SKB

TECHNICAL REPORT

93-34

SKB ANNUAL REPORT 1993

Including Summaries of Technical Reports Issued during 1993

Stockholm, May 1994

SVENSK KÄRNBRÄNSLEHANTERING AB
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SKB ANNUAL REPORT 1993

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FOREWORD

The Annual Report on SKB's activities during 1993 covers planning, constructing and operational activities as well as research, development, demonstration work and information activities.

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

For the remaining facilities – the encapsulation plant and the final repository for spent nuclear fuel – comprehensive research and planning activities is well under way. The siting process for the final repository for spent fuel has started with discussions and feasibility studies in a few Swedish municipalities which have expressed interest in expanding their knowledge on how a repository would influence their region.

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

Stockholm in June 1994

SWEDISH NUCLEAR FUEL AND WASTE MANAGEMENT CO – SKB

Sten Bjurström

President

ABSTRACT

This is the annual report on the activities of the Swedish Nuclear Fuel and Waste Management Co, SKB. It contains in part I an overview of SKB activities in different fields. Part II gives a description of the research and development work on nuclear waste disposal performed during 1993.

Lectures and publications during 1993 as well as reports issued in the SKB technical report series are listed in part III. Part III also contains listing of consultants which have contributed to the SKB work and of postgraduate theses supported by SKB.

Part IV contains the summaries of all technical reports issued during 1993.

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 1993 in total 1 885 tonnes of spent fuel (measured as uranium) have been received. Transportation from the nuclear sites to CLAB is made by a special ship, M/S Sigyn.

At Forsmark the final repository for Radioactive Waste – SFR – was taken into operation in April 1988. The repository is situated in crystalline rock under the Baltic Sea. The first construction phase includes rock caverns for 60 000 m^3 of waste. A second phase for additional 30 000 m^3 is planned to be built and commissioned around the year 2000. At the end of 1993 a total of 13 000 m^3 of waste have been deposited in SFR.

SKB is in charge of a comprehensive research and development programme on geological disposal of nuclear waste. The total cost for R&D during 1993 was 180.3 MSEK of which 78.2 MSEK were investments in the Äspö Hard Rock Laboratory.

Some of the main areas for SKB research are:

- Groundwater movements.
- Bedrock stability.
- Groundwater chemistry and nuclide migration.
- Methods and instruments for in situ characterization of crystalline bedrock.
- Characterization and leaching of spent nuclear fuel.
- Properties of bentonite for buffer, backfilling and sealing.
- Radionuclide transport in biosphere and dose evaluations.
- Development of performance and safety assessment methodology and assessment models.
- Construction of an underground research laboratory.

Geological site-investigations are a substantial part of the programme. In the Äspö Hard Rock Laboratory methodologies for characterizing rock are refined and evaluated. In May 1994 there are 8 foreign organizations participating in the Äspö HRL project.

The siting activities for a deep repository includes general background studies (overview studies) and feasibility studies in municipalities having a good potential for hosting a repository and being interested in such a study. Presently (May 1994) the municipalities of Storuman and Malå have decided to participate in feasibility studies.

Cost calculations for the total nuclear waste management system, including decommissioning of all reactors, are updated annually. The total cost is estimated to 57 billion SEK.

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

Consulting services from SKB and associated expert groups are available on a commercial basis. From the start of these services in 1985 and up to the end of 1993 about 100 assignments have been accomplished in a variety of areas.

Information activities are an integrated and important part of the Swedish radioactive waste management system. During 1993 successful public information activities have been carried out using mobile exhibitions in a tailor-made trailer and on the SKB ship M/S Sigyn.

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Part I

Overview of SKB Activities

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1 GENERAL BACKGROUND

1.1 THE SWEDISH NUCLEAR POWER PROGRAMME

The nuclear power programme of Sweden consists of 12 nuclear reactors located at four different sites and with a combined capacity of 10 000 MW net electric power. Main data and location of the 12 units are shown in Figure 1-1. The nuclear power plants generated about 42% of the total Swedish electric power produced in 1993.

Swedish reactors

Reactor		Power MWe	Commercial operation	Energy availability in 1993 %
Oskarshamn 1	BWR	440	1972	–
Oskarshamn 2	BWR	605	1974	55
Oskarshamn 3	BWR	1160	1985	92
Barsebäck 1	BWR	600	1975	62
Barsebäck 2	BWR	600	1977	63
Ringhals 1	BWR	795	1976	71
Ringhals 2	PWR	875	1975	37
Ringhals 3	PWR	915	1981	90
Ringhals 4	PWR	915	1983	89
Forsmark 1	BWR	970	1980	92
Forsmark 2	BWR	970	1981	89
Forsmark 3	BWR	1155	1985	93

1.2 LEGAL AND ORGANIZATIONAL FRAMEWORK

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

- Vattenfall AB is the largest electricity producer in Sweden and owns the Ringhals plant.
- Barsebäck Kraft AB (subsidiary of Sydkraft AB) is the owner of the Barsebäck plant.
- OKG AB is the owner of the Oskarshamn plant. Sydkraft is the major shareholder of OKG.
- Forsmark Kraftgrupp AB (FKA) is the owner of the Forsmark plant. Vattenfall has 74.5% of the shares in FKA.

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

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

The total central staff of SKB is about 70 persons. The organization is shown in Appendix 1. For the bulk of the work a large number of organizations and individuals outside SKB are contracted. As a whole about 600 persons are involved in SKB waste handling and research work.

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

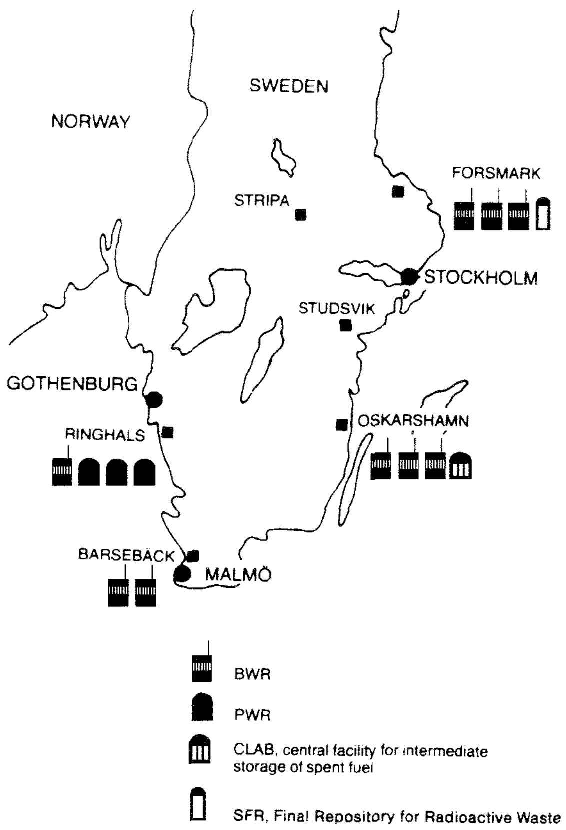


Figure 1-1. The Swedish nuclear power programme.

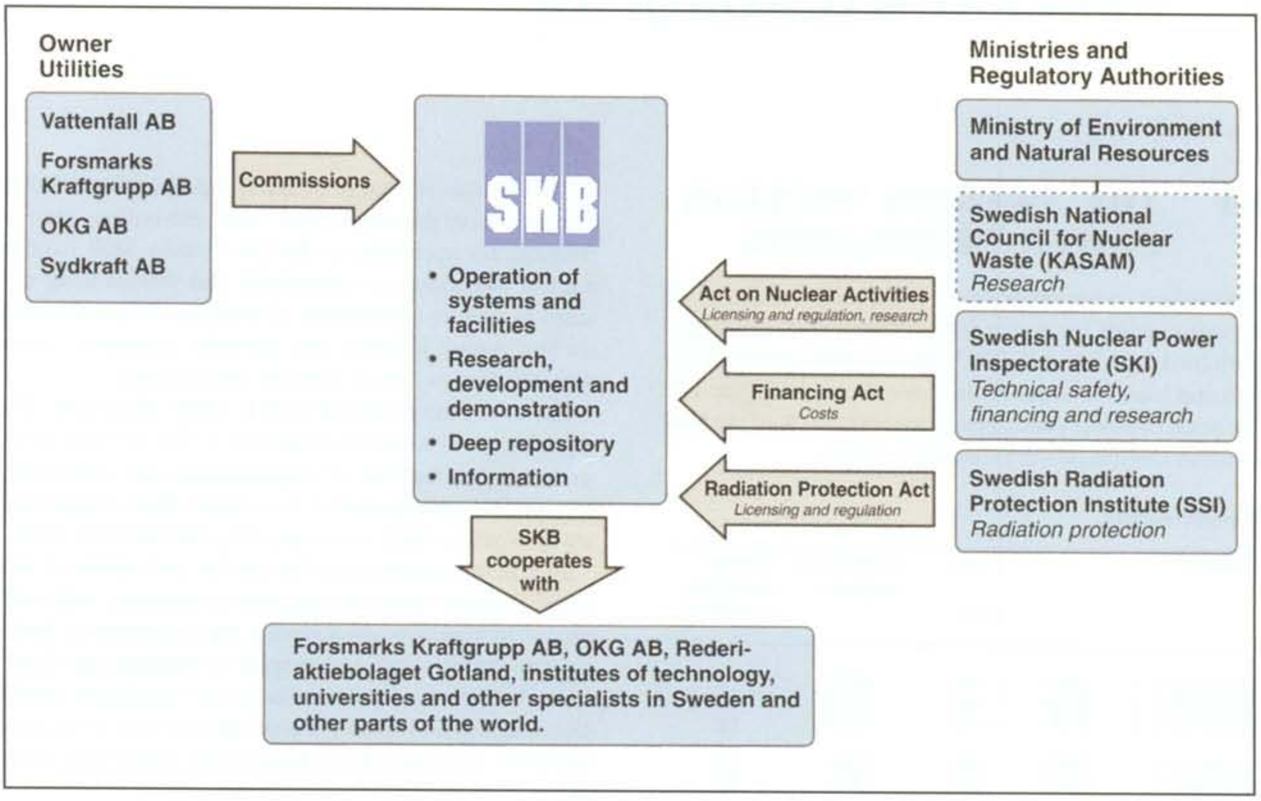


Figure 1-2. *Legal framework for activities of SKB.*

There are three important laws which regulate the nuclear activities.

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

The Act on Nuclear Activities /1-1/ puts the primary responsibility for the safety on the owner of a nuclear installation. The owner is thus responsible for safety during design, construction and operation of nuclear facilities, for the handling and final disposal of nuclear wastes and for the dismantling and decommissioning of the facility. The responsibility also includes the necessary research and development in the waste management field. According to the act a research programme must be submitted to the authorities every three years. The first programme was submitted in September 1986, the second in September 1989 and the third in September 1992.

The authority for supervision of the safety provisions in the Act on Nuclear Activities as well as the SKB research programme is the Swedish Nuclear Power Inspectorate (SKI). The National Institute for Radiation Protection (SSI) is supervising provisions of the Radiation Protection Act.

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

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

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

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

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

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

Table 1-1. Waste categories.

WASTE CATEGORY	ORIGIN	WASTE FORM	PROPERTIES	QUANTITY
1 Spent fuel	Operation of nuclear reactors	Fuel rods encapsulated in canisters	High activity level. Contains long-lived nuclides	4 500 canisters (7 900 tU)
2 Transuranic-bearing waste	Waste from the Studsvik research facility	Solidified in concrete	Low- to medium-level. Contains long-lived nuclides	1 500 m^3
3 Core components and internals	Scrap metal from inside reactor vessels	Untreated or cast in concrete	Low- to medium-level. Contains some long-lived nuclides.	9 700 m^3
4 Reactor waste	Operating waste from nuclear power plants etc.	Solidified in concrete or bitumen. Compacted waste	Low- to medium-level. Short-lived	91 200 m^3
5 Decommissioning waste	From dismantling of nuclear facilities	Untreated for the most part	Low- to medium-level. Short-lived	111 700 m^3

1.3 THE SWEDISH NUCLEAR WASTE MANAGEMENT SYSTEM

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

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

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

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

The first construction stage of the Swedish Final Repository for Radioactive Waste, SFR, was taken into operation in 1988. SFR may later on be extended to accommodate waste also from the decommissioning of the nuclear reactors. For spent fuel a central interim storage facility, CLAB, was taken into operation in July 1985. This facility has a current capacity of 5 000 tonnes of spent fuel.

The spent fuel will be stored in CLAB for about 40 years. It will then be encapsulated in a corrosion-resistant canister and deposited at depth in the Swedish bedrock. According to the time schedule presented in the RD&D-Programme 92 SKB plans to expand the CLAB facility with an encapsulation plant in order to make encapsulated fuel available for disposal around 2008.

The construction of the deep repository will be made in steps. A first stage of the repository, for 5 – 10% of the fuel, is planned to be put in operation in 2008. The next stage for the full repository will only be built after a thorough evaluation of the experiences of the first stage and a renewed licensing. The site for the deep repository has not yet been chosen.

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

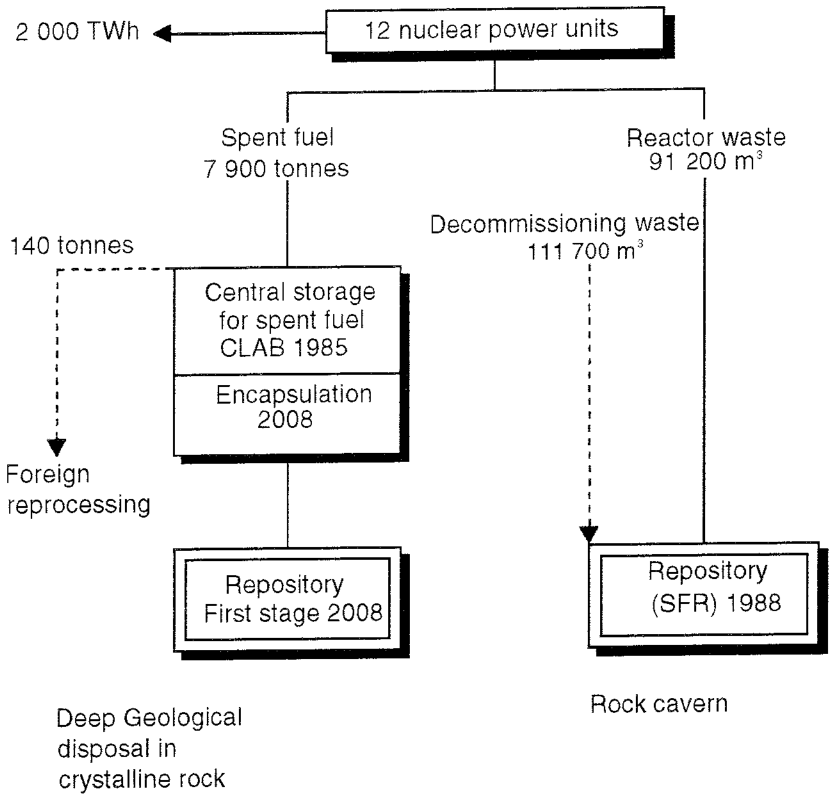


Figure 1-3. *Main system for management of radioactive waste in Sweden.*

2 INTERIM STORAGE OF SPENT FUEL, CLAB

2.1 GENERAL

The Swedish interim spent nuclear fuel storage facility, CLAB, located on the Simpevarp peninsula adjacent to the Oskarshamn nuclear power station, was taken into active operation in July, 1985, see Figure 2-1.

The facility has five underground pools with a storage capacity of 5000 tonnes of uranium (tU). The receiving building and the buildings for auxiliary systems and offices are located on ground level. The facility is designed to receive at least 300 tU per year equivalent to about 100 fuel transport casks and some 10-20 casks containing highly active reactor core components, see Figure 2-2. For the operation SKB has contracted OKG AB, one of SKB's shareholders, operating three reactors at the site.

2.2 OPERATING EXPERIENCES

By the end of 1993 CLAB has been in operation for 8.5 years and the performance of the facility has been excellent since the start of operation. Improvements have gradually been introduced along with the experiences gained. In total 1885 tU from the Swedish reactors have been shipped to the facility and placed in storage.

In 1993, 66 casks containing spent fuel assemblies were received together with one shipment of fuel residues from post irradiation examination at the Studsvik Nuclear Research Center. The total quantity shipped to CLAB during the year amounted to 201 tU. One of the shipments included a number of fuel assemblies with minor leaks. These assemblies were placed in special bottles for failed fuel and were transported together with undamaged assemblies. In parallel to the fuel receiving activities 38 BWR assemblies and 266 PWR assemblies have been transferred from old canisters to new compact storage canisters, see section 2.3.

The total occupational dose in 1993 was 117 mmanSv, which is very low – about 40% of the value calculated in the safety assessment made during the design phase. The dose is about 13% lower than in 1992 in spite of some potentially dose creating repair activities in the waste solidification plant and on the transport casks during 1993.

Figure 2-1. *The Oskarshamn Nuclear Site. CLAB in the foreground.*

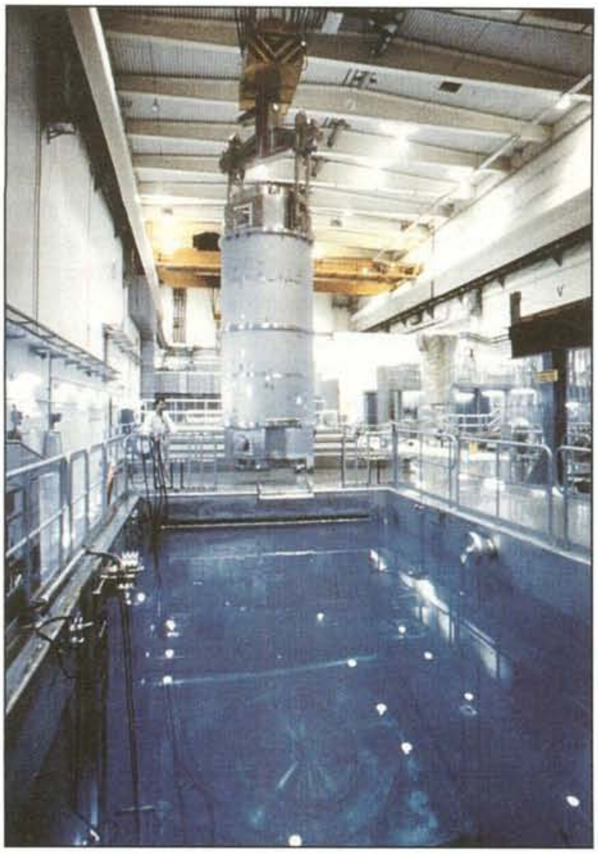


Figure 2-2. *Fuel cask with protective shirt being moved from the cooling cell to the unloading pool.*

The release of radioactivity to the environment during 1993 has been negligible, amounting to around 0,01% of the permissible release at the site (from CLAB and the three adjacent reactors together). The release values have been of the same order of magnitude since the start of operation.

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

The experiences from more than eight years of operation are continuously used in the project work on the Encapsulation Plant, see Chapter 6, which according to current plans will be built in connection to CLAB.

2.3 INCREASED STORAGE CAPACITY

The storage capacity of the pools was originally 3000 tU, which would cover the need until 1996. Preparations for a future expansion with additional caverns and pools were made during the construction of the facility in the early eighties. A study performed in 1988 showed that there was a great advantage if the expansion could be postponed by better utilization of the space available in the existing pools.

This has been achieved by using new compact storage canisters with borated stainless steel as neutron absorbing material, allowing the number of fuel assemblies to be increased from 16 to 25 and from 5 to 9 per canister for BWR respectively PWR fuel, see Figure 2-3. Due to this, a new cavern with pools will not be needed until around 2003-2004.

The new canisters came into regular operation in the autumn 1992 and have since then been used for all the fuel arriving from the reactors and for fuel unloaded from old type canisters. These old canisters are decontaminated and conditioned before being shipped away from the facility.

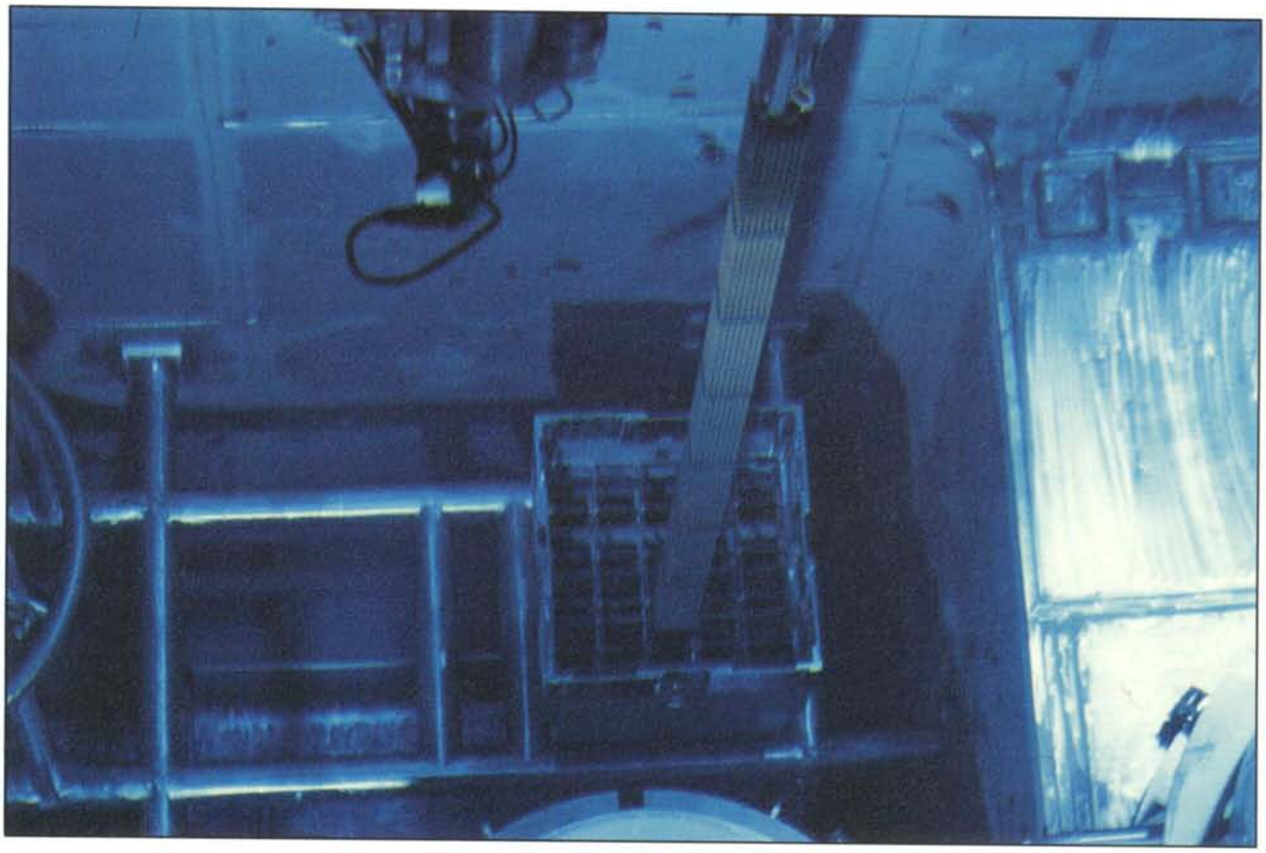


Figure 2-3. *A BWR fuel assembly being loaded into a compact storage canister.*

3 TRANSPORTATION

3.1 GENERAL

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

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

3.2 OPERATING EXPERIENCES

In 1993 the ship M/S Sigyn sailed around 34 100 n.m. during 130 days. The transports of spent fuel and reactor waste from the Swedish reactors to the CLAB facility and to the repository, SFR, have been performed without disturbances. Due to other priorities in some power plants, the number of transported casks was somewhat reduced compared to the annual planning. In total 66 transport casks with spent fuel and 91 IP-2 containers (ATB) with reactor waste have been transported with the transportation system during the year, see Figure 3-1. Like earlier years, no measurable dose rates have been registered to the ship's crew.

In the beginning of the year damages on the stainless steel cavity liner was found on one of the transport casks. After checking all casks, it was found that only one cask had these damages, which probably originated from the manufacturing. The cask will be repaired at the CLAB facility and taken into operation during the second half of 1994.

When the ordinary transport schedule has permitted, M/S Sigyn has been used on commercial basis for transports of heavy equipment. During 1993 one transport of UF_6-cylinders from Russia to Sweden has been performed. Other examples are transport of a generator from Västerås to Ringhals and a large steel cylinder from Örnsköldsvik to Simpevarp.

In the spring time an aid transport with agricultural equipment to Estonia took place from Ringhals.

Figure 3-1. *Loading of ATB-container on board M/S Sigyn.*

During the summer period M/S Sigyn was used as a floating exhibition of the Swedish nuclear waste handling system making a voyage along the Swedish coast and visiting 16 cities, including the capital Stockholm.

4 FINAL REPOSITORY FOR RADIOACTIVE WASTE, SFR

4.1 GENERAL

The Swedish Final repository for Radioactive Waste, SFR, was put into active operation in April, 1988. It is built in the bedrock under the Baltic Sea close to Forsmark nuclear power plant. 60 metres of rock covers the repository caverns under the sea bed, see Figure 4-1. The first stage of SFR, which is in operation, includes buildings on ground level, tunnels, operating buildings and disposal caverns for 60 000 m^3 of waste. A second stage for approximately 30 000 m^3 is planned to be built and commissioned after the year 2000.

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

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

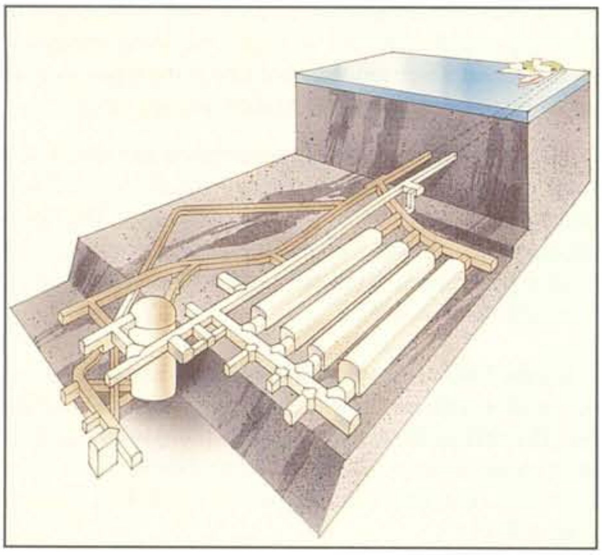


Figure 4-1. Overview of tunnels and storage chambers in the first construction stage of SFR.

At the end of 1993 a total of 13 000 m^3 of waste have been deposited in SFR. All waste producers have delivered waste. The experiences from the operation have been good and the irradiation exposures to the personnel have been very low.

4.2 DESIGN AND CONSTRUCTION

The SFR has been sited under the sea in order to minimize the groundwater flow in the repository area. Engineered barriers are used in order to further reduce the groundwater flow inside the caverns and through the waste.

There are different caverns for ILW and LLW in SFR. The ILW-packages containing most of the activity are disposed of in a concrete silo structure and surrounded with a low permeable buffer material, bentonite. The space between the waste packages and the concrete construction in the silo are subsequently filled with a porous concrete.

Waste containing a minor part of the activity content are disposed of in 160 m long caverns with various cross sections. The cavern with the largest cross section, BMA, is equipped with machines for remotely controlled handling, similar to those used in the silo, see Figure 4-2.

LLW is handled with an ordinary, but shielded, forklift truck.

4.3 WASTE ACCEPTANCE

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

All relevant information about each waste package is documented and collected in a computerized waste register. Before the waste is transported to SFR, the contents of the waste register is transferred to a SFR-data base.

The procedure for waste acceptance has been very time consuming. In 1993, 28 waste types (of a total of about 40) were accepted for disposal. In 1993 disposal has been carried out in the rock chambers and in the silo.

4.4 SAFETY ASSESSMENT

In May 1992 a complementary operational permit was granted, which allows also the disposal of waste in the silo on a regular basis and the subsequent grouting around the

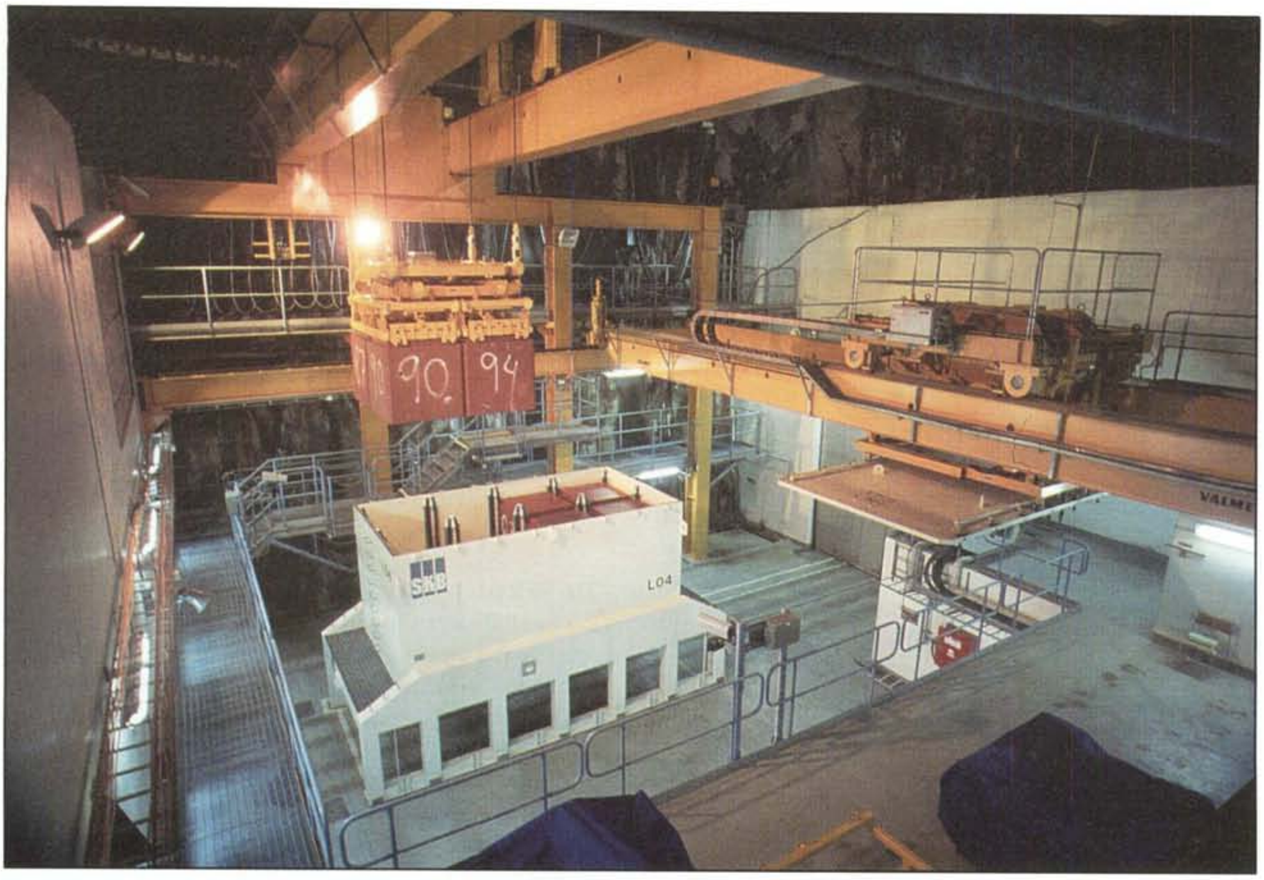


Figure 4-2. The operational waste is transported in special transport containers. In SFR the waste packages are unloaded with remote-controlled handling equipment.

waste. As a basis for this permit, SKB had in August 1991 presented a deepened Safety Assessment to the authorities. This was in accordance with the conditions of the original operating permit from 1988.

Some areas that are covered in detail in the deepened safety assessment are the effects of gas production, the effect of complexing agents from the degradation of cellulose and the change in the hydrological regime due to land rise. Also a systematic scenario analysis is included. The results of this deepened safety assessment confirmed the results of the Final Safety Report.

4.5 OPERATION

The operation of SFR has been subcontracted to Forsmark Kraftgrupp AB (FKA), the operator of the nuclear reactors at Forsmark, and is closely integrated in the local organization. The staff for operation and maintenance of SFR consists of about 16 people.

In full operation the facility has an annual disposal capacity of about 6000 m^3. During the first years of operation SFR has successively been put into active operation area by area, starting with the rock chambers. Up till the end of 1993 a total of 13 000 m^3 of waste has been deposited.

The operating experience is good both with regard to handling and availability. To overcome some remaining problems with high moisture content in the repository air an air drying system has been taken into operation.

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

During 1993 the system for preparation and handling of the cement grout for the waste package in the silo has been installed and finally tested. A demonstration of the system with a silo mock-up filled with waste packages was done mid 1993. The first grouting in the silo shaft is planned early 1994.

5 DEEP REPOSITORY PROJECT

5.1 GENERAL

Siting and construction of a deep repository for final disposal of spent nuclear fuel and other long-lived waste is one of the main remaining tasks within the Swedish nuclear waste programme. In the RD&D programme 1992 plans were presented for the work to start implementing deep disposal for a first stage by about the year 2008. A deep repository project has been set up and during 1993 the activities have been focused on:

- Background and national overview studies concerning different aspects of siting a deep repository.
- The setting up of feasibility studies in cooperation with interested and potentially suitable municipalities.
- Technical studies of the repository system.
- Planning of a site-investigation programme.
- Environmental impact assessment studies.

5.2 THE PLANNED SITING PROCESS

The overall plan for siting and construction of a deep repository is presented in Figure 5-1. Siting and construction is made in well-defined phases. The first phase will

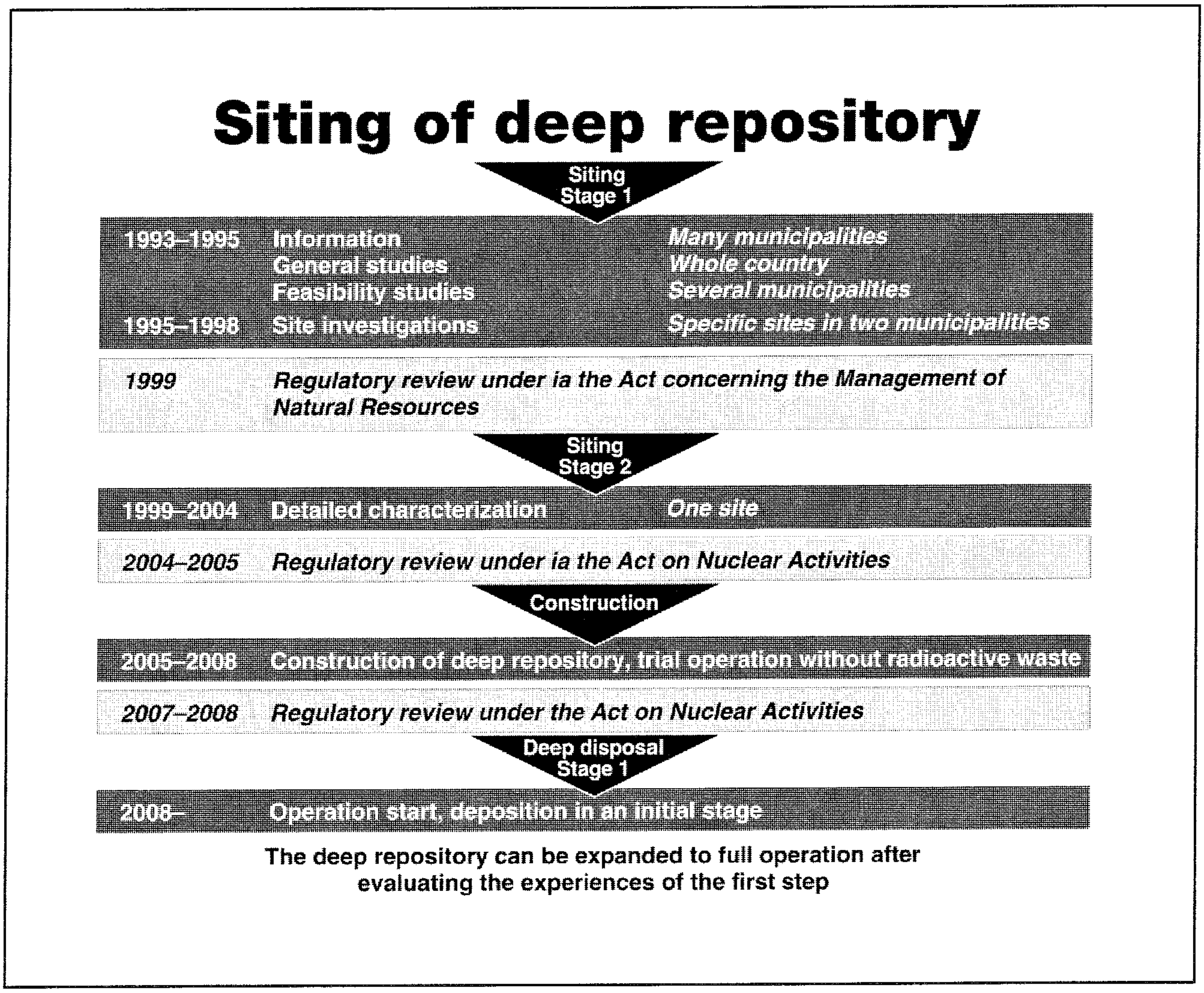


Figure 5-1. *Overall plan.*

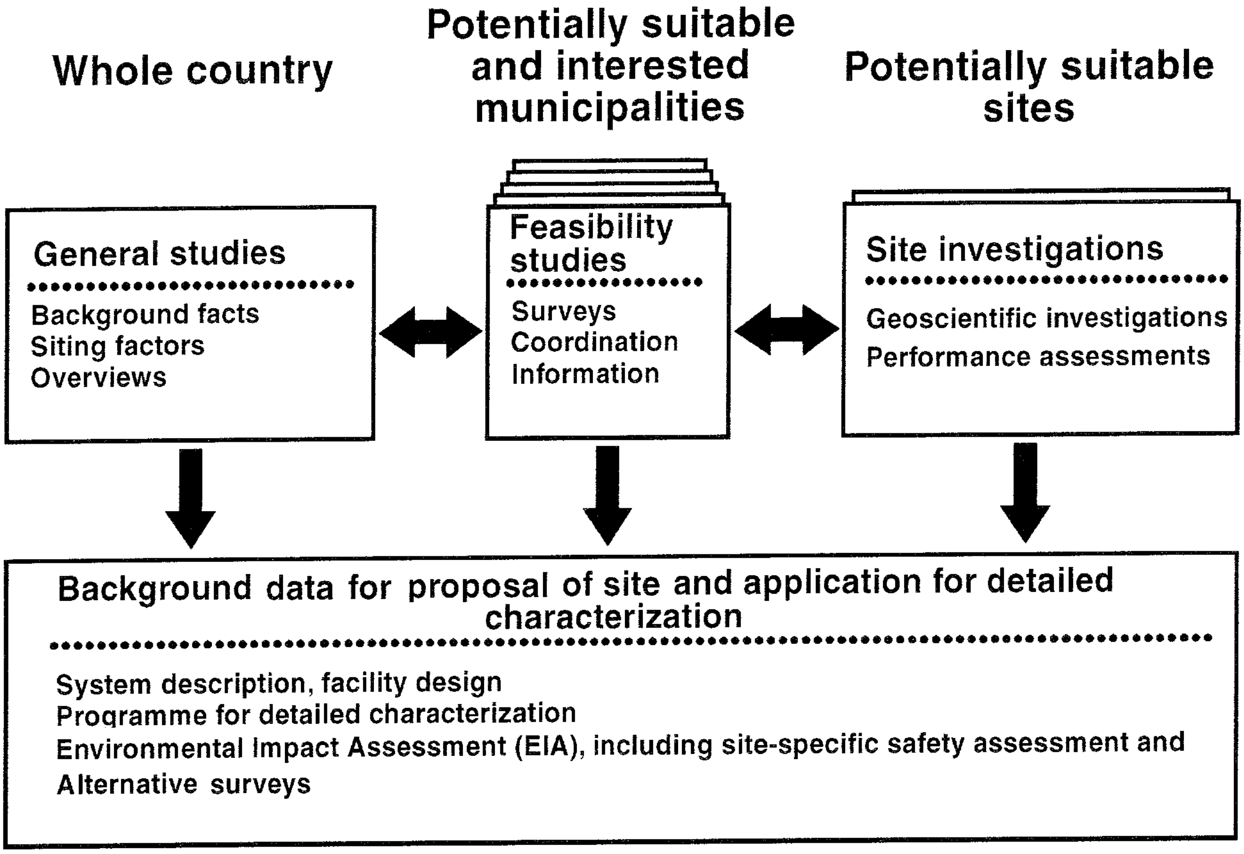


Figure 5-2. Siting activities, phase 1.

end up in a proposal by SKB of a site for detailed site characterisation, including shaft-sinking or tunnel down to planned repository depth. To start detailed site characterisation work approval from the municipality, the relevant authorities and the government is needed.

