Furthermore, 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 also during Phase 3. The work pertains to a high -resolution and direction-sensing borehole radar and to an improved technology for high-resolution seismics in boreholes.

A new research field in Phase 3 is techniques 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 sealing materials to limit or prevent the migration of radionuclides from the repository. Phase 3 includes an extensive research effort in this area. Among other things, the properties of different materials for injection grouting of rock will be studied. A large-scale grouting test has been discussed. Of particular importance is long-term stability in the expected environment around a final repository.

Results of Phase 3 work will be reported in the Stripa report series.

## 19.3 RESULTS OF PHASE 2

Research has been conducted within the following four main areas:

- Geohydrological investigations of the Stripa granite and migration tests with nuclides in simple and complex fracture systems,
- Chemical investigations of the groundwater in the Stripa granite,
- Technique for detecting and characterizing fracture systems in granite,
- Study of bentonite clay for use as a backfilling and sealing material in a fractured bedrock.

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

Some initial conclusions from the work within Phase 2 and findings made during 1986 are presented below.

### 19.3.1 Crosshole Techniques for the Detection and Characterization of Fracture Zones

The purpose of this investigation is to develop crosshole electromagnetic (radar), seismic, and hydraulic methods for bedrock investigation which may determine the location, extent, thickness and physical properties of fracture zones. For each of these methods new equipment has been developed, field tests have been performed, interpretation techniques have been developed and tested on the obtained data. Most of the field tests have been performed at a specially prepared test site in the Stripa Mine named the Crosshole Site.

The field work and the associated data collection to be performed within this investigation program was completed early 1986. The efforts during 1986 have concentrated on the analysis and reporting of the obtained results.

**Radar**

A new borehole radar system was designed during the first stage of the Crosshole program. The radar system is a short pulse system operating in the frequency range 20 to 60 MHz. The system consists of borehole transmitter and receiver probes which are connected to a signal control unit by optical fibers. The signal control unit is used for communication with the borehole probes and for control of the measurement. A field computer unit is used for display on a colour screen, storage, processing and printout of the recorded data. The borehole radar system is designed to be used both in singlehole and crosshole measurements.

In the singlehole reflection measurements fracture zones have been observed at distances of 115 m from the borehole at a frequency of 22 MHz. An example of a radar reflection map is shown in Figure 19-2. If the frequency is increased to 60 MHz the range is roughly halved but the resolution is considerably increased.

Reflections are also observed in crosshole measurements. The reflection geometry is different compared to the singlehole measurements and the data have to be analysed in a different fashion. A new technique has been developed for analysis of crosshole reflection data which in principle allows the orientation of a fracture plane to be determined uniquely if the boreholes are not in the same plane. If the holes are in the same plane there appears an ambiguity between two possible orientations.

In crosshole measurements the travel time and the amplitude of the first arrival have been determined. Tomographic inversion has then been made using both travel times and amplitudes. The measurements were made in such a way as to provide an even distribution of rays in the plane between two boreholes and a high ray density. Six tomographic sections were measured, each containing almost 1300 rays.

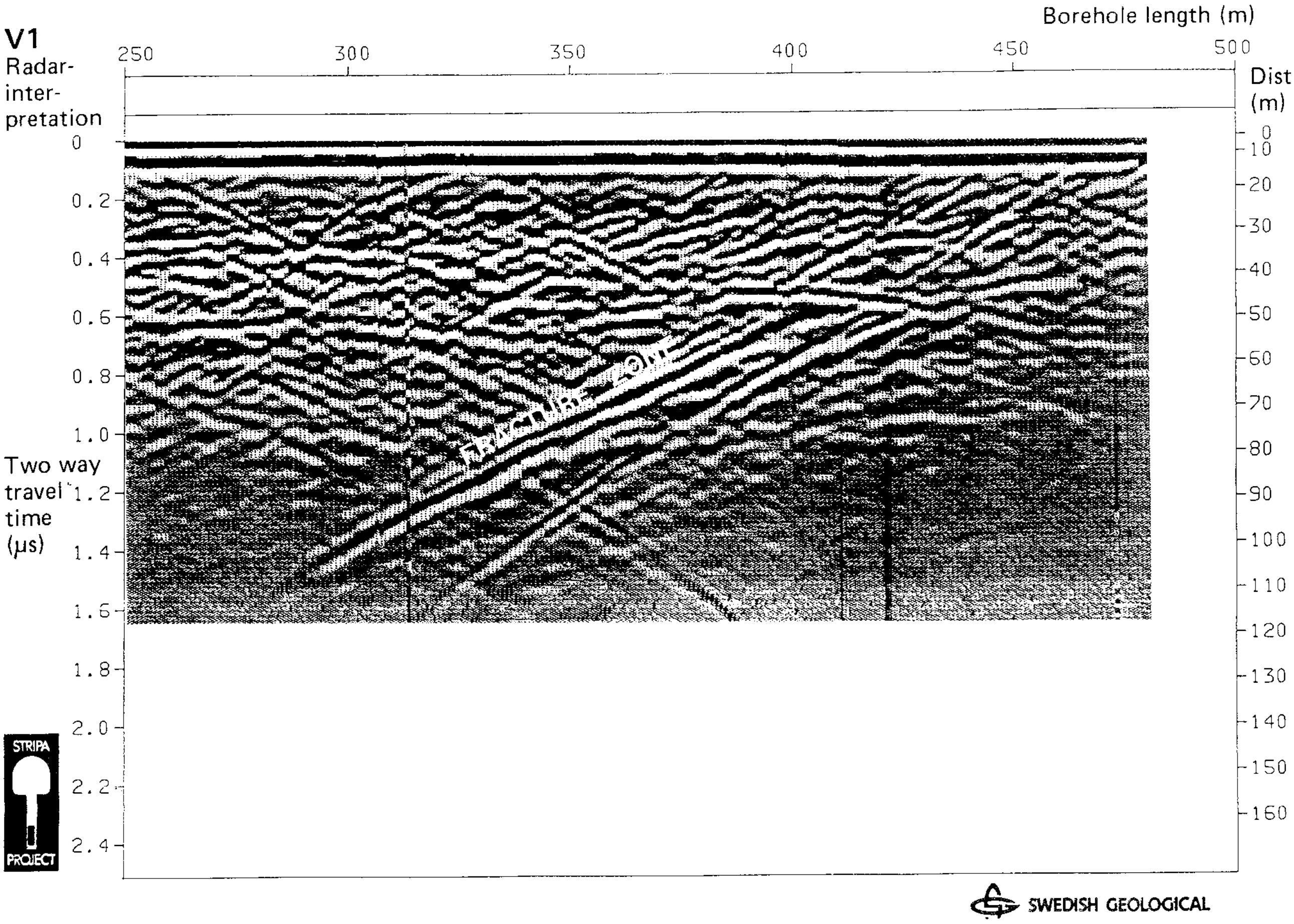



*Figure 19-2. Radar reflection map from the borehole V1 measured with a center frequency of 22 MHz.*

The travel time and the amplitude of the first arrival have been extracted by an automatic procedure. The data have been converted to residual travel and amplitudes after integration with borehole coordinate information. The outcome of a tomographic inversion has turned out to be sensitive to errors in the input data, e.g. coordinate errors and offset errors. Procedures have been developed to identify such errors and correct for them.

**Crosshole seismics**

A substantial part of the program has been devoted to the development of theories of tomographic analysis. Theoretical proofs of uniqueness have been found, showing that with ideal data sets the crosshole method can indeed provide an unambiguous picture of the area under study.

The tomographic analysis is very intensive computationally unless special care is taken. A substantial part of the work during the project has been the development of new fast numerical algorithms for tomographic inversion. A twenty-fold increase in the rate of convergence has been obtained. With the new computer programs it is now possible to analyse a large data set in half an hour on a mini computer.

The tomographic technique has been found to be very sensitive to noise in the input data. Especially, the position of the boreholes and the travel times have to be determined with great accuracy. The computer programs have been adapted for identification of different types of errors and for corrections of them.

**Hydraulics**

The hydraulics testing programme was completed in January 1986. Since that time, effort has concentrated on the analysis and interpretation of the crosshole sinusoidal testing and the steady state head data. The hydraulics programme incorporates two novel features, namely the use of automatic testing equipment and the employment of a form of testing known as sinusoidal pressure tests.

The sinusoidal pressure tests consists of creating a sinusoidally varying flow or pressure in a source zone and monitoring a number of receiver zones for the appearance of the signal. The hydrogeological properties of the rock between the source and receiver zones are derived from the attenuation of the peak amplitude and the lag of the signal at the receiver compared to that at the source. Tests can be carried out at a variety of frequencies and detailed information derived concerning the properties of the intervening rock.

## 19.3.2 Three-Dimensional Migration Experiment

Since the object is to study migration flow paths over distances up to 50 m, the effects of adjacent hydraulic sinks such as drifts and boreholes can be large. Due to this, the test site was excavated in an "undisturbed" but geologically well known part of the mine.

The upper part of the test site has been covered with plastic sheets, each sheet with an area of ~2 m$^2$.

A total number of about 350 sheets serves as sampling areas for water emerging in the upper part of the test site. This sampling arrangement completely covers an area of ~700 m². When sampling over an area and not just at distinct points, the spatial distribution of water flow paths can be obtained. The lay-out of the test site as a cross increases the resolution of the three-dimensional distribution of the tracers in that part of the test site.

Water inflow monitoring started directly after the covering of the upper part of the test site. A compilation of the results is given in Figure 19-3. From Figure 19-3 it can be clearly seen that water does not flow uniformly in the rock over the scale considered (~700 m²), but seems to be localized to wet areas with large dry areas in between. Measurable amounts of water emerge into just one third of the 350 sampling areas. 10 % of these "wet" sampling areas give more than 50 % of the total water inflow. The total measured water inflow rate was ~700 ml/h.

From the test site which has a total length of 100 m, three vertical holes (length 70 m) were drilled. Within these three holes, 9 different injection zones (each 2.5 m in length) were located. The location of the injection zones within the holes were based on the results from inflow measurements over 2 m sections as well as radar measurements. The space between the injection zones were sealed off with compacted bentonite.

In the injection zones tracers were continuously injected during 20 months using a small over-pressure. The total injection inflow rates were ~10 % of the total water inflow rate into the upper part of the test site.

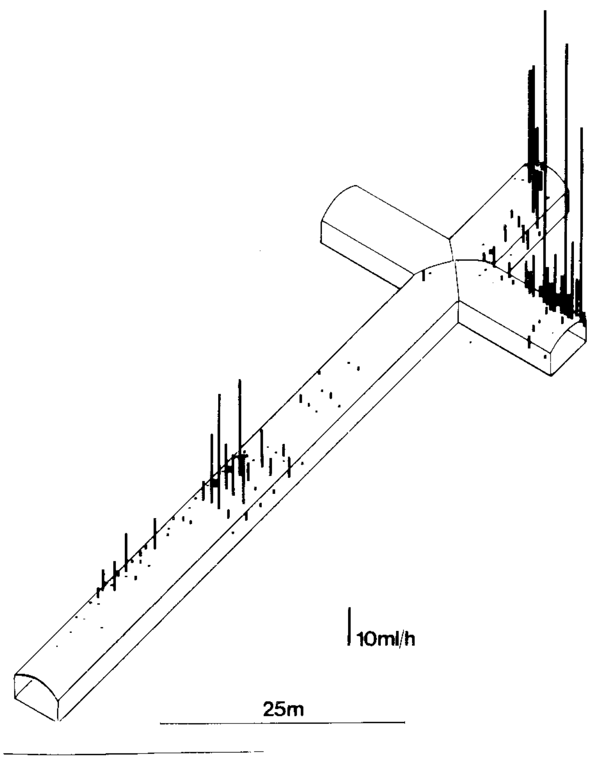



*Figure 19-3. Water inflow rates into the upper part of the drift.*

Before injection, all 11 tracers were tested in the laboratory and found to be stable with time and "non-sorbing" on crushed granite as well as on the materials used in the equipment. Of these 11 tracers, all conservative, 7 were dyes, 3 were salts and the last one was a large molecular weight tracer. The 7 dyes were selected based on tests of ~100 different dyes.

Of the 11 injected tracers, 7 have reached test site within the time of the experiment. Out of 145 water bearing sampling areas, tracers have emerged in ~60. The tracers injected close to the right arm of the cross, which is the wettest area in the test site, did not appear there, but emerged 30 m away, in the middle part of the long drift, see Figure 19-4. In some sampling sheets in this part of the test site, all 7 tracers appear. The first appearance of tracers was after 3 weeks. The last of the 7 tracers to appear (Duasyn) emerged after about 20 months. This appearance coincided with the work done (excavations and drillings) in preparation for the Stripa Project Phase 3.

The obtained breakthrough curves are evaluated using the Advection-Dispersion-Matrix diffusion model, which gives the mean residence time, Pe-number (Longitudinal dispersion), interaction with the rock matrix (diffusion into the porous matrix) and the dilution factor.

### 19.3.3 Borehole, Shaft and Tunnel Sealing Test

The field activities were finished in 1986, the last part being the excavation of the tunnel plug for comprehensive clay sampling. This gave a true picture of the distribution of absorbed water in the bentonite clay and of the clay/rock interaction, by which the sealing function of the plug became fully understood.

All three tests, i.e. the borehole, shaft, and tunnel sealing tests were evaluated and reported in the course of 1986, a brief summary being given in the subsequent text.

The general objective of the tests was to investigate the sealing power of highly compacted sodium bentonite. The clay was applied in the form of dense blocks of compacted commercial MX-80 powder, the major item being to measure how fast the clay absorbed water and swelled to form tight plugs.

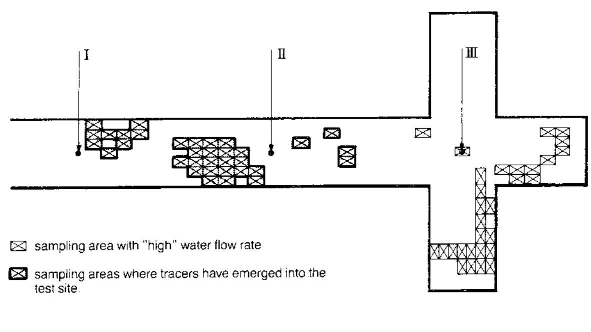



*Figure 19-4. Tracer distribution.*

**Borehole plugging test**

The Borehole Plugging Experiment comprised three field tests, in which the function and practicality in handling and application of such plugs were tested under real conditions. The design principle was that cylindrical blocks of compacted clay powder were contained in perforated casings of copper. After insertion in the boreholes, which were water-filled from the start, the clay was expected to absorb water and swell out through the perforation. Laboratory tests and pilot field tests had indicated that the expansion of the clay leads to complete embedding of the casing if there is sufficient access to water. The main purpose of the field tests was to investigate the rate and uniformity of the water uptake.

The plugging of a 100 m long, 56 mm diameter, almost horizontal borehole demonstrated the practicality of this plugging technique also in very long holes and this test also showed that the maturation of the plugs was sufficiently fast to resist piping or distortion by high hydraulic gradients already after about one week. The uniformity of the water content of a recovered section was determined after about 2,5 years and it was found to be very high. The clay was completely water saturated despite the large variation in fracture frequency of the rock, which indicates that water had passed through frequent fine fissures in the confining rock, leading to uniform uptake over the entire clay/rock interface.