The present siting activities, phase 1, are schematically illustrated in Figure 5-2. They aim at collecting all the necessary information needed for SKB to be able to propose a potentially suitable site for a deep repository and to apply for a permit to perform detailed site-characterisation at this site. This work, siting phase 1, is estimated to take about another 4 years.

General background studies (overview studies) are being made for the whole country to provide an overview of possibilities and restrictions concerning siting of a deep repository in Sweden. Feasibility studies will be performed for municipalities having a good potential for hosting a repository and being interested in such a study. SKB is planning to do 5-10 feasibility studies.

A feasibility study is estimated to take about one year and is supposed to examine the following questions:

- What are the general prospects for siting of a deep repository in the municipality?
- Within which parts of the municipality might suitable sites for a deep repository be located, considering geoscientific and societal factors?
- How can the deep repository be designed with respect to local conditions?
- How can transportation be arranged?
- What are the important environmental and safety issues?
- What might the consequences be (positive and negative) for the environment, the local economy, tourism and other business sectors within the municipality and the region?

The studies are being conducted for the most part by universities and consultants. Between 20 and 30 subject reports will constitute the background material of a feasibility study.

A preliminary assessment of whether it is possible or not to site a deep repository in a municipality will be made in a final report.

In parallel with the general and feasibility studies, the following phases in the work are being planned. The coming site investigations must be conducted according to a carefully worked-out plan. The work of preparing a programme for the site investigations has therefore continued throughout 1993. Analyses have been carried out of previous experience in Sweden (study sites, Stripa, Äspö etc.) and in other countries, especially Finland and Canada. These studies now form the basis for the new site investigation programme, which is scheduled to be finished in 1994.

5.3 PRESENT SITING ACTIVITIES

The work of gathering a broad body of information for future site selection got fully under way during 1993. The general studies for the whole country continued, with collection and analysis of background facts and data on geoscientific and societal siting factors. Information was furnished to many municipalities, and discussions held at various locations in the country. Storuman municipality and Malå municipality in Västerbotten County have both decided to participate in feasibility studies of the prospects for siting of a deep repository within the municipality. The feasibility study in Storuman was commenced during the autumn of 1993, and the feasibility study in Malå started at the beginning of 1994.

The feasibility study of Storuman is managed by a steering group consisting of representatives from SKB and from the municipality. A project leader supervises the daily work together with a coordinator appointed by the municipality.

The municipality has also formed a reference group consisting of twenty-four members representing political parties, environmental groups, laplanders, forestry and agriculture, tourism, trade and industry etc. Regular meetings are held to discuss the progress of the feasibility study. In addition, seminars are held about every second month where specific items are discussed in depth.

The feasibility study is divided into seven subjects. Most studies are made by organisations outside SKB such as Universities, the Geological Survey of Sweden or consulting companies. The subjects and corresponding study items are listed in Figure 5-4.

According to the agreement between SKB and the Storuman municipality all activities will be completed before July 1995. The agreement also states that the result of the study should be presented in such a way that it could be used as a basis for a local referendum. Of course, this will only apply if the feasibility study shows that a deep repository is likely to have an overall positive effect on the municipality and that the geological conditions can be expected to be favourable.

Since October 1993 an SKB office has been established at Storuman managed by a locally recruited SKB employee. The office includes working space for researchers, an exhibition showing the Swedish system for managing radioactive waste and preliminary results from the feasibility study.

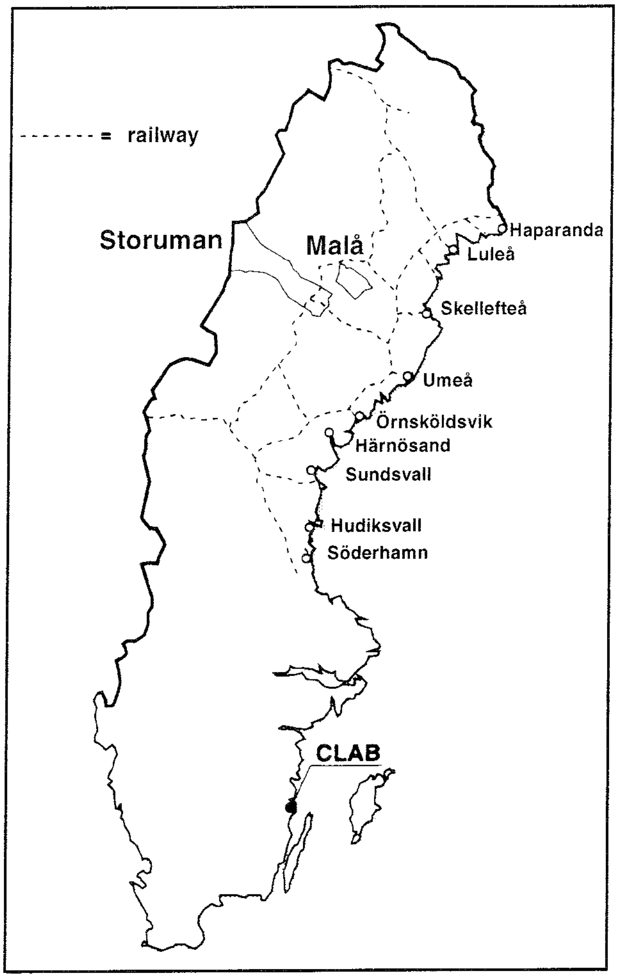


Figure 5-3. *Location of the municipalities Storuman and Malå. The central interim storage facility for spent nuclear fuel is located at CLAB. If the deep repository is located at Storuman or Malå spent fuel will probably be transported by ship to a harbour in the northern part of the Baltic sea and by train to the repository.*

Overview studies

The overview studies aim to review relevant factors for the siting of a deep repository of spent nuclear fuel. The country as a whole will be considered and a database adequately representing those factors will be produced. The siting factors will include both geological, technical and social issues. The results of the overview studies will be used to present and discuss the feasibility of a studied site, or a municipality, in a regional or nationwide context.

All data are stored in a digital form using the GIS (Geographical Information System) database at SKB. This greatly simplifies the handling and analyses of data and the production of maps in various scales. At the end of 1993 the database contained more than fifty data sets. For most data sets information is available for the whole of Sweden.

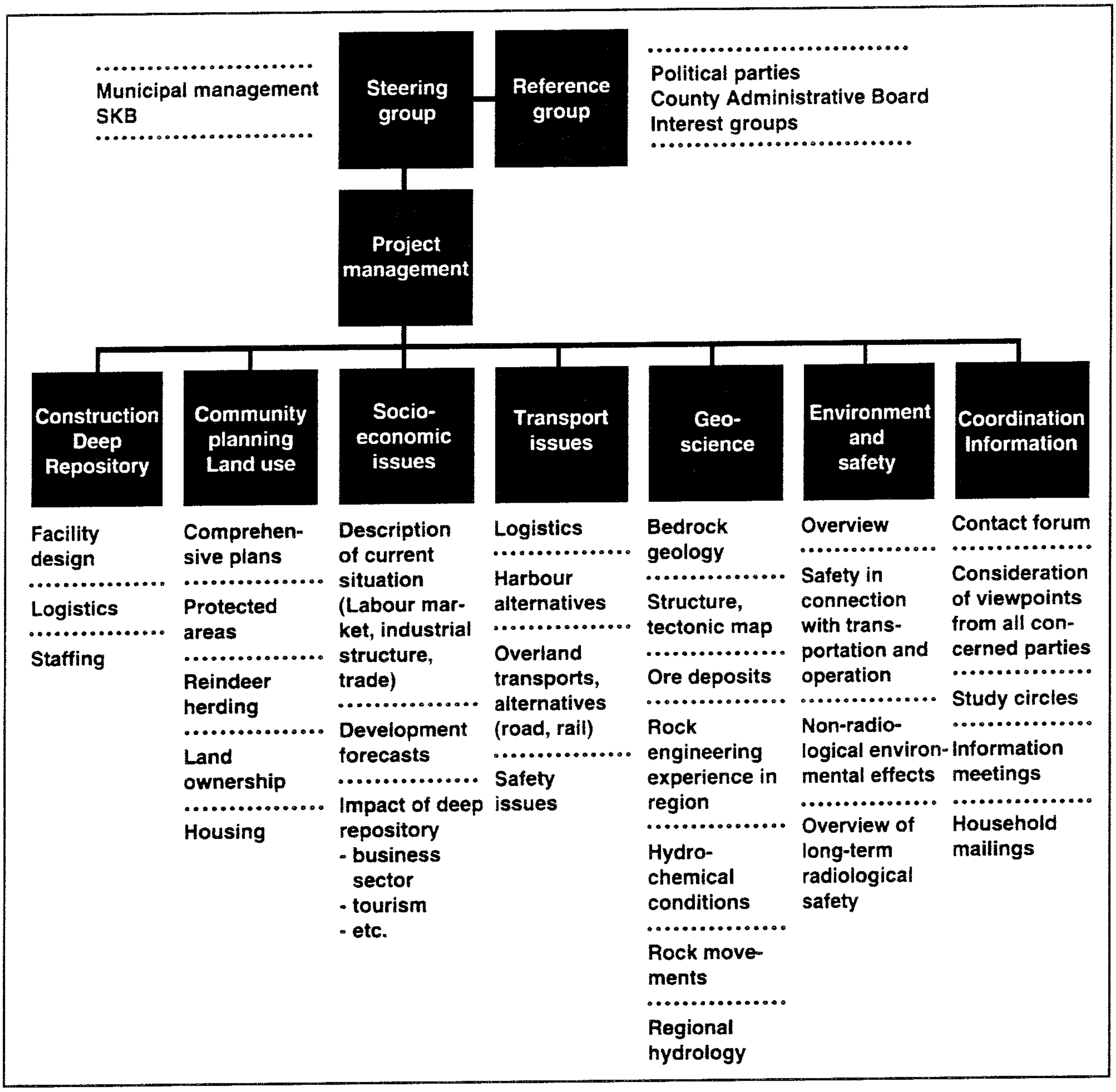


Figure 5-4. Organisation and main subjects in the feasibility study of the Storuman municipality. Items being studied are listed below each subject.

5.4 TECHNICAL STUDIES OF A DEEP REPOSITORY SYSTEM

During the last about ten years four alternative disposal concepts have been studied in parallel to the development of the KBS-3 system. The work has consisted of analyses of technical feasibility, cost calculations and performance assessment, as well as comparison with KBS-3 and ranking of the concepts. One major conclusion drawn in the studies is that all concepts are judged to be able to fulfil safety requirements, implying that the long-term safety demands have no disqualifying influence.

The studied systems are shown in Figure 5-5.

The result of the analyses and the comparison between the concepts was that the KBS-3 design was judged to provide the most favourable possibilities in the Swedish crystalline bedrock. Consequently the more detailed planning of the repository, which started in 1993, is based on the KBS-3 system.

The technical studies comprise the work which is devoted to developing and adapting known technologies, R&D results etc. to the repository conditions by applying well established engineering methods. One major part of the work is the planning of above ground and underground facilities. The other is to choose and develop e g deposition method in detail including equipment, underground excavation methods, compaction technique for the bento-

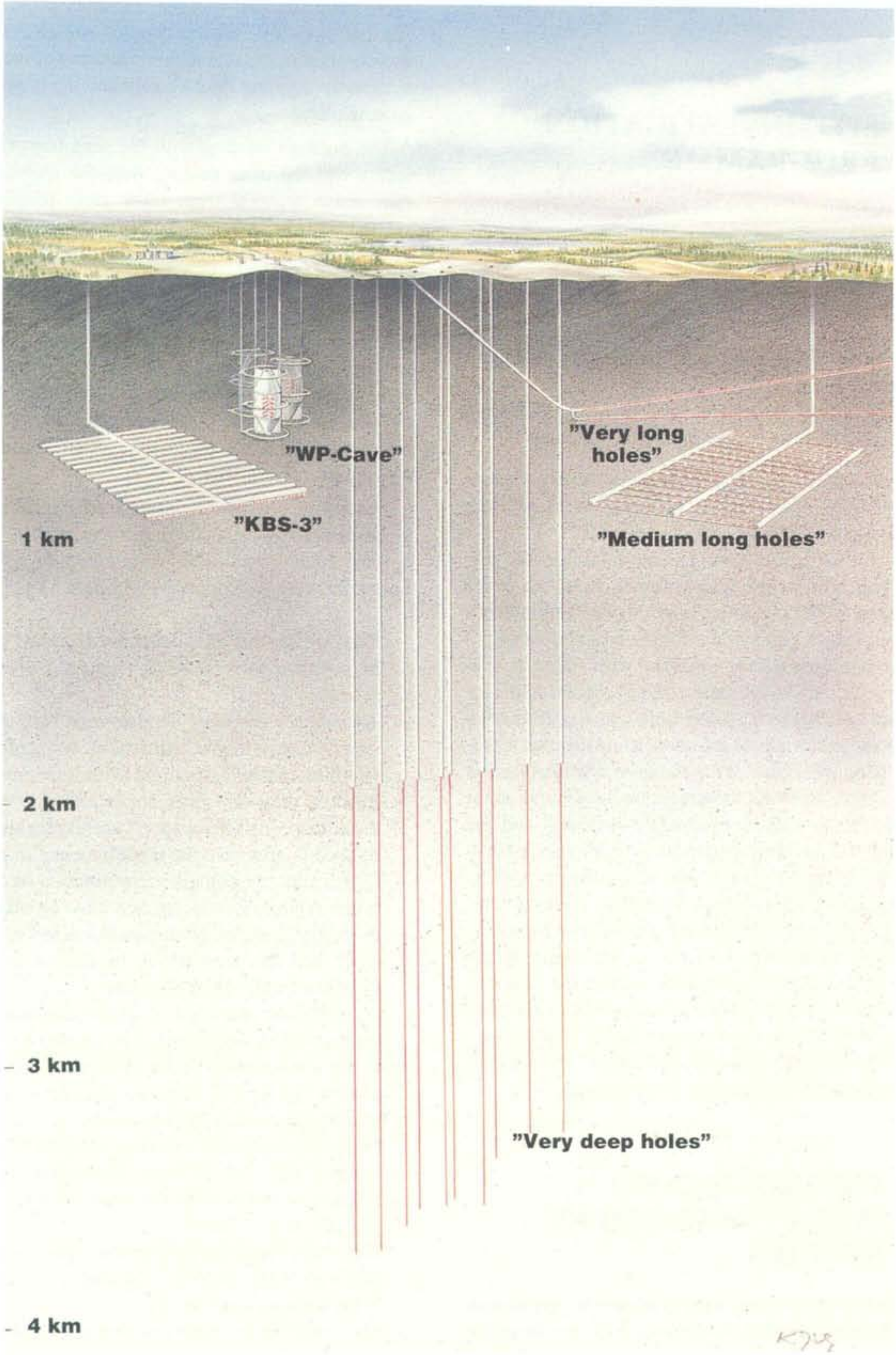


Figure 5-5. Alternative designs of deep repository.

nite blocks, design and application of plugs and seals after disposal. Studies, discussions and planning have taken place on a broad range of topics during 1993. A more detailed presentation of these studies are given in Chapter 13.

5.5 SITE-INVESTIGATION PROGRAMME

As a preparation for the forthcoming site investigations for candidate repository sites, work has been carried out in the following fields:

- development of the geoscientific investigation programme,
- preparation of techniques and routines for data management,
- preparation of instruments and methods, including development, refinement and investment, etc.

A general base for the planning work is the experiences from earlier site investigations, including the Äspö Hard Rock Laboratory (HRL), conducted by SKB.

A first outline of the geoscientific investigation programme was written as a SKB internal document in the beginning of 1993. The aim was to propose a framework of an investigation programme for internal review and to be a reference for resource planning work. The "framework for geoscientific characterization" discussed the investigation and characterization work with regard to need for safety and performance assessment and detailed investigation. The subdivision of the site investigation phase in a siting stage, baseline investigation stage and complementary stage will be thoroughly reviewed and the programme will be developed more in detail during 1994.

According to present plans site investigations will be carried out at two sites, almost in parallel. This calls for efficiency in all investigation work, among which the field work maybe is the most critical. As for preparing the planning of this, practical experiences from the field and need of resources for the different field activities has been reviewed. Work has also continued on technical documentation of instruments specially developed by SKB and planned to be used in future site investigations.

5.6 ENVIRONMENTAL IMPACT ASSESSMENT STUDIES

SKB plans for the deep repository include the preparation of Environmental Impact Statements. EISs are formally required for certain facilities in accordance with the Swedish Act on the Conservation of Natural Resources. The deep repository is such a facility.

The first, formal EIS has to be presented before licences of the detailed site characterization. In 1993 the SKB prepared what could be referred to as a preliminary work, based on a repository design, not linked to a given site.

The studies include the impacts expected from all the activities associated with the repository project, from the site investigation, via the detailed site characterization, construction of the repository, operation of the repository system through the final closure and the long-term post-closure phase.

The portions dealing with the long-term radiological safety and the ones dealing with the transportation of radioactive material were taken from previous studies carried out by SKB and from the collected experience from eight years of successful operation of the present SKB transportation system.

An Environmental Impact Statement should also contain assessments of non-radiological impact on land use, wildlife habitats, air and water etc. Four separate studies were made dealing with the site investigation and the detailed investigation phases, construction of the repository, operation of the repository system, and the closure operations, respectively.

The detail to which the assessment can be taken is of course somewhat limited in generic studies, but a few general conclusions as to what could be more or less important were nevertheless identified:

- The impacts during the site investigation phase must be regarded as very small, regardless of what site is selected.
- The surface facilities require some forty hectares of land at full operation. The detailed siting of the surface facilities can be carried out with a certain degree of freedom since they must not be placed directly above the underground repository. Careful planning can then be used to minimize the environmental impact.
- During site investigation, construction and operation of the repository, special care must be taken to limit the impacts on the groundwater caused by the draw-down and the necessity to reinfiltrate or otherwise dispose of water from the sump.
- Air pollution and noise from the repository and the transportation system will only be minor.
- If the rock masses from excavation could not be vended and thus be disposed of directly, special consideration is necessary to make the mass disposal area fit into the landscape and, depending on the characteristics of the rock, to make precautions to limit the leaching of heavy metals or other potential pollutants from the disposal area.
- The international guidelines and other good practises followed by the SKB will guarantee the safe operation of the transportation system.
- The land can be well restored after closure of the repository.
- The site-specific long-term safety will be extensively studied in assessments to follow, but previous assessments strongly indicate that very strict safety requirements can be met by many sites in Sweden.

6 ENCAPSULATION PLANT PROJECT

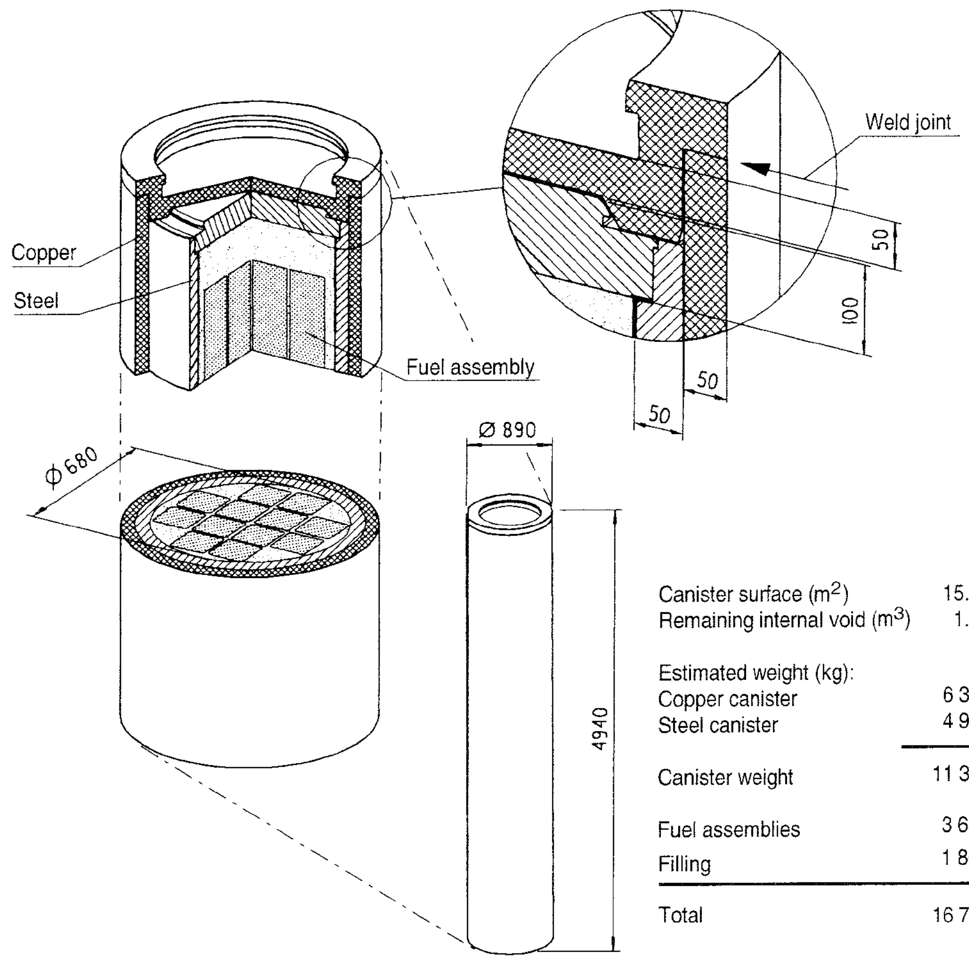
6.1 GENERAL

The spent fuel elements are stored in water pools in the CLAB facility. Before the fuel will be disposed of in a deep geological repository it must be encapsulated in a canister. In the repository the canister is one of the essential barriers. It will keep the fuel elements separated from the groundwater for a very long time. The canister will also provide radiation shielding and protection during the handling of the fuel in the deep repository.

The primary requirement for the canister is that it shall remain tight for a very long time in the environment that will prevail in the deep repository. It must not corrode in the groundwater or break from the pressure it is exposed to. To achieve these properties the canister is planned to be made of an outer canister of copper, which gives protection against corrosion and an inner container of steel, which gives mechanical strength. One canister can hold either 12 BWR fuel elements or 4 PWR fuel elements. The canister is shown in Figure 6-1.

Earlier designs of canisters have also been studied, such as a homogeneous copper canister, made by Hot Isostatic Pressing (HIP) technique, and a copper canister filled with lead around the fuel elements. Both these methods require that the encapsulation is done at a high temperature. This can be avoided with the present copper canister with an inner steel container. This fact has been decisive for the choice of canister design as the long time function is equal for the three types of canisters.

The encapsulation is planned to be made in a new facility to be built in connection to CLAB. This siting gives advantages in comparison with other sites to be



Canister surface (m^2)	15.23
Remaining internal void (m^3)	1.22
Estimated weight (kg):	
Copper canister	6 380
Steel canister	4 950
Canister weight	11 330
Fuel assemblies	3 640
Filling	1 800
Total	16 770

***Figure 6-1.** Design of canister for BWR fuel elements.*

considered for the encapsulation plant. Advantages are e g logistics for the handling, use of existing resources and minimal impact on the environment.

6.2 DEVELOPMENT OF CANISTER DESIGN AND LID WELDING TECHNIQUE

Canister Design

The primary requirement on the canister is that it shall remain tight for a very long time in the environment found in the geological repository. This in turn puts requirements on long-term resistance to external and internal corrosion and on the mechanical strength of the canister. The canister shall further be designed so that criticality is avoided. Other design features will be connected to the manufacturing of the empty canisters and to the handling of the canisters.

The resistance to external corrosion is achieved by the use of copper as canister material and by the design of the copper canister (to avoid stress corrosion and radiolysis). Internal corrosion is avoided by drying the fuel elements before emplacement in the canister and by exchanging the air in the canister by an inert gas.

The mechanical strength of the canister is given by the inner steel container. In 1993 preliminary design of the steel container has been made. The basis has been that the container shall resist an external uniform pressure of 15 MPa with a safety factor of three. This allows the canister to also withstand the increased pressure foreseen with an ice cover of three kilometres. The initial design temperature is assumed to be 100°C. After several thousand years the temperature will decrease to an ambient temperature near 20°C.

Based on scoping analyses using an analytical method and a simplified finite element method, a materials choice of 50 mm steel OX529DM for the cylindrical shell and 100 mm SS steel 2103 for the flat ends was made. Using these materials, a complete finite element model was applied. The final conclusion of this analysis was the true value of the critical pressure is approximately 45 MPa at 100°C and 47 MPa at 20°C. This gives a safety margin of at least a factor of three, which is clearly higher than the margin of 2.0 required in the Swedish Pressure Vessel Code.

For the copper canister design studies are underway. At present a 50 mm thick copper canister is foreseen made of oxygen free copper with a slight addition of phosphorous. The minimum total thickness of steel and copper is determined to avoid radiolysis in the water outside the canister.

Welding Techniques

The sealing of the copper canister will be made by electron beam welding of the lid onto the canister. Development work on electron beam welding of thick copper sections has been done since many years by TWI in Cambridge, UK. During the last years the work has concentrated on the development of a non-vacuum electron beam welding head, as partners in a Eureka Project. This system was finalized in 1992 and is capable of producing electron beams in excess of 100 kW at 270 kV.

The equipment was applied in the non-vacuum mode to the welding of thick section copper during 1992 and it was shown that penetration levels of up to 40 mm could be achieved, but it proved difficult to extend penetration beyond that without encountering problems. During these tests it was recognized that a reduction in welding pressure would be expected to result in substantially increased penetration and improved fusion zone profile in order to avoid root defects.

Work at reduced pressure were carried out in 1993 with the non-vacuum electron beam welding head mounted on a vacuum chamber. The work has to a large extent been concentrated on the elimination of root defects in partially penetrating welds. The results of the work were that reducing the chamber pressure to intermediate vacuum (i e below 10 mbar) penetration depths in excess of 70 mm were readily achieved at long working distances (e g 200 mm) and the root defect level could be controlled. Improvements of the equipment have enabled round bottomed welds to be produced over a wide parameter range, leading to completely defect free welds, both in partly penetrating welds and slope down sequences. It is believed that this represents a major breakthrough in the technology. A metallographic section of an approximately 55 mm deep weld in copper is shown in Figure 6-2.

In parallel with the welding technology development, a chamber for welding full diameter lids onto half-length canisters has been constructed in 1993. This piece of equipment will be commissioned in early 1994. Once full diameter lids can be welded successfully, this chamber can be extended to welding full length canisters.

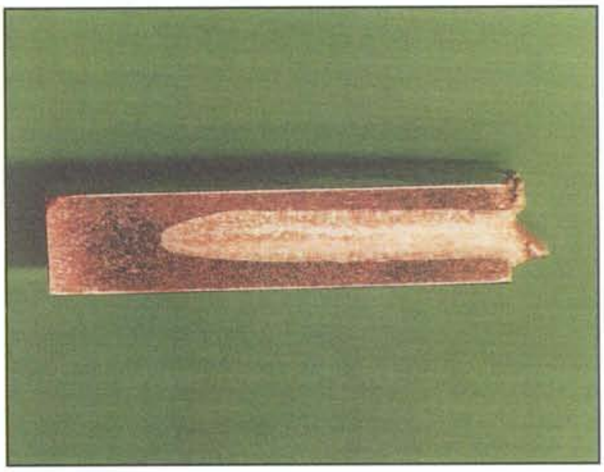


Figure 6-2. *A metallographic section of an approximately 55 mm deep weld in copper.*

Non Destructive Testing

Concurrent with the welding technology development, methods for non destructive testing have been investigated. Both ultrasonic and digital radiography have been tested and the preliminary conclusions are that both methods are viable. For best results with ultrasonic testing, the copper material will have to be relatively fine-grained (< 250 μ). The minimum detectable defects, as estimated from drilled hole targets, were found to be comparable and in the range of 0.5 to 1 mm.

6.3 DESIGN OF THE ENCAPSULATION PLANT

In the encapsulation plant the fuel will be received from the storage pools in CLAB. It shall be monitored and dried before emplacement in the canister. Before the inner steel lid is put on, the air will be evacuated and the void will be filled with inert gas and a particulate filler material such as glass beads. After this the canister will be sealed with a copper lid. High demands are put on this sealing and on the testing for tightness. To meet this requirement the sealing will be done with electron beam welding technique. The canister will then be checked for contamination before it is placed in a buffer storage. The transport to the deep repository will be made in casks similar to those used for transport of spent fuel from the power plants to CLAB.

A preliminary design of the encapsulation process and the plant has been made as a basis for SKB's cost calculation and presented in the SKB report PLAN 93 /6-1/. In order to explore alternative designs and the state of the art for the encapsulation process, feasibility studies were performed during 1993. Ten European companies with experience in this field were invited to a pre-qualification for the feasibility studies. As a result three consultants and one joint venture group were chosen to perform studies. SKB placed four contracts to the selected consultants for separate studies based on their experience from design and operation of facilities for "dry handling" of spent nuclear fuel in hot cells.

The basic requirements for the encapsulation of spent fuel were defined during the spring as a base for the feasibility studies. The studies were started in June and were completed by the end of the year. During the study phase follow up meetings were held with the consultants in the course of their work and visits were made to their reference facilities. Parts of the process needed for encapsulation of spent fuel in a copper canister can be found for instance in the English and French facilities for reprocessing. The German facility for pilot conditioning of spent fuel, which is under construction in Gorleben, is also an example of an interesting facility.

The studies have given many interesting proposals for solutions for the various parts of the encapsulation process based on experiences from the reference facilities. Based on these studies a process flow diagram has been established, see Figure 6-3. It comprises the following steps.

The fuel is transferred from CLAB via the existing fuel elevator. After checking (safeguards), monitoring (power and reactivity) and sorting (to get the right power in the canister) the fuel is transferred to the dry handling cell. In the handling cell the fuel is dried and emplaced in the canister. Before the canister is moved to the next workstation, the filling cell, a temporary lid is fitted to avoid contamination. In the filling cell the air in the canister is replaced by inert gas and a solid filling material eg glass beads is introduced. Finally a steel lid is welded to the inner steel container. In the next cell, the welding cell, the copper lid is put on the canister and electron beam welded. The canister is then transferred to the next cell for machining and non destructive testing and finally contamination check before transfer to the buffer storage.

Some parts of the process need to be tested at an early stage of the project. At the end of the year some preparatory tests were made with establishing vacuum in a container filled with sand and with glass beads. The test showed that the design of these systems has to be tested more during the coming design phases. A preliminary study of service and auxiliary systems needed for the encapsulation and the connections to existing systems in CLAB has been carried out as a base for design work.

Evaluation of the results from the feasibility studies were carried out during the winter 1993/94. For the next design phases – the Conceptual and the Basic Design – an invitation to tender is sent to the companies who have contributed with studies for the feasibility study phase.

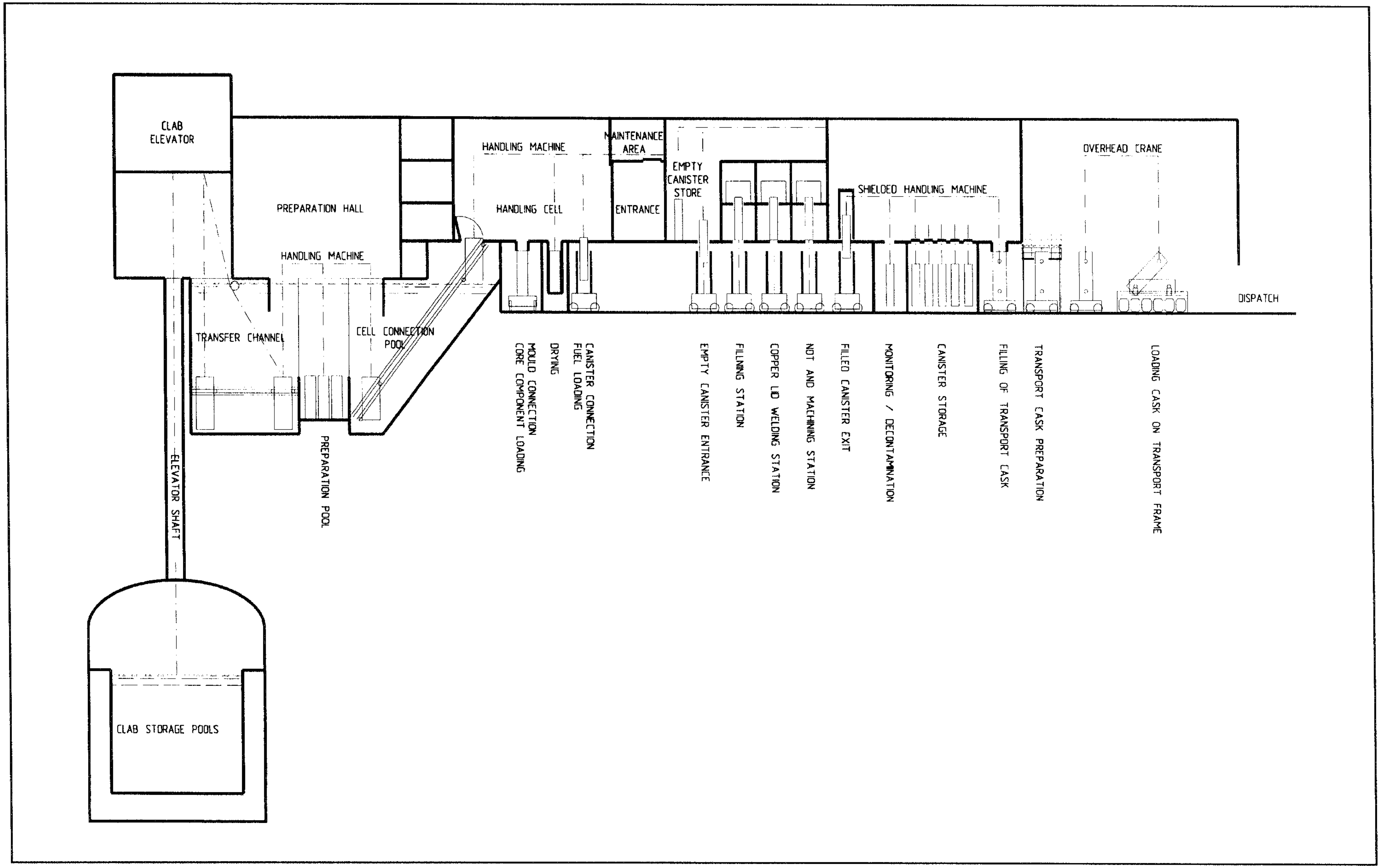


Figure 6-3. *Encapsulation plant – flow layout.*

7 SUMMARY OF RESEARCH, DEVELOPMENT AND DEMONSTRATION ACTIVITIES

7.1 GENERAL

According to the 12§ of the Act on Nuclear Activities the owners of the nuclear power plants are responsible for conducting the necessary research, development and other measures necessary for the safe handling and disposal of radioactive wastes arising from the nuclear power production. A programme for conducting the necessary activities must be submitted to the pertinent authority every third year. By the end of September 1992 SKB accordingly submitted its third RD&D-programme to the Swedish Nuclear Power Inspectorate – SKI. The programme was sent by SKI for review and comment to about 50 different authorities, institutes, universities, local community safetyboards, environmental groups and other organisations. Based on the comments received and their own internal review SKI submitted their comments to the government by the end of March 1993. The highlights of the summarizing statement from SKI are reprinted in section 12.2 (part II). An independent review of the RD&D-programme 92 was made by KASAM – the Swedish National Council for Nuclear Waste Management. They gave their comments in a report to the government by the end of June 1993. These comments are summarized in section 12.3.

The review reports from SKI and KASAM contain some specific recommendations on conditions to be stipulated by the government. SKB was given the opportunity to comment on these proposed stipulations and submitted comments in September 1993. SKBs comments are summarized in section 12.4.

The government decision on the programme was given December 16, 1993 and is summarized in section 12.5. It included the following statements:

"The government finds like SKI that RD&D-Programme 92 meets the requirements expressed in 12§ of the Act on Nuclear Activities."

"Like SKI and KASAM the government accepts SKBs plans for studies of different alternatives and system designs."

"The government finds like SKI and KASAM that the change of the programme has considerable advantages even if the long-term performance of the repository not can be demonstrated...."

"The government decides that the following conditions shall apply for the continued research and development activities.

SKB shall supplement RD&D-programme 92 by accounting for

- the criteria and methods which can form a base for selection of sites suitable for a deep repository,
- a programme for delineation of prerequisites for the encapsulation plant and the repository,
- a programme for the safety analyses that SKB plans to establish,
- an analysis of how different measures and decisions will influence subsequent decisions within the disposal programme."

A supplement covering these points is worked out during 1994.

7.2 SAFETY ANALYSIS

7.2.1 General

The safety assessment activities during 1993 have been focused on planning the assessments needed during the coming site investigations, refinement of the modelling tools and on an assessment of the performance of the copper/steel canister in a KBS-3-like engineered barrier system that was prioritized in the RD&D-Programme 1992.

A workshop was held in Hecla Island, Canada between Safety Assessors from AECL, NAGRA, PNC, TVO and SKB to discuss and compare methods and results in recent or ongoing assessments.

7.2.2 Scenario methodology

The first step in a safety analysis after defining the appropriate system and system boundaries is to develop the scenarios to be analysed. The scenarios should cover a wide range of possible future events and together they should give a broad perspective on the safety margins of the total system. The scenario development strategy has during 1993 been revised.

The first step in the present methodology is to develop a Process System where all known links between the processes involved are addressed. The process System is defined as "the organized assembly of all phenomena required for description of barrier performance and radionuclide behaviour in a repository and its environment, and that can be predicted with at least some degree of determinism from a given set of external conditions". The mapping of all FEPs in the Process System can be done in several ways and during 1991-1993 attempts have been made with several different methods 1) visualization of the FEPs in a tree structure, 2) using Influence diagrams and 3) using the Rock Engineering Systems (RES) approach.

The RES methodology has been used in some applications in SKB and seems so far be a good system to visualize the Process System in a comprehensive and transparent way. Further development and use of the methodology together with a linking to the FEPs database are under way.

The second step in the scenario methodology is to select the actual scenarios to be subjected to numerical evaluation. The above mentioned schemes seem to be helpful tools to find the most important pathways through the Process System and also for finding processes and issues that can be put less emphasis on.

7.2.3 The copper/steel canister

In the event of water ingress to the canister, hydrogen will be generated as a result of anaerobic corrosion of the carbon steel inner canister. The potential overpressurization of the canister and the possible effects of the gas on water movement around the repository have been investigated. The principal objective of this work was to determine the mechanism by which gas can migrate from a canister, to identify possible consequences of gas generation and to determine the likely fate of the gas.

The main conclusions from this preliminary study were:

- Long-term effect of the hydrogen gas generation will depend on the generation rate and the ability of the bentonite barrier to permit the escape of the gas.
- The amount of gas that could escape through the bentonite by dissolution and diffusion is small compared with the maximum gas generation rates that have been considered. Gas-phase flow must therefore be the primary route for the gas through the bentonite.
- Two questions need to be addressed with regard to the passage of gas through the bentonite. They relate to the number of capillary-pathways in the bentonite, and the behaviour of the bentonite in response to increasing gas pressure.
- Once the gas has escaped from the bentonite, it will pass into the tunnel area and the damaged zone. Transport of dissolved gas by diffusion or by advection in the groundwater flow is unlikely to be a significant pathway.
- The gas will eventually pass into the rock overlying the repository. Two alternative approaches have been adopted to assess the ease with which gas can pass upwards through the rock towards the surface. Both models suggest that there is ample transport capacity to the surface.

If radionuclides are released from the waste, they will start to migrate. To be able to include as many transport processes as possible in the near field, it is necessary to have a model that is capable of describing the rather complex geometry. For this purpose a "compartment model" has been developed.

Scoping calculations on cesium, iodine and plutonium have been done with this model. The postulated hole in the copper canister was assumed to grow with time. The effect is small for short-lived nuclides, but there is a considerable increase of the release for the longer lived ones (about one order of magnitude for I-129). The most important transport pathway for all nuclides is to a fracture intersecting the deposition hole. This effect is more pronounced for the short-lived species which otherwise will decay on their way to other sinks located further away. Should there be no fracture intersecting the deposition hole the long lived nuclides will escape approximately at the same rate anyway by the other routes.