**Tunnel plugging test**

The test arrangement consisted of a 9 m long and 1.5 m diameter steel tube, surrounded by sand and cast in concrete plugs at each end. These plugs contained bentonite blocks arranged in the form of "O-ring" sealings at the rock/concrete interface. The test arrangement is illustrated in Figure 19-5. This simulated

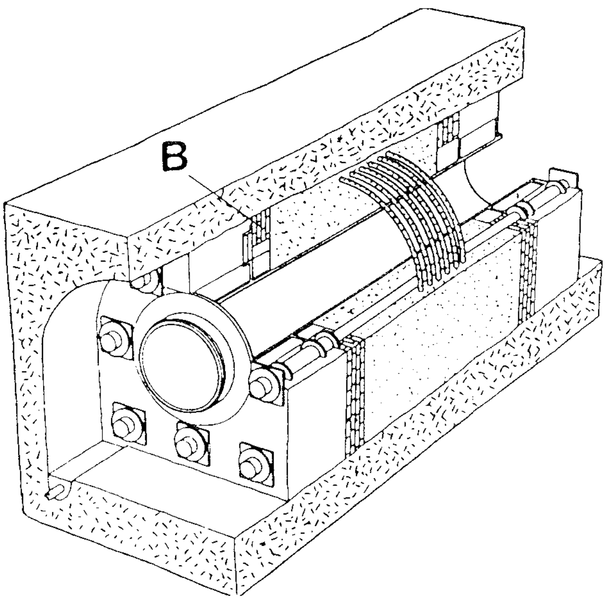



*Figure 19-5. General view of the test arrangement with the central steel casing and tie-rods passing through the concrete plugs with bentonite sealings (B) at the ends and the sand-filled chamber. The latter simulated a richly water-bearing rock zone.*

a temporary sealing of a water-bearing rock zone penetrated by a repository tunnel, allowing for transports through the plug construction while minimizing the water inflow into the tunnel. The water pressure in the sand fill was raised to 3 MPa in the course of the test and the associated inflow and leakage were accurately measured by flow meters and by collecting water that leaked from the plug. The swelling pressure exerted on the rock and on the sand by the expanding bentonite was measured by Gloetzl cells, and the deformation and displacement of the plug components recorded by use of extensometers.

The predicted outflow from the sand-filled injection chamber was about 1000 l/hour if no bentonite sealings had been applied, and 60-600 l/hour at 3 MPa water pressure at the end of the test with the tested, bentonite-equipped plug construction.

The actual leakage turned out to be about 200 l/hour at 100 kPa water pressure early in the test but it dropped successively in the course of the test and became 75 l/hour at 3 MPa pressure at the end of the about 20 months long test. During the 3 MPa pressure period, which lasted for about 10 months, the leakage dropped from about 200 l/hours to 75 l/hours and this very significant reduction was found to be caused by three effects. The major one was the establishment of a very tight contact between the rock and the bentonite, while the flow-reducing influence of the swelling pressure on certain rock fractures and the penetration of bentonite into certain wider fractures were less important but still of some significance.

It was expected that some erosion of the bentonite would take place in the early part of the test when the flow rate of leaking water along the rock/clay contact was very high. No such effect appeared, however. The physical stability of the bentonite and its excellent sealing efficiency over long periods of time were thereby demonstrated.

# 20 JSS-PROJECT

The studies of waste glass are performed entirely within the JSS-Project. (A joint project between SKB, NAGRA, Switzerland and CRIEPI, Japan.) The JSS-Project has been subdivided into five phases, where the bulk of the experimental data were collected in phases I-III and phases IV-V dealt more specifically with modelling of the interactions in the system glass/bentonite/water/steel corrosion products. The ultimate objective of the JSS-Project will be to model the waste glass performance for conceptual repository in order to evaluate the potential significance of the model in the frame of future safety analyses.

The Phase III of the project has been completed and reported /20-1/. The Phase III contained studies of the interactions between glass and flowing solutions. It was found that the observed solution concentrations, showing a maximum after a few weeks and thereafter decreasing to steady state values, could be explained assuming a silica transport control in the leached surface layer of the glass. A comparison between experimental and theoretical results are shown in Figure 20-1.

During 1986, Phase IV of the project was completed. Phase IV involved the development of a predictive model for glass dissolution under repository conditions. The mechanism of glass dissolution is interpreted with help of reversible and irreversible thermodynamics and with transition state theory. As a function of glass and solution composition and environmental parameters such as temperature, pH, solution volume, glass surface area, and solution flow rate, an overall model has been developed, which describes glass network dissolution, formation of solid reaction products, changes in solution chemistry, silica saturation and the formation of surface layers as potential transport barriers.

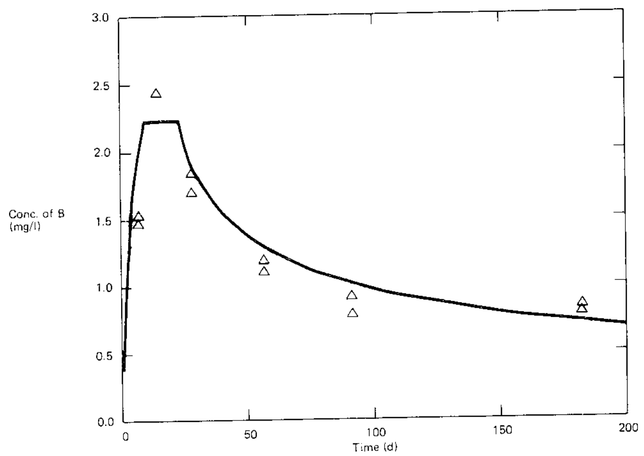



*Figure 20-1. Boron concentration versus time for dynamic leaching of simulated high level waste glass.*

A final Phase V of the project has been started. In this last phase of the project, more accurate date for the long-term corrosion rate will be measured. Studies will also be performed, aiming at model validation with the help of more detailed information to be derived from naturally altered basalt glasses.

# 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, see Figure 21-1.

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

The natural analogue studies are divided into two 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 oxidising and reducing conditions.
2. To study colloid formation and mobility in natural groundwaters and the role of colloids in radionuclide transport.

The most important goals of the subprojects are as follows:

1 – Validate equilibrium models for different watermineral systems.
  – Understand the mechanisms for the dissolution and precipitation of uranium and other elements around the redox front.
  – 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.

The introductory phase started in May 1986 with drilling and sampling of minerals and groundwater in the Osamu Utsumi mine /21-1/ see Figure 21-2 and 21-3. The first year of the project is primarily being devoted to a preparatory investigation including drilling, sampling and analyses of the most important samples. Drilling and sampling has also been started in Morro do Ferro /21-2/.

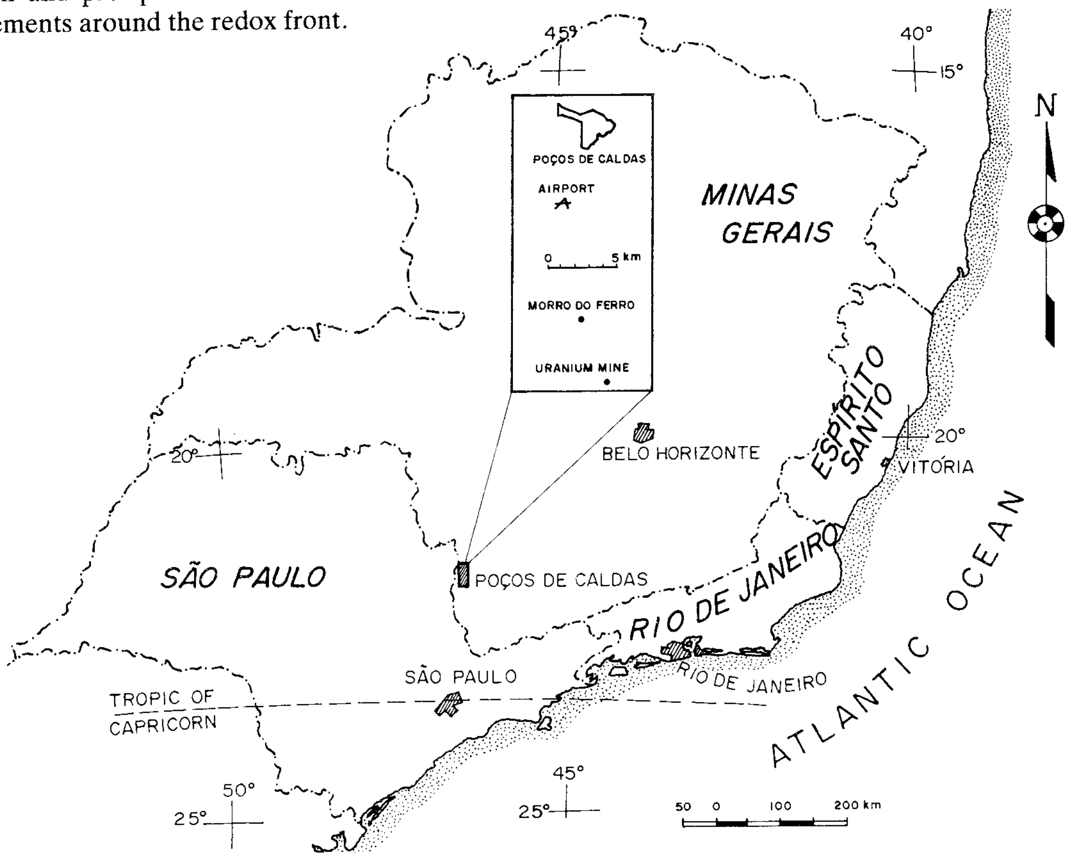



*Figure 21-1. Map showing location of Poços de Caldas and Morro do Ferro, Brazil.*

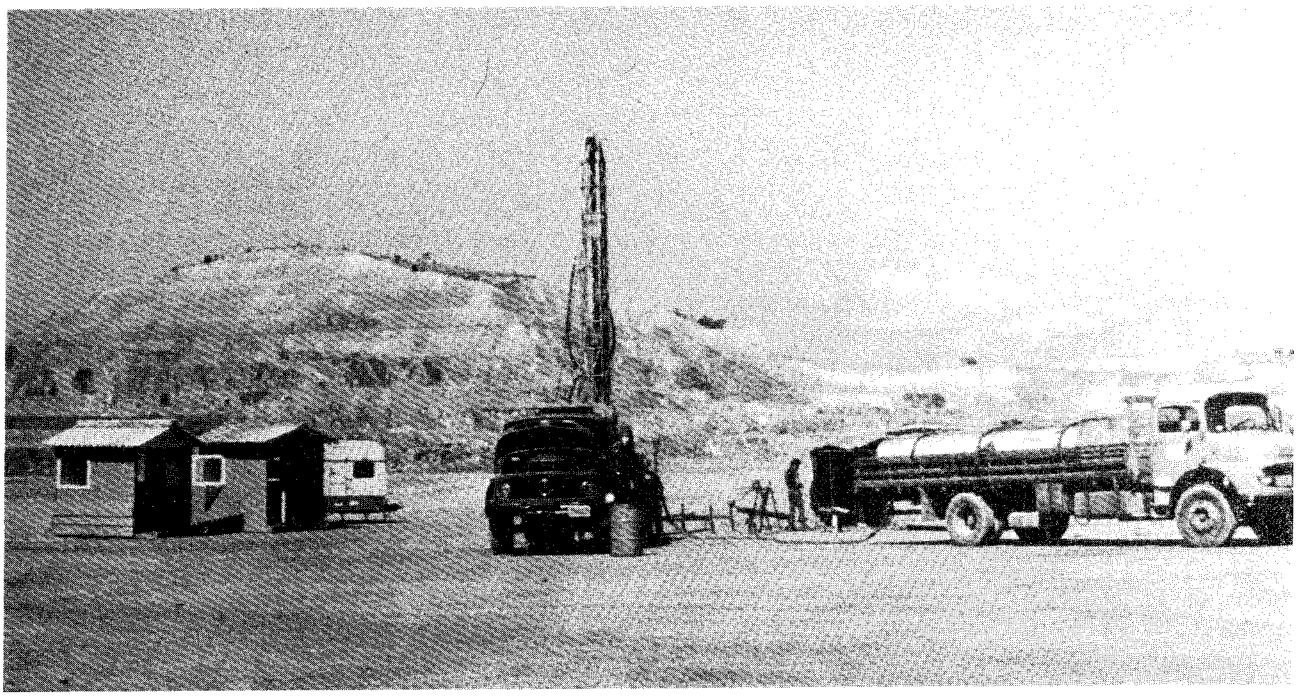


*Figure 21-2. Drilling operation in the uranium mine C-09.*

*Figure 21-3. Sampling of surface water in the uranium mine C-09.*

# 22 DOCUMENTATION

The results obtained 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, Plan 86 and the R&D-programme 86,
- in the series of SKB technical reports,
- in internal SKB working 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. A complete list of all Technical reports published in 1986 is given in Appendix 4. Part IV includes summaries of the 1986 Technical Reports.

## 22.2 SKB DATA BASE SYSTEM

The large amount of data generated from the geological site investigations and from the laboratory experiments has to be administered in a systematic way. To this end a computerized data base is under development at SKB. The objectives are to:

- accomplish a centralized storage of data directly connected to SKB, which has the overall program responsibility,
- promote quality assurance and long-term retrievability of data,
- collect and structure data sets in a common data base, that is readily available to the scientists doing R&D and assessment work for SKB,
- provide a tool for making statistical analyses of data,
- provide tools for graphical presentation of data.

The hardware of the system is a VAX-11/750 computer. A flexible system for loading, storing and retrieving data has been developed based on a relational data base system called MIMER. The data are organized in separate data sets on geology, geophysics, hydrogeology and groundwater chemistry. For each of these areas the data generation and the data flow are being analyzed in detail to determine how, at what stage and with what quality control procedures data should be stored. The system is now partly in operation but a lot of data will still be transferred to the system during 1987.

# REFERENCES PART II


## CHAPTER 10

**10-1 SKB. Handling and Final Disposal of Nuclear Waste. Programme for Research, Development and other Measures**
R&D-programme-86
SKB, September 1986.

**10-2 SKB. Handling and Final Disposal of Nuclear Waste. Alternative Disposal Methods**
Background report to R&D-programme-86
SKB, September 1986.

**10-3 SKB. Kärnkraftavfallets Behandling och Slutförvaring**
Internationell och Utländsk Verksamhet
Underlagsrapport till FoU-program-86
SKB, September 1986 (In Swedish only).

## CHAPTER 11

**11-1 See ref. 10-2**

**11-2 SKN. NAK WP-Cave Project**
Report on the research and development stage
Boliden WP-Contech AB, May 1984 to October 1985

**11-3 Boliden. Cut-and-fill Mining at Boliden**
Boliden, Pulp and Paper, October 1982
Miller Freeman Publications, 1982

## CHAPTER 12

**12-1 Forsyth; R. S., Werme; L. O. and Bruno; J.**
The corrosion of spent $UO_2$ fuel in synthetic groundwater
J. Nucl. Mat., 138 (1986) 1.

**12-2 Bruno; J., Casas; I., Lagerman; B. and Muñoz; M.**
The determination of the solubility of amorphous $UO_2(s)$ and the monomolecular hydrolysis constants of uranium(IV) at 25°C
The Scientific Basis for Nuclear Waste Management-X, eds.: W.B. Seefeldt and J.K. Bates, The Materials Research Society, 1987 (In print).