The copper/steel canister has, in general, about the same properties as the lead filled type.

7.2.4 Bentonite – groundwater interaction

Understanding the surface chemical properties of montmorillonite in near-neutral and alkaline media is essential for establishing a chemical model of the bentonite/water interaction under repository conditions. The bentonite-groundwater interactions and implications for near field chemistry have therefore been investigated. Model computations indicate that the edge OH groups of montmorillonite excert a strong control on the buffer capacity in highly compacted bentonite.

Long-term predictions of the near field chemistry have been made. The evolution of the chemical composition of bentonite porewater and the relative proportion of exchangeable cations on montmorillonite for different groundwaters have been evaluated. The model suggests that pH and alkalinity of the porewater are controlled by the buffering capacity of the edge surface sites and calcite dissolution.

The transformation of Na-bentonite to Ca-bentonite strongly depends on the amount of calcite present in bentonite and the chemical composition of the groundwater. Once the carbonate pool is depleted, the conversion of Na-bentonite to Ca-bentonite proceeds at a much lower rate.

7.2.5 Modelling of transport in the far field

Predictive modelling of groundwater flow in fractured, low-permeable rock is complex since the flow is concentrated within fractures. Nevertheless, calculations of water movement and transport of radionuclides are an important part of the safety analysis. Conceptual, mathematical and numerical models need to be further refined, and the impact of different conceptual models on the simulated results needs to be shown.

Verification and testing of models are extremely important. Therefore, modelling of groundwater flow and transport of solutes has been initiated within the Äspö Hard Rock Laboratory project. The work will increase our understanding of the fundamental processes and give an opportunity to test the models.

The channeling network approach describes the flowpaths in fractured rock as a network of connected channels with different lengths, conductivities, volumes and widths. The model can simulate the transport of a solute through this network where the solute may diffuse into the rock matrix. The Channeling Network Model has been applied to data from the Äspö site as a part of the Äspö Task Force work. The results of the simulations of the LPT-2 pumping and tracer experiment are expected during 1994, and will be compared with other modelling approaches.

HYDRASTAR is a code for stochastic continuum modelling of groundwater flow used in SKB 91. Realizations of the hydraulic conductivity field are generated and can be conditioned on measured values of the conductivity using kriging.

A modelling of the regional groundwater flow conditions in the area surrounding the Finnsjön site has been performed. In the study, it was of special interest to see if any possible case could result in an upward movement of groundwater in the region designed to be the repository area in the SKB 91 performance assessment. A number of different model geometries and assumptions concerning the geological structural model, were analyzed. None of the analyzed cases implied that the results concerning the groundwater residence times from the SKB 91 study were non-conservative.

7.3 SUPPORTING RESEARCH AND DEVELOPMENT

7.3.1 General

Chapter 15 in part II summarizes activities both on general development of understanding and databases in areas relevant for repository safety, and on specific supportive research actions that have been initiated to clarify unresolved issues. It is divided into sections on Spent Fuel, Canisters, Buffer and Backfill, Geoscience, Chemistry, Natural Analogue Studies, and The Biosphere.

7.3.2 Engineered barriers

The studies of spent fuel behaviour in the repository environment have provided results on the fuel pellet rim zone, on fuel corrosion, on alpha radiolysis and on fuel natural analogues.

The work on canister materials has been concentrated on anaerobic corrosion of steel and on the evolution of oxygen in the repository after closure. Long-term corrosion of steel is estimated to be in the range 0.1 – 1.0 μm/year. The time for the initial oxygen concentration to decrease to 1% is in the range a week to a year.

Studies of buffer and backfill include testing and modelling of the physical behaviour and heat conductivity of water saturated and non-saturated bentonite. Documentation of bentonite longevity has continued as well as the studies of cement-clay interaction.

7.3.3 Geoscience

It would be advantageous if nuclide transport models to a higher degree could be conceptualized on geological and hydrogeochemical features. Special interest has been paid to the red-coloured altered environment which often surrounds fractures in granitic rocks. Samples from the Äspö granite show obvious changes in respect of chemical features as well as petrophysical properties. E g phyllosilicates including clay minerals are increasingly occurring in the hydrothermal altered zone. Furthermore Na and K is gained and Ca is loosed. The effective porosity is significantly increased in the zone and the density is reduced. The magnetite content is changed by oxidation to hematite and Fe-hydroxides. This type of differences concerning the conceptual conditions most probably could be further developed in order to improve the knowledge of transport and matrix diffusion processes in crystalline rocks.

The preliminary groundwater chemistry results from the Laxemar Deep Drilling present extreme high salinity values at depths exceeding 1000 m. At 1700 m the salinity amounts to approx 8% compared to the ocean values of 3.6% or the value of the Baltic Sea at Äspö, 0.5%. The change of constituents as well as the concentration profile need a thorough interpretation. Hopefully the groundwater chemical results will indicate a "fingerprint" of the hydrogeological evolution of the area in a regional perspective.

Besides regional groundwater modelling under today's climatic situation, it is essential to shed light on the hydraulic conditions in connection with future glaciations and deglaciations. A time dependent glaciation model of Scandinavia was developed in 1992. The model also includes surface boundary conditions for loading and melting flows.

The evaluation of meltwater fluxes according to the glaciation and deglaciation has continued. A comprehensive sensitivity test of the complex numerical model which has been developed at the University of Edinburgh, shows very interesting results. The "confidence building" has mainly been done as a correlation exercise between esker frequencies (perpendicular to the ice-front) along three transects. There is a very strong indication that the esker frequency reflects the bedrock transmissivity in a regional perspective. These results imply possibilities for ground water flux calculations at greater depths during scenarios of ice covers and glaciation recovery stages.

7.3.4 Chemistry

The chemistry program comprises radionuclide chemistry and chemical conditions which determine radionuclide solubility, mobility and retention in a waste repository. Investigations of groundwater and geochemistry are part of the geoscience program and included in the research at the Äspö Hard Rock Laboratory. Geochemical research is also being conducted within the frame of the natural analogue investigations.

The thermodynamic constants that determine the solubility are being measured carefully in the laboratory. The relevant chemical environment is deep groundwater or bentonite pore water. It has been argued that tetravalent actinides like Th(IV), U(VI) and Pu(IV) would be influenced by phosphate ions in the near-field. This conclusion is based on calculations using constants measured in the early sixties. These constants are widely used, but unfortunately they are incorrect. Recent measurements within the chemistry program have given us better constants and we can now conclude that phosphate complexes are not strong enough to be of any concern in the near-field of a spent fuel repository.

Humic substances, colloidal particles and microbes exist in groundwater. At least potentially they can influence radionuclide solubility and mobility. Therefore they are carefully investigated. Sampling is to a large extent concentrated to Äspö. The relatively new technique of DNA-analysis (16S-rRNA) is being tested as a means of identifying the bacteria.

Surface complexation and ion exchange models are being tested by laboratory experiments in an attempt to describe sorption of radionuclides on rock minerals and bentonite particles in a more fundamental way.

Cement has many applications in underground construction such as concrete structures, pavement, cement grouting of fractures and shotcrete on tunnel walls. However, the normal Portland Cement contain portlandite and other hydroxides which create a high pH in the pore water. British Geological Survey is performing laboratory studies on the geochemical changes induced by cement pore water. The BGS-studies are jointly supported by NAGRA, NIREX and SKB.

7.3.5 Natural analogues

The uranium mineralisation at Cigar Lake in northern Saskatchewan, Canada, has been studied by AECL as a natural analogue to deep disposal of spent fuel since 1984. SKB joined the project in 1989 and Los Alamos National Laboratory, supported by US DOE, participates since 1991. The three year phase starting in 1989 was finished in 1992 and the final report will appear in the AECL and SKB report series of 1994.

Conclusions related to performance assessment of barriers in a spent fuel repository have been drawn in the following areas: 1) UO_2 dissolution and stability, 2) clay sealing, 3) colloids, 4) groundwater chemistry, 5) radiolysis and 6) radionuclide migration. Most of the evaluations are in fact focused on repository near-field issues for which Cigar Lake is a very good analogue. This is true also for the last point where near-field release models were successfully applied to calculate the release of helium generated in the ore, through the clay halo.

The 2 billion years old reactor zones in Oklo, Okelobondo and Bangombé are being investigated as analogues to waste repositories. The study is directed by the French CEA and supported by CEC. Organisations from other countries including SKB are participating in the study. Our involvement has during 1993 to a large extent been devoted to the fossil reactor in Bangombé, which is situated about 20 km away from Oklo and Okelobondo. This reactor zone is close to the ground surface but has been seemingly well preserved. In 1993, a total of 7 boreholes were core drilled both into the zone and outside. The samples (cores and water) and hydraulic measurements were analyzed and evaluated. SKB also participates in the studies at Oklo and Okelobondo.

The natural hyperalcaline areas found in Jordan are being studied as analogues to underground repositories for low- and intermediate level waste. Concrete in the waste and in the construction of such a repository will have a high pH pore water. Typical solid cement phases will form and the high pH may influence for example radionuclides and organic materials in the waste. The pH of groundwater in Jordan hyperalcaline areas reaches values of about 12.5 and even higher than that. Typical solid cement phases are occurring as natural minerals and the environment is rich in elements, some of which are similar to waste nuclides. The first phase of the project was jointly funded by NAGRA, NIREX and Ontario Hydro. Together with NAGRA and NIREX, SKB has been supporting the second phase of the study. A proposal for a third phase has been made.

Anthropogenic analogues of concrete have also been studied within the SKB program. The most recent example is an old (1906) concrete clad water reservoir in Uppsala. The concrete is remarkably unaltered despite an almost 90 year contact with soft water and even the steel has been well protected.

7.3.6 Biosphere

The biosphere studies treat the transport of radionuclides from the bedrock via primary receptors (e g sediments), redistribution in nature and finally calculate the exposure dose to man and other biota.

The activities have gradually switched from investigation of general data, processes and methods, to confirmation of the models and methods used and acquisition of relevant site specific data.

International cooperation is very important in the process of model confirmation. SKB follows and takes active part in several international projects i e BIOMOVS II, VAMP and PAAG.

One way of understanding long time transport processes in the biosphere is to study transport of natural occurring elements. Some well defined peat bog areas have been selected for preliminary analysis of leaching elements from the surrounding till and the history registrations in the bog sediments.

Site specific data are studied in the Äspö area, and have been studied in the Gideå area since the Chernobyl fallout in 1986. These results are being used to calculate the realistic dose distribution to critical group, from eventually released nuclides. Emphasis is also payed to describing the uncertainty and variation in parameter data separately.

7.4 OTHER LONG-LIVED WASTES

In addition to spent fuel and short-lived low and intermediate level waste (LLW and ILW) there is also a third category of waste: long-lived LLW and ILW. The quantities are relatively minor and the main sources are waste from research activities and some components from the power reactors which have been situated inside or near the reactor core (core components and reactor internals). Core components are being stored at CLAB and research waste is being collected, stored and conditioned at Studsvik.

The present concept is to build a facility for disposal of this waste. It will consist of three parts: SFL 3, 4 and 5.

- The SFL 3 is designed for long-lived LLW and ILW from Studsvik, which originates from research, industry and medicine. It shall also receive operational waste from CLAB and the encapsulation plant.
- The SFL 4 is intended for decommissioning waste from CLAB and the encapsulation plant.
- The SFL 5 is designed for the disposal of concrete containers with reactor core components and internal parts.

The total volume of waste is estimated to about 25 000 m^3, but strictly taken not all of this falls into the category of long-lived waste. More than half of the total volume consist of waste which could in principle be disposed of in SFR such as operational waste and decommissioning waste from CLAB and the encapsulation plant. However, SFL 3-5 is also intended to receive all LLW and ILW that arises in the post-closure period of SFR.

It will of course be necessary to demonstrate the long term safety of disposal for this waste as for any radioactive waste. A prestudy project was started at the end of 1992 in order to prepare for future safety assessments. The following general aims were adopted:

- Make an inventory of existing waste for SFL 3-5 and make a forecast of the waste that is being produced.
- Continue work on the design of the repository for long-lived LLW and ILW.
- Prepare and gather data for the safety assessments.

A specific aim for the prestudy was to make a first preliminary and simplified assessment of the near-field barriers to radionuclide dispersion. The prestudy will be finished and reported in 1994 and a new phase will continue with the same aims, at least until mid 1996. By that time it may be appropriate to start the first safety assessment.

In an international perspective the Swedish quantities of this waste are small. Countries with reprocessing as a part of their fuel cycle have more long-lived LLW and ILW. An important task for SKB is therefore to follow the developments in other countries and in particular an informal exchange of experience has been established between SKB and the organisations ANDRA, NAGRA and NIREX.

7.5 ÄSPÖ HARD ROCK LABORATORY

The Äspö Hard Rock Laboratory is being constructed in preparation for the deep geological repository of spent fuel in Sweden. An Annual Report 1993 /13-5/ and Chapter 17 contains more detailed overviews of the work conducted.

Present work is focused on verification of pre-investigation methods and development of the detailed investigation methodology. Construction of the facility and investigation of the bedrock are being carried out in parallel. December 1993 2760 m of the tunnel had been excavated to a depth of 370 m below surface. The ongoing construction of the access ramp to a depth of c. 450 m is used to check the predictive models set up from the pre-investigation phase, to develop methodology for construction/testing integration and to increase the database on the bedrock in order to improve models on groundwater flow and radionuclide migration.

The management of the large quantities of data has been developed to the point where SKB is now in possession of a data production methodology that meets exacting requirements on quality and overview. The methodology has been developed for conventional tunnelling.

When the deep repository is built a few years after the turn of the century, full face boring will undoubtedly be the dominant method for underground rock construction. In view of the above, about 400 m of the facility will be excavated with a 5 m diameter tunnel boring machine (TBM) during 1994.

To obtain a better understanding of the properties of the disturbed zone and its dependence on the method of excavation ANDRA, UK Nirex, and SKB have decided to perform a joint study of disturbed zone effects.

The Äspö HRL provides an opportunity for demonstrating technology that will provide this necessary quality. The need to integrate existing knowledge and build an (inactive) prototype of a deep repository is currently being discussed within SKB. The objectives include translating scientific knowledge into engineering practice, testing and demonstrating the feasibility of the various techniques, and demonstrating that it is possible to build with adequate quality. In conjunction with construction of the prototype different types of models will be used to describe the performance of the prototype in conjunction with water absorption and restoration of groundwater pressures, etc. The prototype will then be monitored via a large number of measurement points for a period of 5-15 years. Following this there will be an opportunity to study in detail any chemical and physical changes in e g the bentonite surrounding the canisters.

An important and integrated part of the work is further refinement of conceptual and numerical models for groundwater flow and radionuclide migration. Detailed plans have been done for several experiments to be conducted after the end of the construction work.

A "Task Force" with representatives of the project's international participants has been formed for numerical modelling of groundwater flow and solute transport. This offers excellent opportunities for trying out alternative models in a way that would not have been possible without international cooperation. After remodelling the combined long-time pumping and radioactive tracer test LPT-2 several groups have performed scoping calculations for the planned experiments.

Eight organizations from seven countries participate now in the work at the Äspö Hard Rock Laboratory and contribute in several ways to the achievements. The results of the work are reported in Äspö International Cooperation Reports.

7.6 ALTERNATIVE METHODS

The main direction of the SKB RD&D-programme is towards completing the first step with deposition of some 5-10% of the spent fuel in a repository within about 20 years time. In parallel the work on alternative treatment and disposal methods is followed and supported in a limited scale.

During the last few years the possibility for partitioning and transmutation has attracted renewed interest. SKB supports some work in this area at the Royal Institute of Technology (KTH) in Stockholm and at Chalmers Institute of Technology (CTH) in Gothenburg. The work at KTH is emphasized on safety related issues and at CTH on processes for partitioning.

During 1993 the KTH group completed an introductory study of accelerator transmutation of wastes (ATW) which was published as SKB TR 93-23. A brief account of the work conducted by the CTH group is given in Chapter 18.

SKB is also planning further research work related to the disposal in very deep boreholes. During 1993 a unique compilation of data from drilling of very deep boreholes in former Soviet Union was published on initiative from SKB; see SKB TR 92-39. The report summarizes data from three holes – Kola 12260 m deep; Krivoy Rog about 5000 m deep; Tyrnauz about 4000 m deep.

7.7 INTERNATIONAL COOPERATION

SKB has considerable programmes for international cooperation. The most prominent are through several bilateral information exchange agreements and the international participation in the Äspö Hard Rock Laboratory. These programmes are summarized in Chapter 19 of Part II.

8 COST CALCULATIONS

8.1 COST CALCULATIONS AND BACK-END FEE

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

Each year SKB calculates the future electricity production and the future costs for the back-end operations related to this electricity production. The results of the 1993 calculations were presented in PLAN 93 /8-1/. The total future electricity production (from 1993) was estimated to be about 1 210 TWh, if all twelve reactors are operated to the year 2010. Up to the end of 1992 about 800 TWh have been produced making a total of about 2 010 TWh in the Swedish programme. For this production a fuel amount of about 7 850 tonnes of U is required.

The total future back-end costs were estimated to be about GSEK 48.3 (price level of January 1993) 1 GSEK $= 10^9$ SEK $\approx 0.13 \cdot 10^9$ US\$. Up to and including 1993 already GSEK 9.2 have been spent. The total cost for the back-end of the nuclear fuel cycle is thus about GSEK 57.5. The breakdown of the costs are roughly (old reprocessing costs excluded):

Transportation of waste	5%
Interim storage of spent fuel	17%
Encapsulation and final disposal of spent fuel and long-lived waste	40%
Final disposal of operational and nuclear power plant decommissioning waste	5%
Decommissioning and dismantling of nuclear power plants	22%
Miscellaneous including R&D, pilot facilities, and siting	11%

Based on SKB's cost calculations and a discussion about the time of operation of the reactors and the estimated real interest rate, the government has decided that the fee for 1994 shall be SEK 0.019 per kWh on an average. This is the same fee as for the last eleven years.

The fee is periodically paid into funds at the Bank of Sweden. These funds are administrated by The Swedish Nuclear Power Inspectorate (SKI), who in 1992 took over this responsibility from the previous National Board for Spent Nuclear Fuel, SKN. The total sum in the four funds was at the end of 1993 about GSEK 13.3, an increase by GSEK 1.8 during 1993.

8.2 REPROCESSING

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

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

8.3 DECOMMISSIONING OF NUCLEAR POWER PLANTS

During 1993 SKB's engagement continued in the international cooperative programme, which is sponsored by OECD/NEA. SKB is responsible for the programme coordinator function. This programme comprises 22 decommissioning projects in 11 countries. The majority of the projects are small first generation power demonstration reactors.

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

Earlier studies of the dismantling of the Swedish reactors have shown that there is no immediate need for substantial decommissioning R&D in Sweden. A study of the possibilities to remove the reactor pressure vessel in one piece, and transport it intact for disposal is, however, in progress.

The costs of decommissioning constitute a large part of the total backend costs. The costs used are based on a study performed in 1986. A new cost study to update the costs based on the latest developments has almost been completed. In this a detailed study of the decommissioning of one of the newest BWRs is performed.

9 NUCLEAR FUEL SUPPLY

Sweden imports all uranium for its nuclear power plants, and the purchasing is normally handled by the utilities.

SKB is in charge of industry-wide coordination and matters relating to market surveys, strategic stockpiling of enriched uranium and certain purchases of enriched uranium.

9.1 NATURAL URANIUM

The Swedish nuclear power plants have an annual requirement of about 1 600 tonnes of natural uranium. Most of this requirement is met by long-term contracts between the nuclear utilities and producers in e.g. Australia and Canada. The uranium is mined in modern mines, mostly open pit mines. Great efforts have been made at these mines to protect the environment.

There are important stocks of uranium both in the west and in CIS-countries. As these stocks are now being sold, both the long term price and the spot price have been lowered in recent years, in spite of the fact that uranium production is declining, see Figure 9-1. A new source is coming to the market as high enriched uranium from nuclear weapons disarmament will be diluted to low enriched uranium in the Russian Federation and sold to the US.

In Sweden there are low-grade uranium resources, however the cost of producing from these resources would be much above world market prices. There was some production in southern Sweden from shales near Ranstad in the late 1960-ies. That area is now being restored by the SKB sister company SVAFO.

9.2 CONVERSION AND ENRICHMENT

Conversion is a chemical process for production of uranium hexafluoride from uranium concentrates. Natural uranium contains 0.71% of the isotope uranium-235. Enrichment is a process to increase this content. Low enriched uranium up to 3-5% of uranium-235, is a suitable fuel for light water reactors used in Sweden.

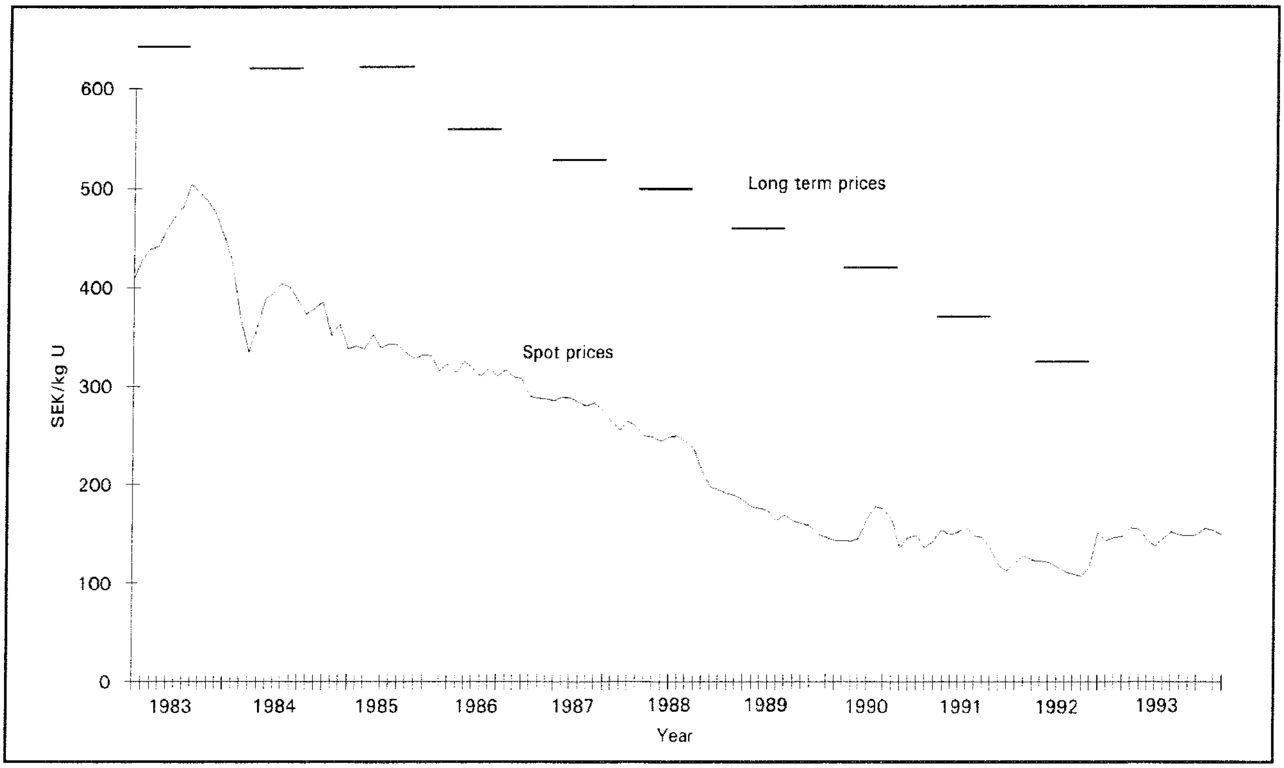


Figure 9-1. *Long term and spot prices for uranium.*

Long term price = *Average price for long term deliveries to the European Community.*
Spot price = *Average spot price each month for the unrestricted market, published by the German company NUKEM.*

Figure 9-2. Gas centrifuges in the Ural Electrochemical Integrated Plant for enrichment of uranium.

The Swedish utilities have a diversified and reliable supply of conversion services from Canada, France, United Kingdom and the USA. There is also a reliable supply of enrichment services from Eurodif in France, Urenco in the Netherlands, the United Kingdom and Germany, and USEC in the USA.

Techsnabexport Co Ltd in the Russian Federation delivers low enriched uranium to the Swedish utilities, which means that this includes both natural uranium, conversion and enrichment. Deliveries to Sweden come from the Ural Electrochemical Integrated Plant near Ekaterinburg, see Figure 9-2. SKB transports such low enriched uranium by the ship M/S Sigyn from the port of St Petersburg to the fuel fabrication plant in Västerås, Sweden.

9.3 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 ABB Atom, but also orders from French, German, Spanish and US companies.

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

Fuel fabrication at ABB Atom was around 250 tonnes of UO_2 for nuclear fuel during 1993. Of this volume about 110 tonnes were exported to Belgium, Finland, France, Germany and Switzerland.

The fuel assembly design SVEA 96/100 where the fuel rods are devided into four minibundles with 5 x 5 rods separated by a water cross, is now the dominating BWR fuel manufactured in Sweden. About 2/3 of the ABB Atom BWR deliveries in 1993 were of this design.

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

9.4 NUCLEAR FUEL STOCKPILE

SKB is responsible for holding a strategic stockpile of low enriched uranium and zirkaloy, corresponding to an electricity production of 35 TWh. This amount has been decided by the Swedish parliament.

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

Table 9-1. Costs for nuclear fuel in 1993

	SEK/kWh	Million SEK in 1993
Natural uranium	0.008	470
Conversion	0.001	60
Isotope enrichment	0.009	530
Fuel fabrication	0.009	530
Strategic stockpile	0.001	60
Total nuclear fuel	**0.028**	**1 650**

9.5 COSTS

The costs for front end supply of nuclear fuel in 1993 in Sweden are shown in Table 9-1 (the production of nuclear electricity was 58.8 TWh in 1993).

The costs for nuclear fuel have decreased in recent years, however there was an increase in 1993 in SEK due to the lower value of the SEK in comparison with currencies such as USD, DEM and FRF. This is shown in Figure 9-3.

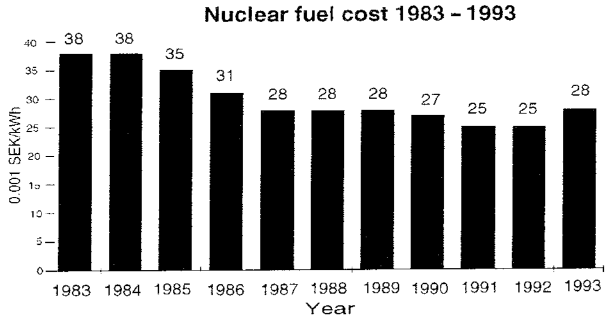


Figure 9-3. Nuclear fuel costs 1983 – 1993.

10 CONSULTING SERVICES

10.1 BACKGROUND

The international review of the KBS reports (1978-84) made SKB's activities internationally recognized. Since then SKB has actively participated in international co-operation activities and strengthened its position as an attractive partner. As a consequence foreign organizations have shown an interest in contracting SKB for services in their own programs.

The international interest for SKB has several reasons. Sweden has developed a well functioning system for transports and disposal of radioactive waste. SKB has a facility for interim storage of spent fuel (CLAB) and a repository for low- and intermediate-level waste (SFR). In addition SKB has a comprehensive RD&D program and a broad distribution of technical reports.

Since 1984 there is a special group – NWM (Nuclear Waste Management) – within SKB for marketing and management of external services. For each assignment a tailored project team is organized with due consideration of the competence required, see Figure 10-1. It may be experts from SKB's own staff or from groups contracted for different tasks in the Swedish radioactive waste management program.

SKB's external services shall, of course, carry their own costs with some margin. They are, however, also of value by stimulating the staff, improving their competence and broaden their views.

Since 1984 some 100 assignments have been accomplished for organizations in Australia, Belgium, Canada, former Czechoslovakia, Finland, Hungary, Japan, Lithuania, South Korea, Spain, Switzerland, Taiwan, United Kingdom and USA. The assignments have dealt with long-term safety, overall planning, canister and buffer materials, transports, field investigations, site selection and facility design.

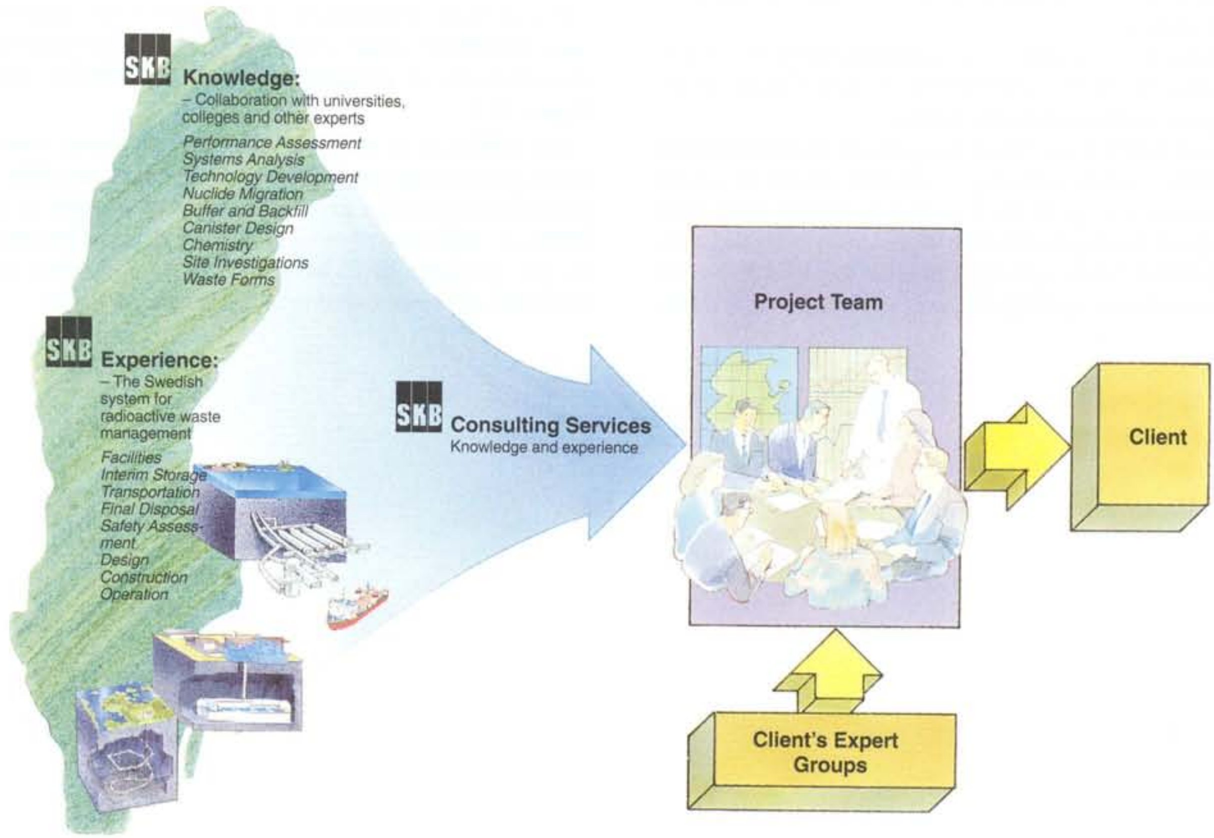


Figure 10-1. The SKB Consulting Services.

10.2 NWM WORK DURING 1993

During 1993 SKB was contracted by organizations in Spain, Canada, United Kingdom, Lithuania, Japan, Republic of Korea and USA. Marketing activities have been going on in a number of countries among them some east European countries. Some general frame agreements have also been signed during the year. In all, some thirteen assignments have been concluded, distributed over seven countries.

The marketing has during 1993 continued to be focused on contacts in East Asia and Eastern Europe. Waste management activities on a potential market, South Korea, are still suffering from delays, primarily depending on a negative public attitude connected to the siting of the waste facilities.

Most of the East European countries seem to be without a long term national strategy for the management of radioactive waste. Of special interest is the SKBs assignments in Lithuania, where SKB has been entrusted with the responsible task to be the prime advisor to the Ministry of Energy in the implementation of a dry interim storage facility for spent nuclear fuel. An agreement was signed during December 1993 between the German company Gesellschaft für Nuklear-Behälter mbH and the Lithuanian Ministry of Energy regarding supply of dry storage casks, see Figure 10-2. SKB is also assisting in the realization of a cement immobilization facility for spent resin and a compactor for low-level waste. A national long-term waste management strategy plan is also under preparation for Lithuania.

Delivery of supplementary equipment to the previously supplied RAMAC-equipment to as well Canada as the Republic of Korea has taken place.

For ENRESA, the Spanish organization corresponding to SKB, studies regarding a suitable design of a final repository for spent nuclear fuel in granite have been finalized. In cooperation with the Spanish geological company ITGE, SKB is giving support in the development of instruments for hydrogeological borehole measurements.

Figure 10-2. *An agreement is signed by Ignalina NPP in Lithuania and Gesellschaft für Nuklear-Behälter mbH in Germany regarding the supply of dry storage casks. The project management is entrusted to SKB.*

Japan Nuclear Fuel Ltd, JNFL, is operating a final repository for low-level waste in Rokkashomura located in the north of Japan. SKB has been entrusted with studies on gas formation and the possible impact from the gas to the engineered barriers. Of special interest to JNFL has been SKBs experience from SFR on similar matters.

A study has been performed on behalf of Sumitomo in Japan regarding SKBs experience on the possible application of burn-up credit for spent nuclear fuel.

United States Department of the Interior has ordered one CHEMMAC-sond, which will be used for pH and Eh measurements of groundwater in deep boreholes, see Figure 10-3.

UK NIREX is at the Sellafield area conducting a site investigation program aiming to the realization of a underground repository for low- and intermediate waste at a depth of ~800 meters below ground level. In connection to this program SKB has carried out a number of RAMAC-measurements down to 2000 meters depth.

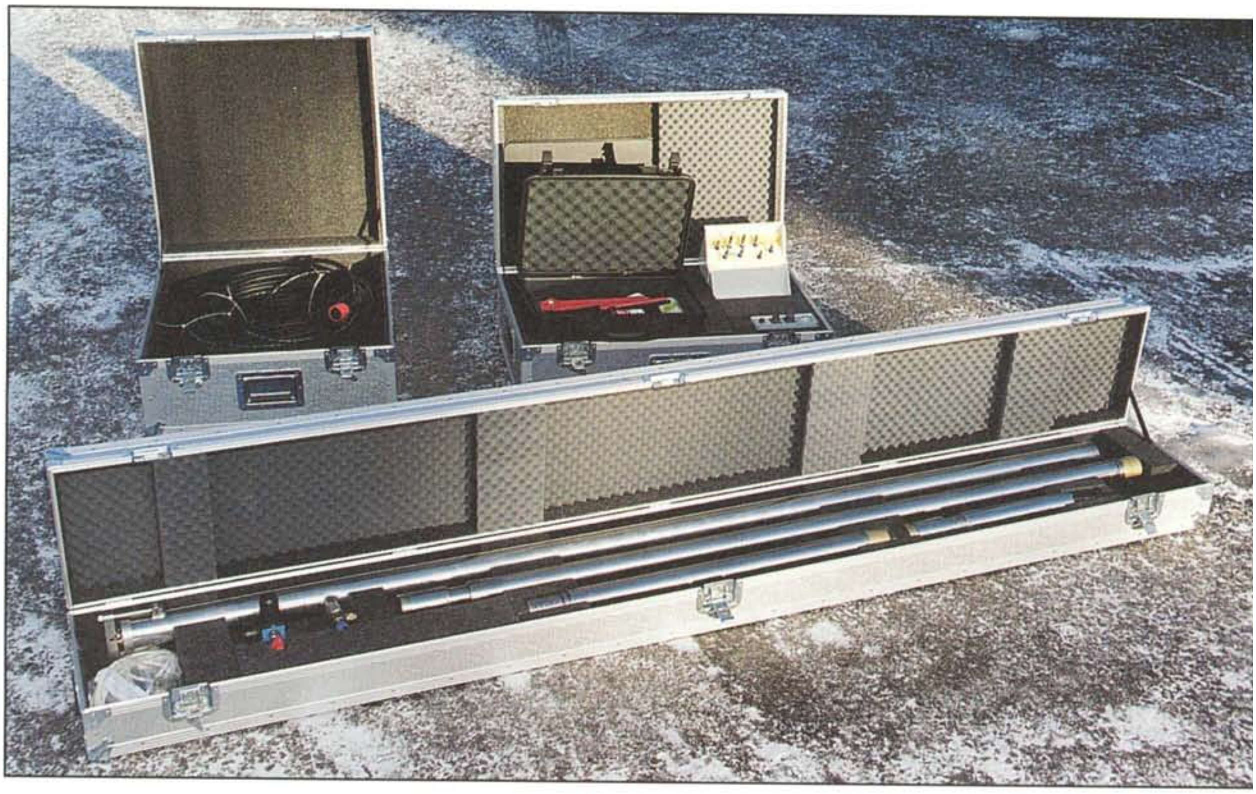


Figure 10-3. CHEMMAC-sond (measurement of pH and Eh) ready for delivery to USA.

11 PUBLIC AFFAIRS AND MEDIA RELATIONS

11.1 GENERAL

According to Swedish law, the nuclear power utilities are obliged to adopt whatever measures are needed to manage and dispose of the nuclear waste in a safe manner. It is SKB who bears the responsibility for this in practice. In order to be able to build and operate the necessary facilities, SKB must win society's confidence in the methods that have been developed. A fundamental prerequisite is, of course, that SKB should conduct its activities with a high level of scientific and technical quality. But it is also important to disseminate information in society about the nature of the waste, in what way it can be dangerous, the research being conducted and the solutions that have been arrived at.

In this context it is important to enable the public to view the nuclear waste issue in its proper perspective. Its importance must neither be exaggerated nor underestimated. Then we can have a dispassionate debate that focuses on the relevant issues, rather than myths and misconceptions. Factual information and an open dialogue are also needed to meet society's justified demand for insight into nuclear activities and to ensure a democratic decision-making process. The electricity consumers who are already paying the costs of waste management today are entitled to comprehensible information.

The goal of SKB's information is to broaden and deepen the public's knowledge regarding:

- The radioactive waste – its properties, in what way it can be dangerous, how much waste there is today and how much there will be altogether.
- The fundamental ethical and technical principles that guide Swedish waste management policy. The nuclear waste shall be dealt with in a responsible fashion with high standards of safety. The planned systems must be designed so that we do not shift any environmental or financial burdens to future generations.
- The system we have built up in Sweden and that is already being used to dispose of all radioactive waste for a long time to come.
- The research work that has been conducted since the mid-70s by SKB, universities and other expert organizations, leading up to SKB's present work of siting a deep repository for spent nuclear fuel.

11.2 SKB INFORMATION ACTIVITIES

The most effective way to disseminate information is two-way human communication. SKB therefore holds exhibitions on a large scale, employing its own mobile exhibition trailer for this purpose, see Figure 11-1. Visits to schools, municipalities and expos/fairs of various kinds are made throughout the year.

In the summer there is an exhibition on board the waste transport ship M/S Sigyn. Here SKB meets the public, school classes and political and community leaders face-to-face.

SKB's facilities – CLAB, SFR and the Äspö Hard Rock Laboratory – are open to visitors by appointment and have permanent exhibitions that can be visited year-round.

As in previous years, SKB pursued ambulatory information activities during 1993. SKB's exhibition trailer visited nine expos/fairs and 59 schools. In addition, SKB went to some municipalities that particularly wanted to have more information on the deep repository for spent nuclear fuel. Visits were made to 494 school classes, and a total of 13,075 pupils were exposed to SKB's information during the year. During the summer, 16 ports were visited by the transport ship M/S Sigyn, which served as a floating exhibition hall, see Figure 11-2.

At the exhibitions, SKB's personnel provided information on waste management, research and siting of the deep repository. As in previous years, visitors were able to view models and mock-ups of equipment used to handle the waste, as well as real equipment, such as transport casks. The exhibitions once again attracted a great deal of interest, with some 100,000 visitors from the general public, school classes, local community and government leaders, and public-interest groups.

SKB's facilities CLAB, SFR and the Äspö Hard Rock Laboratory were visited by nearly 30,000 people during 1993.

In Storuman, where SKB has initiated a feasibility study, there is also a site office with its own exhibition, see Figure 11-3. A similar office with exhibition is planned in Malå.