## CHAPTER 13

**13-1 Marsh; G. P., Taylor; K. J., Sharland; S. M. and Tasker; P. M.**
An approach for evaluating the general and localized corrosion of carbon steel containers for nuclear waste disposal
The Scientific Basis for Nuclear Waste Management-X, eds.: W.B. Seefeldt and J.K. Bates, The Materials Research Society, 1987 (In print).

## CHAPTER 14

**14-1 Pusch; R. and Karnland; O.**
Aspects of the physical state of smectite-adsorbed water.
SKB Technical Report TR 86-25.

**14-2 Pusch; R.**
Settlement of canisters with smectite clay envelopes in deposition holes.
SKB Technical Report TR 86-23.

**14-3 Börgesson; L.**
Model shear tests of canisters with smectite clay envelopes in deposition holes.
SKB Technical Report TR 86-26.

**14-4 Erlström, M.**
Pressure solution of minerals in quartz-type buffer materials.
SKB Technical Report TR 86-28.

## CHAPTER 15

**15-1 See ref. 10-1.**

**15-2 Ahlbom; K., Andersson; P., Ekman; L., Gustafsson; E., Smellie; J. and Tullborg; E-L.**
Preliminary investigations of fracture zones in the Brändan Area, Finnsjön study-site
SKB Technical Report TR 86-05.

**15-3 Bäckblom; G. and Stanfors; R.**
The Bolmen Tunnel - Tunnelling through the Staverhult Fault Zone
Engineering Geology, 23, 45-57, 1986.

**15-4 Almén; K-E., Andersson; O., Fridh; B., Johansson; B-E., Sehlstedt; M., Gustafsson; E., Hansson; K., Olsson; O., Nilsson; G., Axelsen; K. and Wikberg; P.**
Site Investigation Equipment for Geological, Geophysical, Hydrogeological and Hydrochemical Characterization
SKB Technical Report TR 86-11.

**15-5 Almén; K-E., Andersson; J-E., Carlsson; L., Hansson; K. and Larsson; N-Å.**
Hydraulic testing in crystalline rock. A comparative study of single-hole test methods
SKB Technical Report TR 86-27.

**15-6 Thunvik; R. and Braester; C.**
Hydrothermal conditions around a radioactive waste repository
SKB Technical Report 80-19.

**15-7 Grundfeldt; B.**
GWHRT – A finite element solution to the coupled ground water flow and heat transport problem in three dimensions
SKB Technical Report TR 83-51.

**15-8 Lindbom; B.**
Steady-State Flow in a Rock Mass Intersected by Permeable Fracture Zones. Calculations on Case 2 with the GWHRT-code within Level 1 of the HYDROCOIN Project.
SKB Technical Report TR 86-21.

**15-9 Davison; C. C. and Guvanasen; V.**
Hydrogeological Characterization, Modelling and Monitoring of the Site of Canada's Underground Research Laboratory
Proc 17th Int Ass Hydrogeologists Cong. on the Hydrogeology of Rocks of Low Permeability, 1985.

**15-10 Talbot; C.**
A Preliminary Structural Analysis of the Pattern of Post-Glacial Faults in Northern Sweden
SKB Technical Report TR 86-20.

**15-11 Olkiewicz; A. and Stejskal; V.**
Geological and tectonic description of the Klipperås study-site
SKB Technical Report TR 86-06.

**15-12 Sehlstedt; S. and Stenberg; L.**
Geophysical investigations at the Klipperås study-site
SKB Technical Report TR 86-07.

**15-13 Gentzschein; B.**
Hydrogeological investigations at the Klipperås study-site
SKB Technical Report TR 86-08.

**15-14 Stenberg; L.**
Geophysical laboratory investigations on core samples from the Klipperås study-site
SKB Technical Report TR 86-09.

**15-15 Tullborg; E-L.**
Fissure fillings from the Klipperås study-site
SKB Technical Report TR 86-10.

**15-16 Laurent; S.**
Analysis of Groundwater from Deep Boreholes in Klipperås
SKB Technical Report TR 86-17.

**15-17 Bjarnason; B. and Stephansson; O.**
Hydraulic fracturing rock stress measurements in borehole Gi-1, Gideå Study-site Sweden
SKB Technical Report TR 86-11.

**15-18 Ericsson; L. O. and Ronge; B.**
Correlation between Tectonic Lineaments and Permeability Values of Crystalline Bedrock in the Gideå Area
SKB Technical Report TR 86-19.

# CHAPTER 17

**17-1 Karlsson; F., and Wikberg; P.**
Some highlights on the isotope geochemistry studies within the Swedish research program on radioactive waste disposal
Applied Geochemistry 2 (1), 1987, (In print).

**17-2 Tullborg; E-L.**
$^{14}C$-measurements of fissure filling calcite with accelerometer masspectrometry. A pilot study
Swedish Geological AB, Technical Report (ID 86407), 1986.

**17-3 Fritz; B. and Kam; M.**
Interactions between bentonite-calcite and Stripa water V1 at 25°C and 100°C. Acid or alkaline titrations.
Centre de Sedimentologie et de Geochemie de la Surface, Université Louis Pasteur
(Preliminary report, February 1987).

**17-4 Bruno; J., Casas; I., Grenthe; I., Lagerman; B. and MuÑoz; M.**
The determination of the solubility of amorphous $UO_2$ (s) and the mononuclear hydrolysis constants of uranium (IV) at 25°C in Scientific Basis for Nuclear Waste Management X ed J K Bates and W Seefeldt
MRS Symposium Series 1987 (In print).

**17-5 Bruno; J., Casas; I., Grenthe; I. and Lagerman; B.**
Complex formation in the $Th(IV)$-$H_2O$-$CO_2(g)$ system
To be published in the 2nd International Conference on the Basis and Applied Chemistry of Lanthanides, Actinides and Related Elements
Lisboa (Portugal) 6-10 April 1987.

**17-6 Grenthe; I., Riglet; C. and Vitorge; P.**
Composition and equilibria of trinuclear neptunium (VI)- and plutonium (VI)-carbonate complexes
Inorganic Chemistry 25 (1986), 1679.

**17-7 Grenthe; I., Robouch; P. and Vitorge; P.**
Chemical equilibria in actinide carbonate systems
Journal of the Less-Common Metals 122 (1986), 225.

**17-8 Moulin; V., Allard; B., Basso; B., Tran; M.T. and Stammose; D.**
Influence of humic materials on the adsorption of americium(III) on aluminia
CEA-R Commissariat a Energie Atomic, Paris, 1987 (In print).

**17-9 Ephraim; J. H.**
The interaction of Fe and Ca(II) with Armadale fulvic acid
State University of New York at Buffalo (Preliminary report, February 1987).

## CHAPTER 18

**18-1 See ref. 10-1.**

## CHAPTER 19

**19-1 Swedish-American Cooperative Program on Radioactive Waste Storage in Mined Caverns in Crystalline Rock.**
Technical Information Reports No. 1-54 with various authors.
The most recent report was written by Binnall and McEvoy and is designated LBL-12670, SAC-54, UC-70. It was published in October 1985 and contains a complete list of all SAC reports.

**19-2 Stripa Project TR 86-05.**
Annual Report 1985
SKB, August 1986.

## CHAPTER 20

**20-1** Final report JSS project phase III: Static corrosion of radioactive glass at 40°C and corrosion of radioactive glass under dynamic conditions
JSS-Project Technical Report 86-01, SKB, Stockholm (1986).

## CHAPTER 21

**21-1 Poços de Caldas Project**
Progress Report June through August 1986
Stockholm, Sweden.

**21-2 Poços de Caldas Project**
Progress Report September through November 1986
Stockholm, Sweden.

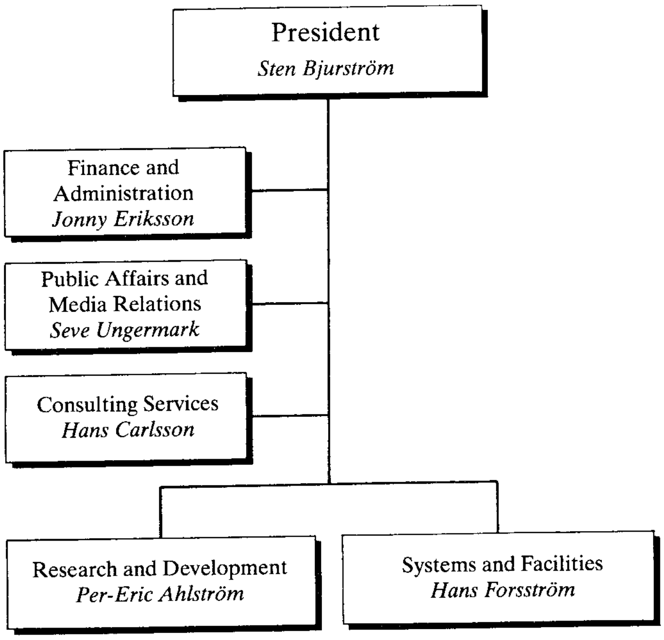
# SKB ANNUAL REPORT 1986
# Part III

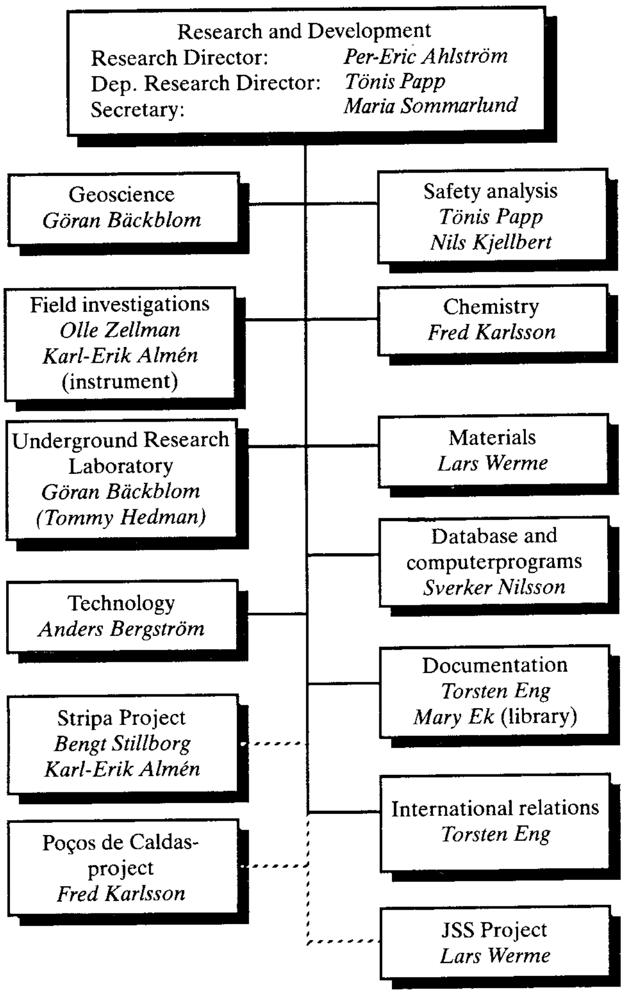
# Appendices

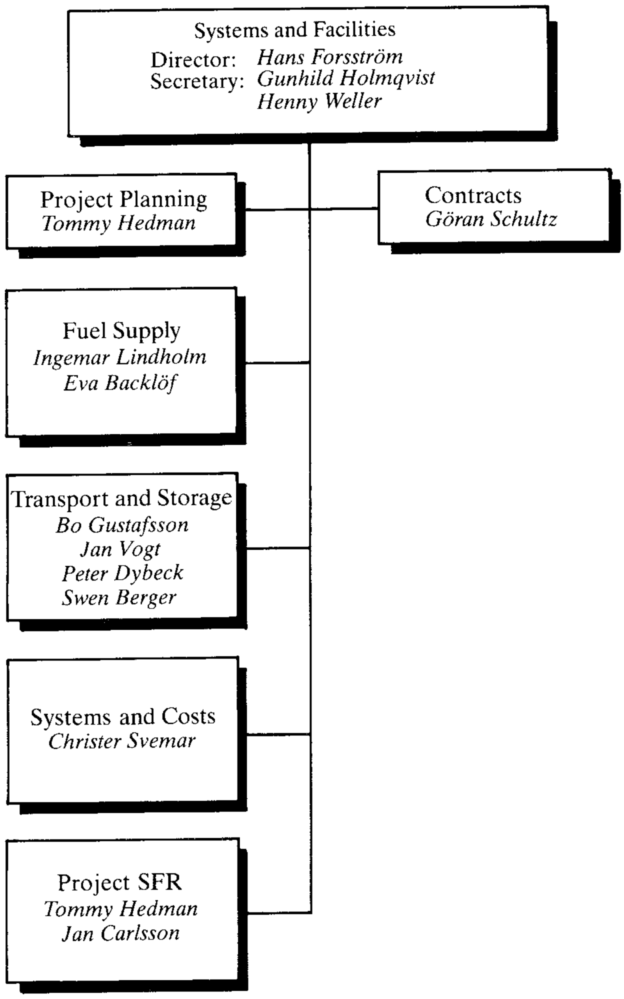
# CONTENTS OF PART III


| | | Page |
|---|---|---|
| Appendix 1 | SKB Organization | 93 |
| 2 | Lectures and Publications 1986 | 95 |
| 3 | List of SKB Annual Reports 1977-85 | 99 |
| 4 | List of SKB Technical Reports 1986 | 101 |
| 5 | Authors of SKB Technical Reports 1986 in Alphabetical Order | 105 |

# ORGANIZATION CHARTS FOR SKB AND ITS DIVISIONS
## (with staff as of May 1987)



# LECTURES AND PUBLICATIONS 1986

**Direct disposal of spent nuclear fuel – key research areas**
Ahlström; P.-E. and Papp; T., SKB
Waste Management '86 in Tucson, Arizona, March 1986.

**Borosilicate glass corrosion in the presence of steel corrosion products**
Bart; G., Zwicky; H-U., Aerne; E. T., Graber; Th., and Z'Berg; D.
The Scientific Basis for Nuclear Waste Management-X, eds.: Seefeldt; W. B. and Bates; J. K., The Materials Research Society, (In print)

**Temporary and permanent storages in the Swedish system for directly disposal of spent nuclear fuel**
Bjurström; S., ENC 86, Geneve, Switzerland, June 1-6, 1986.

**The Swedish programme for radioactive waste management**
Bjurström; S. and Forsström; H., SKB
World Energy Conference, Cannes, October 1986.

**Experience from operation of the Swedish Central Intermediate Storage Facility**
Brundin; B. and Vogt; J.
IAEA technical committee meeting on "Behaviour of spent fuel assemblies and storage equipment under long-term wet storage conditions",
Leningrad, USSR, 26-30 May, 1986.

**The determination of the solubility of amorphous $UO_2(s)$ and the monomolecular hydrolysis constants of uranium(IV) at 25°C**
Bruno; J., Casas; I., Lagerman; B. and Muñoz; M.
The Scientific Basis for Nuclear Waste Management-X, eds.: Seefeldt; W. B. and Bates; J. K., The Materials Research Society, (In print)

**Tunnelling of the Swedish undersea repository for low- and intermediate reactor waste**
Carlsson; A. and Hedman; T., SKB
Tunnelling and Underground Space Technology, Vol. 1 1986, Pergamon Press.