11.3 SKB INFORMATION MATERIAL

SKB has a wide selection of information material, such as brochures and reports, video films, overhead transparencies with accompanying narrative scripts, audio cassettes, mini-exhibitions, touch-screen computers etc.

To make it easier for the public to obtain information, SKB offers to pay the postage on letters of inquiry mailed in Sweden (Freepost) and has a toll-free number for callers in Sweden, where information can be ordered at any hour of the day for the cost of a local call.

The basic philosophy is that anyone who wants should be able to obtain information on facts, principles and

Figure 11-1. A mobile exhibition trailer visits schools, towns and rural districts almost all year round, to inform people about radioactive waste management. In 1993, the SKB trailer mostly visited schools.

future plans for the radioactive waste, and to discuss these matters with representatives of SKB.

In 1993 several fact sheets were produced. The fact sheets describe in a popular fashion parts of the research and other items of general interest.

SKB's school information package "At Depth" for upper secondary school pupils was evaluated during the year. It is used very widely in schools, and teachers in general feel that the material provides a good picture of SKB's activities.

Lagerbladet, SKB's newsletter, had more than 27,000 subscribers in 1993.

The Freepost service is available from abroad under the address, FRISVAR, Svensk Kärnbränslehantering AB, S-110 05 Stockholm, Sweden.

Figure 11-2. *SKB's transport vessel M/S Sigyn is used during the summer as a floating exhibition hall. In the cargo hold, visitors meet SKB's personnel, who tell them about Sweden's radioactive waste.*

Figure 11-3. *SKBs site office in Storuman, where a feasibility study has been initiated.*

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Chapter 6

6-1 PLAN 93
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Chapter 8

8-1 See 6-1.

SKB ANNUAL REPORT 1993

Part II

Research, Development and Demonstration during 1993

CONTENTS PART II

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12 REVIEW OF RD&D-PROGRAMME 92

12.1 BACKGROUND

According to the 12§ of the Act on Nuclear Activities the owners of the nuclear power plants are responsible for conducting the necessary research, development and other measures necessary for the safe handling and disposal of radioactive wastes arising from the nuclear power production. A programme for conducting the necessary activities must be submitted to the pertinent authority every third year. By the end of September 1992 SKB accordingly submitted its third RD&D-programme /12-1/ to the Swedish Nuclear Power Inspectorate – SKI. The programme was sent by SKI for review and comment to about 50 different authorities, institutes, universities, local community safetyboards, environmental groups and other organisations. Based on the comments received /12-2/ and their own internal review /12-3/ SKI submitted their comments to the government by the end of March 1993 /12-4/. The highlights of the summarizing statement from SKI are reprinted in section 12.2.

An independent review of the RD&D-Programme 92 was made by KASAM – the Swedish National Council for Nuclear Waste Management. They gave their comments in a report to the government by the end of June 1993 /12-5/. These comments are summarized in section 12.3.

The review reports from SKI and KASAM contain some specific recommendations on conditions to be stipulated by the government. SKB was given the opportunity to comment on these proposed stipulations and submitted comments in September 1993 /12-6/. SKBs comments are summarized in section 12.4.

The government decision on the programme /12-7/ was given in December 1993 and is summarized in section 12.5.

12.2 SKIs EVALUATION OF RD&D-PROGRAMME 92

The following is an excerpt from the SKI statement to the government March 31, 1993 concerning the RD&D-Programme 92.

"STATEMENT

Premises

In its decision dated December 12, 1990 and subsequent to its examination of SKB's R&D Programme 89, the Government specified the essential premises for an evaluation of RD&D-Programme 92. This decision emphasized that SKB's R&D work should comprise alternative methods for the handling and final disposal of spent nuclear fuel and that SKB should not commit itself to a particular method before sufficient knowledge has been obtained to fully understand and assess the existing problems relating to safety and radiation protection. In addition, the Government stated that SKB should investigate the possibility of carrying out the final disposal in stages, including the construction of a demonstration-scale repository. Furthermore, the Government stated that, in its view, deep boreholes and long tunnels under the Baltic seabed appeared to be less suitable methods of disposal. As regards the siting process, the Government noted that SKB's selection of suitable repository sites would be examined by various authorities in connection with SKB's application for a permit to carry out detailed characterizations and that Bill 1989/90:125 specifies how so-called exceptional matters should be handled. Moreover, the Government stated that adequate public insight into the site selection process is desirable. Thus, in its next R&D programme (1992) SKB was urged by the Government to provide information on the basis for the selection of suitable sites and, in general, in the course of work, to keep the authorities and municipalities concerned informed. In addition, in its next R&D programme, SKB was explicitly advised to report any measures taken which deviated from those recommended by the Government.

In addition to the above statements by the Government, SKI has based its evaluation on the expertise and data it has acquired through conducting its own safety assessments and research work, largely in the form of joint international projects, as well as on the comments by the reviewing bodies.

Commitment to a particular method and site selection criteria

According to SKB, the current state of knowledge is adequate to provide a basis for selecting a preferred disposal system design which would, in all essentials, be based on the KBS-3 concept. It is therefore planned that further RD&D work will focus on this type of solution and that increasing emphasis will be placed on the development of the technical details, design and construction. According to SKB, the current state of knowledge is also adequate to provide a basis for selecting candidate sites for the siting of a repository and for adapting the repository to local conditions.

Thus, over the next few years, SKB will start planning an encapsulation plant which will be co-sited with the central interim storage facility for spent nuclear fuel (CLAB) with a view to submitting an application for a construction and operating permit, in accordance with the

Act on Nuclear Activities at the beginning of 1997. According to RD&D-Programme 92, the work is focusing on a composite canister. In addition, SKB is planning, in the near future, to announce a couple of selected candidate sites for pre-investigations. Then, in 1996/97, SKB plans to submit an application for the detailed characterization of one, or possibly, two sites, in accordance with the Act concerning the Management of Natural Resources etc.

SKB maintains that these time-schedules are preliminary and specifies the 'earliest possible completion dates' for each activity. Nonetheless, SKB's RD&D-Programme 92 means that a number of technical and financial commitments will be made over the next 3 to 5 years. Resources are already being channelled into work on a method based on KBS-3 and additional commitments on a detailed level are being made, in practice, in connection with the planning of an encapsulation plant and the selection of candidate sites. A main issue will clearly be whether these commitments are based on a sufficiently thorough understanding, assessment and presentation of the various problems relating to safety and radiation protection.

SKB mainly bases its intention to concentrate on developing the KBS-3 method upon the report on the Project on Alternative Studies for Final Disposal (PASS report). This, in turn, is based upon the comprehensive data obtained by SKB since the KBS-3 study was conducted in the early eighties. The PASS report has not been subjected to any special, in-depth review by authorities and independent experts. The report has been criticized on the grounds that the group which evaluated the different alternative methods in the report has been closely involved in the work on system solutions of the KBS-3 type. Other criticisms include the view that the data on the suitability of the alternative methods were not sufficiently investigated and evaluated.

SKI can accept the intention to focus further RD&D work on a method of the KBS-3 type. As far as SKI can judge, on the basis of its participation in joint international work and other premises, there is no other method which appears to be essentially superior from the point of view of safety and which can be realized in Sweden without a considerable extension of the time frame, compared with SKB's plans. It should also be possible to develop a disposal method similar to the KBS-3 method so that it incorporates a reasonable balance between the possibility of abandonment, retrievability and inaccessibility with regard to the fissile material deposited. Extremely high demands on inaccessibility from the point of view of safeguards are hardly reasonable bearing in mind the alternatives for producing fissile material which are always available.

However, in SKI's opinion, alternative methods of managing the spent fuel should be carefully investigated and evaluated and the necessary expertise and knowledge base should be maintained as far as is reasonably achievable, to re-evaluate the main alternative if any new information should emerge which would warrant such a re-evaluation. Thus, SKB should continue to monitor international developments regarding alternative methods of managing spent nuclear fuel and should supplement the evaluations made in the PASS report, bearing in mind the comments made by SKI in its evaluation report and the comments of the reviewing bodies. With regard to the comments of the reviewing bodies, this work should involve certain supplementary studies of deep boreholes. However, maintaining freedom of choice with regard to the disposal method, should not entail postponing the deposition of the spent fuel in a repository many more decades into the future, in relation to SKB's time-schedule. This is important with regard to the growing uncertainty, with time, concerning the stability of the future society and its ability to finance such an undertaking.

However, focusing on the KBS-3 concept as the main direction of the continued RD&D programme, should not involve a premature and irreversible commitment to the detailed design of the system (canister design, repository depth, selection of the geological formation), but should reflect a thorough understanding and assessment of all the relevant issues relating to safety and radiation protection. Since the KBS-3 study was completed in 1983, SKB has not conducted as in-depth and comprehensive a safety assessment of the entire final disposal system which gives such an integrated view of the technical requirements which should be made on different components (canister, geology, fill material etc.) in the system and how these requirements can be weighed up in relation to each other with regard to various types of uncertainties in the underlying data. Although very useful detailed data have been obtained in various technical areas within the framework of SKB's research programme, there is no integrated safety assessment of the same scope as KBS-3, based on the new data and improved methodology. Such an integrated safety assessment would, in SKI's view, provide a much better basis, both for deciding whether to opt for a solution based on the KBS-3 concept as the main direction of further work and for formulating the specifications for the canister and site characteristics. Such an assessment would also provide a direction for the details of further R&D work, focusing it on the most essential, and at the same time, resolvable gaps in knowledge and uncertainties.

As regards the basis for its further site selection work, SKB mainly refers to the safety assessment carried out in the SKB 91 project. According to SKB, this assessment shows that the safety of a disposal system based on KBS-3 is only, to a small degree, dependent upon the capability of the surrounding rock to retard and sorb radioactive substances. In view of this, there are, according to SKB, many sites in Sweden with the geological and technical prerequisites for hosting a safe repository. In its evaluation of SKB's programme, SKI has found – in the light of its own safety assessment, Project 90 – that the above-mentioned conclusions from SKB 91 only apply on the condition that the canister meets very high requirements as regards long-term properties. Among other things, this would require a very high and even manufacturing quality. However, it has not yet been satisfactorily demonstrated that this level of quality can been attained on an industrial scale with the proposed technology. This is a point also made by several of the reviewing bodies. Therefore, in SKI's view, there are sound reasons for seeking to select sites which have the characteristics of a good geological barrier and which, thereby, provide a complete solution which is as 'robust' as reasonably possible with regard to the remaining uncertainties associated with the long-term properties of the canister.

Thus, in SKI's opinion, to proceed to the stage of site selection, largely on the basis of the conclusions drawn in SKB 91, and at the same time, to begin the planning and detailed design of an encapsulation plant, would entail commitments involving significant technical and economic investments in preparation for the subsequent applications for permits in accordance with the Act on Nuclear Activities. SKI questions whether these commitments are being made on the basis of an adequate investigation and overall understanding of the issues involved in the form of a comprehensive, integrated safety assessment. However, R&D work which does not entail long-term commitments should be pursued, e g practical testing of encapsulation methods and obtaining background data for the site selection.

Safety assessment methodology

In the above, SKI has indicated the central role of the safety assessment as regards providing a basis for decision-making both in terms of technical solutions and the direction of further R&D work. SKB should further develop its safety assessment methodology. Above all, the assessments should not be too limited in scope. The processes which affect repository performance must be analyzed as far as reasonably possible and necessary, and the underlying data must be reported.

In connection with this point, SKI finds it remarkable that SKB, when describing the safety assessment, does not define and discuss the validity of the relationship between different factors, models and underlying data on which the assessment is based. In SKI's view, such an account, which can be included in the concept of validation, is an essential part of a safety assessment. SKB is advised to broaden its view on the validation of the models and relationships between different factors which are used in its safety assessments. In connection with this, SKB should also explain how different uncertainties should be described and how they should be weighed up in relation to each other.

Disposal in stages and the 'Demonstration' concept

SKI considers it to be a sound approach to construct the repository in stages and to set up a programme for investigation and research, which, as with the operating experience, can be used to an advantage within the deep repository project, e g for evaluating the detailed solutions selected. However, in SKI's view, the concept 'demonstration' is misleading in this context, even if the spent nuclear fuel can be retrieved. Long-term properties cannot be 'demonstrated' by constructing a repository on a limited scale. Major parts of the system that require considerable capital must still be constructed on a full scale, and evaluation of the system by the authorities must be conducted with largely the same focus and scope as for a full-scale repository.

Site selection process and environmental impact statement

Of all the measures planned by SKB within the framework of RD&D-Programme 92, the actual site selection process attracts considerable interest. Several reviewing bodies have commented on related issues. These issues also play a central part in SKI's DIALOG project in which authorities, municipal politicians and environmental groups have participated. Confidence in the decision-making process for such a sensitive issue is obviously of great importance. It is vital, therefore, that the various stages of the process and what is expected of the various parties involved should be clearly defined and made known to the parties concerned in advance.

The selected site and the design of the repository shall be evaluated in accordance with the Act concerning the Management of Natural Resources etc., the Act on Nuclear Activities and the Radiation Protection Act. These acts stipulate requirements which are related but not completely unambiguous, e g as regards the extent to which the applicant shall be able to prove that an essentially superior combination of technical design and site cannot be found by a reasonable amount of effort, and as regards the criteria for determining the 'best solution that can be achieved by reasonable means'. SKI will take the initiative of ensuring that the authorities concerned (the Swedish Nuclear Power Inspectorate, the Swedish Radiation Protection Institute, the National Environmental Protection Board and the National Housing Board) start joint work with the aim of preparing a coordinated specification for the Environmental Impact Statement (EIS) and of specifying how the viewpoints of the various parties involved should be elicited and compiled. SKI does not exclude the possibility that this joint work could result in a proposal that certain legislation, particularly ordinances, should be reviewed.

With regard to this matter, the issue has been raised of providing financial support, primarily to the municipalities involved and even to other parties concerned, so that independent experts can be commissioned to evaluate SKB's proposals and applications for permits and thereby provide supplementary information to the residents of the municipalities. SKI proposes that the Government should consider taking the appropriate measures on this matter.

Summary of SKI's evaluation. Proposed conditions

In its evaluation SKI has found that the holders of licences to operate nuclear power reactors in Sweden fulfil, through SKB RD&D-Programme 92, the basic requirements made on a programme for research and development in accordance with Section 12 of the Act on Nuclear Activities with regard to goal, breadth and depth. The work in several areas is of a high quality, seen from an international perspective. However, in SKI's view, SKB has not yet succeeded in showing, in a coordinated manner, how the work in the various areas shall be integrated to find a solution, which is of as high a quality as is reasonably achievable, to the final disposal of spent nuclear fuel. SKI's evaluation and the comments by reviewing bodies have thus indicated certain tangible deficiencies in SKB's RD&D-Programme 92, particularly with regard to presenting integrated assessments of high quality as a basis for making decisions involving commitments. With regard to the findings which have emerged during the evaluation process, SKI thereby proposes that the Government should stipulate the following conditions in accordance with the same section of the above-mentioned act:

1. Before SKB determines the design bases and manufacturing method for the canister and before SKB submits an application for a permit to start the detailed characterization of a site for a deep repository, a comprehensive safety assessment shall be submitted to SKI. In particular, the safety assessment should define the significance of different uncertainties as regards the long-term properties of the repository, how these should affect the detailed technical design and the selection of a suitable site (i e the design bases) and which conclusions can be drawn as regards the future direction of further R&D work. Before the end of 1993, SKB shall submit a plan for this work to SKI. The plan shall state the purpose as well as the scope and other premises of the safety assessment. The plan shall also include an account of how it will be possible to use, in the assessment, site-specific data from future site investigations as well as a description of the scenarios which should be applied in a comprehensive safety assessment. The work should be reported on a regular basis and in a way which allows for an independent evaluation and follow-up.

2. Before the end of 1993, SKB shall submit to SKI, a plan for defining the canister design and the manufacturing method, including the design bases, methods for sealing and quality control as well as the layout of the encapsulation plant.

3. Before the candidate sites are presented to SKI, SKB shall specify which areas in Sweden are less suitable for the siting of a repository. At the same time, SKB shall report how the specified criteria (technical and societal) have been weighed up in relation to each other in the process of site elimination. This report shall provide a basis for the selection of a site or sites for pre-investigations.

4. No later than March 31, 1994, SKB shall report to SKI on how SKB, in general, intends to adopt the comments and recommendations which SKI has presented in its evaluation of SKB's RD&D-Programme 92.

This matter has been decided upon by SKI's Board."

12.3 KASAMs EVALUATION OF RD&D-PROGRAMME 92

The following is an excerpt of the summary and the conclusions and recommendations from KASAMs review of RD&D-Programme 92:

"SUMMARY

Scope of the review

Unlike previous reviews which it has carried out, this time, KASAM has been commissioned directly by the Government. KASAM has had a longer time in which to submit its review than other reviewing bodies, including the Swedish Radiation Protection Institute (SSI) and the Swedish Nuclear Power Inspectorate (SKI). Thus, KASAM has had the opportunity of examining the other reviews and evaluations before completing its own review.

However, KASAM does not consider its role to be superior to that of the other reviewing bodies with regard to the review of SKB's RD&D-Programme 92 and does not consider that its task is to evaluate previous reviews and to make the ultimate evaluation. First and foremost, KASAM has made an independent evaluation of those aspects of SKB's new plan, such as demonstration deposition, system selection, siting and the new canister design, which will determine the direction of SKB's continued work and which the Government can, therefore, regard as being warranted for consideration in connection with its decision on SKB's programme.

Deep repository for demonstration deposition

In the government decision on SKB's R&D Programme 89 it was stated that 'SKB should, in its next R&D programme, in accordance with the Act on Nuclear Activities, investigate the possibilities of allowing a demonstration-scale repository to be included as a stage in the work on designing a repository.' SKB has done more than was requested by having decided to alter its previous plan and to build a deep repository for demonstration deposition. The amended plan will have an impact on major parts of the RD&D programme.

In its overall assessment of these consequences, KASAM – like SKB – finds that the new plan entails considerable advantages. Thus, KASAM recommends:

- that SKB should focus its RD&D activities during the period of 1993-1998 on a demonstration-scale repository, with retrievability of the deposited fuel as the first stage in the final disposal of spent nuclear fuel,

- that this stage should comprise 5 – 10% of the entire estimated quantity of spent nuclear fuel from the Swedish nuclear power programme, and
- that, for the time being, SKB should not commit itself to any specific handling and disposal method for the future management of the remaining quantity of spent nuclear fuel.

System selection

SKB has reached the conclusion that its previous reference design for a repository – the KBS-3 model – is the most suitable for a demonstration deposition of spent nuclear fuel. Following a summary evaluation of the properties of the different disposal systems which have been studied, KASAM has found that KBS-3 is a reasonable choice of method for the demonstration deposition.

However, KASAM considers it to be important that SKB should also continue to set aside resources to actively follow and report international developments within the area of the treatment and final disposal of spent nuclear fuel. In its next RD&D Programme, SKB should present its evaluation of the state-of-the-art with regard to other alternatives which could be relevant for the disposal of Swedish spent nuclear fuel.

Siting of the repository

SKB has changed the previous siting procedure – which was sanctioned by the Government – in several ways which are remarkable. The number of sites for detailed characterization has been reduced from two to one. No selection process other than that of finding interested municipalities is proposed. Thus, KASAM has thoroughly examined and evaluated SKB's new siting procedure.

It is KASAM's firm opinion that SKB must not dissociate itself from the idea of selecting candidate sites on the basis of geological merit by, instead, primarily looking for candidate sites in municipalities which "display an interest".

In KASAM's view, SKB should conduct in-depth studies and assessments of the regional differences in terms of feasibility of construction which experience has shown to exist among different regions of the Swedish crystalline bedrock. Such studies will show that considerable differences exist, with regard to the occurrence of structural weaknesses and other unfavourable heterogeneities, among different provinces of the bedrock and between different parts of these provinces. On the basis of this information, it should be possible for SKB to select two or more candidate sites in those regions with the best chances of conducting successful detailed characterizations.

In KASAM's view, SKB must specify acceptance limits for different properties of the bedrock at the candidate sites before starting the investigations. It may be difficult for SKB to make its selection of a site for detailed characterization site credible if it conducts its candidate site investigations without pre-defined acceptance limits and, subsequently, explains that the investigations have indicated that the bedrock is adequate.

On these conditions, KASAM can recommend that SKB limit its application for detailed site investigations, in accordance with the Act concerning the Management of Natural Resources, etc., to a single site.

The municipalities where the site investigations are carried out should be given the financial support to enlist the help of external experts on a consultancy basis so that these experts can examine and evaluate SKB's site investigation work from the presentation of the programme to the statement of the results. One way of enabling this to be done, which KASAM finds suitable, is for the municipality to be allocated funds, for such consultations, from the nuclear waste management fund.

As regards decisions on issues involving large sections of the general public, it is especially important that the decision-making process should be open and easy-to-understand and that it should also be perceived as such. Otherwise, the citizens may feel that they are being misled or may receive the impression that the outcome of the issue has already been determined in advance. KASAM considers the fact that a municipality which is involved in siting may have to make a decision in connection with three different licensing issues and, thereby, formally be able to give its veto on all three occasions to be a threat to the credibility of the decision-making process. In KASAM's interpretation of the law, the municipality's right of veto appears to be unrestricted with regard to the detailed site investigations. However, if the municipality has approved of the detailed site investigations, it would be possible for the Government to rescind a subsequent municipal veto against the demonstration-scale repository or the full-scale repository on account of the national importance of the facility.

In KASAM's view, it is important that the entire decision-making process should be presented to the municipalities which express an interest in detailed site investigations in such a way that it is made clear that the municipality cannot, on its own accord, on three different occasions prevent a project like this from being realized.

An environmental impact assessment (EIA) must be attached to the application to conduct detailed site investigations, in accordance with the Act concerning the Management of Natural Resources, etc. and to subsequent applications concerning the deep repository. Several acts, which all require an EIA, will apply in connection with the granting of a siting permit for a deep repository. It should be possible to use a single EIA as a basis for making a decision in connection with licensing in accordance with all these acts. This requires that the demands of the different authorities on the content of the EIA, should be adequately coordinated. It seems unsuitable to allow one of these authorities, which may also represent the interests of a particular sector, to assume responsibility for this coordination. KASAM is convinced that a special EIA commission, possibly based on the Dutch model, could play a vital role with regard to obtaining EIA which are correct and scientifically well-founded for the different stages involved in the final disposal.

Encapsulation of spent Nuclear fuel

SKB intends to apply for a siting permit and licence for the construction of an encapsulation plant at year-end 1996. Furthermore, SKB has introduced a new canister design feature involving a pressure vessel of steel which will surround the spent nuclear fuel. The copper jacket around the steel pressure vessel will provide the desired corrosion protection as with previous designs.

SKB's new steel-copper canister has potential advantages and disadvantages compared with the lead-filled copper canister of the KBS-3 model. In KASAM's view, the advantages of the new design probably outweigh the disadvantages. However, so far, the steel-copper concept has not been fully investigated. In its RD&D-Programme 1993-98, SKB should include studies of filling material to be used inside the steel canister which can reinforce the performance of the canister as a barrier.

KASAM supports SKB's selection of the steel-copper concept as the main alternative for further investigations. However, if this design should prove to be unsatisfactory, it must be possible to return to the KBS-3 concept.

SKB proposes that the encapsulation plant should be located adjacent to the central interim storage facility for spent nuclear fuel (CLAB). Another obvious alternative is to locate the plant adjacent to the deep repository. The outcome of the processing of the siting application should not be taken for granted in SKB's planning. It may become necessary to carry out the licensing processes for the encapsulation plant and for the detailed site investigations in parallel due to the requirement that alternative sites should be specified in the EIA relating to the encapsulation plant. SKB should take this requirement into account in its time-schedule for activities planned during the six-year period to be covered by RD&D-Programme 92.

Safety assessment

Both SKI and SSI discuss the safety assessment in their evaluations. SKI has spent considerable effort on evaluating methodology and results with regard to long-term safety assessment. KASAM shares SKI's view within this area and wishes to especially emphasize the need for improving the description of the methodology used for the long-term safety assessment as well as the need for a comprehensive safety assessment of both the engineered and the geological barriers in the multi-barrier system. SKB 91 is entirely unsatisfactory in terms of its description of methodology as well as in terms of its comprehensiveness. Thus, KASAM considers SKB's claims with regard to the limited function of the rock in guaranteeing the safety of a system based on the KBS-3 concept to be unproven.

A description of the interaction between the groundwater and the engineered barriers is lacking from the SKB 91 safety assessment. The assessment must be complemented in this respect and must also include an account of the sequence of events which will occur when the engineered barriers fail. This comprehensive safety assessment should then be used to specify, in the form of acceptance limits, the requirements which must be fulfilled by the bedrock at a candidate site so that it can be selected as a site for detailed characterization and – in the next stage – to specify corresponding requirements so that this site can be approved for the demonstration-scale repository.

It is important that the safety assessment should be designed so as to obtain a comprehensive view of safety-related issues involved in the handling stage and in the long term. SKB's programme lacks such an overall assessment. Such a comprehensive view requires that radiation doses to individuals during different stages of work should be quantified, balanced in relation to each other and the aggregate dose established. In the short term, it is known that some personnel will be exposed to radiation, in the long term, doses to 'possible' persons are estimated. In this respect, there is a need for the total optimization of risks which cannot simply be compared on the basis of data which are not equivalent.

Äspö Hard Rock Laboratory

From the start, the work on the Äspö Hard Rock Laboratory was planned by SKB partly as a general rehearsal for candidate site investigations and detailed characterizations. Prognoses relating to the quality of the bedrock, modelling of the bedrock and model validation are especially important, in this context.

In KASAM's view, SKB should, in several ways, be careful of committing an oversight or of making oversimplifications in connection with the modelling of the bedrock at the candidate sites and should use the further work at Äspö to improve its modelling methodology.

In addition, SKB needs to develop its methods of locating sub-horizontal, water-bearing fracture zones and fractures filled with brittle or weathering-prone minerals. The occurrence of such zones at repository depth could have serious consequences. SKB should use the excellent opportunities provided by Äspö to develop such methods.

Further work at Äspö should be planned so as to prioritize investigations and tests which provide information and data for fulfilling pressing needs within the areas of safety assessment, site investigation methodology and methods as well as the deep repository design.

Other supporting RD&D activities

One of the most noticeable features of SKB's 'Detailed R&D Programme 1993-1998' is that it has been affected to such an insignificant extent by SKB's revised plan, and by the conclusions which SKB has drawn in SKB 91. In general, the programme is more or less as it has always been. In KASAM's view, an explanatory description is lacking of how the R&D activities will he coordinated with the activities which are included in the implementing stage which has now been planned.

Prior to gaining permission to site the encapsulation plant and the demonstration-scale repository, SKB must present safety assessments of the facilities as well as obtain data on which the environmental impact assessments (EIA) can he based. To a great extent, SKB's supporting R&D activity must focus on fulfilling these specific requirements on reporting.

From the beginning, SKB's design philosophy for the repository has been to incorporate as much safety as possible into the engineered barriers.

The most important, common prerequisite for the long lifetime of the engineered barriers is that the total quantity of aggressive components that the engineered barriers are exposed to should be 'sufficiently' low. SKB should, therefore, give priority to investigations aimed at determining what is a sufficiently low quantity as well as continue its studies of how aggressive components reach the engineered barriers.

Time-schedules

It is obvious to KASAM, that the time-schedules presented by SKB in RD&D-Programme 92 are unrealistic.

SKB's time-schedules attracted relatively little attention in connection with previous reviews of SKB's R&D programme. This time, SKB's time-schedules are more important since they contain deadlines for commitments and for licensing relating to the encapsulation of the fuel and the detailed site investigations in which the regulatory authorities are involved and which, according to SKB, will occur within the next six-year period. SKI and SSI have reacted to this, and have required extra reports to be submitted before the next RD&D Programme, as stipulated by law, is to be submitted in 1995. These requirements may prove to be premature. In order to establish whether or not this is the case, it is KASAM's opinion that SKB should conduct a thorough examination and review of its time-schedules and present them to the authorities, no later than March 1994."

12.4 SKBs COMMENTS WITH RESPECT TO SKIs AND KASAMs EVALUATION OF RD&D-PROGRAMME 92

By the end of September, 1993 SKB in a memorandum to the government gave its comments to the conclusions and recommendations given by the authorities in their review. In summary the comments from SKB were as follows.

"GENERAL

The review of RD&D-Programme 92 and the evaluations by SKI and KASAM give valuable contributions and support to the work on a method for final handling and disposal of the long-lived radioactive waste in Sweden, in particular spent nuclear fuel, in a credible way considering the stringent requirements for safety.

SKB observes that SKI and KASAM give support to the main direction of the programme for the next 10 to 15 years presented in RD&D-Programme 92.

SKI and KASAM and several other reviewers criticise parts of the programme. The criticism mainly concerns the time schedule, the siting process and the scope of the planned safety analyses.

The time schedule

The basis for SKBs planning is that each step of the work shall be founded on adequate technical investigations. The work shall also be organized in such a way that authorities, local communities and others directly affected shall be able to thoroughly evaluate the issues before important decisions.

At the same time it is important that the work is conducted in a concentrated and goal oriented fashion to maintain a high technical quality.

In SKBs opinion good opportunities are at hand to site and construct an encapsulation plant for spent fuel as well as the first step of a deep repository within the next fifteen years. The size and the technical complexity of these plants are not of the kind that more time is needed.

SKB means that a revision of the time schedule should be postponed until the feasibility studies constituting a part of the siting work have made some reasonable progress i e by the end of 1994 at the earliest.

The siting process

The basis for SKBs work on siting of a deep repository is that only sites which are judged to be able to meet the stringent safety requirements can be considered. The important thing is in the final end to find **one** suitable and acceptable site and show that this site meets these requirements.

The way towards deposited fuel is marked by many successive evaluations and decisions. The design and the siting of the repository finally selected and implemented will independent of previous work be reviewed and evaluated very thoroughly by the authorities.

SKB considers that the statement by the government in the decision on R&D-Programme 89 concerning the time for the authorities review of SKBs selection of site for the repository provides an appropriate plan *[...that SKBs selection of sites suitable for a repository will be reviewed by different authorities in connection with SKBs submission of an application for a permit to make detailed investigations ...]*.

The work on an EIS and decisions in this connection will be demanding. The existing authorities and organizations do however have a good competence to manage these issues. The work on EIS etc does however require some financial support to those municipalities which will directly be affected by the planned facilities. SKB finds it important that this question is resolved as soon as possible e g through reimbursements from the nuclear waste funds.

Safety analyses

The ambition of SKB is that future evaluations by the authorities shall be conducted based upon thoroughly performed safety analyses. These will 'based upon available facts and data' give a comprehensive assessment of all those factors that relevant to the license permit.

SKB intends to submit a thorough safety analysis concerning the long-term safety of a repository based on data from preliminary site investigations on (at least) one candidate site before or at the latest in conjunction with the application for permits according to the act on conservation of natural resources and the Act on Nuclear Activities to site and construct an encapsulation plant for spent nuclear fuel.

SKB will further continuously inform the authorities on the work with and results from safety assessments for a deep repository being conducted before submitting the application for a permit to make detailed site investigations.

Other matters

SKB would like to emphasize that the work on designing, siting, construction and licensing of an encapsulation plant and a deep repository is a complex process. The evaluation by society through several authorities et al involves a number of laws and will require a harmonized application of these laws. Thew work as well as the evaluation will require broad experience from integrated technical systems.

SKB observes that many of the views expressed in the review of RD&D-Programme 92 implies far reaching demands on *how* the work shall be conducted also in the early stages when no important commitments have been made. Without questioning the value of the proposals presented SKB means, considering the clauses on responsibilities in the Act on Nuclear Activities, that some restraint must be exercised concerning conditions and recommendations. Contacts between SKB and the authorities must be made under such framework that they on one hand are compatible with SKBs unique responsibility according to the Act on Nuclear Activities and on the other hand leaves the authorities free at their review of the bases for the forthcoming applications for permits. The intent must at the same time be to reach sufficient scope and quality on the basic material and data brought forward for these applications. Independently on *how* SKB conducts its work the main emphasize in the evaluations from society and from the authorities must concern matters directly related to those facilities which in the end will be built an operated."

Further comments

The above comments from SKB gave rise to additional comments from SKI and KASAM and then again some additional comments from SKB before the government decision.

12.5 GOVERNMENT DECISION ON RD&D-PROGRAMME 92

The governments decision was taken December 16, 1993 and included the following main statements (SKB internal translation):

'The government finds like SKI that RD&D-Programme 92 meets the requirements expressed in 12§ of the Act on Nuclear Activities.

The government observes that SKB in RD&D-Programme 92 reports on alternative methods for treatment and disposal of spent fuel which have been studied or are studied in other countries. Like SKI and KASAM the government accepts SKBs plans for studies of different alternatives and system designs. The government considers that the requirement on comprehensiveness and alternatives in the R&D-programme remains. The government therefore finds it important that SKB also in the future actively follows and reports on the international developments in the area treatment and disposal of spent nuclear fuel.

The government observes that SKB has changed its previous planning and indicated that work on deposition of spent nuclear fuel and nuclear waste in a deep repository is planned to be conducted in two main phases, i e demonstration deposition and final disposal. The demonstration deposition is according to SKB planned to include 5 – 10% of the total amount of spent fuel with a possibility to retrieve the fuel during the demonstration phase. The decision on final disposal should according to SKBs plans not be taken until after that the demonstration deposition has been completed and the results from that activity has been evaluated and other alternatives considered.

The government finds like SKI and KASAM that the change of the programme has considerable advantages even if the long-term performance of the repository not can be demonstrated. The government wants to emphasize that even if the KBS 3-method should be a reasonable choice, SKB should not commit itself for any specific handling- and deposition-method until a comprehensive and indepth analysis of the pertinent safety and radiation protection issues have been accounted for.

The government observes that SKB in comparison to what was accounted for in R&D-programme 89 has changed the method for selection of sites suitable for a repository. The government shares the view expressed by SKI as well as KASAM that it is not clear from RD&D programme which methods or criteria will be used in the site selection process.

According to the governments opinion is a good public insight desirable into the site selection process. SKB should give information on its work in this respect to SKI, SSI, KASAM, the Swedish Planning and Building Authority as well as to affected county boards and municipalities.

The government shares SKIs view that decisions concerning the system for final disposal and technical design basis for this system must be based on safety analyses. The government finds like SKI and KASAM that the methods used by SKB for safety analyses should be further developed in particular with respect to the description, evaluation and accounting for of different uncertainties. A strategy for evaluation of the validity of the models considering the demands constituted by the safety analysis should be developed by SKB.

The government further shares SSIs view that an overall comprehensive view on radiation protection issues is required. SKB should be able to account for safety and radiation protection issues for the operating phase as well as for the final disposal phase.

The government finds that SKIs and KASAMs recommendations should be observed considering studies of canister design, continued work at the Äspö HRL and other supporting research in the areas spent nuclear fuel, buffer material och backfill, geology, hydrology and rock mechanics.

The government decides that the following conditions shall apply for the continued research and development activities.

SKB shall supplement RD&D-Programme 92 by accounting for

- the criteria and methods which can form a base for selection of sites suitable for a deep repository,
- a programme for delineation of prerequisites for the encapsulation plant and the repository,
- a programme for the safety analyses that SKB plans to establish,
- an analysis of how different measures and decisions will influence subsequent decisions within the disposal programme.

The recommendations proposed by SKI and KASAM in their evaluations should be considered when supplementing the RD&D programme. The supplements shall be submitted to SKI not later than July 1, 1994.

SKB shall in the next research and development programme give its evaluation of the knowledge about alternative disposal options that might be adopted for final disposal of spent nuclear fuel and long-lived nuclear waste in Sweden.

SKB shall continuously report to SKI on changes in time schedules that are given in RD&D-Programme 92."

13 TECHNICAL PLANNING OF SITE INVESTIGATIONS AND CONSTRUCTION OF A DEEP REPOSITORY

13.1 PREPARATION OF A SITE INVESTIGATION PROGRAMME

13.1.1 General

As a preparation for the forthcoming site investigations for candidate repository sites, work has been carried out in the following fields:

- development of the geoscientific investigation programme,
- preparation of techniques and routines for data management,
- preparation of instruments and methods, including development, refinement and investment, etc.

A general base for the planning work is the experiences from earlier site investigations, including the Äspö Hard Rock Laboratory (HRL), conducted by SKB.

13.1.2 Geoscientific investigation programme

A first outline of the geoscientific investigation programme was written as a SKB internal document in the beginning of 1993. The aim was to propose a framework of an investigation programme for internal review and to be a reference for resource planning work. The "framework for geoscientific characterization" discussed the investigation and characterization work with regard to need for safety and performance assessment and layout studies during different phases; site investigation and detailed investigation. The subdivision of the site investigation phase in a siting stage, baseline investigation stage and complementary stage will be thoroughly reviewed and the programme will be developed more in detail during 1994.

One major experience base for the investigation programme is the Äspö HRL, pre-investigation phase. The Äspö project is preparing an evaluation report on the feasibility and usefulness of site investigation methods, to be published in 1994. Experiences from all SKB Study Site investigations with regard to strategies, usefulness of methods, uncertainness in results etc, will be summarised in a report, also to be released during 1994.

Experiences from similar site investigation programme abroad will also be of value for SKB. For that purpose such summarizing reports of AECL experiences in Canada and TVO experiences in Finland are under preparation.

Two consulting companies have given their comments to the "framework document" earlier mentioned and complementary proposals to details of a site investigation programme. Golder & Associates concentrated on the hydrogeological characterization /13-1/ while Geosigma gave detailed comments to the whole programme /13-2/.

According to present plans site investigations will be carried out at two sites, almost in parallel. This calls for efficiency in all investigation work, among which the field work maybe is the most critical. As for preparing the planning of this, practical experiences from the field and need of resources for the different field activities have been reviewed. Further on, a preliminary logistic plan for the field work at the two sites, based on the "framework document", has been developed. The aim was to identify the total amount of resources needed (personnel and instruments) for this programme, and to compare this need with the amount of resources which are available or existing. Output from this study was the identification of instruments which have to be procured and ideas of in which areas, and to what amount, field investigators have to be educated, in one way or another.

13.1.3 Techniques and routines for data management

Efficiency and correctness in the management if data is of most importance for a site investigation programme. Strict handling of data will be needed for the quality assurance of the investigations, in which the traceability of data of all steps in the data refinement chain, from data collection to final result, is a major task. Detailed manuals for all investigations will be written, some of them will be adopted more or less directly from the Äspö HRL, while other manuals must be written separately.

A central database for the site investigations will be used. The intention is that the database will be used as a collection and retrieval system for data during the investigations and as a quality controlled data storage system for all data from the site investigations. The second goal has been met by the GEOTAB database of SKB. The first goal calls for not only correct but also rapid management of data in all stages of the site investigations. A modified database is under development in the Äspö project. A pre-study has defined the criteria for the site investigation database and reviewed the new Äspö HRL database. The work will continue during 1994.

In conjunction with the Äspö HRL a 3-D CAD, computer-based, rock modelling system "Rock Visualization System" is developed. Based in the Microstation CAD system various application programme modules will be developed for different tasks of the modelling work. Major goals for the integrated Rock Visualization System are:

- to visualize the main rock elements; rock types and structures of a site,
- to present existing and planned boreholes in the rock model,
- to present and adapt the layout of underground construction to the rock conditions,
- efficiency in the modelling work, in data exchange with other databases, visualisation etc.

A thorough planning work for the development has been made by preparing a detailed functional design description of the Rock Visualization System.

13.1.4 Instruments and methods

Major sub-horizontal fracture zones can be of significant importance for the repository performance, depending on their localization and behaviour. Hence, a sub-horizontal fracture zone below a repository must be avoided as transport pathways from the repository can be concentrated to such a zone /13-3/. Therefore it would be beneficial to be able to detect such zones before an extensive investigation drilling programme starts.