**Rock stresses and geological structures in the Forsmark area**
Carlsson; A. and Christiansson; R.
International Symposium on Rock Stress and Rock Stress Measurements, Stockholm, September 1-3 1986.

**Recent achievements of the Nuclear Energy Agency International Stripa Project on in-situ experiments for the disposal of radioactive waste in granite**
Carlsson; H. S., SKB and Carlyle; S. G., NEA
ENC'86, Geneva, Switzerland, June 1-6, 1986.

**Introduction and summary of natural analogue workshop**
Chapman; N.A. and Smellie; J.A.T.
Chem. Geol. 55, 167-173, 1986

**Radiation induced dissolution of $UO_2$**
Christensen; H. and Bjergbakke; E.
The Scientific Basis for Nuclear Waste Management-X, eds.: Seefeldt; W. B. and Bates; J. K., The Materials Research Society, (In print)

**Application of CHEMSIMUL for groundwater radiolysis**
Christensen; H. and Bjergbakke; E.
Nuclear and Chemical Waste Management 6, 265-270, 1986.

**Progress of the Swedish radioactive waste management program**
Forsström; H. G., SKB
CNS second int. conf. on radioactive waste mangement, Winnipeg, Manitoba, September 7-11, 1986.

**Progress in Swedish spent fuel and radioactive waste mangement program**
Forsström; H., SKB
World Nuclear Fuel Market 13th annual meeting and int. conf. on Nuclear Energy, Brugge, Belgium, October 19-21, 1986.

**The corrosion of spent $UO_2$ fuel in synthetic groundwater**
Forsyth; R. S., Werme; L. O. and Bruno; J.
J. Nucl. Mat. 138, 1986, 1

**Modelling of the effects of iron corrosion products on nuclear waste glass performance**
Grambow; B., Zwicky; H. U., Bart; G., Björner; I. K. and Werme, L. O.
The Scientific Basis for Nuclear Waste Management-X, eds.: Seefeldt; W. B. and Bates; J. K., The Materials Research Society, 1987, (In print)

**Reaction of nuclear waste glass with slowly flowing solutions**
Grambow; B., Hermansson; H-P., Björner; I-K., Christensen; H. and Werme; L.
Advances in Ceramics, Vol. 20: Nuclear Waste Management II, eds.: Clark; D. E. and Machiels; A. J., The American Ceramic Society, (In print)

**The realization of the central interim storage facility for spent nuclear fuel, CLAB, in Sweden**
Gustavsson; B., SKB, Jansson; O., ASEA-ATOM and Chevrier; G., SGN – France
ENC '86, Geneva, Switzerland, June 1-6, 1986.

**Packaging and transportation of radioactive materials**
Gustavsson; B. and Ekendahl; A., SKB
PATRAM '86 International symposium on the packaging and transportation of radioactive materials, Davos, June 16-20, 1986.

**The Swedish final repository for reactor waste (SFR)**
Hedman; T. and Aronsson; I.
IAEA International Symposium
Hannover, FRG 3-7 March 1986

**Migration of trace elements through water exposed surfaces of crystalline rocks**
Ittner; T., Allard; B. and Torstenfelt; B.
5th International Symposium on Water-Rock Interaction, Reykjavik, Iceland, 15. Aug, 1986

**Role, status and development of performance assessment in the Swedish nuclear waste management program**
Kjellbert; N. A., Papp; T. and Thegerström; C., SKB
IAEA, Hannover, March 3-7, 1986.

**Some highlights on the isotope geochemistry studies within the Swedish research program on radioactive waste disposal**
Karlsson; F., SKB and Wikberg; P., Royal Institute of Technology
Conf. on Isotope Geochemistry of Groundwater and Fracture Material in Plutonic Rock, Mont Ste Marie, Quebec, Canada, October 1-3, 1986.

**Experience on the use of isotope techniques in fractured rocks – The Swedish program on radioactive disposal**
Karlsson; F., SKB
IAEA – adv. group meeting on "The application of isotope techniques in the study of the hydrogeology of fractured fissured rocks", Vienna, November 17-21, 1986.

**A silo in bedrock for nuclear waste**
Larsson; H. and Christiansson; R.
Large rock caverns, International Symposium, Helsinki, Finland, August 25-28, 1986.

**SIMS analysis of leached layers formed on SRL glasses during burial**
Lodding; A. R., Engström; E. U., Clark; D. E., Werme; L. O. and Wicks; G. G.
Advances in Ceramics, Vol. 20: Nuclear Waste Management II, eds.: Clark; D. E. and Machiels; A. J., The American Ceramic Society, (In print)

**An approach for evaluating the general and localized corrosion of carbon steel containers for nuclear waste disposal**
Marsh; G. P., Taylor; K. J., Sharland; S. M. and Tasker; P.W.
The Scientific Basis for Nuclear Waste Management-X, eds.: Seefeldt; W. B. and Bates; J. K.. The Materials Research Society, 1987, (In print)

**Contaminant transport through a fractured porous rock. – Impact of the inlet boundary condition on the concentration profile in the rock matrix**
Moreno; L. and Rasmuson; A., Royal Institute of Technology, Sweden
Water Resour. Res. 22, (1986), 1728-1730

**Radionuclide transport - data collection and validation tests**
Neretnieks; I., Royal Institute of Technology, Sweden
IAEA symposium on the Siting, Design and Construction of Underground Repositories for Radioactive Waste, Hannover, March 3-7, 1986

**Field experiments in Stripa on flow and tracer transport**
Neretnieks; I., Royal Institute of Technology, Sweden
Université de Neuchatel, March 19, 1986

**Some uses of analogues for safety analysis**
Neretnieks; I., Royal Institute of Technology, Sweden
CEC Natural Analogue Working Group, 2nd Meeting, June 1986

**Use of sorption data in safety assessment models**
Neretnieks; I., Royal Institute of Technology, Sweden
OECD/NEA Workshop on the use of ISIRS, Paris, June 24-25, 1986

**Geological disposal of LLW in Sweden**
Nilsson; L.-B. and Hedman; T., SKB
Int. symposium on alternative low-level waste technologies organized by Illinois Department of Nuclear Safety, Chicago, February, 1986

**The role of the canister in a system for the final disposal of spent fuel or high-level waste**
Papp; T., SKB
Phil. Trans. R. Soc., London A319, (1986), 39-47

**Bentonite-based isolation of waste products**
Pusch; R., University of Technical and Natural Sciences, Lund
Proc. Nordic Symp. Clay Minerals - Modern Society, Uppsala, Sweden, 1985

**Settlement of clay-enveloped radioactive canisters**
Pusch; R., University of Technical and Natural Sciences, Lund
Applied Clay Science, No 1, 1986

**Fältförsök med bentonit som isolering av varma kapslar med högaktivt avfall**
Pusch; R., University of Technical and Natural Sciences, Lund Väg- och Vattenbyggaren, No 3, 1986

**Radionuclide migration by water flow and diffusion through smectite barriers**
Pusch; R., University of Technical and Natural Sciences, Lund
Proc. Workshop on Mathematical Modelling for Radioactive Waste Products, Madrid, 1986, (In print)

**Permanent crystal lattice contraction – A primary mechanism in thermally induced alteration of Na-bentonite**
Pusch; R., University of Technical and Natural Sciences, Lund
Proc. Material Research Society, Fall Meeting, Boston, 1986, (In print)

**Identification of Na-smectite hydration by use of "Humid Cell" high voltage microscopy**
Pusch; R., University of Technical and Natural Sciences, Lund
Applied Clay Science, 1987, (In print)

**Radionuclide migration in strongly fissured zones – The sensitivity to some assumptions and parameters**
Rasmuson; A. and Neretnieks; I., Royal Institute of Technology, Sweden
Water Resour. Res. 22, (1986), 559-569

**Radionuclide transport in fast channels in crystalline rock**
Rasmuson; A. and Neretnieks; I., Royal Institute of Technology, Sweden
Water Resour. Res. 22, (1986), 1247-1256

**Can high power electron beam welding encapsulate nuclear waste for 100,000 years?**
Sanderson; A. and Werme; L. O.
Presented at First International Conference on Power Beam Technology, Brighton 10-12 September 1986
The Welding Institute

**Porosities and diffusivities of some nonsorbing species in crystalline rocks**
Skagius; K. and Neretnieks; I., Royal Institute of Technology, Sweden
Water Resour. Res. 22, (1986), 389-398

**Diffusivity measurements and electrical resistivity measurements in rock samples under mechanical stress**
Skagius; K. and Neretnieks; I., Royal Institute of Technology, Sweden
Water Resour. Res. 22, (1986), 570-580

**An analogue study of natural radionuclide migration in crystalline rocks using uranium-series disequilibrium studies**
Smellie; J.A.T., MacKenzie; A.B. and Scott; R.D.
Chem. Geol., 55, (1986), 233-254

**The Poços de Caldas Project**
Smellie; J.A.T., SGAB
Natural Analogue Working Group (NAEG), Second Meeting, June, 1986, Interlaken, Switzerland

**The influence of recharge water on fissure filling minerals from Klipperås, Southern Sweden**
Tullborg; E-L., and Larsson; S-Å.
Water Rock Interaction, no 5, Iceland, Aug. 1986
Published in extended abstracts – proceedings International Association of Geochemistry and Cosmo-Chemistry

**C-14 analyses of fracture filling calcite in order to unveil groundwater circulation**
Tullborg; E-L.
Conference on isotope geochemistry of groundwater and fracture material in plutonic rock
Canada, Oct. 1986
Abstract will be published in Applied Geochemistry during 1987

**Development and validation of models for waste package long-term performance; current tends**
Werme; L. O. and Grambow; B.
The Scientific Basis for Nuclear Waste Management-X, eds.: Seefeldt; W. B., and Bates; J. K., The Materials Research Society, 1987, (In print)

**Method and instrument needs for detailed site characterization for a repository for spent nuclear fuel in Sweden**
Åhagen; H., Heiner; A. and Ahlbom; K.
Proceedings of a Symposium on the siting, design and construction of underground repositories for radioactive wastes, Hannover, March 3-7, 1986, IAEA

# LIST OF SKB ANNUAL REPORTS 1977 – 1985

In order to have the full reports available to all interested persons, they have been filed as microfish at
INIS CLEARINGHOUSE
International Atomic Energy Agency
P O Box 100
A-1400 VIENNA, AUSTRIA

Summaries of Technical Reports from 1977 to 1985 are found in the following documents:

1977-78
TR 121
**KBS Technical Reports 1–120.**
Summaries. Stockholm, May 1979.

1979
TR 79-28
**The KBS Annual Report 1979.**
KBS Technical Reports 79-01–79-27.
Summaries. Stockholm, March 1980.

1980
TR 80-26
**The KBS Annual Report 1980.**
KBS Technical Reports 80-01–80-25.
Summaries. Stockholm, March 1981.

1981
TR 81-17
**The KBS Annual Report 1981.**
KBS Technical Reports 81-01–81-16.
Summaries. Stockholm, April 1982.

1982
TR 82-28
**The KBS Annual Report 1982.**
KBS Technical Reports 82-01–82-27.
Summaries. Stockholm, July 1983.

1983
TR 83-77
**The KBS Annual Report 1983.**
KBS Technical Reports 83-01–83-76.
Summaries. Stockholm, June 1984.

1984
TR 85-01
**Annual Research and Development Report 1984.**
SKB Technical Reports 84-01–84-19.
Summaries. Stockholm, June 1984.

1985
TR 85-20
**SKB Annual Report 1985**
Including Summaries of Technical Reports
Issued during 1985, Stockholm, May 1986.

# LIST OF SKB TECHNICAL REPORTS 1986

In order to have the full reports available to all interested persons, they have been filed as microfish at
INIS CLEARINGHOUSE
International Atomic Energy Agency
P O Box 100
A-1400 VIENNA, AUSTRIA

TR 86-01
**I: AN ANALOGUE VALIDATION STUDY OF NATURAL RADIONUCLIDE MIGRATION IN CRYSTALLINE ROCK USING URANIUM-SERIES DISEQUILIBRIUM STUDIES**
**II: A COMPARISON OF NEUTRON ACTIVATION AND ALPHA SPECTROSCOPY ANALYSES OF THORIUM IN CRYSTALLINE ROCKS**
A T Smellie, Swedish Geological Co
E S Scott and A B MacKenzie, Scottish Universities Research Reactor Centre
February 1986

TR 86-02
**FORMATION AND TRANSPORT OF AMERICIUM PSEUDOCOLLOIDS IN AQUEOUS SYSTEMS**
U Olofsson
Chalmers University of Technology, Gothenburg, Sweden
B Allard
University of Linköping, Sweden
March 26

TR 86-03
**REDOX CHEMISTRY OF DEEP GROUNDWATERS IN SWEDEN**
D Kirk Nordstrom
US Geological Survey, Menlo Park, USA
Ignasi Puigdomenech
Royal Institute of Technology, Stockholm, Sweden
April 1, 1986

TR 86-04
**HYDROGEN PRODUCTION IN ALPHA-IRRADIATED BENTONITE**
Trygve Eriksen
Royal Institute of Technology, Stockholm, Sweden
Hilbert Christensen
Studsvik Energiteknik AB, Nyköping, Sweden
Erling Bjergbakke
Risö National Laboratory, Roskilde, Denmark
March 1986

TR 86-05
**PRELIMINARY INVESTIGATIONS OF FRACTURE ZONES IN THE BRÄNDAN AREA, FINNSJÖN STUDY SITE**
Kaj Ahlbom, Peter Andersson, Lennart Ekman, Erik Gustafsson, John Smellie, Swedish Geological Co, Uppsala
Eva-Lena Tullborg, Swedish Geological Co, Göteborg
February 25, 1986

TR 86-06
**GEOLOGICAL AND TECTONIC DESCRIPTION OF THE KLIPPER—Å—S STUDY SITE**
Andrzej Olkiewicz, Vladislav Stejskal
Swedish Geological Company, Uppsala
October 1986

TR 86-07
**GEOPHYSICAL INVESTIGATIONS AT THE KLIPPERÅS STUDY SITE**
Stefan Sehlstedt, Leif Stenberg
Swedish Geological Company, Luleå
July 1986

TR 86-08
**HYDROGEOLOGICAL INVESTIGATIONS AT THE KLIPPERÅS STUDY SITE**
Bengt Gentzschein
Swedish Geological Company, Uppsala
June 1986

TR 86-09
**GEOPHYSICAL LABORATORY INVESTIGATIONS ON CORE SAMPLES FROM THE KLIPPERÅS STUDY SITE**
Leif Stenberg
Swedish Geological Company, Luleå
July 1986

TR 86-10
**FISSURE FILLINGS FROM THE KLIPPERÅS STUDY SITE**
Eva-Lena Tullborg
Swedish Geological Company, Göteborg
July 1986

TR 86-11
**HYDRAULIC FRACTURING ROCK STRESS MEASUREMENTS IN BOREHOLE Gi-1, GIDEÅ STUDY SITE, SWEDEN**
Bjarni Bjarnason and Ove Stephansson
Division of Rock Mechanics,
Luleå University of Technology, Sweden
April 1986