Aiming at detecting such zones from the surface SKB has concentrated efforts on the reflection seismic method. New processing algorithms were used on a data set from an old reflection seismic survey over the Finnsjön sub-horizontal fracture zone, situated at about 300 m depth. The old data processing was unsuccessful in detecting the zone. This time two different organizations, the Department of Geophysics at University of Uppsala and Vibrometric OY (Finland) were reprocessing the old data set, resulting in ability to see structures from about 100 m to 2000 m. The extension of the (from borehole investigations detected) sub-horizontal zone can easily be seen in Figure 13-1, like other zones at greater depths /13-4/. The report also evaluated the sensitivity to different types of

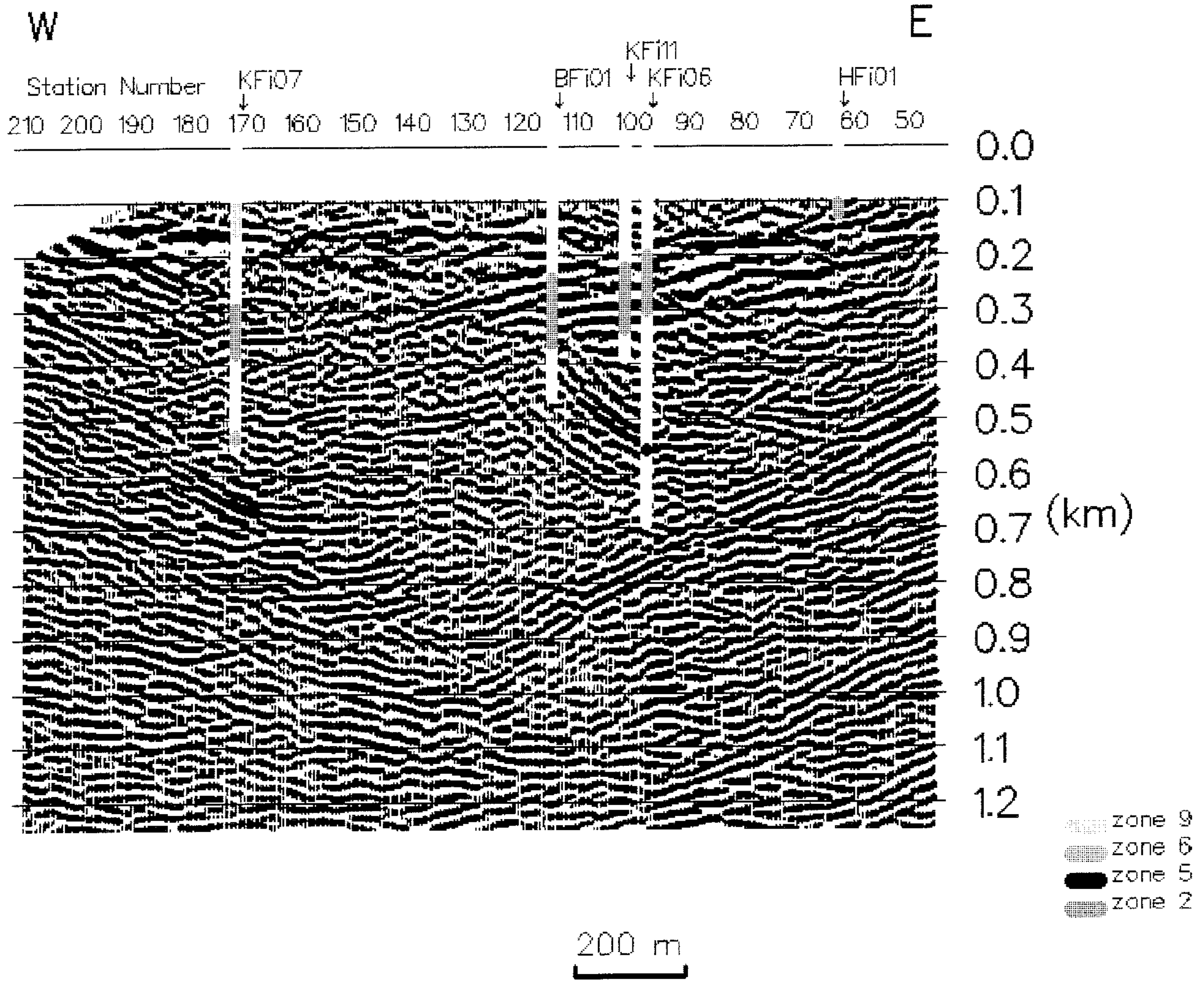


Figure 13-1. Seismic reflection profile from the Finnsjön area. Results from re-processing clearly show the sub-horizontal zone at about 200 to 300 m depth, also compared with interpretations from borehole investigations.

source and receiver techniques, and gave recommendations on a possible reflection seismic survey for a site investigation programme.

The Pipe String System for hydraulic tests (injection and pumping) has been refined and a new computer system has been implemented. A new mobile unit for chemical sampling is under development, also involving a new version of the CHEMMAC system, downhole and surface probes.

For the determination of fracture orientations in boreholes, SKB will improve the borehole TV technique with regard to the analysis of the borehole images. One way is to use a japanese borehole TV system, with which a demonstration was made in Sweden last autumn. The demonstration was promising, but a new demonstrational borehole survey with modified technique will be made before any conclusion can be made.

Beside the described development work also work on technical documentation of SKB developed instruments is in progress. The documentation level must be relatively high in order to fulfil the goals for the quality assurance of site investigations.

Instrument development projects of more basic nature are reported under Supporting Research and Development, section 15.4.8. The point dilution probe for in-situ groundwater measurements, depth calibration technique for investigations in boreholes, drilling with reverse flushing when uncontaminated water samples are needed and measurement techniques to depths more than 1000 m are discussed in that section.

Instruments and methods related to the ongoing phase of the Äspö HRL, i e underground investigation methods like hydraulic testing technique at high groundwater pressure, Hydro Monitoring System (HMS) for on-line recording of groundwater monitoring points in surface boreholes and in the tunnel and the CHEMLAB borehole laboratory for nuclide migration experiments are reported in the Annual Report 1993 of the Äspö HRL /13-5/.

13.2 TECHNICAL STUDIES CONCERNING THE CONSTRUCTION OF A DEEP REPOSITORY SYSTEM

13.2.1 Repository planning studies

Introduction

During the last about ten years four alternative disposal concepts have been studied in parallel to the development of the KBS-3 system. The work has consisted of analyses of technical feasibility, cost calculations and performance assessment, as well as comparison with KBS-3 and ranking of the concepts. One major conclusion drawn in the studies is that all concepts are judged to be able to fulfil safety requirements, implying that the long-term safety demands have no disqualifying influence.

The studied systems are shown in Figure 5-5.

KBS-3. Canisters are placed in holes bored vertically downwards in the bottom of tunnels. Each canister is totally surrounded by a buffer consisting of bentonite clay. The tunnels are placed parallel in a pattern that adopts to the rock characteristics.

WP-Cave. Canisters are placed in a row in inclined disposal holes, which are bored from a shaft in stories in a "tree-like" pattern. The slot between the canister and the rock wall is backfilled with crushed rock. This central part is at a distance totally surrounded by a bentonite/sand barrier, which is excavated and backfilled /13-6, 13-7/.

Very Deep Holes. Canisters are stacked on top of each other in lined boreholes from about 4000 m and up to about 2000 m depth. The canisters are surrounded by bentonite /13-8, 13-9/.

Very Long Holes. Canisters are placed horizontally in long tunnels (several 1000 m long) and surrounded by bentonite /13-9, 13-10/.

Medium Long Holes. Canisters are placed horizontally in medium-long (in the range of 250 m) holes, which are excavated in parallel in a pattern similar to the disposal tunnels in the KBS-3 concept /13-9/.

The result of the analyses and the comparison between the concepts was that the KBS-3 design was judged to provide the most favourable possibilities in the Swedish crystalline bedrock. Consequently the more detailed planning of the repository, which started in 1993, is based on the KBS-3 system.

The technical studies comprise the work which is devoted to developing and adapting known technologies, R&D results etc to the repository conditions by applying well established engineering methods. One major part of the work is the planning of above ground and underground facilities. The other is to choose and develop e g deposition method in detail including equipment, underground excavation methods, compaction technique for the bentonite blocks, design and application of plugs and seals after disposal. Studies, discussions and planning have taken place on a broad range of topics during 1993, but in this report only the results are reported from those projects which have been carried through and documented during the year.

Deep repository facility planning programme

The process for planning and constructing of the repository has been developed in accordance with the experience gained by Vattenfall AB in major electric power projects. It is separated into five phases, which step-by-step goes into more and more details of design, layout and equipment. Each phase is to be documented in a programme containing criteria, considerations, drawings and descriptions. The exact content of these programmes is dependent on which part of the repository that is

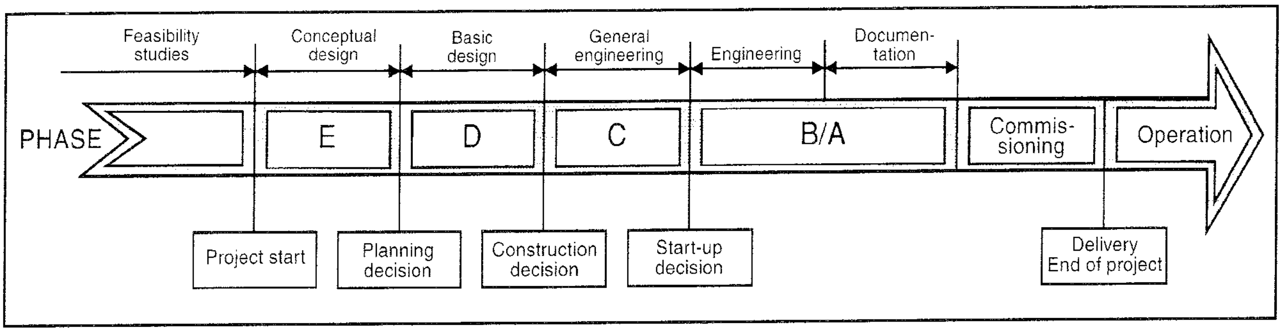


Figure 13-2. *Step-by-step repository planning approach.*

studied. The different phases of the step-by-step planning model are briefly indicated in Figure 13-2.

The main objectives with the programme work are to:

- provide a systematic base for the repository planning and construction,
- outline an uniform methodology,
- document the demands and considerations as well as the consequent requirements on design, layout etc.,
- develop and compile the basis for excavation and construction of surface and underground buildings and caverns complete with systems and equipment,
- provide a complete basis for project management, designers, engineers etc.,
- document labour safety requirements,
- provide information and basis for Environmental Impact Statement (in Swedish-MKB) and repository performance assessments,
- provide uniform facts for information on the project.

The first phase of the planning process, Layout E, was conducted during 1993. The site for the deep repository is not known and the work is, therefore, based on general rock characteristics, which are valid for many sites in Sweden.

The surface facilities have, in this first planning phase, been assumed to be located on "green field" in the inland of Sweden.

Facilities

Surface facilities

The spent fuel and other waste are planned to arrive to the repository site in conditioned form in transportation containers for radiation protection in accordance with the IAEA standard. The containers with the waste are transported from the harbour to the site by train or by road.

Underground facilities

The underground part is separated in several sections, which are planned to be excavated in executive stages. Before the specific site is known there are several options for locating the underground sections. For instance, each of these can be located within one block of rock, as is indicated in Figure 13-3, or they can be merged into fewer blocks if these are large enough. The spent fuel sections can also be separated into several but smaller blocks.

Access between surface and repository level

Three alternatives are being considered: a) Long straight ramp with either a parallel ramp or vertical shafts along the route for ventilation and emergency evacuation, b) Vertical shafts for the heavy transports, c) A spiral ramp for heavy transports and shafts for personnel transport and ventilation. Figure 13-3 show option a).

Central service area underground

The area is located where ramps and shafts reach the repository level. The functions in the area differ somewhat depending on which access alternative that is chosen.

Spent fuel deposition area 1

The disposal process is planned to start on a small scale with some 10% of the total amount of spent fuel. After disposal and evaluation of the result, which will focus on the quality by which the disposal operation is executed, the repository may be expanded to the full-scale capacity.

Spent fuel deposition area 2

The full-scale disposal operation is assumed to take place in a separate section. Depending on the rock characteristics this disposal area may be separated into two or more rock blocks.

Deposition area for other nuclear waste

Other long-lived waste than spent fuel is planned to be disposed of in the repository as well, but in a separate section at a distance from the spent fuel disposal areas 1 and 2 due to the large amount of concrete that is used in the conditioning process. Operating waste from CLAB (central interim storage for spent fuel) and the Encapsulation plant are also planned to be disposed of in this area as a consequence of closure of the SFR facility (repository for low-and medium-level waste) after decommissioning of the nuclear power plants.

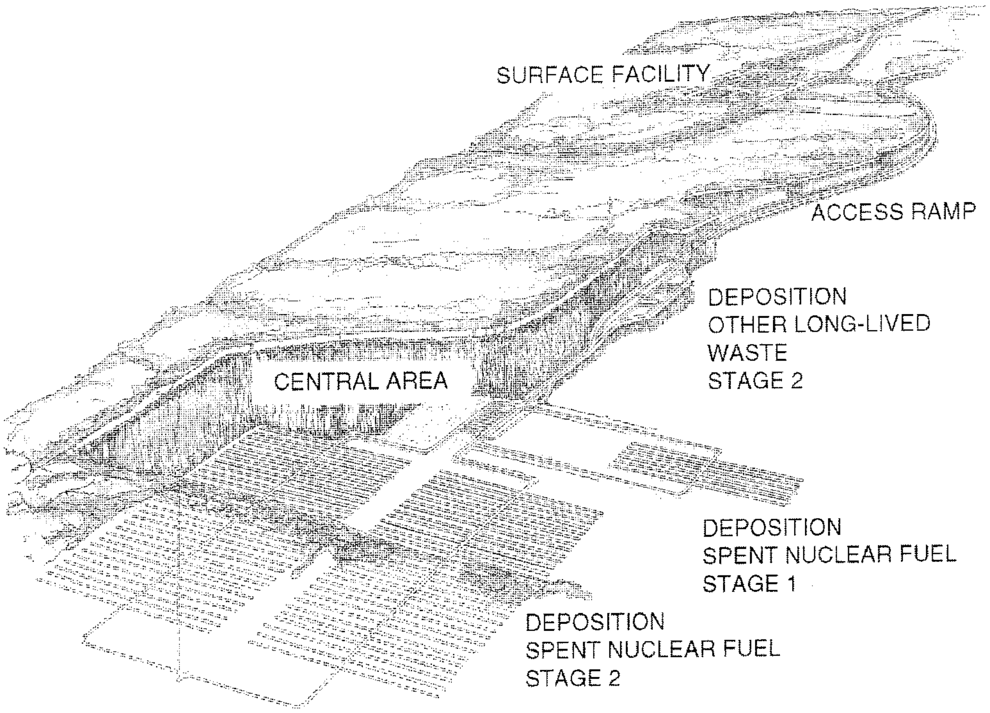


Figure 13-3. *Schematic drawing of deep repository – straight ramp alternative.*

Step-by-step construction

Detailed investigation stage

Rock excavation work starts as a part of the detailed investigation stage, which follows after site investigations on the ground surface, authority reviews, issuing of necessary permits etc. The detailed investigation stage comprises the excavation of accesses to the repository level as well as tunnel excavation on the level and geotechnical and geoscientific investigations of the different disposal areas from underground positions. In parallel with the excavation of the accesses and the underground tunnels the characteristics of the rock are observed and among other things compared with the predictions made on data from the surface investigations.

In the course of the detailed investigations the following construction work is conducted.

On surface

- Establishing of construction area including access roads.
- Construction of temporary facilities such as office, canteen, warehouse, store and information centre. In case of shaft sinking also a temporary headframe above the shaft is required.
- Fencing of the construction area.
- Supply of electricity, water etc.
- Planning of area for excavated rock.
- Construction of ventilation building.

Underground

- Excavation of ramp or shaft dependent on access alternative.
- Raiseboring of shafts.
- Tunnelling on the repository level in direction towards target disposal areas.
- Excavation of necessary parts of the central service area.
- Installation of service systems.

First operation stage

The first stage comprises the excavation of the spent fuel disposal area 1, and disposal of about 10% of the total program of spent fuel on a semi-scale operation capacity level.

The first operation stage includes the following activities.

On surface

- Site preparation for the surface area including road and railway systems.
- Construction of railway wagon defrosting, sand unloading, transport cask handling, bentonite and backfill, information and canteen, offices and work-

shop, and personnel and store buildings. Extension of the ventilation building.

Underground

- Excavation of the total central service area and additional installations.
- Excavation of additional service shaft in case of shaft accesses.
- Installations in shafts.
- Construction of rescue and service systems.

Operation

- After completed construction and installation all systems are tested in dry runs.
- After completed tests and reception of the operation permit the disposal of canisters with spent fuel may start.

Second operation stage

After evaluation of the first operation stage, authority's review, etc. the second operation stage starts provided that the evaluation of stage 1 concludes that final disposal according to the KBS-3 method is the preferred option. The objective with this stage is to carry through disposal of the whole Swedish programme on nuclear waste from the nuclear power reactors and the facilities involved in the back-end cycle, and prepare for sealing of the deep repository and land reclamation.

The second operation stage includes the following activities.

On surface

- Buildings above the exhaust air shafts.
- Continuous preparation of the land for the excavated rock piles.

Underground

- Excavation of the main transport tunnels to as well as through each of the disposal sections.
- Raiseboring of exhaust air shafts in each disposal section.
- Excavation of disposal tunnels, some before the disposal starts, and the major amount continuously during the operation of the repository.
- Excavation of disposal vaults in the section for other waste.

Operation

- Dry runs of additional parts of the repository.
- Re-start of the disposal operation of canisters.
- Excavation of canister disposal tunnels, disposal and backfill in parallel.

The second operation stage includes, after disposal of all waste from the nuclear power stations, the disposal of decommissioning waste from the CLAB and the encapsulation plant.

Sealing of repository and land reclamation

The planning also includes the time period when all waste has been disposed of and the repository may be sealed off.

All excavated volumes underground are planned to be backfilled. Plugs in the tunnels and in the accesses are considered to be constructed in accordance with the existing rock conditions with the objective of decreasing the risk for leaving high transmissivity pathways for water once caused by the excavation of the openings. Installations and other structures underground possible to dismantle are possible to take back up to the surface. Tunnels and open rooms may be backfilled.

The buildings on the surface can be taken care of in several ways, which depend on the actual needs or preferences at the shutdown time.

14 SAFETY ANALYSIS

14.1 GENERAL

The safety assessment activities during 1993 have been focused on planning the assessments needed during the coming site investigations, refinement of the modelling tools and on an assessment of the performance of the copper/steel canister in a KBS-3-like engineered barrier system that was prioritized in the RD&D-Programme 1992.

A workshop was held in Hecla Island, Canada between Safety Assessors from AECL, NAGRA, PNC, TVO and SKB to discuss and compare methods and results in recent or ongoing assessments.

14.2 SCENARIO METHODOLOGY

14.2.1 Scenario development strategy

The first step in a safety analysis after defining the appropriate system and system boundaries is to develop the scenarios to be analysed. The scenarios should cover a wide range of possible future events and together they should give a broad perspective on the safety margins of the total system. The scenario development strategy has during 1993 been revised. The different steps in the scenario development process have to be documented to give the necessary transparency for future review and updating. High demands will be put on completeness in the material and that all critical issues for the safe disposal of radioactive waste have been addressed.

14.2.2 Main steps of the scenario methodology

The structuring of the scenario methodology started in a joint work between SKI and SKB in 1988. In 1989 the joint study resulted in a report /14-1/ which is the basis for the present scenario development work. In the study all the relevant features, event and processes (FEPs) that where addressed were assigned to either what is called a Process System or regarded as external FEPs that might influence the Process System. The Process System is defined as "the organized assembly of all phenomena required for description of barrier performance and radionuclide behaviour in a repository and its environment, and that can be predicted with at least some degree of determinism from a given set of external conditions".

The first step in the present methodology is to construct the Process System in text and with visual methods so that all known links between the processes involved are addressed. The mapping of all FEPs in the Process System can be done in several ways and during 1991–1993 attempts have been made with several different methods 1) visualization of the FEPs in a tree structure, /14-2/, 2) using Influence diagrams and 3) using the Rock Engineering Systems (RES) approach /14-3/.

The influence diagram methodology research was in 1993 mainly driven by SKI but is currently used by SKB in a study concerning other longlived wastes than spent nuclear fuel, see Chapter 16.

The RES methodology has been tested by SKB in some applications and seems so far be a good system to visualize the Process System in a comprehensive and transparent way. Further development and use of the methodology together with a linking to the FEPs database are under way.

The second step in the scenario methodology is to select the actual scenarios to be subjected to evaluation. The above mentioned schemes seem to be helpful tools to find the most important pathways through the Process System and also for finding processes and issues that can be put less emphasis on. All decisions can be documented and put in relation to the schemes, thereby giving a clear overview of the decision process.

There will always be a certain amount of expert judgement in some parts of the scenario selection process but with a careful documentation of the above mentioned steps these more subjective expert judgements can be put to a minimum.

14.3 THE COPPER/STEEL CANISTER

14.3.1 Gas generation and migration

In the event of water ingress to the canister, hydrogen will be generated as a result of anaerobic corrosion of the carbon steel inner canister. A study /14-4/ has addressed the potential overpressurization of the canister and the possible effects of the gas on water movement around the repository. The principal objective of this work was to determine the mechanism by which gas can migrate from a canister, to identify the possible consequences of gas generation and to determine the likely fate of the gas.

The main conclusions from this preliminary study were as follows:

- The long-term effect of the hydrogen gas generation will depend on the generation rate and the ability of the bentonite barrier to permit the escape of the gas.
- A number of alternative gas migration routes through the bentonite have been considered, including both the dissolution of gas in the groundwater and the flow of a gas phase. The amount of gas that could escape

through the bentonite by dissolving in the groundwater and diffusing away from the canister is small compared with the maximum gas generation rates that have been considered. Gas-phase flow through the bentonite must therefore represent the primary route for the gas to escape.

- The relationship between the pressure drop across the bentonite and the resulting gas-phase flow has been addressed. The scope of the analysis has been limited by the lack of availability of experimental data relating to the mechanisms controlling gas-phase flow through water-saturated bentonite.
- Two crucial questions need to be addressed in the future with regard to the passage of gas through the bentonite and the degree of overpressurization of the canister. These questions relate to:
  - The numbers (and size) of capillary-like pathways that are present in the bentonite. If the pathways present in the bentonite are sufficient in numbers and in size to permit gas-phase flow at the maximum generation rate without approaching the swelling pressure too closely, then the gas will be able to escape through the bentonite and make its way in due course to the surface.
  - The behaviour of the bentonite in response to increasing gas pressure, with respect to the enlargement of existing pathways and the formation of new pathways. If the pathways are insufficient, then it becomes important to consider the formation and enlargement of pathways by the displacement of clay aggregates. The effectiveness of this process will determine whether the gas can escape while avoiding any excessive increase in gas pressure in the canister that might compromise the integrity of the repository.
- Once the gas has escaped from the bentonite, it will pass into the tunnel area and the damaged zone. Gas-trapping in these zones could cause a small delay in the passage of the gas to the surface, but is unlikely to be significant over the long time scales that are considered in performance assessment. Transport of dissolved gas by diffusion or by advection in the groundwater flow is unlikely to represent a significant transport pathway at the gas generation rates considered.
- The gas will eventually pass into the rock overlying the repository. Two alternative approaches have been adopted to assess the ease with which gas can pass upwards through the rock towards the surface. Both the continuum model and the discrete fracture model results suggest that there is ample capacity to transport gas away from the repository and up towards the surface.

14.3.2 Radionuclide transport from the canister

If radionuclides are released from the waste, they will start to migrate. To be able to include as many transport processes as possible in the near field, it is necessary to have a model that is capable of describing the rather complex geometry. For this purpose a "compartment model" has been developed /14-5/. The model is based on dividing the complex geometry into several compartments. The number of compartments can be kept low by a special technique based on analytical and semi-analytical solutions at the mouths of the fracture in the rock and at the mouth of the hole through the canister wall. Because of the course compartmentalization the code is very flexible and can be adapted to different geometries. This is important when making variation and uncertainty analysis, since simplification of geometry and omission of transport resistances may lead to overestimation of the importance of certain parameters.

Scoping calculations on cesium, iodine and plutonium have been done with this model /14-6/. Iodine and cesium were selected because they have been main dose contributors in earlier performance assessments and plutonium because it is considered the worst hazard from radioactive waste. The two uranium daughters, radium and protactinium, which gave contribution to the total dose in some variation cases in SKB 91, are not included at this stage, mainly because the near field retardation of them is rather limited with the present model and variation of the near field parameters will therefore have very limited effect.

The nuclide transport in the interior of the canister was analyzed. It shows that the canister interior may be modelled as a well-mixed tank with an equivalent resistance at the outlet. The volume of this tank is the water in the damaged zircaloy tubes plus that in the filling material between the zircaloy tubes. For a large number of damaged tubes, the resistance is equivalent to that in the canister wall. For a few damaged tubes (less than 20), the resistance in the zircaloy tube has to be included. The analysis of the transport resistance in the zircaloy tube shows that the resistance is only important for those nuclides initially located at the fuel surface. For the nuclides embedded in the fuel matrix, the resistance in the zircaloy tube is negligible due to that there is no large variation of the concentration within the tube. The dissolution of the matrix occurs everywhere.

In general the number of damaged tubes strongly influences the total release of nuclides. The more tubes that are damaged the greater the total release will be. For the nuclides embedded in the matrix the release is directly proportional to the number of damaged tubes. For those nuclides which are present at the fuel surface the release rate is also influenced by the half-life of the nuclide and the water volume inside the canister and tubes.

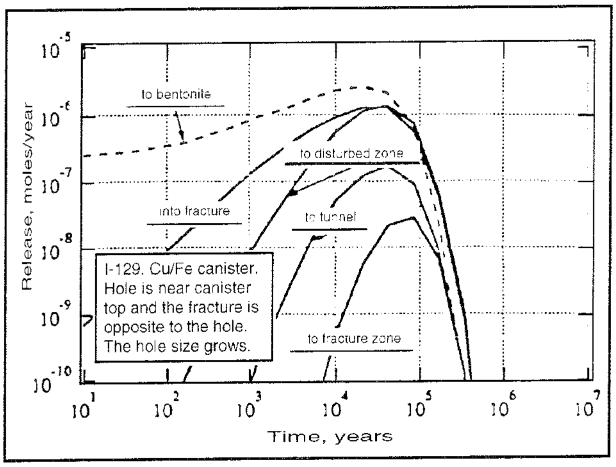


Figure 14-1. Release of I-129.

The larger void volume inside significantly decreases the release of soluble nuclides like cesium and iodine.

In this study the hole in the copper canister was assumed to grow with time. The effect of a growing hole has been investigated and the effect is small for short-lived nuclides, but there is a considerable increase of the release for the longer lived ones (about one order of magnitude for I-129), see Figure 14-1.

The most important pathway for all nuclides is to a fracture intersecting the deposition hole. This effect is more pronounced for the short-lived species which otherwise will decay on their way to other sinks located further away. Should there be no fracture intersecting the deposition hole the long lived nuclides will escape approximately at the same rate anyway by the other routes.

The copper/steel canister has, in general, about the same properties as the lead filled type. There are, however, two minor differences. Even if the hole in the copper will not grow with time, the canister will lose its mechanical integrity when enough steel has corroded. This process can be modelled as if there were no transport resistance at all in the canister wall. This will, of course increase the radionuclide release. There is, on the other hand, an advantage with the larger void volume inside the canister, which will delay the release of highly soluble, short-lived nuclides like Cs-137 and Sr-90.

14.4 BENTONITE – GROUNDWATER INTERACTION

Understanding the surface – chemical properties of montmorillonite in near-neutral and alkaline media is essential for establishing a chemical model of the bentonite/water interaction applicable for repository conditions. Thermodynamic modelling of bentonite-groundwater interactions and implications for near field chemistry in a repository for spent fuel have therefore been investigated in a special study /14-7/.

A pretreated and well-characterised Wyoming MX-80 bentonite has been used for investigating the acid/base characteristics of Na-montmorillonite. The cation exchange capacity (CEC) of Na-montmorillonite was determined to 108 meq/100 g for pretreated bentonite and to 85 meq/100 g for the bulk material. The surface area (BET) was (31.53 ± 10.16) m^2/g.

Potentiometric titrations of montmorillonite suspensions at ionic strengths I = 0.005 M, 0.05 M and 0.5 M were conducted as batch-type experiments. Deprotonation of surface OH groups possibly exposed at the edge surface causes an overall negative charge (given by a negative value in the proton balance) on the surface of montmorillonite in the alkaline pH range. In this pH range, the protolysis degree of OH groups increases with increasing pH and ionic strength. The proton density on the surface of montmorillonite increases with decreasing pH in the acidic pH range (pH < 7.5). In this pH range, two simultaneously occurring surface reactions account for the observed proton density on montmorillonite: Protonation of edge OH groups and ion exchange of the major cations for H^+ at the structural-charge sites.

The experimental results are interpreted in terms of a two-site model with structural-charge surface sites and variable-charge surface sites (edge OH groups) as the reactive surface functionalities. The total population of the surface sites is estimated for the OH groups to 2.84×10^{-5} mol/g, and for the surface sites to 2.2×10^{-5} mol/g. The intrinsic acidity constants for the OH groups are determined to $pK_{a1}^{int} = (5.4 \pm 0.1)$ and $pK_{a2}^{int} = (6.7 \pm 0.1)$, respectively, using the configuration of the diffuse double layer model (DDLM). The thermodynamic constant for the Na/H exchange at structural-charge sites is estimated to $\log K_X^o = (4.6 \pm 0.2)$.

Experimental data of the potentiometric titration of montmorillonite which are reported in the open literature can be interpreted within the scope of the presented two-site model for montmorillonite by implementing a third type of surface sites. The characteristic parameters for these sites are: Total population is 1.06×10^{-3} mol/g for pretreated Wyoming MX-80 bentonite and 8.3×10^{-4} mol/g for raw Wyoming MX-80 bentonite, respectively, and $\log K_X^o = 3.0$.

Ca-Na-exchange isotherms were measured on pretreated Wyoming MX-80 bentonite. The thermodynamic exchange constant was estimated to $\log K_X^o = (0.43 \pm 0.17)$.

The near field chemistry under repository conditions is predicted based on the proposed threesite bentonite model. Model computations indicate that the edge OH groups of montmorillonite excerpt a strong control on the buffer capacity in highly compacted bentonite. Model calculations predict a pH value of 7.3 and an alkalinity of 1.92×10^{-2} eq/dm^3 in the porewater of highly compacted bentonite.

Long-term predictions of the near field chemistry are presented on the basis of the mixing tank model. The evolution of the chemical composition of bentonite porewater and the relative proportion of exchangeable cations on montmorillonite are established for Allard and Äspö groundwaters in contact with compacted bentonite. The model suggests that pH and alkalinity of the porewater are controlled by the buffering capacity of the edge surface sites and calcite dissolution. In contact with Allard groundwater, the pH values of the porewater in compacted bentonite range from pH = 7.1 – 8.4 depending on the stage of conversion of Na-bentonite to Ca-bentonite. The corresponding pH range for Äspö groundwater is pH = 6.0 – 6.5. The transformation of Na-bentonite to Ca-bentonite strongly depends on the amount of calcite present in bentonite and the chemical composition of the groundwater. Once the carbonate pool is depleted, the conversion of Na-bentonite to Ca-bentonite proceeds at a much lower rate.

14.5 MODELLING OF TRANSPORT IN THE FAR FIELD

14.5.1 Background

Predictive modelling of groundwater flow in fractured, low-permeable rock is complex since the flow is concentrated within fractures. Still, calculations of water movement and transport of radionuclides constitute an important part of the safety analysis. Conceptual, mathematical and numerical models need to be further refined. SKB needs to show the impact of different conceptual models on the simulated results.

Verification and testing of models are extremely important. Therefore, the modelling of groundwater flow and transport of solutes within the Äspö Hard Rock Laboratory project is of special interest. The work will increase our understanding of the fundamental processes as well as give an opportunity to test our models with site-specific data.

14.5.2 Development of models

The channeling network approach describes the flowpaths in fractured rock as a network of connected channels with different lengths, conductivities, volumes and widths. The model can simulate the transport of a solute through this network where the solute may diffuse into the rock matrix. It is the water-conductive channels and not the fractures in the rock that constitute the basis for the model. The development has been focused on how to enable the model to use site specific data.

HYDRASTAR is a code for stochastic continuum modelling of groundwater flow used in SKB 91 /13-3/. Realizations of the hydraulic conductivity field are generated using the Turning Bands algorithm and can be conditioned on measured values of the conductivity using kriging. Version 1.3 is provided with a user-friendly input data interface. Furthermore the documentation has been substantially improved /14-8, 14-9/.

The methodology in HYDRASTAR will be further developed. Calibration procedures for taking account of both steady-state and transient groundwater head data are examined /14-10, 14-11/. Use of hydraulic interference tests in a large scale will probably improve simulation results.

HYDRASTAR simulations are based on stochastic models representing the hydraulic conductivity field. The INFERENS code has been designed to provide robust covariance functions for conductivity data determined from single hole packer tests. The extended version 1.1 includes among other things the following capabilities:

- More general forms of covariance models.
- Improved automatic fitting procedures.
- User-friendly input data interface as well as documentation /14-12, 14-13/.

INFERENS was used in a verification and demonstration exercise during 1993 /14-14/. The results indicated that, for the simpler synthetic models tested, the procedures produced useful and accurate variograms. However, using site-specific data, the cross-validation statistics were not significantly improved with the new, more complex covariance functions.

The preprocessor for groundwater flow modelling, HYPAC, has been developed in order to use elevation data from the SKB Geographical Information System. This will considerably facilitate numerical modelling in the future /14-15/.

14.5.3 Application of models

A modelling of the regional groundwater flow conditions in the area surrounding the Finnsjön site has been performed /14-16/. It originates from the final phase of SKB 91 but also contains some valuable experiences for the forthcoming site evaluation program.

In the study, it was of special interest to see if any possible case could result in an upward movement of groundwater in the region designed to be the repository area in the SKB 91 performance assessment. A number of different model geometries, with different assumptions concerning the geological structural model, were analyzed for a vertical section. None of the analyzed cases implied that the results concerning the groundwater residence times from the SKB 91 study were non-conservative.

The Channeling Network Model has been applied to data from the Äspö site as a part of the Äspö Task Force work. The task in question is the large scale pumping and tracer test LPT-2. The Task Force group will focus on modelling of groundwater flow and transport of solutes using the available large data base at Äspö. The results of the simulations of the LPT-2 pumping and tracer experiment are expected during 1994. The results of the channel network approach will be compared with a number of different modelling approaches. This will enable an evaluation of the first task of the Äspö Task Force.

14.5.4 Planned work

The channel network model will be further developed. This includes a new method in order to model fracture zones in the channel network model concept, improvement of the dispersion behaviour of the model by introducing the notion of self similar structures and investigations of the importance of the fluid mixing process at channel intersections.

Version 1.4 of HYDRASTAR will include a transient solver in order to make it possible to simulate pumping tests. Use of steady-state and transient head data will be necessary and probably performed with some kind of automatic calibration procedure. Further verification of HYDRASTAR is planned as well as improved documentation.

Further work will be headed towards alternative stochastic approaches for groundwater flow simulation and the effect on transport predictions. The goal is to show the effect of conceptual model uncertainty.

15 SUPPORTING RESEARCH AND DEVELOPMENT

This chapter presents the activities both on general development of understanding and databases in areas relevant for repository safety, and on specific supportive research actions that have been initiated to clearify unresolved issues. It is divided into the sections Spent Fuel, Canisters, Buffer and Backfill, Geoscience, Chemistry, Natural Analogue Studies, and The Biosphere.

Activities related to the development and testing of methodology and tools for performance and safety assessments have in general been presented in Chapter 14. The investigations regarding longlived radioactive wastes other than spent nuclear fuel are presented in Chapter 16. All the in-situ experiments and sampling made in the HRL are reported in Chapter 17.

15.1 SPENT FUEL

The cooperation with other groups in the world performing similar studies has continued during 1993, through the spent fuel workshop that was held in Santa Fe, New Mexico, and arranged by the University of New Mexico. More direct cooperative work has also been performed with Atomic Energy of Canada Ltd.

15.1.1 Fuel pellet rim zone

During the past two years ceramographic specimens from all reference fuels have been examined by micro-probe analysis in order to determine the radial distribution of selected fission products including neodymium. By volume weighing the Nd/U ratio across the radius to the bulk fuel burnup, the local values of burnup can be established. During this period, this has been performed on three specimens from the Series 11 corrosion experiments. Series 11 corrosion tests were performed on a BWR segment rod with burnup varying from 21 MWd/kgU to 49 MWd/kgU along the length of the rod. The three specimens were also submitted to alpha radiography in order to semi-quantitatively determine the radial distribution of alpha activity.

Figures 15.1-1 and 15.1-2 present the radial distribution curves for burnup and alpha activity. The burnup values given in the figure captions are those for the bulk pellet burnup. Burnups within a few micrometres of the pellet peripheries were found to be about 40% higher than the bulk burnups. Inspection of the figures shows that whereas bulk burnup along the pellet column vary with a factor of about a 2.5, the local alpha activity varies from the centre

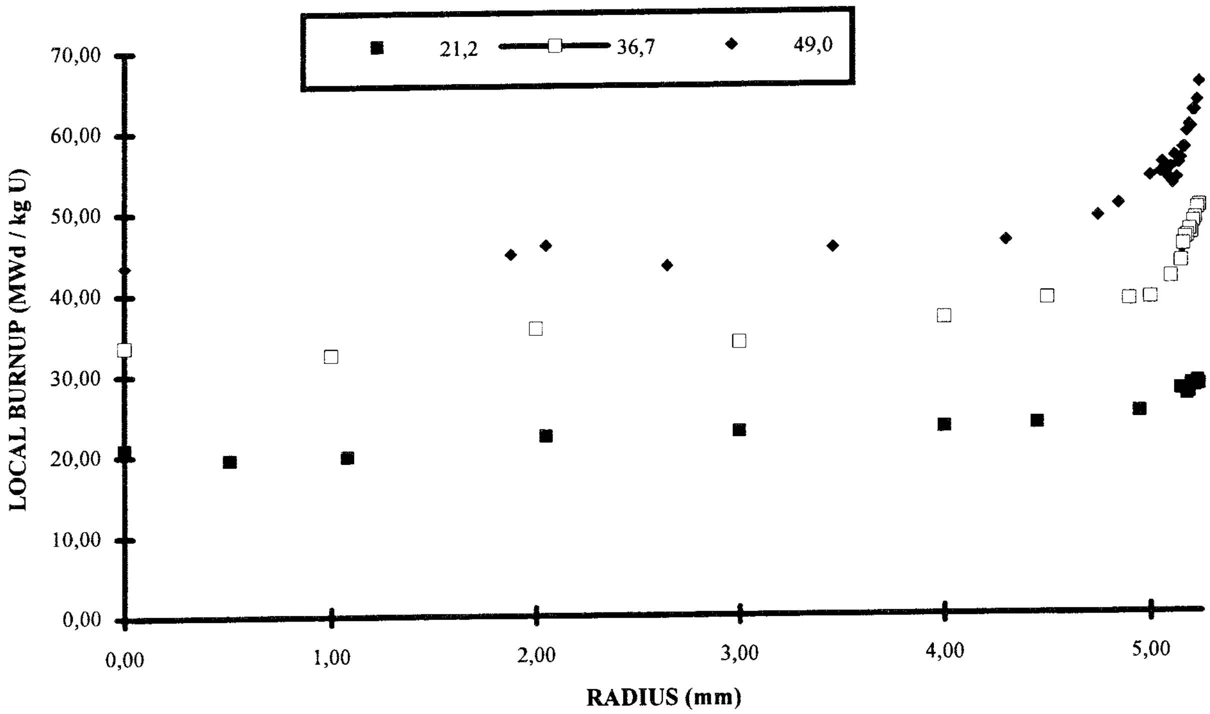


Figure 15.1-1. Burnup distributions over pellet radius for different burnups.