TR 86-12
**PLAN 86 – COST FOR MANAGEMENT OF THE RADIOACTIVE WASTE FROM NUCLEAR POWER PRODUCTION**
June 1986 (English translation)

TR 86-13
**RADIONUCLIDE TRANSPORT IN FAST CHANNELS IN CRYSTALLINE ROCK**
Anders Rasmuson, Ivars Neretnieks
Department of Chemical Engineering
Royal Institute of Technology, Stockholm
March 1985, Revised February 1986

TR 86-14
**MIGRATION OF FISSION PRODUCTS AND ACTINIDES IN COMPACTED BENTONITE**
Börje Torstenfelt
Department of Nuclear Chemistry, Chalmers University of Technology, Göteborg
Bert Allard
Department of water in environment and society, Linköping University, Linköping
April 24, 1986

TR 86-15
**BIOSPHERE DATA BASE REVISION**
Ulla Bergström, Karin Andersson, Björn Sundblad
Studsvik Energiteknik AB, Nyköping
December 1985

TR 86-16
**SITE INVESTIGATION**
**EQUIPMENT FOR GEOLOGICAL, GEOPHYSICAL, HYDROGEOLOGICAL AND HYDROCHEMICAL CHARACTERIZATION**
Karl-Erik Almén, SKB, Stockholm
Olle Andersson, IPA-Konsult AB, Oskarshamn
Bengt Fridh, Bengt-Erik Johansson, Mikael Sehlstedt, Swedish Geological Co, Malå
Erik Gustafsson, Kenth Hansson, Olle Olsson, Swedish Geological Co, Uppsala
Göran Nilsson, Swedish Geological Co, Luleå
Karin Axelsen, Peter Wikberg, Royal Institute of Technology, Stockholm
November 1986

TR 86-17
**ANALYSIS OF GROUNDWATER FROM DEEP BOREHOLES IN KLIPPERÅS**
S Laurent, Swedish Environmental Research Institute
September 1986

TR 86-18
**TECHNOLOGY AND COSTS FOR DECOMMISSIONING THE SWEDISH NUCLEAR POWER PLANTS**
May 1986

TR 86-19
**CORRELATION BETWEEN TECTONIC LINEAMENTS AND PERMEABILITY VALUES OF CRYSTALLINE BEDROCK IN THE GIDEÅ AREA**
Lars O Ericsson, Bo Ronge, VIAK, Vällingby
November 1986

TR 86-20
**A PRELIMINARY STRUCTURAL ANALYSIS OF THE PATTERN OF POST-GLACIAL FAULTS IN NORTHERN SWEDEN**
Christopher Talbot, Uppsala University
October 1986

TR 86-21
**STEADY-STATE FLOW IN A ROCK MASS INTERSECTED BY PERMEABLE FRACTURE ZONES. CALCULATIONS ON CASE 2 WITH THE GWHRT-CODE WITHIN LEVEL 1 OF THE HYDROCOIN PROJECT**
Björn Lindbom, KEMAKTA Consultants Co, Stockholm
December 1986

TR 86-22
**DESCRIPTION OF HYDROGEOLOGICAL DATA IN SKBs DATABASE GEOTAB**
Bengt Gentzschein, Swedish Geological Co, Uppsala
December 1986

TR 86-23
**SETTLEMENT OF CANISTERS WITH SMECTITE CLAY ENVELOPES IN DEPOSITION HOLES**
Roland Pusch, Swedish Geological Co, Lund
December 1986

TR 86-24
**MIGRATION OF THORIUM, RADIUM AND Cs-137 IN TILL SOILS AND THEIR UPTAKE IN ORGANIC MATTER AND PEAT**
Ove Landström, Björn Sundblad, Studsvik Energiteknik AB, Nyköping
October 1986

TR 86-25
**ASPECTS OF THE PHYSICAL STATE OF SMECTITE-ADSORBED WATER**
Roland Pusch, Ola Karnland, Swedish Geological Co, Lund
December 1986

TR 86-26
**MODEL SHEAR TESTS OF CANISTERS WITH SMECTITE CLAY ENVELOPES IN DEPOSITION HOLES**
Lennart Börgesson, Swedish Geological Co, Lund
December 1986

TR 86-27
**HYDRAULIC TESTING IN CRYSTALLINE ROCK. A COMPARATIVE STUDY OF SINGLE-HOLE TEST METHODS**
Karl-Erik Almén*, Jan-Eric Andersson, Leif Carlsson, Kent Hansson, Nils-Åke Larsson
Swedish Geological Co, Uppsala
*Since February 1986 with SKB
December 1986

TR 86-28
**PRESSURE SOLUTION OF MINERALS IN QUARTZ-TYPE BUFFER MATERIALS**
Mikael Erlström
Swedish Geological Co, Lund
December 1986

TR 86-29
**QUANTITATIVE ESTIMATES OF SEDIMENTATION RATES AND SEDIMENT GROWTH IN TWO SWEDISH LAKES**
Sverker Evans
Studsvik Energiteknik AB, Nyköping
October 1986

TR 86-30
**RECIPIENT EVOLUTION - TRANSPORT AND DISTRIBUTION OF ELEMENTS IN THE LAKE SIBBO-TROBBOFJÄRDEN AREA**
Björn Sundblad
Studsvik Energiteknik AB, Nyköping
December 1986

# AUTHORS OF SKB TECHNICAL REPORTS 1986 IN ALPHABETICAL ORDER

| AUTHORS | TECHNICAL REPORT NO |
|---|---|
| Ahlbom, Kaj<br>Swedish Geological Co, Uppsala | 05 |
| Allard, B<br>University of Linköping | 02, 14 |
| Almén, Karl-Erik<br>SKB | 16, 27 |
| Andersson, Jan-Eric<br>Swedish Geological Co, Uppsala | 27 |
| Andersson, Karin<br>Studsvik Energiteknik AB, Nyköping | 15 |
| Andersson, Olle<br>IPA-Konsult AB, Oskarshamn | 16 |
| Andersson, Peter<br>Swedish Geological Co, Uppsala | 05 |
| Axelsen, Karin<br>Royal Institute of Technology | 16 |
| Bergström, Ulla<br>Studsvik Energiteknik AB, Nyköping | 15 |
| Bjarnason, Bjarni<br>Luleå University of Technology | 11 |
| Bjergbakke, Erling<br>Risö National Laboratory, Roskilde | 04 |
| Börgesson, Lennart<br>Swedish Geological Co, Lund | 26 |
| Carlsson, Leif<br>Swedish Geological Co, Uppsala | 27 |
| Christensen, Hilbert<br>Studsvik Energiteknik AB, Nyköping | 04 |
| Ekman, Lennart<br>Swedish Geological Co, Uppsala | 05 |
| Ericsson, Lars O<br>VIAK, Vällingby | 19 |
| Eriksen, Trygve<br>Royal Institute of Technology, Stockholm | 04 |
| Erlström, Mikael<br>Swedish Geological Co, Lund | 28 |
| Evans, Sverker<br>Studsvik Energiteknik AB, Nyköping | 29 |
| Fridh, Bengt<br>Swedish Geological Co, Malå | 16 |
| Gentzschein, Bengt<br>Swedish Geological Co, Uppsala | 08, 22 |
| Gustavsson, Erik<br>Swedish Geological Co, Uppsala | 05, 16 |
| Hansson, Kent<br>Swedish Geological Co, Uppsala | 16, 27 |
| Johansson, Bengt-Erik<br>Swedish Geological Co, Malå | 16 |
| Larsson, Nils-Åke<br>Swedish Geological Co, Uppsala | 27 |
| Laurent, Sif<br>Swedish Environmental Research Institute | 17 |
| Lindbom, Björn<br>KEMAKTA Consultants Co, Stockholm | 21 |
| MacKenzie, A B<br>Scottish Universities Research Reactor Centre | 01 |
| Neretnieks, Ivars<br>Royal Institute of Technology | 13 |
| Nilsson, Göran<br>Swedish Geological Co, Luleå | 16 |
| Nordstrom, D Kirk<br>US Geological Survey, Menlo Park | 03 |
| Olkiewicz, Andrzej<br>Swedish Geological Co, Uppsala | 06 |
| Olofsson, U<br>Chalmers University of Technology, Gothenburg | 02 |
| Olsson, Olle<br>Swedish Geological Co, Uppsala | 16 |
| Puigdomenech, Ignasi<br>Royal Institute of Technology, Stockholm | 03 |
| Pusch, Roland<br>Swedish Geological Co, Lund | 23, 25 |
| Rasmuson, Anders<br>Royal Institute of Technology | 13 |
| Ronge, Bo<br>VIAK, Vällingby | 19 |
| Scott, E S<br>Scottish Universities Research Reactor Centre | 01 |
| Sehlstedt, Mikael<br>Swedish Geological Co, Malå | 16 |
| Sehlstedt, Stefan<br>Swedish Geological Co, Luleå | 07 |
| Smellie, J A T<br>Swedish Geological Co, Uppsala | 01, 05 |
| Stejskal, Vladislav<br>Swedish Geological Co, Uppsala | 06 |
| Stenberg, Leif<br>Swedish Geological Co, Luleå | 07, 09 |
| Stephansson, Ove<br>Luleå University of Technology | 11 |
| Sundblad, Björn<br>Studsvik Energiteknik AB, Nyköping | 15, 24, 30 |
| Talbot, Christopher<br>Uppsala University | 20 |
| Torstenfelt, Börje<br>Chalmers University of Technology, Gothenburg | 14 |
| Tullborg, Eva-Lena<br>Swedish Geological Co, Göteborg | 05, 10 |
| Wikberg, Peter<br>Royal Institute of Technology | 16 |

# SKB ANNUAL REPORT 1986
# Part IV

## Summaries of Technical Reports Issued During 1986

**SKB Technical Report 86-01**

# I: AN ANALOGUE VALIDATION STUDY OF NATURAL RADIONUCLIDE MIGRATION IN CRYSTALLINE ROCK USING URANIUM-SERIES DISEQUILIBRIUM STUDIES
# II: A COMPARISON OF NEUTRON ACTIVATION AND ALPHA SPECTROSCOPY ANALYSES OF THORIUM IN CRYSTALLINE ROCKS

J A T Smellie, Swedish Geological Co
E S Scott and A B MacKenzie, Scottish Universities Research Reactor Centre
February 1986

**ABSTRACT**

As part of a jointly-funded programme of research between the Swedish Nuclear Fuel and Waste Management Co (SKB) and the Swiss Nationale Genossenschaft für die Lagerung radioaktiver Abfälle (NAGRA), drillcore lengths intersecting suitable water-conducting fracture zones were chosen from three different hydrogeological environments; two in Switzerland (Böttstein and Grimsel) and one in Sweden (Kråkemåla), all located in granite bedrock. The samples represent profiles from the intersected fracture face into the bedrock. Sections cut from the profiles have been investigated using the uranium decay series ($^{238}U$ - $^{234}U$ - $^{230}Th$ - $^{226}Ra$), in conjunction with REE and $Fe^{2+}/Fe^{3+}$ analysis, alpha-track autoradiography, fission-track analysis and detailed mineralogy. The study has shown that radioactive disequilibria resulting from rock-water interactions were observed in two of the cores. These indicated uranium migration along distances of 40 cm or more on a timescale of $10^6$ years in conjunction with thorium immobility under the same conditions. Fracture surface minerals showed a high affinity for radionuclide retardation and a limit of about 3 cm is suggested for the migration of radionuclides from fracture fluids into the saturated rock. This limit may correspond to enhanced matrix porosities resulting from earlier hydrothermal activity along the same channels.

The concentrations of Th in samples of crystalline rock from the three drillcore sections were analysed independently by instrumental neutron activation analysis and by chemical separation and alpha spectroscopy. The two methods show good general agreement over an approximate concentration range of 1 to 100 ppm Th. Variations in results between the two methods are not of a systematic nature and probably arise from sample heterogeneity. The results confirm the reliability of both methods and provide a useful comparison of the standards and reference materials used. The study indicated that, in cases where Th isotopic information is not required, the simpler and ore rapid neutron activation analysis provides a satisfactory method.

**SKB Technical Report 86-02**

# FORMATION AND TRANSPORT OF AMERICIUM PSEUDOCOLLOIDS IN AQUEOUS SYSTEMS

U Olofsson
Chalmers University of Technology, Gothenburg, Sweden
B Allard
University of Linköping, Sweden
March 26, 1986

**ABSTRACT**

The sorption of americium on colloidal quartz and montmorillonite has been studied using a batch technique. The influence of physical and chemical parameters such as storage time (6 h - 6 months), the amount of sorbent material (0.2 g, 0.4 g, 0.8 g per 20 ml solution) and the pH value (6 - 10) has been investigated.

Americium appeared to be distributed between all available surfaces in the system (particles and vessel walls). Distribution coefficients, defined as the ratio of the amount of americium per mass of colloidal matter and the concentration in the solution phase, were estimated to be of the same order of magnitude as obtained in measurements on crushed material of much larger particle sizes.

In the presence of sorbents (alumina or granite) the removal of americium from the solution was enhanced. This can be due to either the desorption of the americium from the particle phase and resorption on all available surfaces or the sorption of the whole colloidal aggregates on the sorbents.

Column experiments, with alumina or granite packing, have also been carried out in order to study the transport of americium sorbed on colloidal matter (here denoted as americium pseudocolloids). No breakthrough was observed after eluating with large

volumes of aqueous phase. However, a minor fraction of the americium passed through the column without significant retention, especially under conditions with high flow rate.

chemical equilibrium computations do show an excellent agreement between the redox potential measured by the platinum electrode and the dissolvedjsulfide developed from total sulfide determinations. This may be one of the first examples of a correlation of this type. Furthermore, redox calculations indicate that there are no significant differences between the two computer programs that were used.

**SKB Technical Report 86-03**

## REDOX CHEMISTRY OF DEEP GROUNDWATERS IN SWEDEN

D Kirk Nordstrom
US Geological Survey, Menlo Park, USA
Ignasi Puigdomenech
Royal Institute of Technology, Stockholm, Sweden
April 1, 1986

**ABSTRACT**

This report examines the redox chemistry from groundwater analyses collected during the Swedish study site investigations (1982–1983) for developing site guidelines for disposal of highlevel radioactive waste. The redox species determinations reported from the study site investigations were evaluated by chemical equilibrium computations using both the WATEQ3 and the EQ3NR computer programs. The results of the calculations indicate that there were major problems with ample collection, sample preservation, and, perhaps in some cases, sample analysis for redox species, and definitive results regarding the behaviour of redox species in these groundwaters is very difficult. Hence, it is not possible to reach conclusions about the redox state of these groundwaters in terms of heterogeneous equilibrium or kinetic processes. Some conclusions, however, can be reached regarding the types of redox species that can be encountered, and possibly their relative importance in determining redox conditions of these groundwaters, and about the usefulness of equilibrium computations. For example, elevated concentrations of dissolved sulfide and dissolved organic carbon were encountered in the groundwaters. These species play at least as important a role, if not a more important role, than the reactions involving iron. At this time it is not known the source of the dissolved sulfide nor the source of the organic carbon, but it is likely that the sulfide is an integral part of the natural conditions that exist at repository depths. The organic carbon could easily be contamination from several possible sources including surface water and drilling fluid. The results of the

**SKB Technical Report 86-04**

## HYDROGEN PRODUCTION IN ALPHA-IRRADIATED BENTONITE

Trygve Eriksen
Royal Institute of Technology, Stockholm, Sweden
Hilbert Christensen
Studsvik Energiteknik AB, Nyköping, Sweden
Erling Bjergbakke
Risö National Laboratory, Roskilde, Denmark
March 1986

**ABSTRACT**

The hydrogen production in α-irradiated (dose rate 73 rad $S^{-1}$) compacted water-saturated bentonite ($\varrho$ = 2.12 g · $cm^{-3}$) has been determined experimentally using a gaschromatographic technique. Hydrogen concentration in the clay pore water and hydrogen diffusion out of the irradiated bentonite have been calculated using a homogeneous reaction model.

The calculated amount of hydrogen diffusing out of the bentonite depends on the $Fe^{2+}$ and $HCO_3^-$ concentration in the pore water.

Agreement between experimental and calculated results can be obtained if it is assumed that a 20 μm layer of water is formed between the clay and the α-source.

SKB Technical Report 86-05

# PRELIMINARY INVESTIGATIONS OF FRACTURE ZONES IN THE BRÄNDAN AREA, FINNSJÖN STUDY SITE

Kaj Ahlbom, Peter Andersson, Lennart Ekman, Erik Gustafsson, John Smellie, Swedish Geological Co, Uppsala
Eva-Lena Tullborg, Swedish Geological Co, Göteborg
February 25, 1986

**ABSTRACT**

The investigations in the Brändan area have defined two major fracture zones.

Zone 1, the Brändan fracture zone, is 20 m wide, strikes NNE and dips 75 degrees towards east. Characteristic for the zone is a high frequency of coated and sealed fractures, 12 and 50 fr/m respectively. Infillings of hematite and asphaltite are common. Hydraulic conductivity determined by single-hole water injection tests varies between $1.2 \cdot 10^{-6}$ and $4.8 \cdot 10^{-5}$ m/s measured at vertical depths between 57 and 76 m.

Zone 2, a subhorizontal fracture zone, is about 70 m wide and strikes N-S with a westerly dip of 17 degrees. The zone is defined in all 4 cored boreholes in the Brändan area, which gives a minimum lateral extent of about 500 m. The boreholes intersect the zone at depths ranging from 100 to 300 m. Characteristic for Zone 2 are sections with mylonite and breccia. Within the zone, the frequency os sealed fractures is high in all boreholes, about 40 fr/m compared to 14 fr/m in the country rock. The frequency of coated fractures varies greatly between different boreholes, 3 to 9 fr/m compared to 2 to 5 fr/m in the country rock. In spite of low frequency of coated fractures for the Zone 2 in some boreholes, the hydraulic conductivity is high in all boreholes. Several values higher than $10^{-4}$ m/s have been observed. Interference tests have established hydraulic connections in Zone 2 between four investigation boreholes at distances up to 450 m.

Saline water of about 5000 mg/l of chlorine is found below the Zone 2. The saline water encountered at such shallow levels indicates that the subhorizontal Zone 2 functions as a hydraulic barrier against draining out and replacement of the saline water by non-saline groundwater. Zone 2 is recommended for the detailed investigations planned for the Fracture Zone Project.

SKB Technical Report 86-06

# GEOLOGICAL AND TECTONIC DESCRIPTION OF THE KLIPPERÅS STUDY SITE

Andrzej Olkiewicz, Vladislav Stejskal
Swedish Geological Company, Uppsala
October 1986

**ABSTRACT**

The Klipperås study site is situated 45 km WNW of Kalmar in south-eastern Sweden. The site is situated between two regional NW-SE oriented lineaments. The site itself does not show any distinct lineaments. The site is flat, covered by till and with few outcrops. The precambrian rocks of this area are thought to be postorogenic in relation to the svecokarelien orogeny. Almost all knowledge on the bedrock is obtained from 14 drill cores and from geophysical surface measurements. According to the statistics based upon the cores, the bedrock consists of 85% granites, 7% greenstones, 5.5% porphyries, 1.5% mafic dykes and 1% aplites.

The granites are normally grey-red, medium grained and massive. They are, in a tectonically undisturbed condition, strongly magnetic.

Closely associated with the granites are aplite dykes. The greenstones are schistos and represent a number of originally different rocks. Some of them are xenolithes, others are dykes. The latter are often associated with dyke porphyries in composite dykes.

The dyke porphyries have variable chemical compositions. Their width is usually 10 m and the directions group between W-WNW. The youngest rocks comprise a number of different, rather wellpreserved mafic dykes. Their direction varies from N to NE. Their width varies from ca 1 m to 10 m.

The geophysical surface measurements display many discontinuities of variable intensity. They are oriented in two main directions, N-S and NE-SW. the boreholes confirm the existence of discontinuities either as fracture zones or dykes. The dip of the fracture zones and the dykes vary from steep to 75°. The horizontal fracture zone at the depth of 780 m is an exception.

The widest investigated fracture zone has a width of 30 m. Most of the fracture zones are associated with greenstones and most of the elastic deformations and joints have a vertical orientation.

The zones have moved several times. At least four

generations of fractures occur. The tectonic movements have affected the bedrock far beyond the zones. The bedrock is divided into blocks of different sizes which are displaced relative to each other.

thin overburden, small quantities of clay in the overburden and distinct fracture zones, are examples of such favourable physical conditions.

**SKB Technical Report 86-07**

## GEOPHYSICAL INVESTIGATIONS AT THE KLIPPERÅS STUDY SITE

Stefan Sehlstedt, Leif Stenberg
Swedish Geological Company, Luleå
July 1986

**ABSTRACT**

The Swedish Nuclear Fuel and Waste Management Co (SKB) currently performs investigations in crystalline bedrock formations in Sweden to find a suitable location for a repository for storage of high level radioactive waste.

The Klipperås study site is situated 45 km west-north-west of Kalmar, Småland County, southern Sweden. From ground surface geophysical measurements, suspected fracture zones were located at the Klipperås study site. The methods used were, the following:
- Horizontal Loop EM (HLEM or slingram)
- Magnetic measurements (proton magnetometer)

The zones indicated became drilling targets for a slim borehole (56 mm) drilling program. After the drilling, each borehole was surveyed by 10 different geophysical methods. These were:
- Borehole orientation
- Natural gamma radiation
- Resistivity, normal and lateral
- Single point resistance
- Self potential (SP)
- Sonic
- Magnetic susceptibility
- Temperature/liquid resistivity

The logging was performed in 14 slim boreholes, totally 6931 metres. All strong indications, suspected to be zones could be identified as fracture zones or as mafic dykes in the boreholes from geological core mapping and borehole logging. The investigation shows that surface geophysical measurements and borehole logging is a powerful combination to identify tectonic features, i.e. fracture zones, if the physical conditions are favourable. Magnetic bedrock, rather

**SKB Technical Report 86-08**

## HYDROGEOLOGICAL INVESTIGATIONS AT THE KLIPPERÅS STUDY SITE

Bengt Gentzschein
Swedish Geological Company, Uppsala
June 1986

**ABSTRACT**

The Klipperås study site is located in the south-east part of Sweden, c. 300 km south of Stockholm. The area has a flat topography with altitudes between c. 166 and 206 meter above sea level.

From water balance studies annual mean values for the study site was estimated: precipitation 760 mm, evaporation 508 mm and runoff 252 – 263 mm.

The ground-water table was registered in 21 boreholes within the study site. 17 boreholes were sealed-off by inflatable packers and the ground-water head above the packers was continuously monitored. The measured ground-water levels in the boreholes at Klipperås varied between c. 196 m and 172 m above the sea level. The variation width of the ground-water levels were relatively small, less than 1 meter in most boreholes.

In seven of the boreholes, with depths varying between 564 m and 958 m, single-hole water injection tests were performed. The water injection tests resulted in relatively high values of hydraulic conductivity in the upper parts of the boreholes, generally between $10^{-9}$ m/s and $10^{-5}$ m/s. High conductivity values were also obtained at depths, but below 500 metres conductivity values from $10^{-11}$ to $10^{-9}$ dominate.

The bedrock in the Klipperås site was divided into two hydraulic units, rock mass and local fracture zones. The depth-dependence of the hydraulic conductivity in the two hydraulic units was calculated from regression analysis. The regression analysis shows that the hydraulic conductivity of the rock mass and the local fracture zones at 500 m depth are $4 \times 10^{-10}$ m/s and $8 \times 10^{-8}$ m/s respectively. The topographic relief of the area implies that there is a low hydraulic gradient in the bedrock. This has also been confirmed by piezometric measurements in the boreholes. With the exception of one measurement section (of totally 241) the pressure differences obtained are lower than 5 m water column.

SKB Technical Report 86-09

# GEOPHYSICAL LABORATORY INVESTIGATIONS ON CORE SAMPLES FROM THE KLIPPERÅS STUDY SITE

Leif Stenberg
Swedish Geological Company, Luleå
July 1986

**ABSTRACT**

Swedish Nuclear Fuel and Waste Management Co (SKB) currently performs investigations in crystalline bedrock formations in Sweden to find a suitable location for a repository for storage of high level radioactive waste.

The Klipperås study site is situated 45 km west-north-west of Kalmar in southern Sweden.

As part of the site investigation program, geophysical measurements have been performed both on the ground surface and in the boreholes. To evaluate the results of the measurements, it is essential that data on the physical properties of the bedrock and its relation to various geological conditions is available. For this purpose, the density, magnetic susceptibility and remanence, resistivity, induced polarization and porosity were all obtained from measurements on drill core samples in the laboratory.

The relationship between the resistivity and the porosity was determined for the core samples from Klipperås. The constants $aR_w$ (effective electrolyte resistivity) and m in Archies law were determined. The coefficient m varied between 1.4 and 2, and the effective electrolyte resistivity varied between 0.1 and 2.9 ohm m. The best fit with data, i.e. the highest correlation coefficient, was obtained with $aR_w = 0.1$ and $m = 2$. The effective electrolyte resistivity, $aR_w$, decreased by several orders (up to 500 times) compared with the resistivity of the solution used for saturation of the samples ($R_w = 50$ ohm m). It is concluded that surface conduction along pore-grain interfaces contribute to the electric conduction through the sample. This effect is most significant in the low porosity range, say less than about 1 percent.

In summary, great care must be exercised in the calculation of the apparent fracture porosity from in-situ logging data. Large errors may occur if surface conduction is neglected, especially in the low porosity range. The apparent porosity, calculated from sections of unfractured, intact rock may be calibrated with porosity determinations made on core samples.

SKB Technical Report 86-10

# FISSURE FILLINGS FROM THE KLIPPERÅS STUDY SITE

Eva-Lena Tullborg
Swedish Geological Company, Göteborg
July 1986

**ABSTRACT**

The Klipperås study site is located within the Småland-Värmland granitoid belt in southern Sweden. The area investigated can be subdivided into blocks with different hydraulic character and fracture frequency of the rocks. A fissure filling study has been carried out within the area. This includes identification of the minerals, mineral frequency, textures within the fissures and isotope analyses of calcites.

Four generations of fissure fillings, within the time space c. 1600 M.a. to present, has been distinguished. These are I) quartz; II) epidote + muscovite and adularia + hematite; III) calcite + chlorite +/hematite; IV) calcite, clay minerals and Fe-oxyhydroxide.

It is observed that the surface water affects the uppermost part of the bedrock resulting in calcite dissolution, break down of pyrite and precipitation of Fe-oxyhydroxide. It is also obvious from the fracture calcite frequency that calcite dissolution is more intensive close to and within the fracture zones. There, Fe-oxyhydroxide can be found down to at least 400 m depth. This gives valuable information about the physico-chemical character of the groundwater within the bedrock.

Several fracture zones have been reactivated. It is also suspected that relatively late movements have taken place causing crushing of the rock and only a slight cementation of the crushed material is visible.

Some of the fracture zones corresponds to mafic dikes. These zones exhibit lower hydraulic conductivity than other zones due to fracture sealing by clay minerals but also by chlorite and calcite. In accordance with this the stable isotope analyses of calcites show that fractures within the basic dikes are less affected by low temperature-meteoric water than fracture calcites in the surrounding rocks in Klipperås.

SKB Technical Report 86-11

# HYDRAULIC FRACTURING ROCK STRESS MEASUREMENTS IN BOREHOLE Gi-1, GIDEÅ STUDY SITE, SWEDEN

Bjarni Bjarnason and Ove Stephansson
Division of Rock Mechanics,
Luleå University of Technology
April 1986

**ABSTRACT**

This report presents the results from rock stress measurements conducted by the hydraulic fracturing method at Gideå in Northern Sweden. The Gideå area is one of the sites selected for extensive investigation within the Swedish programme for final disposal of radioactive waste in deep seated repositories in crystalline rock. The measurements were conducted in a vertical borehole within one of the repository blocks in the area. Successful measurements were conducted at 25 test sections, from the ground surface down to a maximum depth of 500 m. The results show moderate rock stresses and no extreme values are recorded. The minimum horizontal stress, $\sigma_h$, increases with depth at a rate close to that of the theoretical vertical stress, $\sigma_v$, representing a stress field close to isotropic in the vertical plane containing $\sigma_h$ and $\sigma_v$. At depth around 300 m there is a change in the gradient of the minimum horizontal stress.

The maximum horizontal stress, $\sigma_H$, is determined according to the second breakdown method, applying tensile strength values from the field measurements. The maximum stress is low at surface but increases at a higher rate than the minimum horizontal stress, maintaining a nearly constant ratio of 1.6 to the minimum horizontal stress at all depths. The average orientation of the maximum horizontal stress, determined from hydrofracture orientations, is N67°E.

SKB Technical Report 86-12

# PLAN 86 - COST FOR MANAGEMENT OF THE RADIOACTIVE WASTE FROM NUCLEAR POWER PRODUCTION

June 1986

**ABSTRACT**

The Swedish nuclear power utilities are responsible for adopting such measures as are necessary in order to ensure the safe management and disposal of spent nuclear fuel and radioactive waste from the Swedish nuclear power reactors. In order to fulfil this responsibility, the nuclear power utilities are planning, building and operating a number of different facilities and systems. The power utilities have commissioned SKB to execute this work.

This report presents a calculation of the costs for implementing all of these measures. The cost calculations are based on a scenario for management and disposal of the radioactive waste products, which is described in the report.

Since disposal of the high-level (long-lived) waste will not commence until some time into the 21st century, continued R&D activities may reveal new methods, that can affect both system design and costs. This is expected to lead to overall simplifications in the design.

The facilities and systems that exist or have been planned are:

- Transportation system for radioactive waste products.
- Central interim storage facility for spent nuclear fuel, CLAB.
- Encapsulation station for spent nuclear fuel.
- Final repository for spent fuel and long-lived waste.
- Final repository for reactor waste and decommissioning waste, SFR.

The cost calculations also include costs for research and development and for decommissioning and dismantling the reactor plants etc.

The total future costs of the Swedish waste management system, starting in 1987, have been calculated to be SEK 39 billion in January 1986 prices, including contingency allowances for unforeseen costs. These costs will be incurred over a period of about 60 years. SEK 5.3 billion has been spent through 1986.