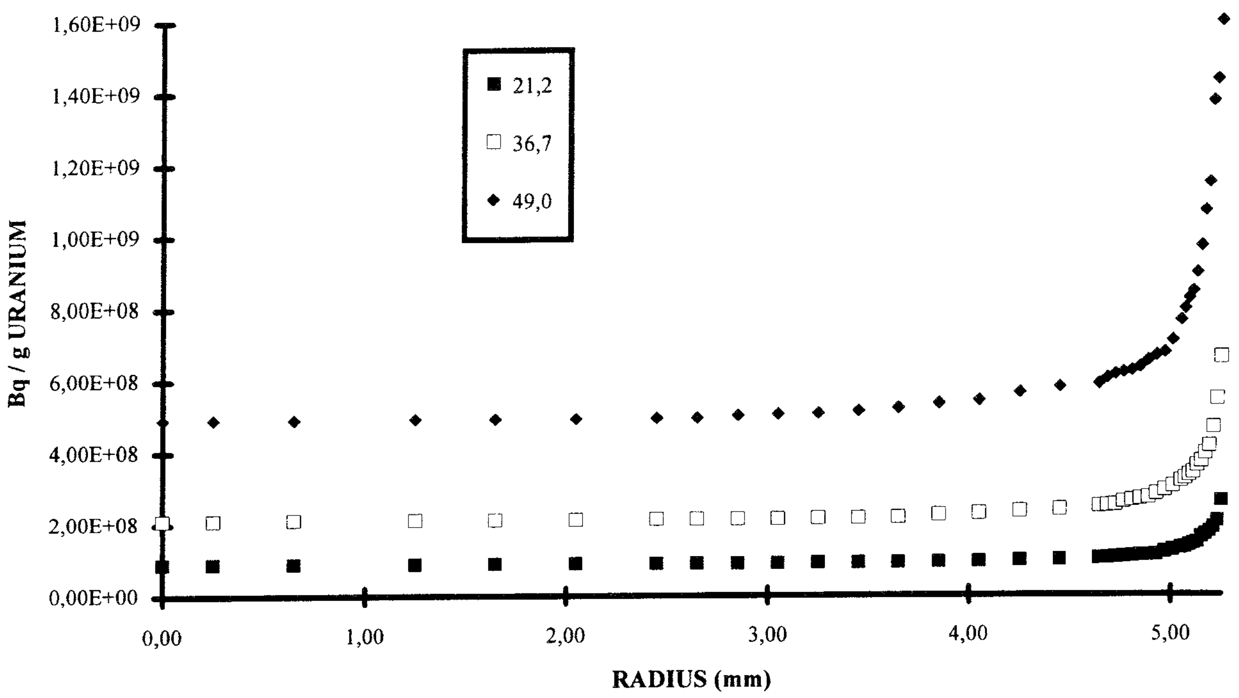


Figure 15.1-2. *Alpha distribution over pellet radius for different burnups.*

of the lowest pellet to the rim of the highest pellet with a factor of about 15. This increased alpha activity is associated with an increased porosity at the periphery of the fuel.

These effects were earlier noted during characterization of the Series 3 reference fuel (BWR fuel; burnup 42.0 MWd/kgU), and apparent evidence of local corrosion in the fule rim zone (porosity link-up) was seen during SEM examination of fragments of this fuel, which had been exposed for several years in 240 ppm bicarbonate groundwater and in deionized water /15.1-1/. Indeed, these observations were the experimental basis for the study of the apparent correlation between selective corrosion and alpha radiolysis at the high porosity rim. However, SEM examinations of two further fuel fragments in the Series 3 tests with longer exposure times to leachants have shown little evidence of rim corrosion. The reason for these differences in corrosion behaviour is currently unknown.

ORIGEN-2 calculations have been performed for the segment rod for a range of bulk burnups from 21 MWd/kgU to 90 MWd/kgU. In Figure 15.1-3, curves for the calculated U-235 and U-236 atom percent values have been fitted to experimental mass spectrometry results. It can be seen that the ratio between U-235 and U-236 increases as a function of burnup. In Figure 15.1-4, the calculated isotopic ratio curves for both bulk and rim are presented for different burnups and compared to the results of the analysis of U-236 and U-235 for all the contact periods in the corrosion experiments performed under oxidising conditions in groundwater. The results obtained suggest corrosion of the bulk of the fuel rather than preferential attack at the rim region.

There are some uncertainties as to the accuracy of the calculations, particularly with respect to the residual U-235 contents, but it is interesting to compare the calculated curves of the variation of the U-236/U-235 ratio with the burnup/pellet radius with results recently obtained by Garcia et al. /15.1-2/ at the Transuranium Institute, Karlsruhe. Figure 15.1-5 shows the radial variation of the isotopic ratio over the radius of a PWR pellet with a burnup of 53 MWd/kgU, as measured by laser ablation of fuel directly into a mass spectrometer from 20 points over the pellet diameter. It is seen that there is a clear radial variation, but this seems to be limited to an increase in the U-236/U-235 ratio from bulk to periphery of only 15-20%. However, the laser ablation technique samples a hemispherical volume with a crater diameter of about 0.5 mm which is large compared with the area of interest so that the results will tend to grossly underestimate the value at the periphery.

15.1.2 Spent fuel corrosion

Current models for the corrosion of spent fuel in groundwater are usually based on three chronologically-overlapping processes:

a) Rapid solubilization of species (e g cesium and iodine) released to fuel/clad surfaces during reactor operation.

b) Dissolution, with or without UO_2 dissolution, of species segregated or enriched at grain boundaries.

c) Matrix dissolution.

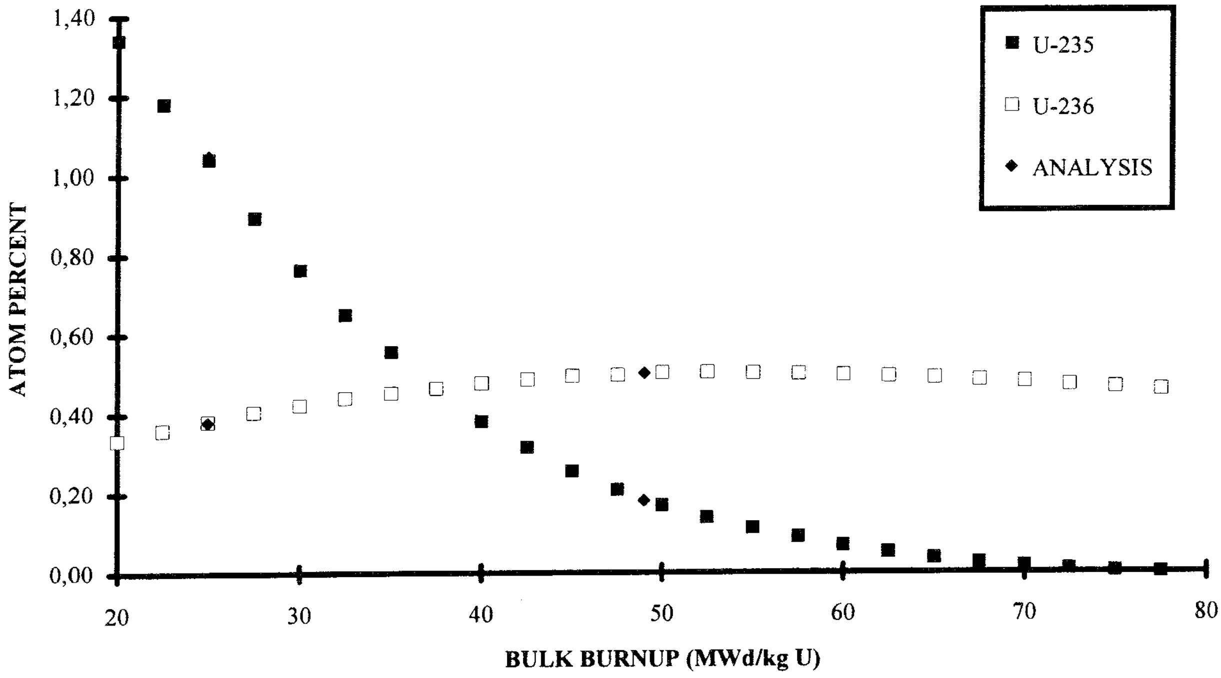


Figure 15.1-3. Uranium composition: ORIGEN-2 values fitted to analytical results.

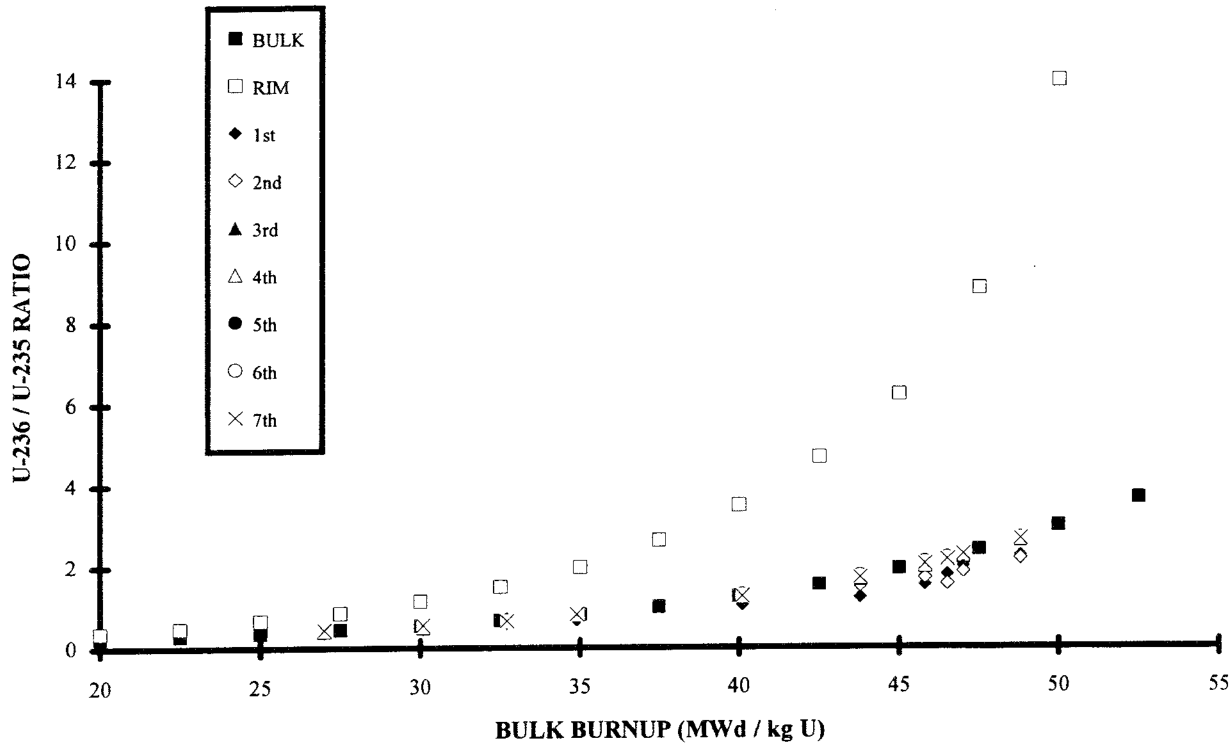


Figure 15.1-4. Isotopic ratios for bulk fuel and pellet rim.

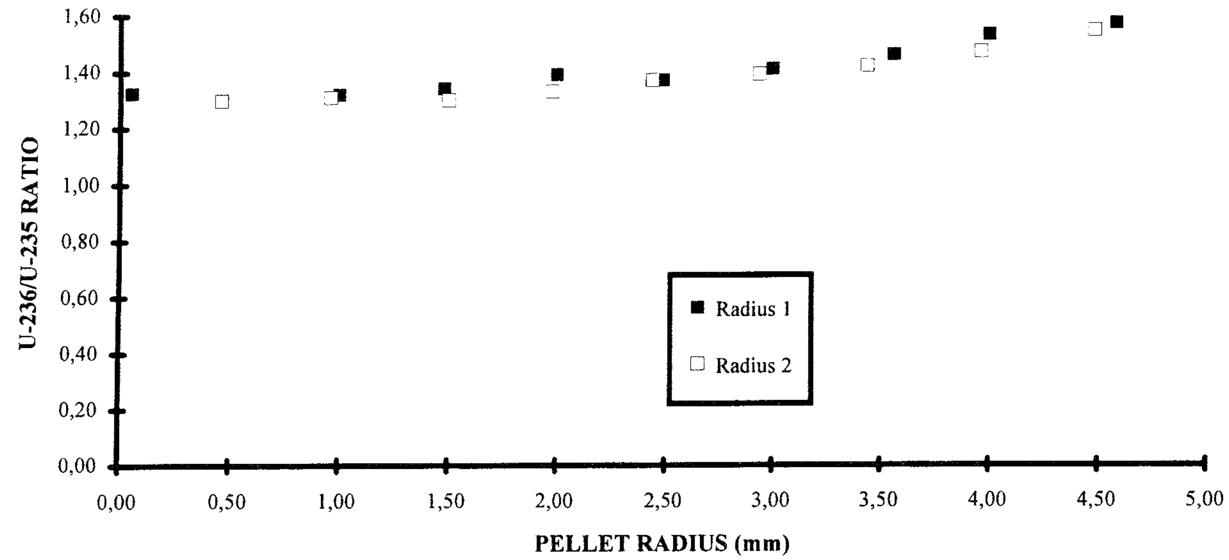


Figure 15.1-5. *Re-plotted data from the paper by Garcia et al. /15.1-2/ on laser ablation mass spectrometry on spent nuclear fuel.*

Although there is a good general understanding of these processes, there is still some uncertainty in quantification of the various terms. Measured release rates of the hitherto best choice of dissolution monitor, Sr-90, have been shown earlier to indicate a dependence on fuel irradiation history and, hence, on migration and segregation during irradiation /15.1-1/. The effect in absolute terms is small (< 1% of the fuel's Sr-90 content) but is significant in relation to the total amount leached. Attempts to identify such segregations in spent fuel by Electron Probe Micro-Analysis (EMPA) have been unsuccessful /15.1-3/. It has been suggested that migration of the precursors of Sr-90, Br-90 and Rb-90, may be the operating mechanism /15.1-4/. Measurements of grain-boundary inventories of Cs-137, Sr-90 and Tc-99 in used CANDU fuel have been made /15.1-5/. Grain boundary inventories of strontium in the range of 0.01 to 0.7% were measured on fuel which had been oxidised in air in order to open the grain boundaries. However, there was no apparent correlation between the release and burnup, power rating and oxidation state of the fuel.

During 1993 a study has been made of the migrational behaviour of selected fission products after imposing a steeper than normal temperature gradient on the fuel by means of a power-bump test and then measuring their aqueous concentrations in a series of short-term leach tests /15.1-6/. The power-bump test was performed at the Studsvik Nuclear's R2 reactor on a short fuel rod refabricated from a full length BWR rod with a burnup of 44-48 MWd/kgU. After conditioning at 25 kW/m the rod power was brought smoothly up to a maximum of 43 kW/m and held there for 3 hours. The axial variation of power (temperature) regimes imposed on the fuel is illustrated in Figure 15.1-6, which also shows the positions of the two fuel/clad specimens used in the subsequent experimental work. For comparison, two specimens from the part of the original fuel rod that had not been subjected to the power-bump were also included in the experiment.

The fractional release rates for Cs-137 and Rb-87 are shown in Figure 15.1-7, where it can be seen that the instant-release phase of release appears to be completed after about three weeks, after which time the rates for reference and power-bump specimens converge. The Sr-90 results, also given in Figure 15.1-7, suggest that no significant strontium migration occurred in the bump test and that the release rates show the same erratic behaviour usually observed in the early stages of aqueous corrosion.

Rubidium fission product nuclides, which have been discussed in connection with the possible formation of segregations of Sr-90 during reactor operations, were shown to migrate in fuel, but to a lesser extent than cesium and iodine. However, within the experimental uncertainty, no evidence for the migration of strontium fission products was observed.

An experiment was started in 1985, where spent fuel corrosion was studied in the presence of compacted bentonite. Part of a fuel pin, 42 MWd/kgU, with its Zircaloy cladding was sawn into 4.8 mm thick slices. Dry compacted bentonite clay with a dry density of 2100 kg/m^3 was placed around each fuel piece. The fuel and clay arrangement was placed in a diffusion cell, which was put in a stainless steel container with 1 dm^3 of synthetic groundwater, which had been pre-equilibrated with the bentonite clay. In some diffusion cells, additives of metallic iron, metallic copper or the mineral vivianite were

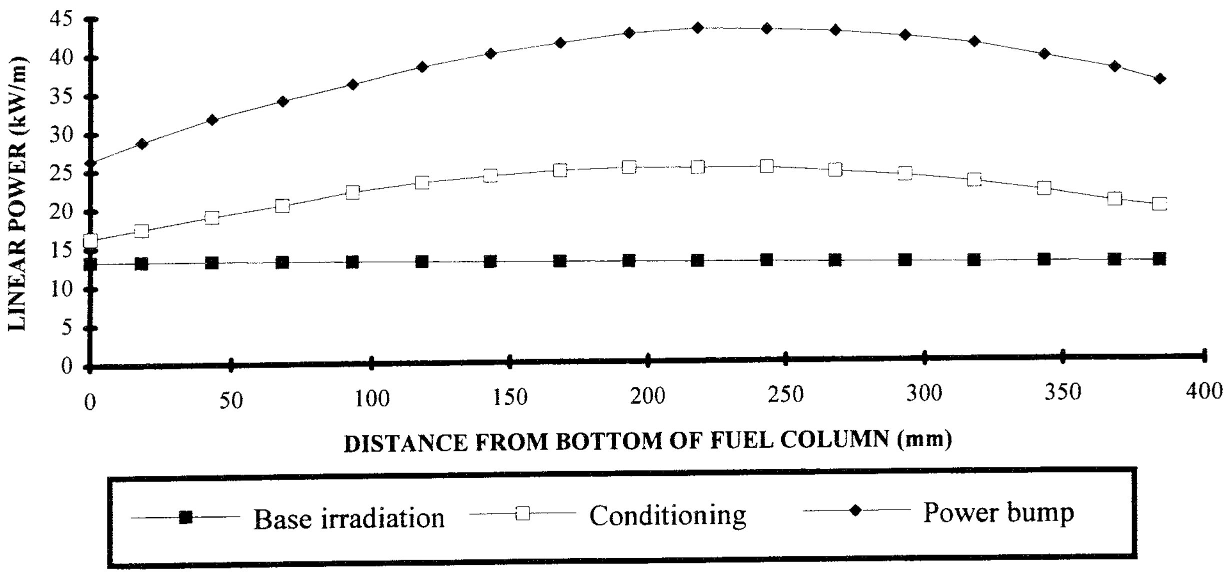


Figure 15.1-6. *The axial variation of linear power during base irradiation and power bump test.*

mixed with the clay. The experimental design and earlier results are described Skålberg et al. /15.1-7/ and by Albinsson et al. /15.1-8/. During 1993, the release and migration of Sr-90 in the clay have been measured and reported after contact times of 101, 197, 386, and 2213 days /15.1-9/.

A diffusion experiment was also performed with Sr-85 in bentonite compacted to a dry density of 1600 kg/m^3. The apparent diffusivity was found to be 1.7 x 10^{-11} m^2/s. From the distribution of Sr-90 from the fuel after 101 days an apparent diffusivity of 6.3 x 10^{-12} m^2/s was determined. This is in good agreement with the dependence of apparent diffusivity on dry density shown by Miyahara et al. for cesium and tritiated water /15.1-10/.

The total amount of strontium released in this experiment was 0.016% of the inventory. In fuel leaching experiments using the same fuel the corresponding amounts were 0.10 to 0.17%. However, experiments under anoxic conditions show a Sr-90 release fraction of 0.02% after one year /15.1-11/. Thus, the present experiment shows release rates more indicative of anoxic conditions. This is consistent with previously reported observation of Tc-99 behaviour /15.1-8/.

15.1.3 Alpha radiolysis

In cooperation with AECL, work aiming at an electrochemistry-based model for the dissolution of UO_2 has been performed. The principles for the model was presented in 1991 /15.1-12/. The oxidative dissolution rates were calculated from corrosion potential measurements and oxidative dissolution was assumed to be possible only at potentials higher than a certain threshold value. For PWR fuel, the estimates were that it would be possible to be above this threshold for a period of 500 to 30 000 years. The uncertainty in this range reflects the poor quality and limited number of corrosion potential measurements. Since then, the measurements of corrosion potentials have been refined and extended. The upper limit for the period for which an electrochemical model is required is now found to be about 2 000 years. The present studies have been performed with only one set of conditions, which are far from what can be expected in a repository (0.1 mol/dm^3 $NaClO_4$, pH=9.5, room temperature). A much wider range of conditions will prevail in a repository, and the factors likely to increase fuel dissolution rates due to alpha radiolysis include an increase in temperature, the presence of U(VI)-complexing agents and a decrease in pH. These must be studied further.

15.1.4 Natural analogues

As a part of the fuel analogue programme, the mechanisms for oxidation of uraninite have been studied /15.1-13/. Samples of uraninite and pitchblende annealed at 1200°C in H_2, and untreated pitchblende were sequentially oxidised in air at 180-190°C, 230°C and 300°C. Uraninite and untreated pitchblende oxidised to the U_4O_9-type oxide and their X-ray symmetry remained isometric up to 300°C. Reduced pitchblende after oxidation to UO_{2+x} and U_4O_9-type oxides transform into α-

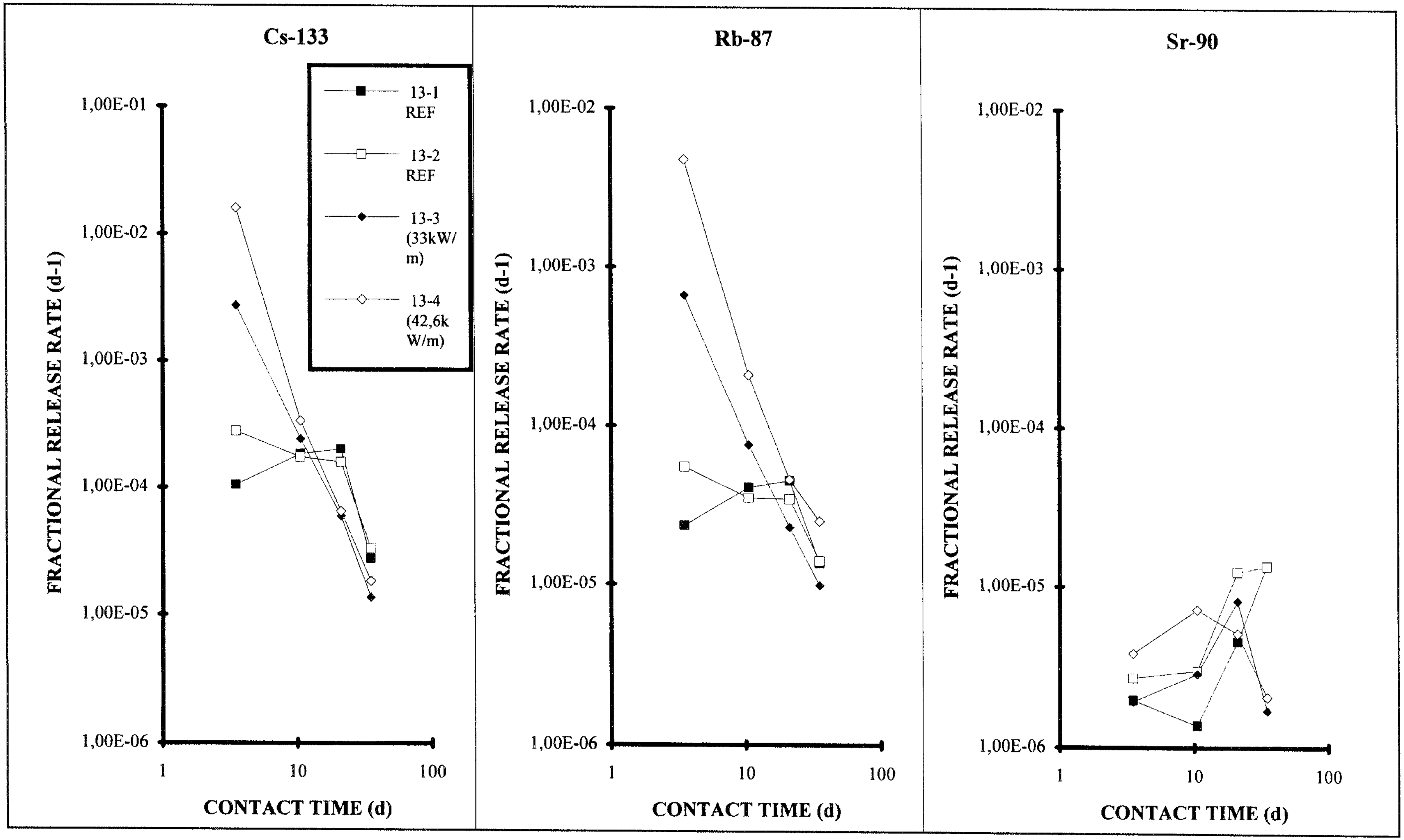


Figure 15.1-7. Fractional release rates for reference and power-bump specimens.

U_3O_8 at 300°C. Two major mechanisms were concluded to control uraninite and untreated pitchblende stability during oxidation:

1) Thorium and rare earth elements maintain charge balance and block oxygen interstitial movement near impurity cations, thus enabling U^{4+} oxidation with limited incorporation of excess oxygen into the uraninite structure.
2) The isometric uraninite structure saturates with respect to excess and radiation-induced oxygen interstitials. Sufficient temperature and/or oxygen partial pressure will transform the isometric structure into orthorombic U_3O_8. This process is unlikely to occur in nature, because of the presence of water that causes the formation of uranium oxide hydrates. Untreated pitchblende during oxidation behaved similarly to irradiated UO_2 in spent fuel /15.1-14/, whereas reduced pitchblende resembled unirradiated UO_2.

An analysis of data in the literature, as well as efforts to identify U_3O_7 in samples from Cigar Lake, Canada, failed to provide conclusive evidence of tetragonal α-U_3O_7 in natural samples. Most probably, reported occurrences of U_3O_7 are mixtures of isometric uraninites with slightly different composition. This is an important observation, because of the proposed role of α-U_3O_7 in geochemical models of the long-term corrosion of the UO_2 in spent nuclear fuel.

15.2 CANISTERS

The work during 1993 has been focused on long-lived canisters with copper as the outer corrosion barrier and an interior steel canister as the load-bearing component. The studies have been focused on design, welding techniques and non-destructive testing. This work is reported in Chapter 6.2. In addition to this, work on the chemical stability of the canister materials has continued. Most of these studies are still in progress and the current status will therefore only be high-lighted in this Chapter.

15.2.1 Steel corrosion

The work during the period has been concentrated on the anaerobic corrosion of carbon steel in granitic groundwater. Most of this work is still in progress, but some results and conclusions are now available. The studies have included a literature survey /15.2-1/ as well as experimental work.

In the experimental studies, a range of methods, both electrochemical and direct gas measurement, has been used to assess the rate of corrosion and the associated hydrogen gas production /15.2-2/. The results indicate that under the conditions of interest carbon steel is protected by an oxide film. Good agreement was found between the various methods of corrosion rate measurements and the long term corrosion rates are in the range 0.1 to 1.0 μm/year. In the range 1 to 100 atmospheres the application of hydrogen overpressure was found to not to significantly effect the corrosion rates observed. Following the long term tests (one to four years) the corrosion products identified, by X-ray diffraction, were mixed phases of magnetite and magnesium carbonate. Scratching electrode tests under anaerobic conditions resulted in the re-growth of a thin oxide film and a return to the pre-scratch corrosion potential.

15.2.2 Copper corrosion

The evolution of oxygen in a HLW repository has been studied using presently available geochemical information /15.2-3/. The important processes affecting the oxygen migration in the near-filed include diffusion and oxidation of pyrite and dissolved Fe(II). The evaluation of time scales of oxygen decrease is carried out with (1) an analytical approach involving the coupling of diffusion and chemical reaction, (2) a numerical geochemical approach involving the application of a newly developed diffusion-extended version of the STEADYQL code /15.2-4/.

Both approaches yield consistent rates of oxygen decrease and indicate that the oxidation of pyrite impurities in the clay is the dominant process. The results obtained from geochemical modelling are interpreted in terms of evolution of redox conditions. Moreover, a sensitivity analysis of major geochemical and physical parameters is performed. These results indicate that the uncertainties associated with reactive pyrite surface area impose the overall uncertainties of prediction time scales. Thus, the obtained time of decrease to 1% of initial O_2 concentrations ranges between 7 and 290 years. The elapsed time at which the transition to anoxic conditions occurs is estimated to be within the same range.

15.3 BUFFER AND BACKFILL

15.3.1 Testing and modelling of the physical behaviour of water saturated bentonite

The laboratory testing and modelling of the rheological properties of bentonite have been continued during 1993. One major result is the implementation of a new improved material model into the finite element code ABAQUS /15.3-1/.

Test calculations made showed that the new model appears to be much more relevant than the earlier one for modelling the physical behaviour of buffer materials. However, they also showed that additional tests are required for the final choice of parameters to the model.

15.3.2 Testing and modelling of the physical behaviour of bentonite which is not water saturated

The behaviour of water unsaturated bentonite with respect to the thermal and mechanical behaviour as well as flow of water is presently investigated and some techniques for modelling these properties have been tested /15.3-2/. The modelling of unsaturated materials has been based on the material models developed for water saturated buffer materials and the tests have been made using the finite element program ABAQUS.

Test calculations and comparisons with laboratory experiments showed that ABAQUS can describe the behaviour of unsaturated buffer materials although some changes have to be made in the code. Several parameters are not known sufficiently well and require more tests. However, some limitations exist since the present version of ABAQUS cannot model vapour flow. This means that the effect of temperature gradient in the material as well as direct connections with the atmosphere cannot be modelled today.

15.3.3 Heat conductivity of buffer materials

The thermal conductivity of the buffer material is an important parameter for the design of a repository. A method for determining the thermal conductivity of buffer materials has been developed and the influence of void ratio, degree of saturation and field conditions have been investigated /15.3-3/.

A literature survey has yielded three proposed methods for theoretical determination of the thermal conductivity. A technique for laboratory determination of the thermal conductivity with a thermal probe has been further developed and investigated by use of FLAC-calculations. A test and evaluation methodology based on these calculations is outlined. Several series of laboratory tests on bentonite with different void ratio and degree of water saturation have been made and the results compared with the theoretical values. Three field tests in the Stripa mine have been used for checking the influence of field conditions on the heat conductivity. These tests have been calculated using the finite element method and the resulting thermal conductivity of the buffer material in the field evaluated from back-calculation of these results and comparison with the theoretical values.

The results from the field tests show that the laboratory and theoretically determined values are applicable under field conditions if the degree of water saturation is very high. However, they also show that the back-calculated values at a low degree of water saturation are lower than expected, probably due to cracks and inhomogeneous conditions from moisture redistribution, see Figure 15.3-1.

All tests and back-calculations of Mx-80 buffer material with a degree of saturation higher than 90% and a density between 1.9 t/m^3 and 2.1 t/m^3 resulted in values of the thermal conductivity between 1.25 W/m,K and 1.35 W/m,K.

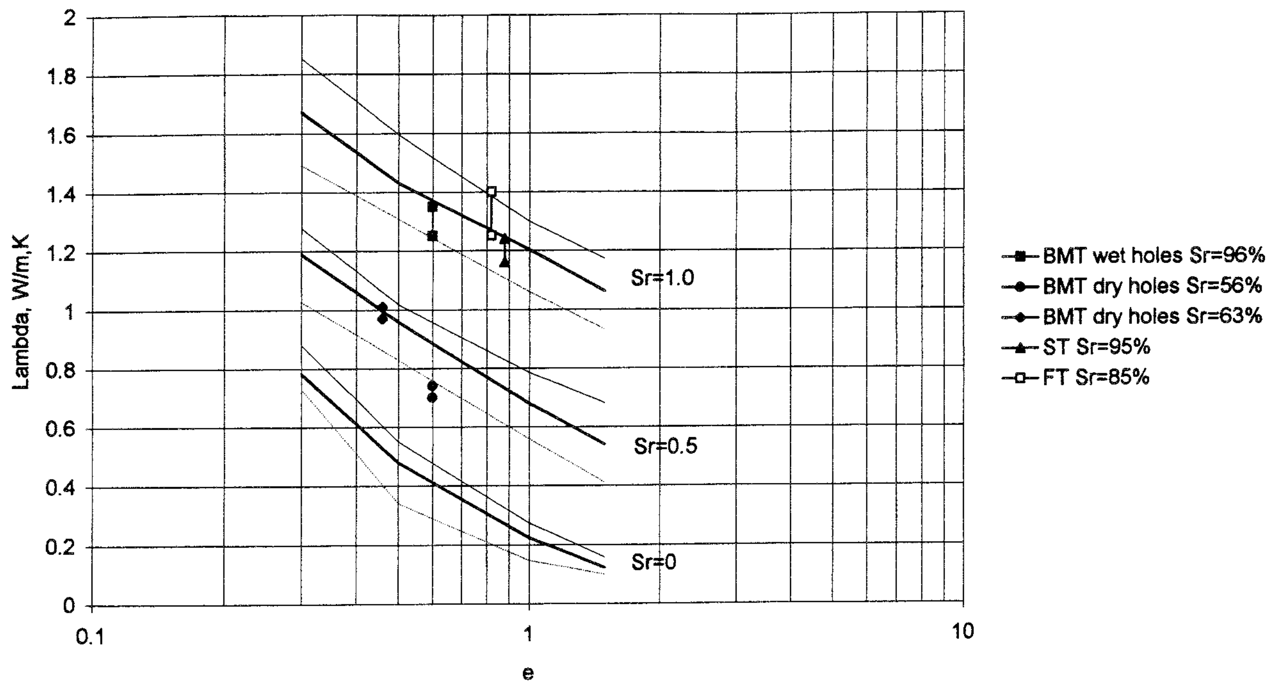


Figure 15.3-1. Comparison of the heat conductivity evaluated from the three field tests and the expected values. The higher value is the field heat conductivity while the lower value is corrected to correspond to room temperature and no confining pressure.

15.3.4 Smectite longevity

Illitization

Historically, investigations in the Gulf area have shown that there is a continuous reaction series of montmorillonite to hydrous mica ("illite"), suggesting a monotonic increase in percent illite within the assumed mixed-layered illite/smectite (I/S) clay phase. The overall reaction was claimed /15.3-4/ to be

Smectite + K + Al = Illite + Si

Other mineralogical changes than K-feldspar dissolution have been identified and a more complete list of mineral alteration associated with the conversion of smectite to illite is:

- Decomposition of mica.
- Decomposition of feldspar (not albite).
- Loss of kaolinite.
- Formation of chlorite or chlorite interlayers in the smectite/illite stacks.
- Formation of quartz, cristobalite and amorphous silica.
- Loss of calcite.

Compilation of field data has given the relations in Figure 15.3-2.

Before 1982 the dominant conversion model was that of charge increase through replacement of tetrahedral silicon by aluminum in the smectite lattice, process I, while, later, the idea of dissolution of smectite and neoformation of illite has been considered as a possible alternative process (process II) /15.3-4/.

It appears that there are great difficulties in distinguishing processes of types I and II unless one can safely identify the nature and origin of the clay minerals. A very important point is that the access to and uptake of potassium is a major factor controlling the rate of conversion for both processes.

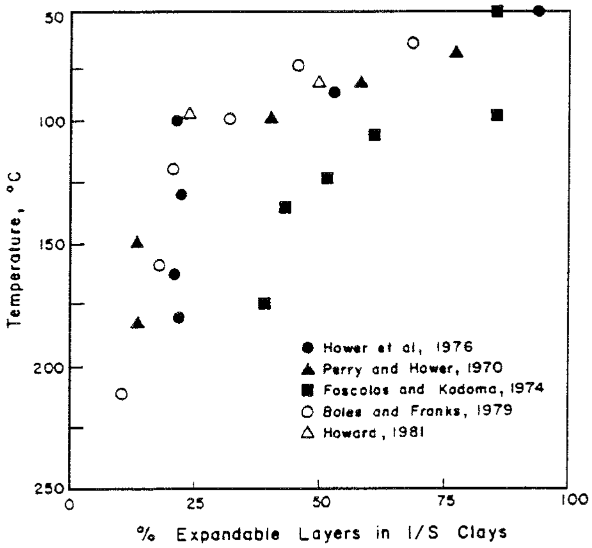


Figure 15.3-2. Percentage of expandable layers in natural I/S mixed-layer minerals vs temperature (Weaver).

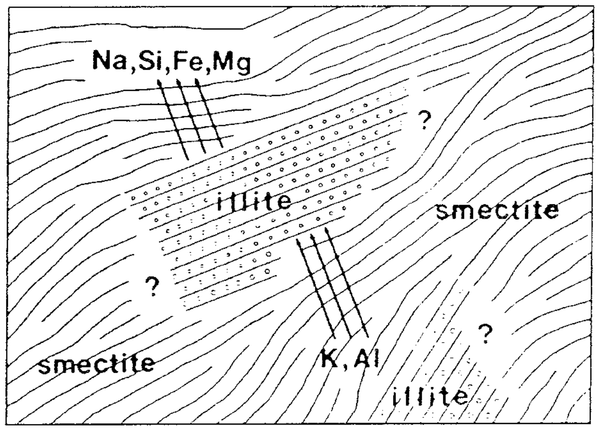


Figure 15.3-3. Schematic picture of conversion of smectite to illite.

Detailed studies of Gulf and North Sea sediments have revealed that smectite domains (aggregates of aligned flakes) dominate initially and that – in the course of conversion – illite stacks (packets or domains) grow within a shrinking matrix of smectite, i e on the expense of parent smectite, see Figure 15.3-3. Ultimately, the clay is characterized by large illite domains with subparallel orientation.

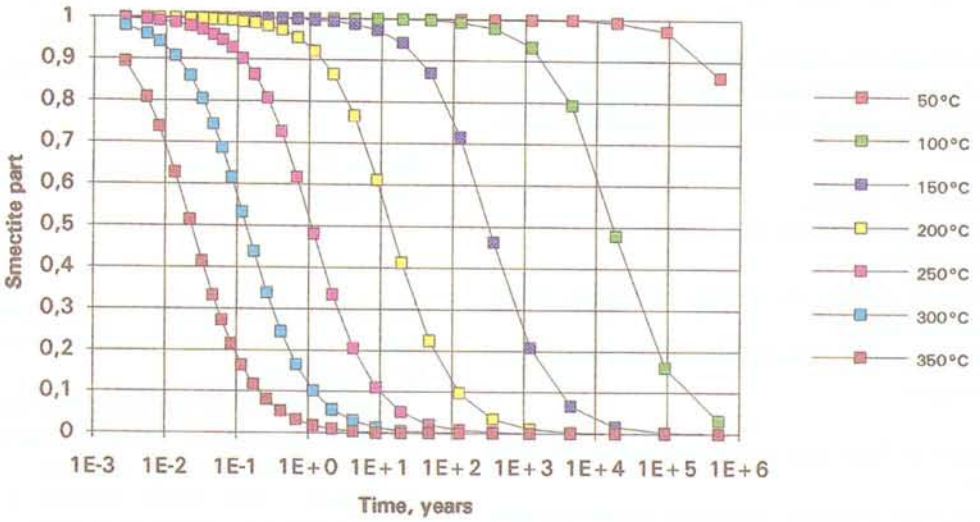
The earlier generally accepted idea that illite/smectite (I/S) mixed-layer minerals form an intermediate phase in the conversion of smectite to illite has been questioned in the last few years. Thus, I/S mixed-layer particles can be regarded as consisting of elementary smectite and illite (K-rectorite) lamellae (flakes) with a thickness of 10 and 20 Å, respectively.

Kinetics involved in the conversion of smectite to illite can be modelled by assuming that reorganization of the crystal lattice or dissolution is an Arrhenius-type process, i e controlled by the temperature. Two such models have been proposed, one by Bethke and Altaner /15.3-5/, which is purely theoretical and assumes that different groupings of smectite and illite lamellae (SSS, SSI, and ISI) have different relative reactivities, and one semi-empirical model proposed by Pytte /15.3-6/, with the K/Na ratio as major parameter in addition to the activation energy and the temperature.

An important finding is that the Pytte model for the two activation energies also fits the four field cases investigated in the SKB research program, i e the Sardinian (Busachi) bentonites /15.3-7/, the two Gotland horizons (Hamra and Burgsvik) /15.3-8/ and the Kinnekulle bentonite /15.3-9/.