# RADIONUCLIDE TRANSPORT IN FAST CHANNELS IN CRYSTALLINE ROCK

Anders Rasmuson, Ivars Neretnieks
Department of Chemical Engineering
Royal Institute of Technology, Stockholm
March 1985, Revised February 1986

**ABSTRACT**
Recent field investigations in crystalline rock give strong indications that water flows in largely isolated channels in fissured rock. The present paper sets out to investigate radionuclide transport in such channels including diffusion into the rock matrix. It is shown that the uptake from a cylindrical hole in a matrix is much more effective, per unit contact area, than a flat surface (semi-infinite solid). Comparison of diffusion from cylindrical and slit-formed channels shows that the differences in interfacial flux are minor. A slit-formed channel may, therefore, be approximated by a cylindrical one. Diffusional transport in the matrix is then treated as 1-D instead of 2-D which gives a considerable numerical simplification. A simple estimate of the "penetration depth" into the cylindrical region, i.e. the location of the diffusional front, is proposed. Using the integrated finite difference method a number of radionuclide transport calculations are performed for the case of flow and dispersion in a cylindrical channel coupled to diffusion and sorption in the matrix.



# MIGRATION OF FISSION PRODUCTS AND ACTINIDES IN COMPACTED BENTONITE

Börje Torstenfelt
Department of Nuclear Chemistry, Chalmers University of Technology, Göteborg

Bert Allard
Department of water in environment and society, Linköping University, Linköping
April 24, 1986

**ABSTRACT**
The migration in compacted bentonite, i.e., the diffusivity, of the fission products strontium, technetium, iodine, and cesium and the actinides thorium, protactinium, uranium, neptunium, plutonium and americium have been studied in laboratory experiments.

The clay used in the experiments was a sodium bentonite, Wyoming Bentonite MX-80, compacted to a density of 2000 kg/m$^3$. The aqueous phase was synthetic groundwater representative of Swedish deep granitic groundwaters, and was preequilibrated with the clay. The influence of complex-forming and redox controlling agents on the diffusion of fission products was studied by mixing the clay with small amounts of the chemical reagents PbO, $KMnO_4$ or powdered iron, or the minerals chalcopyrite/pyrite or cinnabar. Furthermore, the effect of mixing the clay with 1% $Fe_3(PO_4)$ or 0.5% iron powder on the diffusion of uranium and neptunium was examined. the diffusion of uranium and americium after addition of 600 mg/l of $HCO^{-3}$ and the diffusion of uranium after addition of 10 mg/l of humic acid to the aqueous phase was studied, as well.

The diffusivity of strontium was on the order of $10^{-11}$ m$^2$/s. For cesium and technetium (as pertechnetate) under oxidizing conditions the diffusivities are on the order of $10^{-12}$ m$^2$/s and the other one-tenth slower, $10^{-13}$ m$^2$/s, contributing to the observed overall apparent diffusivity.

The apparent diffusivities measured for the penta- and hexavalent actinides-protactinium: Pa(V), neptunium: Np(V), uranium: U(VI) were between 3.7 and 6.5 x $10^{-15}$ m$^2$/s. The metallic iron added to the clay lowered the neptunium diffusivity but had no effect on the uranium diffusivity. While adding bicarbonate to the aqueous phase may have had the effect of decreasing the americium mobility, the addition of bicarbonate or humic acid had no significant effect on

the mobility of uranium.

A small fraction of the uranium, neptunium, and plutonium had diffusivities on the order of $10^{-12}$ $m^2/s$, which is that expected for a non-sorbing species transported through the clay. Uranium and neptunium seem to diffuse by more than one mechanism or species - one fraction with a mobility similar to what was measured for the penta- and hexavalent actinides and the other fraction with a mobility similar to what was observed for the tetravalent actinides.

**SKB Technical Report 86-15**

## BIOSPHERE DATA BASE REVISION

Ulla Bergström, Karin Andersson, Björn Sundblad
Studsvik Energiteknik AB, Nyköping
December 10, 1985

### ABSTRACT

The turnover of long-lived radionuclides in the biosphere has previously been modelled and the exposure to man calculated. The nuclides were long-lived actinides and fission products leaking from a deep rock repository for spent nuclear fuel. The data base for these calculations has been updated in the present work and in addition a number of nuclides that were not included in the earlier work have been treated. Some of the nuclides treated here are not long-lived enough to be expected to leak into the biosphere from a repository for spent fuel. These nuclides may, however, leak from more shallow repositories for low- and intermediate-level waste.

The doses, to critical group individuals and to populations, obtained from continuous unit releases to the biosphere under certain decided conditions have been calculated and called conversion factors. This report gives conversion factors for most of the nuclides appearing in spent fuel.

The model in this case consists of several compartments. Some are naturally of more importance than others for the calculation of the doses to critical groups. These compartments are the surface water and the upper soil reservoir, while in the global area it is only the well-mixed sea reservoir. Accordingly efforts have been concentrated onto the surface water and the upper soil reservoir.

**SKB Technical Report 86-16**

## SITE INVESTIGATION EQUIPMENT FOR GEOLOGICAL, GEOPHYSICAL, HYDROGEOLOGICAL AND HYDROCHEMICAL CHARACTERIZATION

Karl-Erik Almén, SKB, Stockholm
Olle Andersson, IPA-Konsult AB, Oskarshamn
Bengt Fridh, Bengt-Erik Johansson, Mikael Sehlstedt, Swedish Geological Co, Malå
Erik Gustafsson, Kenth Hansson, Olle Olsson, Swedish Geological Co, Uppsala
Göran Nilsson, Swedish Geological Co, Luleå
Karin Axelsen, Peter Wikberg, Royal Institute of Technology, Stockholm
November 1986

### ABSTRACT

An extensive program for the development of equipment and instrumentation for investigations in geological formations is ongoing within the SKB research and development program. Instruments developed and used for geological, geophysical, hydrogeological and hydrochemical characterizations of a formation are presented.

Most of the investigations are performed within the site investigation program, which is briefly mentioned. In total about 60,000 m of cored 56 mm boreholes have been drilled and investigated at eight study sites. A summarized description of the main investigation methods is included.

Instruments for geophysical investigations contains equipment for ground measurements as well as for borehole logging. The geophysical investigations including the borehole radar measurements, which has been very successful, are indirect methods for the geological and hydrogeological characterization of the rock formation.

Great effort has been laid on the development of hydrogeological instruments for hydraulic tests and groundwater head measurements. An umbilical hose system and a pipe string system for injection tests are used to determine the hydraulic conductivity. Groundwater head in one or several sections are monitored with GRUND and PIEZOMAC II respectively. In order to obtain hydrochemical investigations with high quality, a complete system for sampling and analysis of ground water has been developed, including a mobile water laboratory.

A dilution probe have been constructed for the determination of undisturbed groundwater flow. The development of this instrument is still in progress.

SKB Technical Report 86-17

## ANALYSIS OF GROUNDWATER FROM DEEP BOREHOLES IN KLIPPERÅS

S Laurent, Swedish Environmental Research Institute
September 1986

**ABSTRACT**

Groundwater from three boreholes in granitic rock at an investigation site in Klipperås has been sampled and analysed. This is part of a larger program of geological, geophysical and hydrogeological investigations aimed at finding a suitable site for a high level radioactive waste repository.

Water-bearing levels in the boreholes down to the deepest at 777 m were selected. Prior to sampling, the water-bearing level is isolated between packer sleeves. The water is then pumped to the surface where sensitive parameters such as redox potential, pH, sulphide and oxygen content are measured electrochemically on the flowing water in a system isolated from the air. Water, filter and gas samples are sent to several laboratories for further analysis.

During the site investigations i Klipperås a new mobile field laboratory was introduced with the capability to measure certain sensitive parameters such as Eh and pH downhole and to perform rapid, on site analyses of several other groundwater constituents.

The present report is a presentation of the results of the groundwater analyses. The reliability of the results is discussed but there is no evaluation in relation to geology and hydrogeology. This report presents the basic results from the groundwater analyses to be further evaluated by experts in different fields.

SKB Technical Report 86-18

## TECHNOLOGY AND COSTS FOR DECOMMISSIONING THE SWEDISH NUCLEAR POWER PLANTS

May 1986

**ABSTRACT**

When a nuclear power plant is retired from service, parts of it are radioactive and must be dismantled and disposed of in a safe manner. The procedures and costs involved in decommissioning nuclear power plants are described in this study.

The study shows that, from the viewpoint of radiological safety, a nuclear power plant can be dismantled immediately after it has been shut down and the fuel has been removed, which is estimated to take about one year. Most of the equipment that will be used in decommissioning is already available and is used routinely in maintenance and rebuilding work at the nuclear power plants. Special equipment need only be developed for dismantlement of the reactor vessel and for demolishing of heavy concrete structures. Examples of existing equipment that can be used for this after minor modifications are given in the study.

The dismantling of a nuclear power plant can be accomplished in about five years, with an average labour force of about 200 men. The maximum labour force required for Ringhals 1 has been estimated at about 500 men during the first years, when active systems are being dismantled on a number of fronts in the plant. During the last years when the buildings are being demolished, approximately 50 men are required.

In order to limit the labour requirement and the dose burden to the personnel, the material is taken out in as large pieces as possible. This means, for example, that pipes are cut into lengths of 2-5 m and packed directly in refuse containers, and that certain items of equipment are taken out and transported intact.

The study has focused on immediate dismantling. By waiting ten years or so, certain advantages can be gained due to the fact that the radioactivity in the plant declines. In the case of immediate dismantling, the same effect can be achieved by system decontamination. A number of other factors also influence the choice of time of dismantling, for example availability of personnel, need for the site and the availability of a final repository. Non-technical factors will also be of importance. The choice of time of dismantling can therefore vary for different plants.

The cost of decommissioning a boiling water reactor (BWR) of the size of Ringhals 1 has been estimated to be about MSEK 540 in January 1986 prices, and for a pressurized water reactor (PWR, Ringhals 2) about MSEK 460. The costs for the other Swedish nuclear power plants lie in the range of MSEK 410-760. These are the direct costs for the decommissioning work, to which must be added the costs of transportation and disposal of the decommissioning waste, about 100 000 $m^3$. These costs have been estimated to be about MSEK 600 for the 12 Swedish reactors.

Additional costs are incurred for the shutdown period from the time the nuclear power plant is finally taken out of operation until the dismantling work is begun. During this period, the fuel is transported away and some decontamination is carried out. The costs for the shutdown period are heavily dependent on the pace at which the plants are shut down and how long the shutdown period will last.

There are considerable quantities of spare parts, materials and equipment on the reactor sites that can be sold when the plants are closed down. The total value of these materials for all nuclear power plants is estimated to be MSEK 900. To this must be added the value of the land and the infrastructure.

The table below presents the costs of immediate dismantling of the Swedish nuclear power plants.

**Table S-1: Costs for decommissioning etc of the Swedish nuclear power plants (MSEK).**

| | Oskarshamn 1-3 | Barsebäck 1-2 | Ringhals 1-4 | Forsmark 1-3 |
|---|---|---|---|---|
| Shutdown operation | 190 | 110 | 310 | 190 |
| Decommissioning | 1630 | 950 | 1920 | 2090 |
| Transport and final disposal of waste | 150 | 90 | 190 | 170 |
| Total | 1970 | 1150 | 2420 | 2450 |
| Residual value | -230 | -150 | -300 | -230 |

1 SEK = 0.14 USD (May 1986)

**SKB Technical Report 86-19**

## CORRELATION BETWEEN TECTONIC LINEAMENTS AND PERMEABILITY VALUES OF CRYSTALLINE BEDROCK IN THE GIDEÅ AREA

Lars O Ericsson, Bo Ronge, VIAK, Vällingby
November 1986

### ABSTRACT

Using a statistical approach by analysing about 15 000 joint measurements the vertical fractures in the tectonic model have been verified in the area of Gideå. Two main compressional forces have implied shear directions which strike about N 60° W, N 3° E and tension directions which strike about N-S and E-W. While analysing the regional structural geology the presence of foregoing directions of lineaments have been estimated by interpretation of aerial photographs and remote sensing images.

At the well archives of the Swedish Geological Survey discharge capacities are registered for thousands of wells which are drilled in crystalline bedrock. The specific capacity corresponds to a generalized value for the transmissivity in the surroundings of the well.

By classifying wells and injection tests in core drillings, in the region of Gideå, to shear zones, tension fractures and blocks lying between, the transmissivity has been evaluated from a statistical point of view. The vital importance of the tension fractures regarding the permeability has been verified.

Tension fractures thus represent the most important water bearing zones in bedrock. However, the shear zones constitute the most conspicuous lineaments in the landscape and they are comparatively easy to observe. In hydrogeological investigations it is therefore essential to make a proper methodic surveying of fissures, fractures and foliation in the bedrock.

**SKB Technical Report 86-20**

## A PRELIMINARY STRUCTURAL ANALYSIS OF THE PATTERN OF POST-GLACIAL FAULTS IN NORTHERN SWEDEN

Christopher Talbot, Uppsala University
October 1986

**ABSTRACT**

Subvertical displacements of up to about 25 m in the 8 to 9000 year old glacial topography of northern Scandinavia are obvious along 500 km of discontinuous NNE trending fault scarps. Strikeline constructions for these scarps on maps, together with structural analysis of the rare exposures of Precambrian bedrock along them, suggest <1 km thick thrust flakes extruded by oblique transpression along pre-existing steep ESE dipping mega-shears.

Such megalineaments are part of a cubic pattern of ductile shears, cataclasites, recrystallised pseudotachylites and fractures that have reactivated the 1.6-2Ga Proterozoic crustal fabric at various times. Oblique-slip slickensides, post-glacial pop-up and jostle-up horsts, short post-glacial scarps, and sections of sidewalls to the NNE trending thrust scarps, all point to post-glacial reactivation of other components of the cubic structural pattern inherited from Proterozoic times.

The post-glacial kinematics inferred from the structures suggest horizontal NW or WNW compression with lateral relief to the NE at depth below surficial upward relief. These kinematics are sufficiently similar to the kinematics throughout Europe north of the Alps to suspect the neotectonic motion of the Eurasian lithospheric plate over the last 38 or even 58(+/-2)Ma as the causative force. Large displacements appear to have occurred within a hundred years or so (?) of the last ice retreating from any particular part of northern Scandinavia. This suggests a sudden relief during glacial unloading (and melting of ground water) of plate tectonic forces accumulated during glacial loading. Recent earthquakes in the region display similar kinematics to the post-glacial fractures on a regional scale but indications of ground movement along the forested fault scarps in the lifetime of the trees (about 100 years?) is observed at only a few localities. Only geodetic strain measurements or smallearthquake monitoring will resolve whether current ductile orhseismic motion is occurring along the most obvious post-glacial scarps. Such investigations are under way.

Whether the post-glacial near-surface displacements occurred in one large increment is uncertain. However, the forty or so 0.5 - 1 million cubic metre rock falls and soil slips, slides and flows in a zone which was probably between the contemporary highest marine shoreline and ice front suggest small numbers of large earthquakes. Attention is drawn to a less obvious but more general disturbance of bedrock exposures in the same zone. Such disturbances (labelled here the Jericho syndrome) could be due to periglacial ice activity but are considered more likely to provide further evidence for considerably ground shock during major earthquakes immediately following ice retreat. Both the lengths of the post-glacial fault scarps and the displacements along them in Sweden alone indicate at least three earthquakes with magnitudes (Ms) between 7.2 & 8.2.

**SKB Technical Report 86-21**

## STEADY-STATE FLOW IN A ROCK MASS INTERSECTED BY PERMEABLE FRACTURE ZONES. CALCULATIONS ON CASE 2 WITH THE GWHRT-CODE WITHIN LEVEL 1 OF THE HYDROCOIN PROJECT

Björn Lindbom, KEMAKTA Consultants Co, Stockholm
December 1986

**ABSTRACT**

This report describes calculations within Level 1 of the HYDROCOIN project carried out on behalf of the Swedish Nuclear Fuel and Waste Management Co. (SKB). The simulations are made with GWHRT, which is a computer code based on the finite element method.

Level 1 of HYDROCOIN consists of seven well-defined test problems. This paper is concerned with Case 2, which is formulated as a generic groundwater flow situation often found in crystalline rock with highly permeable fracture zones in a less permeable rock mass. The case is two-dimensional and modelled with 8-noded, isoparametric, rectangular elements.

According to the case definition, calculations of hydraulic head and particle tracking are to be performed. The computations are carried out with varying degree of discretisation in order to analyse possible impact on the result with respect to nodal density.

Further calculations have been performed in addition to those stipulated in the case specification. They are mainly devoted to mass balance decisions and how these are affected by permeability contrasts, varying degree of spatial discretisation and distortion of finite elements. Totally seven runs have been performed.

According to the results obtained with the GWHRT-code, the distribution of hydraulic head in the domain is less sensitive to differences in nodal density than the trajectories. The hydraulic heads show similar behaviour for three meshes with varying degrees of discretisation. The particle tracking, on the other hand, seems to be more sensitive to the level of discretisation. The results obtained with a coarse and medium mesh indicate completely different solutions for one of the pathlines. The coarse mesh is too sparsely discretised for the specified problem.

The local mass balance is evaluated for seven runs. The mass balance deviation as introduced in this report seems to be considerably more sensitive to the level of discretisation than to both permeability contrasts and deformation of elements. The permeability contrasts between the rock mass and fracture zones vary from a factor of 1000 to 1 (homogeneous properties) with increments of a factor of 10. These calculations in fact give better mass balance with increasing permeability contrasts, contrary to what could be expected. However, these improvements are marginal and cannot be regarded as significant.

A minor deformation of the element mesh is introduced in the last run. The results indicate only small changes in the mass balance deviation.

A general conclusion regarding the behaviour of the GWHRT-code is that it seems to produce results that agree well with other codes that have been applied to this HYDROCOIN test case.

**SKB Technical Report 86-22**

## DESCRIPTION OF HYDROGEOLOGICAL DATA IN SKBs DATABASE GEOTAB

Bengt Gentzschein, Swedish Geological Co, Uppsala
December 1986

**ABSTRACT**

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

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

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

- Geological data
- Geophysical data
- Hydrogeological data
- Hydrochemical data

In the database background information about the investigations and results are stored on line in the VAX 750, while raw data files are stored on magnetic tapes at KRAB.

This report deals with hydrogeological data and describes the data flow from the measurements at the sites to the result tables in the database. Almost all the hydrogeological investigations were carried out by the Swedish Geological Survey, SGU, before 820701 and by Swedish Geological Co, SGAB, after that date. Thus hydrogeological data have been stored both at SGU and SGAB.

The hydrogeological investigations have been divided into five methods and each method is presented

separately in the database. In addition there are three more methods in GEOTAB. They comprise data that have been evaluated or calculated on the basis of the results from the other five methods., i.e. they constitute hydraulic conductivity values at depths for different hydraulic units of the bedrock. Thus there are eight hydrogeological methods in GEOTAB. They are:

- SHTINJ: Single Hole Transient Injection Tests
- SHSINJ: Single Hole Steady State Tests
- GRWB: Ground Water Level Registrations in Boreholes
- INTR: Interference Tests
- PIEZO: Piezometric Measurements at Depths in Boreholes
- HUFZ: Hydraulic Unit Fracture Zones
- HURM: Hydraulic Unit Rock Mass
- ROCKRM: Hydraulic Unit Rock Types in the Rock Mass

In the report the data flow of each method is described separately..

**SKB Technical Report 86-23**

## SETTLEMENT OF CANISTERS WITH SMECTITE CLAY ENVELOPES IN DEPOSITION HOLES

Roland Pusch, Swedish Geological Co, Lund
December 1986

### ABSTRACT

Settlement of canisters containing radioactive waste and being surrounded by dense smectite clay is caused by the stresses and heat induced in the clay. Consolidation by water expulsion of the clay underlying a model canister with 5 cm diameter and 30 cm length would theoretically account for a maximum finite settlement of about 70 µm in a few weeks, while shear-induced creep in the form of viscous flow under constant volume conditions would yield a settlement of only a few microns in the same time period according to a previously developed theoretical model. These predictions were checked by running a laboratory test in which a dead load of 80 kg was applied to a small cylindrical copper canister embedded in Na bentonite with a density of 2.07 $t/m^3$.

The settlement, which increased in proportion to log time, turned out to be about 6 µm in the first 2.5 months, which indicated that shear-induced creep under constant volume conditions was the major settlement-producing mechanism. This was confirmed at the end of the test when sampling showed that no consolidation had taken place. After the first loading period at room temperature, heating to 50°C and, after a 4 months long "room temperature" period, to 70°C took place. This cycling gave strong, instant settlement and upheaval because of the different thermal expansion of the interacting components of the system: the outer steel casing, the clay, and the canister. After the development of constant temperature conditions in the entire system and completion of the consolidation or expansion that followed from the thermo-mechanical interactions, the settlement proceeded at a rather high rate at 70°C, still following a log time creep law, but with somewhat stronger retardation. At room temperature, i.e. in the post-heating periods, the settlement seemed to cease, on the other hand.

The conclusion from the study is that the canister movements under isothermal conditions were in accordance with the log t-type creep settlement that was predicted on theoretical grounds. Pre-heating and low stresses may account for extraordinary retardation of the settlement.

**SKB Technical Report 86-24**

## MIGRATION OF THORIUM, URANIUM, RADIUM AND Cs-137 IN TILL SOILS AND THEIR UPTAKE IN ORGANIC MATTER AND PEAT

Ove Landström, Björn Sundblad, Studsvik Energiteknik AB, Nyköping
October 1986

### ABSTRACT

The distribution of U-238, Th-232, Th-228, Ra-226, Ra-228, Cs-137 and K-40 have been studied in soil and peat samples. Maximum Th and U values in peat were 215 and 248 ppm ash weight, respectively, with Th/U ratios closed to 1. An increase of Th and U and decrease of Th/U with depth was observed in the studied peat bog. Disequilibrium of Ra-228/Th-232 are interpreted as current or recent migration of these radionuclides i.e. indirectly of groundwater flow. The main

part of Cs-137 in two vertical profiles of the peat bog was found in the lowest zones.

Enrichment of Ra isotopes (by the plant nutrient cycle) and differentiation between Ra-228 and Ra-226 in the upper organic zone of soil profiles were observed.

SKB Technical Report 86-25

## ASPECTS OF THE PHYSICAL STATE OF SMECTITE-ADSORBED WATER

Roland Pusch, Ola Karnland, Swedish Geological Co, Lund
December 1986

**ABSTRACT**

The hydration of Na montmorillonite is currently explained in two ways, which are related to different crystal structure versions of this mineral. Wetting of the Edelman/Favejee structure takes place through formation of an ice-like hydrogen-bonded water lattice that grows from assumed, protruding hydroxyls in the basal planes, yielding interlamellar water of a density well below 1 g/cm$^3$. The hydration of the conventional Hofmann/Endell/Wilm structure instead implies that interlamellar cations hydrate and that the spatial arrangement of the water therefore depends on the location of positive clay lattice charge. The molecular arrangement may thus vary and yield a density of the interlamellar water that may be lower, equal to, or higher than that of free water.

The amount of interlamellar water depends on the microstructure of the clay. At bulk densities exceeding 1.6–1.8 t/m$^3$ it constitutes 40-80% of the total porewater content, while at densities lower than about 1.3 t/m$^3$ this percentage drops to less than 5.

One way of finding out which of the two hydrate models that is valid at room temperature would be to determine the density of interlamellar water. Reinterpretation of published data and the outcome of recent experiments using dilatometer technique all point to an average density of such water of slightly more than 0.9 g/cm$^3$, which suggests that ice-like water lattices are formed in the interlamellar space when Li and Na are adsorbed cations. External surfaces of stacks of montmorillonite flakes are concluded to have a negligible ordering influence on the porewater, which therefore has a density on the same order as free water.

SKB Technical Report 86-26

## MODEL SHEAR TESTS OF CANISTERS WITH SMECTITE CLAY ENVELOPES IN DEPOSITION HOLES

Lennart Börgesson, Swedish Geological Co, Lund
December 1986

**ABSTRACT**

The consequences of rock displacement across a deposition hole has been investigated by some model tests. The model was scaled 1:10 to a real deposition hole. It was filled with a canister made of solid copper surrounded by highly compacted water saturated MX-80 bentonite. Before shear the swelling pressure was measured by six transducers in order to follow the water uptake process. During shear, pressure, strain, force and deformation were measured in altogether 18 points. The shearing was made at different rates in the various tests.

An extensive sampling after shear was made through which the density, water content, degree of saturation, homogenization and the effect of shear on the bentonite and canister could be studied. The results from the shear tests were compared to different calculations. The relevance of the calculations and the need for improved mathematical models could then be studied.

One important conclusion from these tests was that the rate dependence is about 10% increased shear resistance per decade increased rate of shear. This resulted also in a very clear increase in strain in the canister with increased rate. The results also showed that the saturated bentonite has excellent stress distributing properties and that there is no risk of destroying the canister if the rock displacement is smaller than the thickness of the bentonite cover. The high density of the clay ($\varrho_m$ = 2.05 t/m$^3$) makes the bentonite produce such a high swelling pressure (~8 MPa) that the material will be very stiff. In the case of a large shear deformation corresponding to ~50% of the bentonite thickness the result will be a rather large deformation of the canister. A lower density would be preferable if it can be accepted with respect to other required isolating properties.

The results also showed that three-dimensional FEM calculation using non-linear material properties is necessary to simulate the shear process. The rate dependence may be taken into account by adapting the properties to the actual rate of shear but might in a later stage be included in the model by giving the material viscous properties.

**SKB Technical Report 86-27**

# HYDRAULIC TESTING IN CRYSTALLINE ROCK. A COMPARATIVE STUDY OF SINGLE-HOLE TEST METHODS

Karl-Erik Almén*, Jan-Eric Andersson, Leif Carlsson, Kent Hansson, Nils-Åke Larsson
Swedish Geological Co, Uppsala

* Since February 1986 with SKB
December 1986

## ABSTRACT

Swedish Geological Company (SGAB) conducted a literature survey on hydraulic testing in crystalline rock and carried out singlehole hydraulic testing in borehole Fi 6 in the Finnsjön area of central Sweden. The tests were performed during the spring of 1981. The purpose was to make a comprehensive evaluation of different methods applicable in crystalline rocks and to recommend methods for use in current and scheduled investigations in a range of low hydraulic conductivity rocks. A total of eight different methods of testing were compared using the same equipment. This equipment was thoroughly tested as regards the elasticity of the packers and change in volume of the test section. The use of a hydraulically operated down-hole valve enabled all the tests to be conducted.

Twelve different 3-m long sections were tested in borehole Fi 6. The hydraulic conductivity calculated ranged from about 5 x $10^{-14}$ m/s to 1 x $10^{-6}$ m/s. The methods used were water injection under constant head and then at a constant rate-of-flow, each of which was followed by a pressure fall-off period. Water loss, pressure pulse, slug and drill stem tests were also performed. Interpretation was carried out using standard transient evaluation methods for flow in porous media. The methods used showed themselves to be best suited to specific conductivity ranges. Among the less time-consuming methods, water loss, slug and drill stem tests usually gave somewhat higher hydraulic conductivity values but still comparable to those obtained using the more time-consuming tests. These latter tests, however, provided supplementary information on hydraulic andhphysical properties and flow conditions, together with hydraulic conductivity values representing a larger volume of rock.

The methods that in 1981 was recommended for use in the standard hydraulic testing programme was two-hour water injection tests under a constant head, followed by a fall-off period of two hours. The selection was based on the criteria of easy handling and evaluation of a large amount of data, applicability in a wide range of hydraulic conductivities, large influence volume and negligible changes in the volume of the section tested.

**SKB Technical Report 86-28**

# PRESSURE SOLUTION OF MINERALS IN QUARTZ-TYPE BUFFER MATERIALS

Mikael Erlström
Swedish Geological Co, Lund
December 1986

## ABSTRACT

Two samples, pure quartz sand and a sand-bentonite (10%) mixture, were tested under conditions of high pressure (200 bar) and temperature (115°C). The experiment was carried out over a period of 70 days. A series of thin slides were prepared on a resin embedded sample at the end of the test period. A microscopical study was performed as to obtain data concerning the effects of pressure and temperature. It showed that no pressure solution had taken place in the pure quartz sand. However, the individual grains had been severely fractured, thus causing significant internal sedimentation. The mixed sample showed that the clay component coated the quartz grains and significantly decreased the effect of stress in the grains by having a cushioning effect. Relative grain movement was facilitated by the clay, by which the grains rotated and slipped into stable positions with large contact areas and low contact stresses. This probably minimized pressure solution. However, a few contact regions indicated the presence of precipitated silica.

The investigation shows no definite evidence of pressure solution after an experiment duration of 70 days. Since the effect of solution may be time dependent at the applied temperature, it is recommended that further experiments be conducted at higher effective and porewater pressures but still at 115°C.

SKB Technical Report 86-29

# QUANTITATIVE ESTIMATES OF SEDIMENTATION RATES AND SEDIMENT GROWTH IN TWO SWEDISH LAKES

Sverker Evans
Studsvik Energiteknik AB, Nyköping
October 1986

**ABSTRACT**

In order to form the basis for release scenarios of radionuclide dispersion in a lake ecosystem that gradually is silting up to become agricultural land, sediment budgets were performed for two Swedish lakes. The yearly load of sedimenting material was measured in situ during a two-year period using sediment traps. The net sediment growth, integrated over a longer time period, was on the average 2 - 4 mm $y^{-1}$. Resuspension showed to be the single most difficult factor to assess in the budget calculations, and was assumed to contribute 50 - 80% of the sediment catch. For the two lakes under study, Lake Trobbofjärden and Lake Sibbofjärden, the silting up of the lake basins will occur within 1 500 - 3 000 years and 2 200 - 4 500 years, respectively.

SKB Technical Report 86-30

# RECIPIENT EVOLUTION - TRANSPORT AND DISTRIBUTION OF ELEMENTS IN THE LAKE SIBBO-TROBBOFJÄRDEN AREA

Björn Sundblad
Studsvik Energiteknik AB, Nyköping
December 1986

**ABSTRACT**

The field studies in SKB-project Recipient evolution within the Lake Sibbo- and Trobbofjärden areas have given the following results.

Material balance calculations have shown that resuspension is one important parameter for calculations of the turnover of elements in sediment. The leakage of for example chloride from the Lake Trobbofjärden sediment has been determined.

The elemental distribution in sediment cores show minor variations with depth. The redox front is found less than 5 cm from the sediment surface.

The elemental distribution between solid and water phase has been found to be on the order of 1 000 to 10 000.