Figure 15.3-4 shows that at 100°C any significant alteration of smectite would require several tens of thousands or hundreds of thousands of years, provided that the potassium is 20 ppm. Considering the somewhat lower temperature and the short duration of the heating period

smectite fraction at start	SO		0	1	
time	t	s		0	
frequence factor	A	1/s		80800	
activation energy	Ea	cal/mol		25000	
gas constant	R	cal/(deg*mol)		1,987	
temperature	T	K		323	623
K+ concentration	[K+]	mole/l		0,01	



smectite fraction at start	SO		0	1
time	t	s		0
frequence factor	A	1/s		80800
activation energy	Ea	cal/mol		27000
gas constant	R	cal/(deg*mol)		1,987
temperature	T	K		323
K+ concentration	[K+]	mole/l		0,01

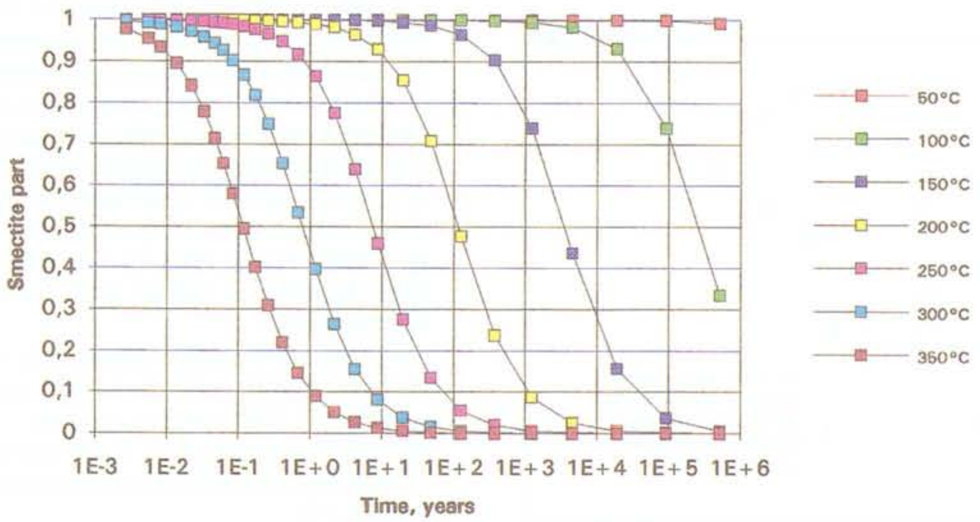


Figure 15.3-4. *Rate of conversion of smectite to illite according to Pytte's model. K^+ concentration of 0.0005 moles per litre (about 200 ppm). Upper: Activation energy 27 kcal/mole. Lower: Activation energy 26 kcal/mole.*

in a KBS-3 repository, one finds that even at 400 ppm K^+, like in ocean water, practically important illitization will not take place.

In recent time field studies have been made /15.3-4, 15.3-10/, that shed considerable light on the nature of I/S minerals and on cementation processes with smectites involved.

An important finding from the field tests is that access to potassium controls the conversion rate at temperatures exceeding 50-100°C. In practice, it can be limited by low conductivity of the surroundings and absence of hydraulic gradients. Where no groundwater flow takes place that can bring new potassium-holding water to the converting smectite clay, the alteration process stagnates and results in a "frozen" illitization profile even in a very long perspective.

Laboratory hydrothermal experiments performed in the SKB research by use of the cell arrangement in Figure 15.3-5 have shown no change in the smectite content in experiments with distilled water, Forsmark water or ocean-type water, but an indication of an alteration to illite in 270 days experiments at 200°C with water containing 200 ppm K^+.

The same insignificant alteration was found in experiments with γ-irradiated samples. XRD spectra showed that the low-charge montmorillonite making up the large majority of Mx-80 remained largely intact at 130°C heating for one year, but they clearly showed complete disappearance of feldspars and sulphate formation (gypsum, anhydrate, and hexahydrate), which led to some cementation, see Figure 15.3-6.

A major conclusion from the comprehensive experimental tests series is that Pytte's semi-empirical illitization model using an activation energy of 27 kcal/ mole and appropriate parameter values applies also to laboratory conditions.

Very recently, geochemical modelling has been applied by Fritz and colleagues for checking whether the models DISSOL, THERMAL, KINDIS and CISSFIT yield data that agree with the laboratory experiments. The agreement is found to be rather good with respect to the types of reaction, while the rate of changes is considerably overestimated.

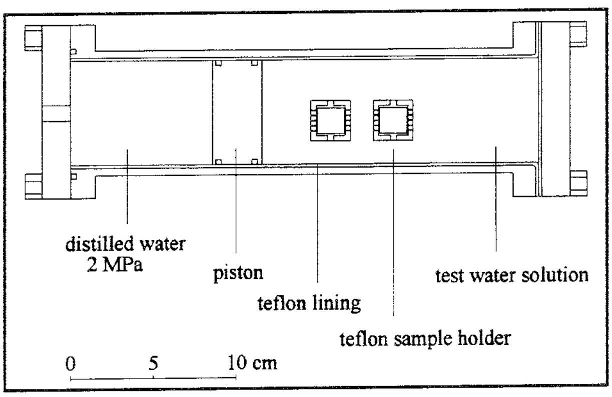


Figure 15.3-5. *Hydrothermal cell arrangement.*

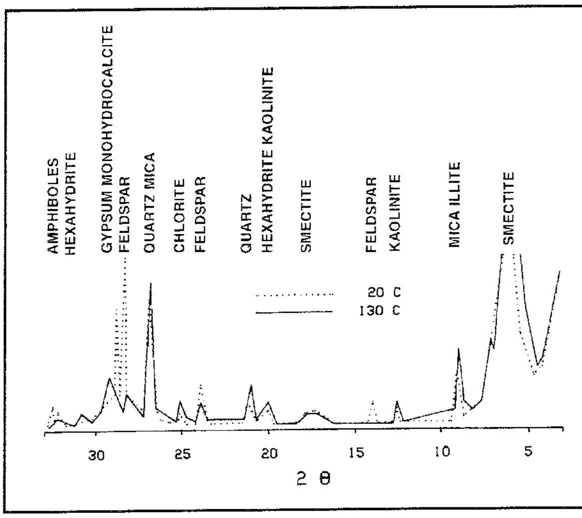


Figure 15.3-6. *Rectified XRD spectra of samples 00 (20°C) and 01 (130°C).*

Investigation of the Kinnekulle bentonite layers

The mountain Kinnekulle, southwestern Sweden, contains bentonite layers that have been the subject of several mineralogical investigations, including a recently completed analysis and a few studies of the physical properties of the clay /15.3-9/. Figure 15.3-7 shows the stratigraphy of the Kinnekulle area with a diabase layer, presently at the top, resulting from lateral penetration of magma in Permian time. Finite element method (FEM) and conodont analyses, have led to the conclusion that the clay layers were exposed to about 150°C for about 300 years, and to about 130°C for another 300 years and subsequently to 100-130°C for 400 years. The temperature then dropped back to the original in an approximately 2000 year long period.

The uppermost part of the about 2 m thick main bentonite bed and adjacent thinner layers are concluded to be more silicified and to have a different mineral content than the equally heated central part. The central part of the bed has a higher smectite content due to less uptake of potassium in the heating period. A pure illite phase is also concluded to be present.

Micrographs demonstrate that the bentonite clay where sampling took place, i e where the present effective overburden pressure is now only 0.1 MPa but where the maximum pre-consolidation pressure has been 5-10 MPa in Permian time and up 30 MPa in the period of Pleistocene glaciation, is rather porous. The porosity in the heating period in Permian time is estimated to have been 30-40%, implying no restraint to mineral neoformation in the voids. The present porosity of the central part of the main bed at the shallow sampling site is on the order of 50% and the dry density about 1.66 g/cm^3 (2.05 g/cm^3 at water saturation), while the more illite-converted part at the upper boundary of the main bed has a porosity of about 38% and a dry density of 2.02 g/cm^3 (2.29 g/cm^3 at water saturation). This difference may have two reasons; 1) silica precipitation in the latter material may have increased the density and reduced the pore volume, and

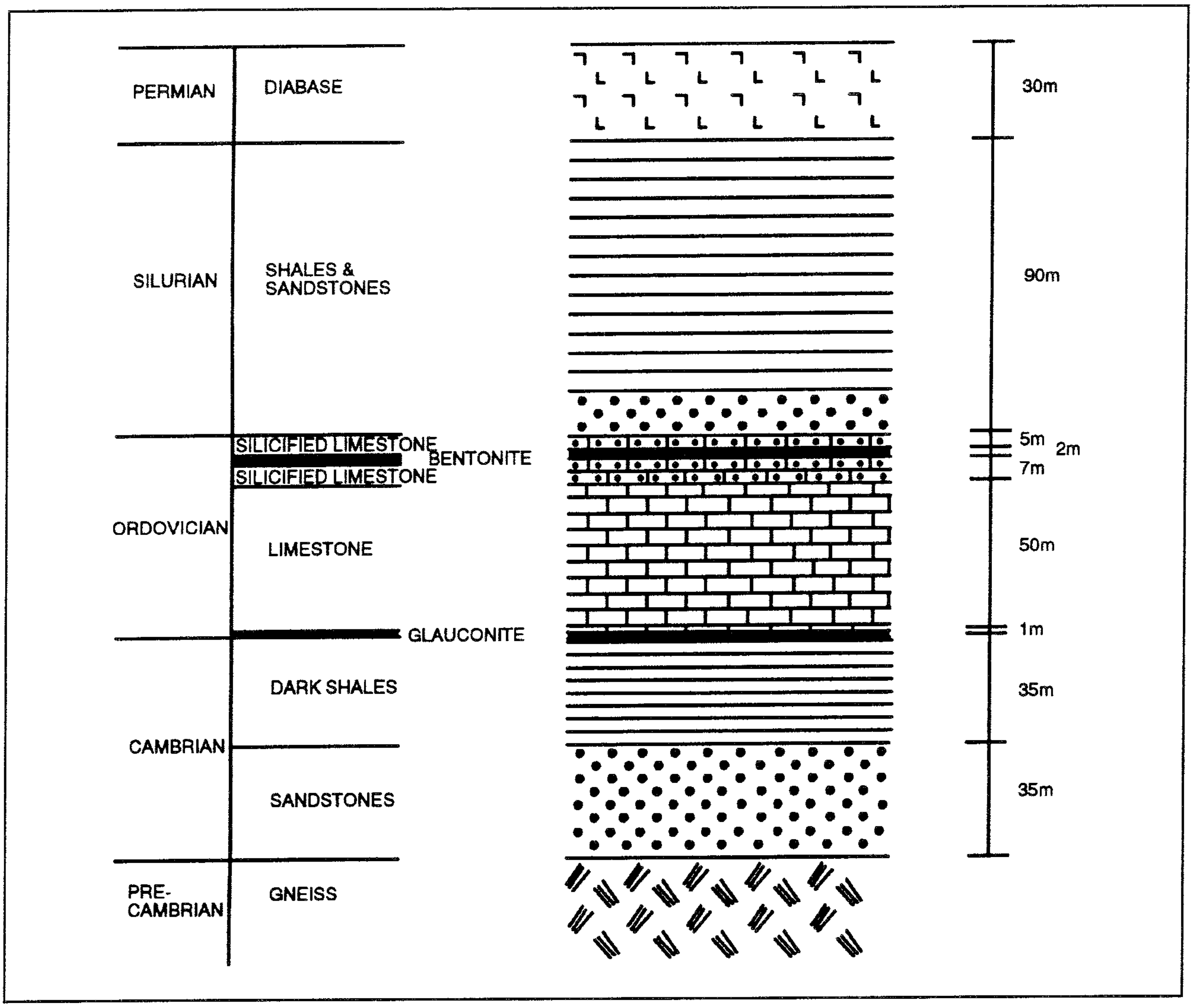


Figure 15.3-7. *The Kinnekulle strata.*

2) the more extensive conversion to illite must – in combination with the stronger silification – have led to less swelling ability and therefore to preservation of the compressed state under earlier heavy overburden pressure.

Application of Pytte's model for smectite/illite conversion, taking the activation energy to be 26-27 kcal/mole, gives good agreement with the actual smectite content of 20-40%. The kinetics are concluded to be controlled by the access to potassium as demonstrated by the fact that the peripheral parts of the uniformly heated main bed (maximum gradient 0.05°C/cm) have undergone significantly more illitization than the central part. The conversion profile is a good proof of the validity of the hypothesis that potassium is transported into the clay by creation of a K-sink in the clay that generates a concentration gradient. The picture of a "frozen" illite profile strongly supports the assumption that the conversion took place in the heating period and not subsequently.

The amount of precipitated silica compounds, which may be quartz, cristobalite or amorphous silica, is estimated to be up to 3%, which seems to be too small to have led to the actual cementation, which is in fact clearly demonstrated by the difficulty in dispersing the material despite intense ultrasonic treatment and boiling in 5% soda solution, see Figure 15.3-8. In this context it is of great interest to see that while conversion of montmorillonite to illite by uptake of external aluminum causes release of slightly more than 4 weight percent of silica, neoformation of illite by dissolution of smectite ("cannibalization") sets about 30% of the mass free in the form of SiO_2. Such an amount of silicious compounds naturally has a significant impact on the porosity and a very strong cementing effect. Still, it is concluded that this was not the major reason for the rather significant cementation, but that neoformed illite and possibly chlorite caused the phenomenon.

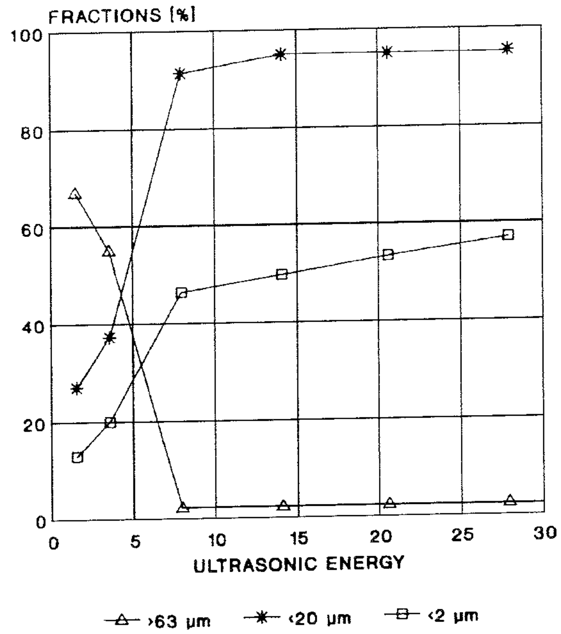


Figure 15.3-8. Grain-size distribution of sample from the central part of the main bed determined by applying different ultrasonic energies expressed in 10^{-8} m^2s. Frequency at 20 kHz.

Conceptual conversion model

With today's perspective it is still not definitely proven if conversion of montmorillonite to illite actually takes place by formation of true I/S minerals or only by illite growth with I/S being only apparent, and by growth of chlorite as a separate phase or as intercalations. Solid-state transformation of smectite from low-charge to high-charge state with replacement of Na^+ or Ca^{2+} by K^+ in the interlamellar space with subsequent dehydration is hardly probable, as indicated by Howard already at the colloquium back in 1982 /15.3-11/. Formation of non-expandable 10 Å minerals with Na^+ or Ca^{2+} in the interlamellar space, i e paragonite-type minerals, may be mistaken for illitization but it requires very high effective pressures and much chlorite to explain the enhanced K-content.

Precipitation of illite (and possibly I/S) is concluded to be the major conversion mechanism. Dissolution of accessory silicate minerals is expected to yield the silica and aluminum as well as some of the potassium that are required for the formation of illite, but potassium available in the groundwater is also an important K^+ supply. Cannibalization of smectite minerals is not assumed to be a major process but merely dissolution of accessory minerals, primarily K-feldspars and micas.

As to cementation, it is clear that sulphates and carbonates may be precipitated to yield cementation, and that neoformed illite and chlorite may also cause cementation. However, the influence on the rheological properties of the clay in bulk is still not known.

15.3.5 Cement-clay interaction

The work concerns possible mineral alteration in contacting concrete and bentonite. The tests comprise 1, 4 and 16 months test series using hydrothermal cell tests, per-

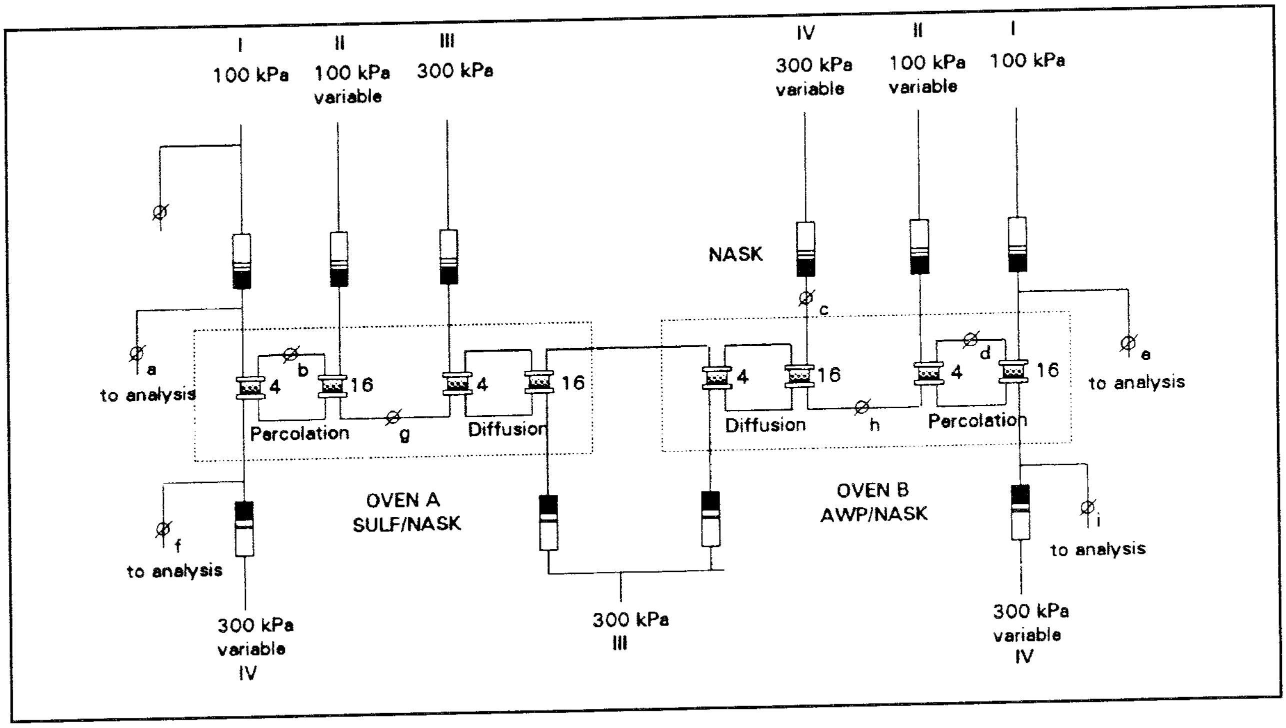


Figure 15.3-9. The percolation and diffusion test set up. The left side of the scheme is contacted to the SULFACEM cement solution and the right side to the Aalborg White Portland (AWP) cement solution.

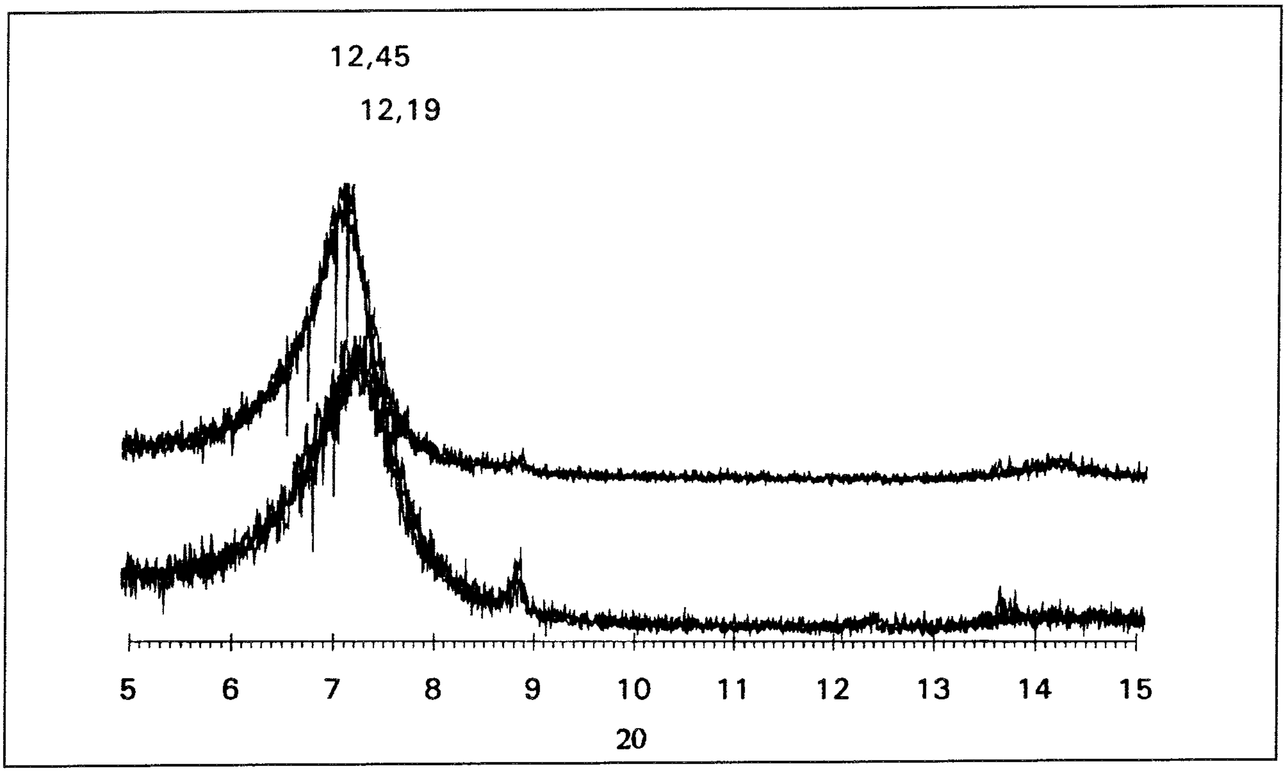


Figure 15.3-10. *Details from the XRD patterns from two samples percolated with AWP (upper) and SULFACEM (lower) cement solutions. An increase in 10 Å minerals is shown in the sample contacted to the SULFACEM solution.*

colation tests and diffusion tests, see Figure 15.3-9. The 1 and 4 month series have been completed during the year and the 16 month series are running /15.3-12/. Mx-80 bentonite from American Colloid Ltd. was used in all tests after conversion to monoionic sodium state. Two types of artificial cement pore water solutions were used; the SULFACEM type dominated by alkali hydroxides and thereby with a very high pH (~13,5), and the Aalborg White Portland (AWP) type dominated by calcium hydroxide and thereby with a more moderate pH (~12.5). The clay density was 1.8 g/cm^3 after saturation with distilled water, and the temperature was held at 40°C in all tests. The swelling pressure and hydraulic conductivity were measured during the whole test period in the percolation tests. After termination, the clay was analyzed with respect to changes in element distribution, mineralogy and physical properties. The water solutions were analyzed with respect to ion content and pH.

Most of the changes in physical properties found in the various samples were induced by the ion equilibrating process between the samples and the test solutions. Steady state conditions seem to have been established after approximately 100 days in the percolated samples. Two significant changes were, however, found in addition to the equilibration, i e a minor decrease in hydraulic conductivity in all samples, and a decrease in swelling pressure in the samples contacted with the SULFACEM cement solution. The change in hydraulic conductivity reflects normal microstructural homogenisation, while the decrease in swelling pressure probably reflects a mineral alteration due to the high pH. Also the chemical changes in the systems are mainly due to the equilibration between the bentonite and the test solutions. A minor general increase in cation exchange capacity (CEC) was, however, found, and an increase in content of 10 Å minerals in the samples contacted to the SULFACEM solution, see Figure 15.3-10. The latter is the most important finding and is likely the cause of the swelling pressure reduction in these samples. The kinetics can not be evaluated at this point, but if the transformation rate does not decrease with time, the clay alteration has to be considered as a substantial problem if a SULFACEM-type of cement is used in combination with bentonite.

15.3.6 Backfilling and sealing studies

Plugs for sealing off axial water flow along tunnels

General

Low permeability tunnel plugs have been suggested as a means of reducing and redirecting the groundwater flow in backfilled nuclear waste repository tunnels. If the plugs extend into slots cut into the tunnel walls the groundwater flow also in the nearfield rock will be re-

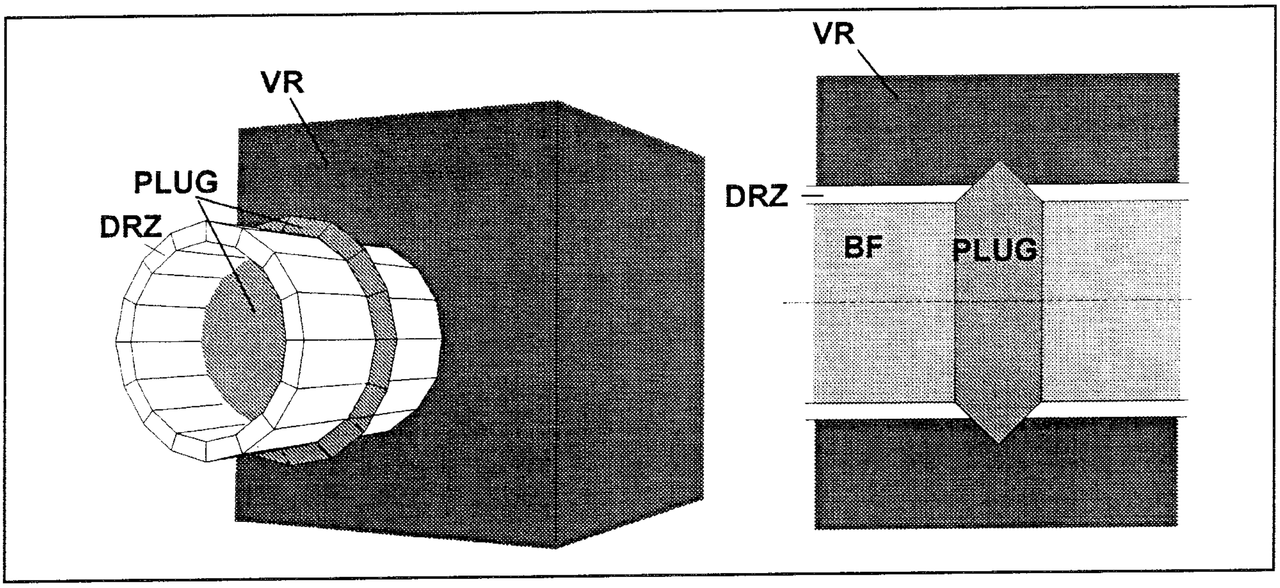


Figure 15.3-11. *System of tunnel, plug and DRZ. VR = virgin rock, BF = backfill.*

duced. This applies in particular to the axial flow within the zone, close to the tunnel walls, that is assumed to have been damaged by excavation and which is characterized by increased conductivity, i e the Disturbed Rock Zone, DRZ. The left part of Figure 15.3-11 shows a schematic view of tunnel, plug and DRZ, while the right part shows a corresponding longitudinal section.

Approach

During 1993 axisymmetric continuum models of the system tunnel/plug/DRZ have been analyzed hydraulically and mechanically /15.3-13/. The hydraulic analyses have concerned the effects of low permeability tunnel plugs on the groundwater flow along the tunnel in the DRZ. The analyses have been of three types:

Type 1 – Simple flow calculations performed without regard to stress effects.

Type 2 – Mechanical calculations.

Type 3 – Flow calculations performed using results from mechanical calculations to specify the input regarding conductivity conditions in the rock outside the DRZ and outside the plug.

Calculations of type 1 were performed using the micro-FLOW FEM code, while calculations of types 2 and 3 were performed using the finite difference code FLAC. The objectives associated with the three types of calculations were:

Type 1 – To investigate the potential for reducing axial DRZ flow rates by installing low permeability tunnel plugs.

Type 2 – To investigate how the mechanical stability in the vicinity of a tunnel plug depends on the slot shape, the slot size and the initial stress state.

Type 3 – To investigate the possible reduction in plug performance that may result from stress relaxation effects, i e the effects of increased transmissivity of flowpaths past the plug, outside the slot, in the virgin rock.

Results

Type 1 calculations show that the reduction of axial DRZ flow rates ranges between 90% and 95% if the ratio of DRZ conductivity to the conductivity of the virgin rock is 1000. For a ratio of 100 the corresponding range is 50% – 60%. These ranges are sensitive to changed assumptions regarding the hydraulic environment, i e to the distance between intersecting fracture zones with constant pressure and to far field permeability conditions, but not very sensitive to reasonable variations in internal DRZ conductivity conditions, i e uniformity and anisotropy, or to variations in slot shape and size.

Type 2 calculations show that the stability of the rock surrounding triangular slots is better than the stability around slots of rectangular shape. Tensile stresses were found in the rectangular slot models but not in the triangular slot models. Figure 15.3-12 shows contours of shear strength to shear stress ratios, calculated with respect to a hypothetical Mohr-Coulomb failure surface corresponding to a friction angle of 50 and a cohesion equal to 2 MPa.

Type 3 calculations show that stress relaxation effects outside slot and DRZ will affect the plug performance. If likely estimates, based on literature data, regarding sensitivity to stress changes are made, the axial DRZ flow rate

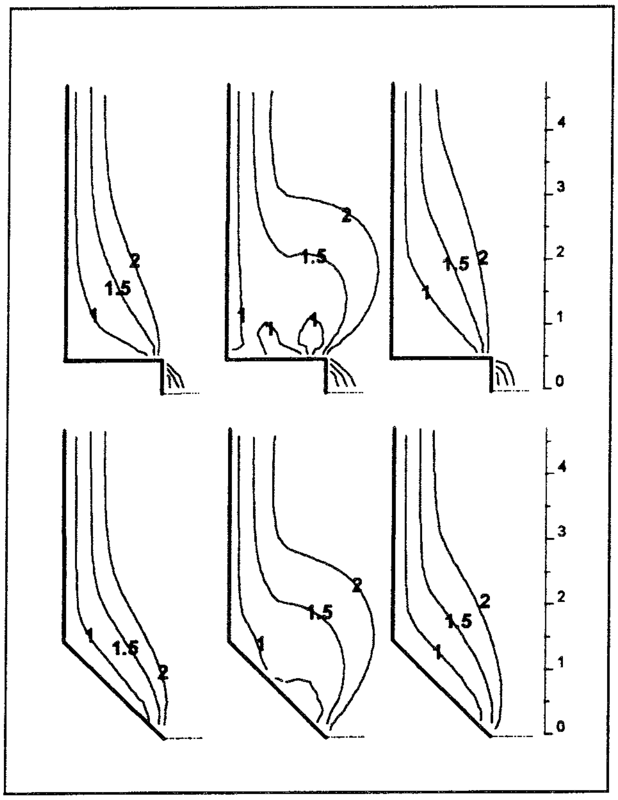


Figure 15.3-12. Contour lines showing shear strength to shear stress ratios around 1.5 m deep slots cut into the walls of a 4 m diameter circular tunnel. Left: isotropic initial stress state. Middle: high initial axial stress. Right: high initial transversal stresses. Scale in right part shows axial distance in meters from the plug centre.

reduction may be about 60% for a case that would have given 80% reduction if stress effects were not considered. Figure 15.3-13 shows flow vectors around a rectangular slot for two different assumptions regarding the sensitivity of the conductivity to stress changes. The left part is based on upper bound estimates regarding sensitivity to stress changes, while the right part represents lower bound estimates.

Remarks

The results obtained so far concern cases where the nearfield rock may be described with continuum models. Further investigations will take into account also the significance of explicitly modelled discrete fractures.

Techniques for compaction of bentonite and bentonite/sand blocks

Background

According to the KBS-3 concept the waste canisters shall be embedded in an approximately 35 cm thick barrier of highly compacted bentonite and the shafts and connecting tunnels shall be filled with a mixture of bentonite and sand. The experience from the Buffer Mass Test in Stripa, regarding compaction of blocks for the buffer and field compaction for the backfilling, showed the following:

Blocks of Mx-80 bentonite can be compacted at its natural water ratio (about 10%) to large blocks with a high density using isostatic compaction. These blocks can be cut to suitable shapes by sawing. However, the cutting

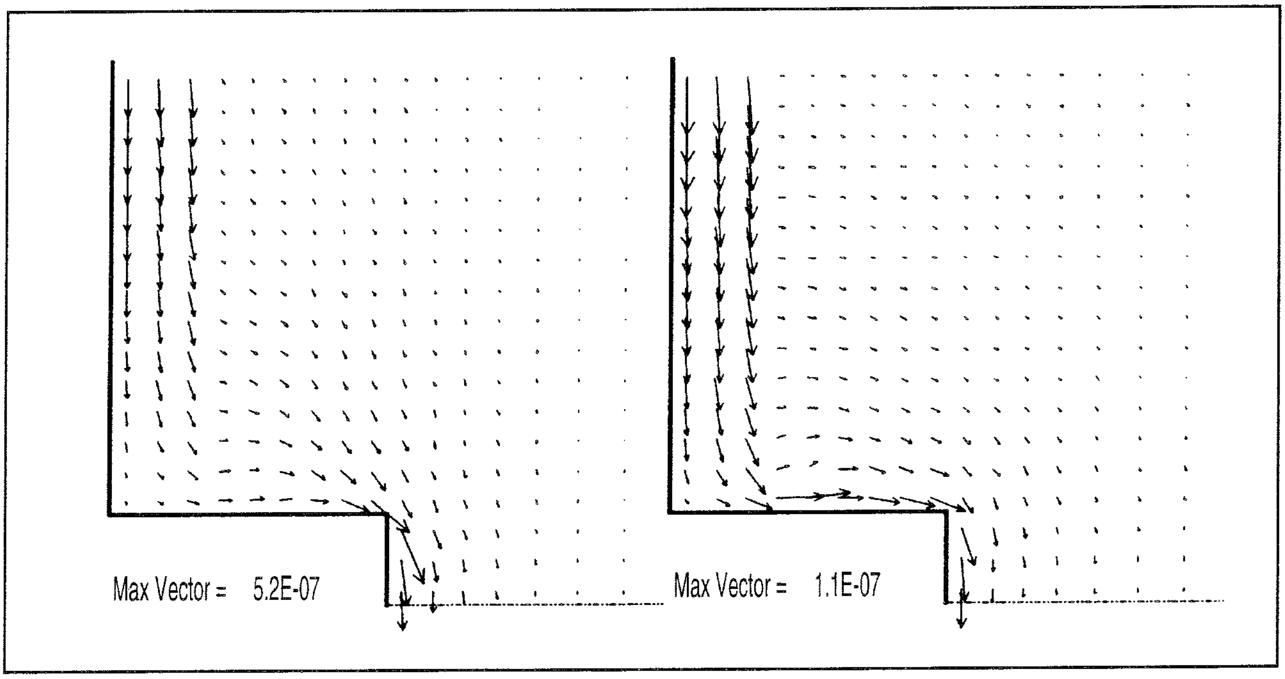


Figure 15.3-13. Flow vectors around 1.5 m deep, 1 m long, rectangular slot cut into the walls of a 4 m diameter circular tunnel.

procedure is very time-consuming and the geometrical precision is not very high. A better compaction technique adapted to industrial production should therefore be developed. The strong influence of the degree of water saturation on the thermal conductivity makes it also desirable to compact blocks with a high water ratio.

In the lower part of the backfill a mixture of 10% bentonite and 90% sand was compacted by plate vibrators while the upper part was filled by a shotcreted mixture of 20% bentonite and 80% sand. The density of the shotcreted material was very low and it was concluded that an alternative technique for backfilling is required. If the tunnels are mechanically excavated e.g by Tunnel Boring Machine (TBM) it would be possible to use precompacted blocks also for the backfilling.

Compaction of blocks for buffer materials in deposition holes

The initial work in the process of developing a suitable technique and optimum material composition for compaction of bentonite blocks as buffer materials was focused on laboratory testing of different compaction techniques and different buffer compositions. The tests were made by using uniaxial compaction in very stiff forms. The aim of the tests has been to understand how different factors influence the properties of the compacted blocks with special reference to the possibility of producing blocks with a very high degree of water saturation /15.3-14/.

Figure 15.3-14 shows results from some compaction series made with different bentonites at the compaction pressure 100 MPa. The diagrams show the void ratio (total volume of voids divided by the volume of solids) and the degree of saturation (volume of water filled voids divided to the total volume of voids) as a function of the water ratio. The conclusion from these tests and similar tests with different water ratios was that wall friction makes it necessary to have a height/diameter relation less than 1:2.5 unless the samples are compacted at such a high water ratio that they become water saturated during the compaction. In the latter case friction completely vanishes due to liquefaction in the material.

These and other tests showed that it is possible to produce blocks by uniaxial compression, but also that the quality of the blocks is a function of several factors. 100 MPa uniaxial compression is sufficient to make blocks with a degree of saturation of 90% and a void ratio of 0.6 if water is added to yield a water ratio of 20%. At higher water ratios the degree of saturation will be higher but the void ratio will also be higher. The elastic swelling at the release from the form after compaction makes it impossible to produce blocks with a degree of saturation higher than 95% at a void ratio lower than 0.8. Another conclusion was that the shape of the form is very important for the homogeneity of the blocks except when the blocks are compacted to complete water saturation in the form (leading to a degree of saturation higher than about 90% after release).

Compaction of blocks for backfilling of shafts and tunnels

The purpose has been to develop proper techniques for mixing and compaction of blocks for backfilling, to determine some important geotechnical properties, and to make preliminary analyses of the performance of bentonite/ballast blocks for backfilling of tunnels /15.3-15/.

Laboratory compaction tests were made on different mixtures and with different techniques in order to study the influence of several factors on the properties of the compacted blocks such as: water ratio, bentonite type, bentonite composition, ballast material composition and origin, and compaction pressure.

The backfill was investigated with reference to the following properties:

- tensile strength of the unsaturated blocks,
- hydraulic conductivity after complete water saturation,
- swelling pressure after complete water saturation,
- swelling and compression properties after complete water saturation,
- shear strength and deviatoric stress-strain properties after complete water saturation.

Figure 15.3-15 shows examples of the tensile strength of small blocks with different composition. The strength increases with increasing bentonite content but the ballast and bentonite types have a strong influence as well.

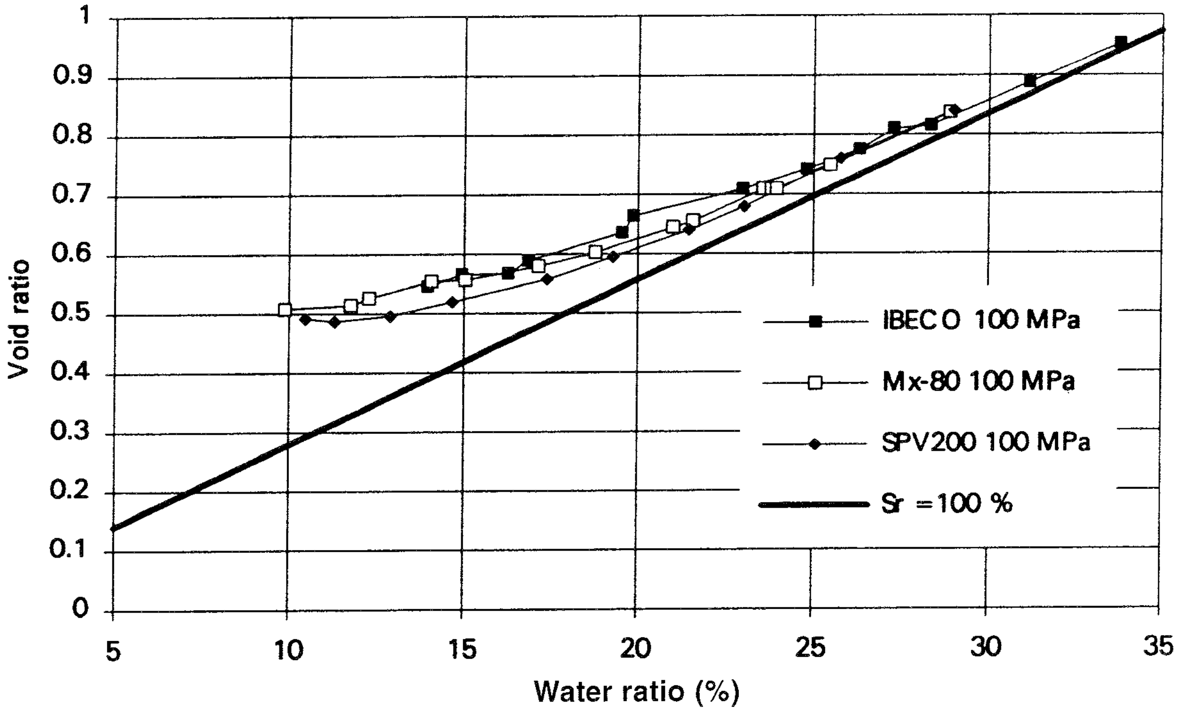
Figure 15.3-16 shows the results from the hydraulic conductivity measurements. The hydraulic conductivity, measured on samples with bentonite contents varying from 10% to 100%, is plotted as a function of the clay void ratio.

The tests and the preliminary performance analysis yielded the main conclusions that blocks can be compacted with a bentonite content as low as 10% if a proper ballast material is used, and that a very fine-grained ballast material like FN150 is not suitable. It was further observed that the swelling pressure and hydraulic conductivity of the mixtures are controlled by the clay void ratio and the homogeneity of the clay structure. The lower limit of the bentonite content in blocks for yielding an acceptable backfill behaviour seems to be 20%–30%.

15.4 GEOSCIENCE

15.4.1 Overview

The geoscientific research at SKB is related to the crystalline bedrock and to the projected repository design. The research work is guided primarily by the need for input data for the long-term safety assessments that are being done. Furthermore, the geoscientific R&D work is supposed to be of benefit in solving the civil engineering problems that are associated with the construction of a deep repository.



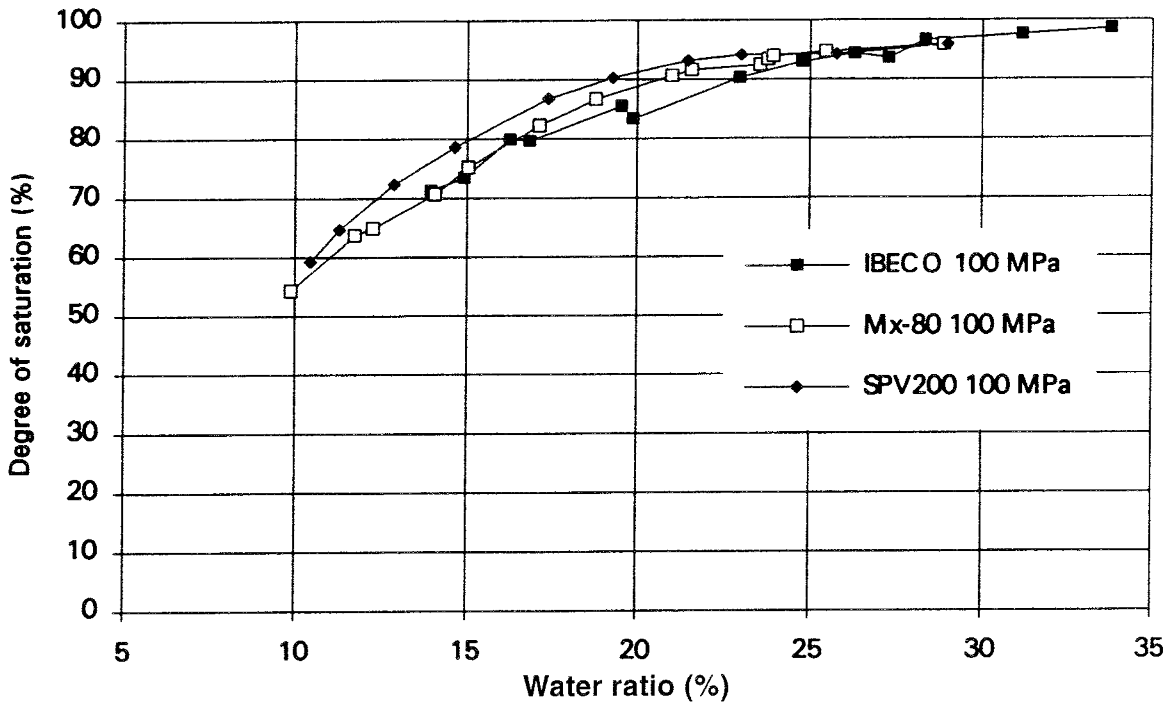


Figure 15.3-14. Void ratio (upper) and degree of saturation plotted as a function of water ratio for three bentonites. Compaction pressure = 100 MPa.

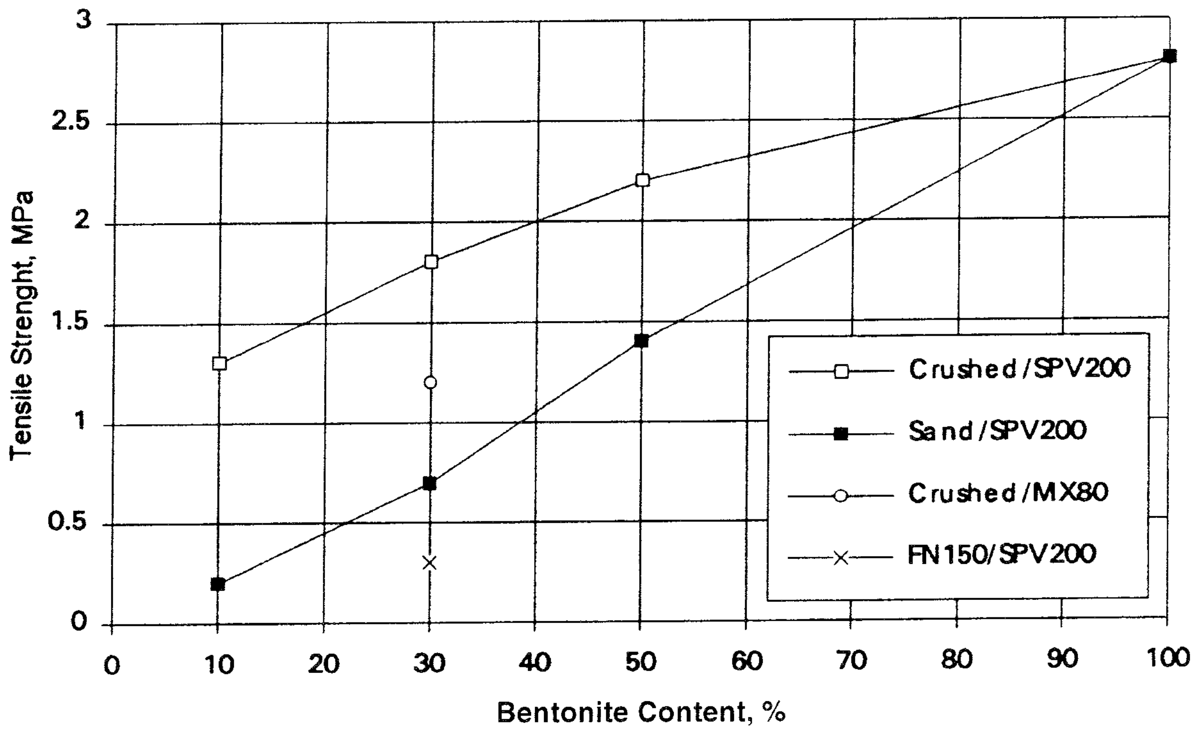


Figure 15.3-15. Measured tensile strength as a function of the bentonite content for different ballast/bentonite mixtures.

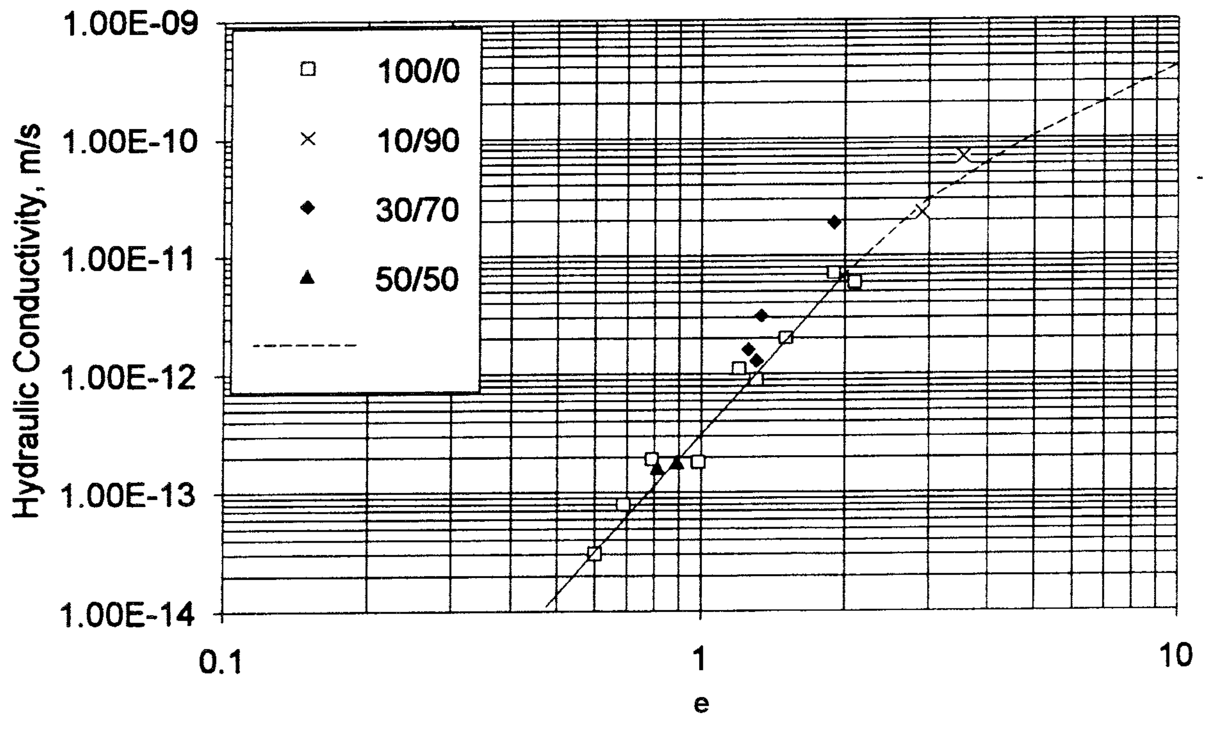


Figure 15.3-16. Measured hydraulic conductivity of different mixtures of bentonite/ballast plotted as a function of the clay void ratio.

The rock has a number of fundamental properties that are being exploited for the long-term performance and safety of the repository. These are:

- mechanical protection,
- chemically stable environment,
- slow and stable groundwater flux.

These properties can be more or less coupled to each other through physical or chemical processes.

The rock provides long-lasting mechanical protection against external forces. A final repository in rock also provides good protection against changes in climate. Climatic changes can result in a changed biosphere with a considerably higher sea level, or alternatively can give rise to permafrost and formation of glaciers, with a lowering of the sea level as a result. The impact of such changes is minimized if a repository is placed in deep geological formations.

It is of fundamental importance for the safety of the repository that the chemical environment is stable. The reducing chemistry of the groundwater is of great importance for the life of the canister and for the slow dissolution of the fuel matrix. Groundwater chemistry is determined for the most part by the mineral composition of the rock, which is stable over long spans of time. The chemical environment of the rock is also important for how radionuclides can be transported. Here the interaction between nuclides and rock is of importance.

The low groundwater flux in the rock is of importance both for the durability of the barriers and for the slow transport of non- or weak sorbing nuclides in the rock. The water flux is generally determined by the topography of the ground surface and by the hydraulic conductivity of the rock, which is in turn dependent on its fracture content.

The geoscientific programme at SKB embraces broad knowledge build-up within geology, geophysics, rock mechanics and geohydrology. The programme also includes method development and development of numerical computer models. A strong link exists to SKB's programme for instrument development.

The activities and the projects within the geoscientific programme are often coordinated with other special areas, such as geochemistry and hydrochemistry. Furthermore, the work is integrated with the research activities that have been conducted or are being conducted within:

- The Äspö Hard Rock Laboratory.
- Safety assessments.
- Natural analogues.
- The siting programme.

The overall objectives and main activities of the geoscience programme are expressed in the SKB RD&D-Programme that was released in September 1992. During 1993 the geoscience programme has involved the following main tasks:

- Groundwater Movements in Rock.
- Bedrock Stability.
- The Laxemar Deep Drilling Project.
- Groundwater and Rock-Mechanical Numerical Modelling.
- Geochemistry.
- The Fracture Zone Project in Finnsjön.
- Development of Instruments and Methods.

Regarding the siting programme research efforts have been oriented towards developing possible strategies for geoscientific classification in the selection of sites /15.4-21/.

In cooperation with the Äspö HRL special interest has been paid to the process of developing site specific conceptual models which in turn are used as simplified geoscientific descriptions aiming at quantitative analyses /15.4-22/.

15.4.2 Groundwater movements in rock

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

The relative importance of the parameters that describe flow in the bedrock can be treated in performance assessments and safety analyses. One of the factors that has importance for assessment of radionuclide transport of non-sorbing and sorbing species is the flow-rate of water. The flow rate of water in the bedrock is dependent on conductivity, connectivity of fractures and the driving forces.

The conceptualization of the groundwater flow distribution is important for the overall assessment of radionuclide transport, both non-sorbing and sorbing.

Geometry and hydraulic characteristics of rock fractures

The geometrical features of the intersections between joints and fractures in rocks have an influence on the groundwater flow and transport. Enlarged apertures along the intersection are more or less supposed to form channels with higher conductivity compared to the average conductive properties of the individual joints.

A three year programme was initialized 1992 in order to develop an investigation method to obtain more information on the void geometry inside joints and their intersections. The method includes drilling cores from joints grouted with polyurethane. The grout layer thickness is assumed to represent the in-situ aperture. The thickness variation of the grout layer is measured on sections of a core and analyzed statistically. The results so far show that this technique can provide valuable information on the hydraulic properties of joints. Thus it has been possible to create groundwater flow models within fractures with a natural-like aperture distribution. Flow in single fractures has been calculated from a transmissivity distribution. The possibility of modelling intersecting joints has also been treated /15.4-1/.

Red-coloured rock adjacent to fractures

It would be advantageous if nuclide transport models to a higher degree could be conceptualized on small-scale geological and hydrochemical features. In order to develop a better understanding of the conditions for the altered surrounding environment of different fractures a special study was set up /15.4-2/.

Narrow zones of red-coloured rock adjacent to fractures are commonly observed in granitic crystalline rocks. The aim of the present study was to investigate the cause of the redness of the coloration in the Äspö granite. An investigation was also made of a weak to rather strong red-coloured granite from the Stripa mine, as well as a weak brownish-red coloration, definitely not hydrothermal in origin, of weathered rinds at and near a glacial polished rock surface in the Bohus granite.

The mineralogy and geochemistry of the altered and red-coloured granites were compared with their unaltered equivalents. The petrophysical properties of effective porosity, density and magnetic susceptibility of the red-coloured rock, as well as of the "uncoloured" wall-rock (protolith), were also investigated.

The fracture network in the Äspö area is characterised by the red-coloured selvages, generally a few centimetres wide, occurring beside the fracture planes. The microscopic investigation shows that the red coloration of the granite adjacent to the fractures is mainly caused by the presence of dispersed, very fine-grained, reddish Fe-oxy-hydroxides/hydroxides 1) in saussuritic and clouded plagioclase grains, 2) along grain boundaries and 3) subordinately along microfractures within individual grains. The clouding of plagioclase is also partly a result of the optical effect of the extremely fine-grained nature of the alteration products and the common occurrence of micropores.

The reddish colouring of the granite spatially coincides with the hydrothermal metamorphic alteration mineralogy occurring along the fracture planes. This fact, together with the observed oxidised mineral assemblage in the hydrothermally metamorphosed zones, indicates that the formation of the ferric compounds (colouring) is contemporaneous with, and a function of, the hydrothermal alteration.

The most striking chemical features of the altered Äspö granite are:

- The high H_2O^+ content (loss of ignition) of the altered granite. This is mainly caused by the high content of hydrated minerals, mostly phyllosilicates (e g chlorite, muscovite, prehnite and clay minerals) and disseminated calcite.
- The gain of up to 26 and 22% of K and Na, respectively. This indicate to high activities of potassium and sodium in the hydrothermal fluid. These elements participated in the formation of the secondary phases sericite, K-feldspar and albite.
- The loss of up to 20% of Ca. This suggests that it partly has been re-precipitated as the Ca-rich fracture fillings calcite, epidote and prehnite.
- The decrease in FeO. This reflects the observed oxidation of magnetite with the formation of hematite and, subordinately, Fe-oxyhydroxides.

The petrophysical properties of porosity, density and magnetic susceptibility exhibit a good correlation with the intensity of alteration. This illustrates the importance of these parameters for identifying fractures/fracture zones in the Äspö area.

In general, the petrophysical properties show the following characteristics:

- There is a two to three-fold increase in the effective porosity of the hydrothermally altered and red-coloured rims adjacent to the fractures.
- The density of the altered granite is reduced by 0.7 to 1.5%.
- The magnetic susceptibility is reduced generally two to five times in the altered granite.

The increased effective porosity is responsible for less than approximately 40% of the density reduction displayed by the altered granite. Closed pores and the "low-density" hydrothermal assemblage are responsible for the remainder of the density reduction displayed by the altered granite.

The mineralogy of the red-coloured Stripa granite is characteristic, although only slightly modified compared with the protolith. The amount of quartz and feldspar is unchanged when going from the fresh into the altered granite. In the red-coloured granite the secondary chlorite (pseudomorphing biotite at a late magmatic stage) is to a very large degree altered/oxidised to muscovite hematite and, subordinately, Fe-oxyhydroxides.

The red coloration of the granite is caused by impregnation of extremely small (generally < 5-$10\ \mu m$) hematite and, subordinately, Fe-oxyhydroxide grains along 1) cracks and microfractures, 2) grain boundaries and 3) subordinately within the main salic minerals. Oxidisation and re-precipitation of iron liberated during a retrograde muscovitisation is interpreted to be the cause of the formation of the ferric oxides.

The alteration occurred at slightly oxidising conditions in a basically isochemical system. The rather homogeneous density and porosity values of the grey and of the red-coloured, altered granites from the so called drill core D3 reflect the rather minor change in the mineralogy when going from fresh into altered granite. The very low magnetic susceptibility of both fresh and altered Stripa granite is a reflection of the very low content of magnetic oxides in the granite.

The weathering rind below a rock surface of Bohus granite, polished during the Weichselian glaciation (i e <12.000 years), is composed of an upper 1 to 3 mm thick, bleached, greyish-white zone. It is followed by a 2 to 5 cm wide, reddish-brown zone with a slight yellowish tint.

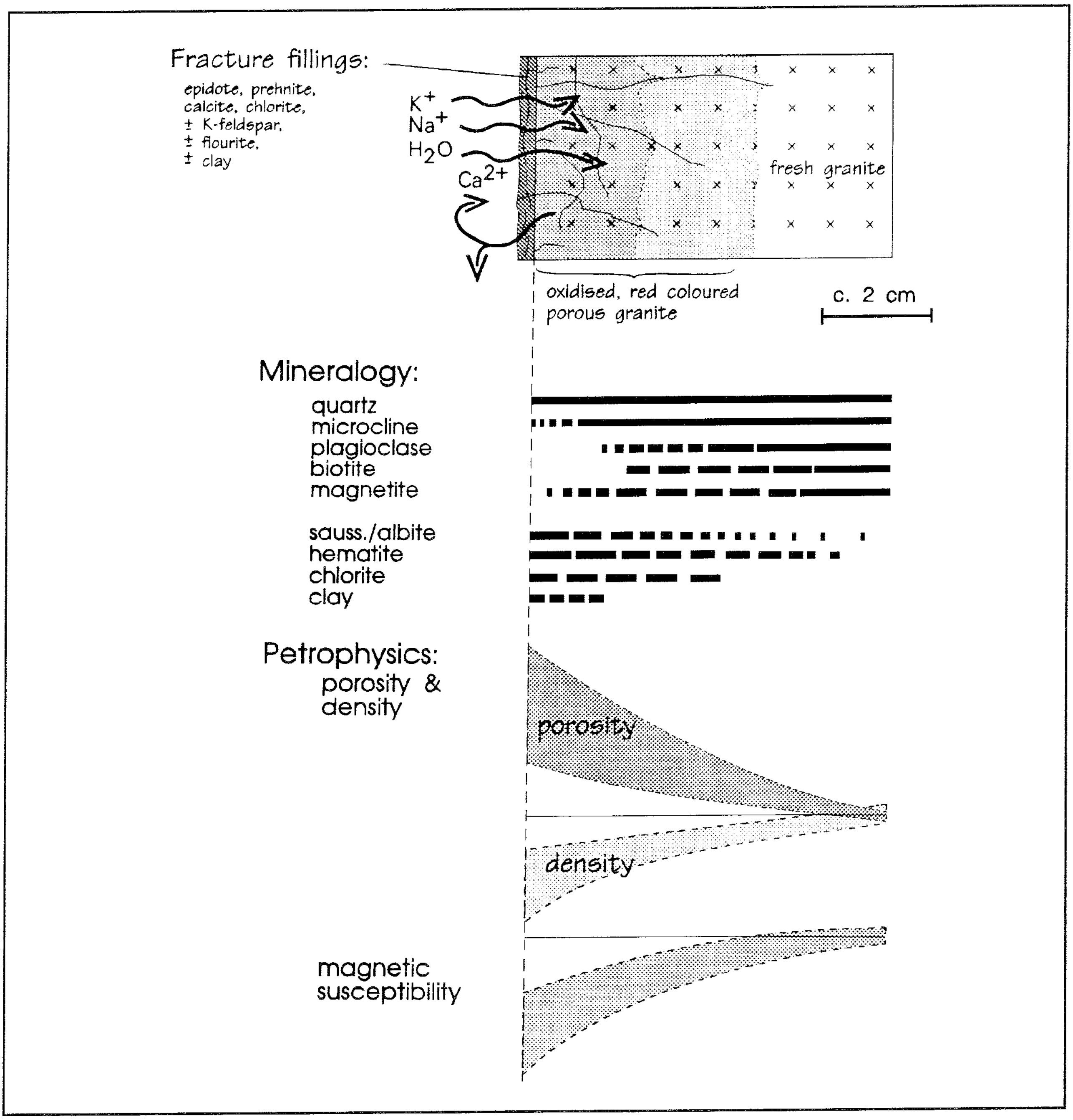


Figure 15.4-1. *Schematic illustration of the most important alteration features in the red-coloured wall rock along fracture in the Äspö granite (from /15.4-2/).*

Weathering (incipient argillitisation) and whitening of plagioclase in the bleached zone and precipitation of small quantities of Fe-oxyhydroxides/hydroxides in the brownish-red zone is responsible for the coloration of the rock.

There is a marked increase (3 to 4 times) in porosity from the interior fresh (c. 0.4-0.5%) towards exterior bleached zone (c. 1.5-2%) of the subaerially weathered Bohus granite surface. The constant grain density (dry density-porosity) reflects the unchanged mineralogy within the weathering profile. The incipient decomposition of magnetite is shown as a slight lowering of the magnetic susceptibility of the weathered granite.

15.4.3 Bedrock stability

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

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

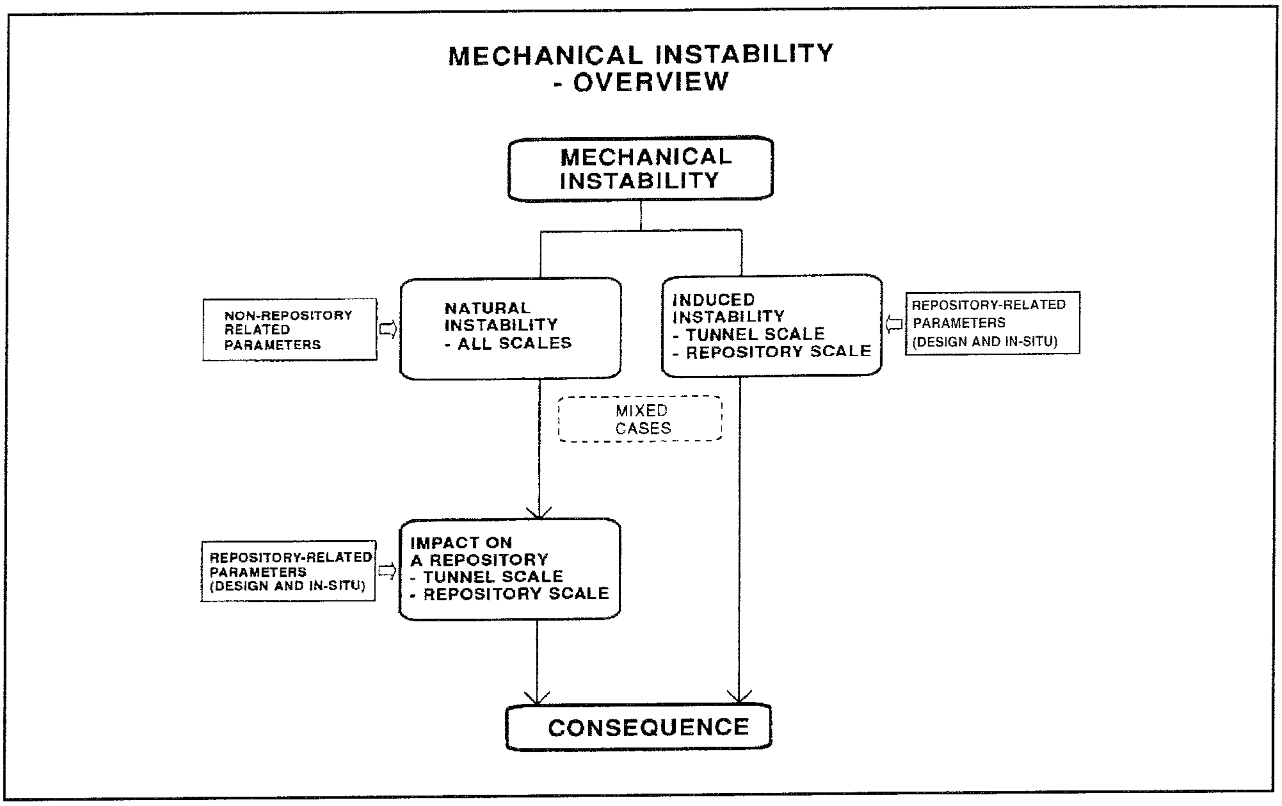


Figure 15.4-2. *Mechanical instability overview (from /15.4-3/).*

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

Overview of mechanical instability

During 1993 an "Ad Hoc-group on bedrock moveability" was created. The overall objective of the group was to formulate state of the art in general terms and identify future R&D-activities in the subject for SKB on the basis of a well structured overview, see Figure 15.4-2.

Tectonic regimes in the southern part of the Baltic Shield during the last 1200 Ma

A compilation work about tectonic regimes in the southern part of the Baltic shield has continued. Such a review is meant to give an introduction for scientists dealing with different fields of radioactive waste disposal not familiar with the tectonic history of Sweden /15.4-4/.

The review is focused on tectonics and palaeostress regimes in the southern part of the Baltic shield during the last 1.2 Ga, i e from the onset of the Sveconorwegian period to present. This time period was chosen to include both orogenic and anorogenic events. Some time-definable objects like fractures, dykes an faulted markers have been used (with less attention to Skåne and the Caledonides). The features were created during specific stress regimes and have also estimated the thickness of sedimentary covers.

The authors conclude that the present surface in southern Baltica exhibits a fracture pattern and other hetrogenities formed and developed during a time period of many hundreds of million years. Although specific patterns are recorded from different areas within the southern part of the Baltic shield most fracture directions are represented within each of them. The experience shows that deformed/fractured rocks will generally be deformed by subsequent events along preexistent anisotropies. Active stress during the next 100 000 years will thus most probably reactive older zones and fractures of weakness within the crust.

The present situation of passive response to the Mid-Atlantic ocean floor spreading as an anorogenic period of the Baltic shield history will not change substantially within the closes future and will thus also prevail within the next 100 000 years. However, one has to consider a future ice cover which will influence the stress situation of the upper crust within this time period.

Post-glacial faulting

Post-glacial faults have been recognized in the northern Baltic shield for several decades.

It is important to evaluate whether such neotectonic movements can lead to new fracturing or decisively alter the geohydrological or geohydrochemical situation around a final repository for spent nuclear fuel.

The post-glacial Lansjärv fault was chosen for a interdisciplinary study because of its relative accessibility. The first phase of the Lansjärv study was conducted 1986-1989. The second phase of the Lansjärv study 1989-1992, comprised a more detailed study of one of the faults – the Molberget fault /15.4-6/.

Based on the results from a seismic refraction survey three trenches were excavated across the Molberget fault. Three cored boreholes were also drilled across the fault-line. A mineralogical study of samples from the bedrock in the trenches and from drillcores indicate that reactivation has occurred, perhaps repeatedly, along the mylonitic/cataclastic zone – along the fault scarp – which is characterized by crushed granitic fragments and clays. Sliding Micrometer measurements were performed in two boreholes at the Molberget fault during 1990-1991.

The study of deformations according to different types of deposits in the Lansjärv was continued. Investigations in a number of trenches and pits gave further arguments to the theory that extensive occurrence of soft sediment deformation in the Lansjärv area can be explained by early post-glacial co-seismic movements in the fault set.

As a final of the field-work in the Lansjärv area a meeting combined with a field excursion was arranged by SKB in June 1991 for a group of international experts. Comments from the expert group on the excursion and the overall Lansjärv Project are presented /15.4-5/.

One of the major conclusions is that the Lansjärv post-glacial fault reactivated pre-existing old structures and that the causes of the post-glacial movements are a combination of plate tectonics and deglaciation.

Seismotectonics of Sweden

A project entitled "A review of the seismotectonics of Sweden" was reported during 1993 /15.4-7/. The project reviewed all the various forms of data relating to the structure (tectonics), and properties (stress and temperature) of the crust that constrain the distribution and style of deformation (strain and seismicity), both under present day conditions and those prevailing through the glaciation/deglaciation cycle. These data have then been combined in a seismotectonic synthesis in an attempt to understand the causes, styles, sizes and locations of earthquakes in particular through the past 13 000 years since the ice-sheet began to retreat from southern Sweden. The various data-sets are in different stages of integration and in all cases an attempt was made to apply some kind of quality criteria for revealing the nature of the inherent errors and uncertainties.

Fennoscandia is a cratonic region, stabilised more than 1000 million years ago, and subsequently subject to only modest and declining deformation. The chief phase of post-cratonic tectonics across the shield was an episode of minor late-Precambrian rifting. The last episode of significant tectonic activity within the Baltic Basin involved strike-slip and reverse faulting at the time of the final (ca 400 Ma) Caledonian collision. A localised phase of rifting and volcanism in the Oslo Graben dates from the Permian (ca 290 Ma). Significant subsequent Mesozoic rifting and faulting is concentrated along the Fennoscandian Border Zone and the west Norwegian coast and continental margin. No evidence has been found for any Tertiary faulting within the shield, and any movements through this period are likely to have been minor.

In a review of evidence for neotectontic faulting in Fennoscandia a proposal is made to establish criteria by which neotectonic claims can be graded for their credibility. Many of the localities claimed as neotectonic have not been properly investigated or documented and some probably have a non-neotectonic explanation. However, evidence suggestive of neotectonics is known from the Fennoscandian Border Zone in the Kattegat, and in certain localities along the coast of western and northern Norway and Russian Kola. However, the most spectacular neotectonic examples are clustered in the Lapland late-glacial fault province that lies in northern Sweden, Finland and Finnmark, Norway.

Mechanical properties of fracture zones

Not only are data on the mechanical characteristics of fracture zones sparse, but they occur over a wide range of geoscience, including structural geology, seismotectonics, mining and civil engineering. A separate project was set up in order to bring together information from some of these sources, and to compile it in such a way that it facilitates proper consideration of fracture zones in analysis of geomechanical problems related to construction and performance of nuclear waste repositories in hard rock /15.4-8/. Problems posed in this field include assessment of the risk for future shear displacements along fracture zones, which can directly or indirectly affect repository integrity. Such movements may be induced by future load changes attributable to natural processes such as glaciation, possibly assisted by disturbances caused by the repository itself. Furthermore, since repository excavations shall likely penetrate fracture zones, their mechanical properties are of concern also with regard to local stability during repository construction.

Information was gathered primarily from the rock engineering field, and the data compilation focused parameters describing deformational properties and shear strength. Available data fall into two categories:

- Indirect estimates of fracture zone parameters on the basis of small-scale observations, primarily by means of boreholes, of the properties of the components of the zones, i e intact rock, fractures and various low-strength materials like fault gouge and alteration products.
- Direct observations of fracture zone behaviour, either by means of specifically designed experiments or in connection with rock engineering efforts involving large-scale load changes.

The cohesive contribution to the shear strength of fracture zones is generally insignificant. Frictional properties were extracted from observations in mining and from stress measurements in seismically active areas. Values of friction angles were found to vary within the range 20-40^o, but clustered at some 30-35^o. Data are insufficient to discuss possible relationships between friction angel and level of normal stress. Furthermore, no correlation could be established between size (taken as in-plane dimensions) of fracture zones and frictional strength. This is as would be expected, considering the fact that surface irregularities, decisively influencing shear resistance, occur on all scales.

With respect to representation of fracture zones in geomechanical models, conclusions from the present study are as follows:

- The internal structure of fracture zones can conceptually be represented in several ways by geomechanical models (distinct discontinuity, equivalent rock mass, fractured medium etc). The choice depends on, among other things, the relation between the scale of the problem to be analyzed and the size (in-plane dimensions and thickness) of the fracture zone. Although this is well recognized, mistakes are not uncommon.
- In geomechanical models, fracture zones are macroscopically almost invariably simulated as planar features, to which properties describing strength and deformability can be assigned. The inherent assumption is that surface irregularities controlling, for example, frictional resistance, occur on a scale that is much smaller than the scale of the fracture zone or problem under study. However, this assumption may be invalid since undulations and surface irregularities are found on all scales. The substitution of the fracture zone with a planar frictional feature may thus be principally incorrect.
- It follows that the current focus on more accurate determination of "standard" mechanics properties, as requested by the models, and on parametric studies to investigate the effects of these properties, needs to be complemented by investigations to clarify the actual geometry and morphology of fracture zones, such that they can be more realistically represented, Borehole investigations are not sufficient for this purpose. Existing knowledge in structural geology can contribute, but there is also a need for direct field investigations, including observations from underground facilities.
- Current modelling technology is essentially incapable to resemble the complex combination of stable shear deformation and stick-slip behaviour that characterize fault slip, as induced by natural or artificial forces.

Fault dating techniques

During the past few years new dating techniques and new methods of investigating geological structures have implied research on this subject /15.4-9/. The sampling activities were undertaken in the access ramp to the Äspö Hard Rock Laboratory. Petrographic, Palaeomagnetic, Electron Spin Resonance (ESR) and Isotope techniques were employed in attempts to assess the age of the most recent movements on some faults at Äspö.

Some seventy rock samples were collected from the Äspö HRL and examined to provide information on the history of fault movements and to assess the suitability of the samples for dating.

The ages given by the various dating methods reflect both inherent differences in the techniques and differences in the phase or phenomenon being dated. Nevertheless, the results of the K-Ar analyses of gouges strongly suggest that authigenic (in-situ) clay mineral growth in the sample strands of fracture zones NE-4 and NE-3 together with two minor faults took place at least 300 million years ago. The youngest fault movements are interpreted to precede this mineral growth.

15.4.4 The Laxemar deep drilling project

The natural groundwater flux at repository level is not necessarily controlled by the local flow gradients, but is more likely governed by regional topographic conditions. It is judged essential to further refine regional flow models that shed light on long-term transient changes. This is especially true for coastal repositories, where the transient flow changes can be affected by glaciation, deglaciation, land uplift and the salt/fresh water boundary, which in turn alter the boundary conditions of the calculation models. To obtain a better understanding of the water flux in a regional perspective, surrounding Äspö HRL, and at depths exceeding 1000 m, a hole was drilled in autumn 1992. The coredrilling was carried out in the Laxemar area near the Simpevarp peninsula in the municipality of Oskarshamn. The drilling reached a depth of 1700.5 m, see Figure 15.4-3.

During 1993 the investigation phase commenced /15.4-10, 15.4-11/. The following activities were accomplished:

- Mineralogical and petrographic core mapping.
- Geophysical loggings.
- Borehole radar measurements.
- Groundwater chemistry sampling and analyses.

In 1994 the hydraulic testing programme will be elaborated and successively the rock-mechanical aspects will be emphasized. An integrated analysis and interpretation is foreseen to late 1995 or 1996.

15.4.5 Groundwater and rock mechanical modelling

Numerical models are primarily refined within the framework of the activities at the Äspö Hard Rock Laboratory. However, some supplementary efforts emphasizing coupled processes are pursued within the SKB general R&D programme.

Figure 15.4-3. The KLX02 Drilling Site at Laxemar.

Thermal-Hydro-Mechanical modelling

In the DECOVALEX project initiated by SKI (international cooperative project for de DEvelopment of COupled models and their VALidation against EXperiments in nuclear waste isolation), development and verification of coupled thermo-hydro-mechanical models are taking place. SKB is a member of the Steering Committee of the DECOVALEX. Within the DECOVALEX project SKB emphasizes the analytical approaches for a better understanding of the calculation results and their dependence on boundary conditions and dimensionality /15.4-12/, /15.4-13/.

On behalf of SKB the so called Bench Mark Test 3 within the DECOVALEX programme has been modelled /15.4-14/. The bench-mark test concerns the excavation of a tunnel, located 500 m below the ground surface, and the establishment of mechanical equilibrium and steady-state flow. Following this, a thermal heating due to nuclear waste, stored in a borehole below the tunnel, was simulated. The results are reported at: 30 days after tunnel excavation, steady state, one year after thermal heating and at the time of maximum temperature.

Fracture mechanisms

A study was carried out aiming at developing a numerical model which will be used to study generic rock fracture mechanisms /15.4-15/. Results are presented from seven numerical models which examine the influence of: different loading conditions, different model shapes and different internal block sizes (i e, different sizes of Voronoi-generated blocks). All numerical simulations were performed using the two-dimensional distinct element code UDEC (Universal Distinct Element Code).

The modelling concept was based on an initially unfractured volume of rock which was subjected to a tectonic stress which induced subsequent fracturing. The initially intact rock material was represented by an assembly of irregular blocks separated by contact surfaces. The blocks and contact surfaces were given properties so that the unfractured rock volume behaved as a homogeneous, isotropic material. All models simulated unaxial loading. The loading was increased up to and beyond failure depending on whether stress- or strain-controlled loading was used.

Time dependent glaciation modelling

Besides regional groundwater modelling under today's climatic situation, it is essential to shed light on the hydraulic conditions in connection with future glaciations and deglaciations. During an ongoing three year programme a time dependent glaciation model of Scandinavia has been developed for the coming 120 000 years /15.4-16/.

The patterns of past global climate change have been shown to correlate with variations in the intensity of solar radiation reaching the earth as a consequence of variations in the earth's orbit around the sun. It is therefore concluded that these orbital variations are the pace-makers of climatic change on earth. Moreover orbital variations can be reconstructed in the past and predicted into the future as they depend only on the gravitational relationships between the planets, which are predictable using Hewtonian mechanics. As a consequence, the correlations between orbital variations and global change can be used to predict the pattern of future "natural" global change. In evaluating the consequences of global change for at particular waste repository, one need to know the local component of global change. To do this one must investigate the correlation between records of past global change and past local records in order to be able to predict local changes from the prediction of future global changes.

Ice sheets are made up of the simplest material, ice, which covers a large part of the Earth's surface. The ice sheets of Greenland and Antarctica at the present day have predictable surface profiles, internal thermal regimes and patterns of flow which reflect the relatively simple and predictable flow properties of the ice which makes it up. We therefore suppose that the European and North American ice sheets of the recent past can be reconstructed using understanding of the same physical laws and theories. A mathematical model of ice sheet behaviour has therefore been developed. It is driven by changes in the elevation of the permanent snowline on its surface an by air temperature. The ice sheet acts as a conveyor belt to transport ice which accumulates at a high elevation on its surface to a low elevation, were it melts. The rate at which this occurs depends on the flow properties of ice, which are known. It also depends on the temperature of the ice. Flow of the ice also transports cold ice from a high elevation to a low elevation, and therefore changes the distribution of internal temperature. An ice sheet is thus a coupled thermomechanical system, and the numerical model that has been developed describes and predicts its behaviour when driven by given atmospheric conditions (temperature and equilibrium line altitude (ELA)), and for an earth's surface of given form and given mechanical properties which determine how the surface will flew when an ice sheet grows and decays on it.

The ice sheet model has been "tuned" so that it reproduces the pattern of fluctuation of the ice sheet during the last glacial cycle in Europe. It was tested against the precise areal pattern of expansion and decay of the ice sheet; the pattern of erosion and deposition generated by the ice sheet in the southern Baltic and adjacent areas of Poland/Germany; the pattern of lithosphere flexure, and therefore of post-glacial relative sea-level change.

Calculations of future Milankovitch-variations are used to calculate future climate, including future N.E. Atlantic SSTs. These are then used to compute future ELA variations and future ice sheet variations, including basal temperatures, melting rates, etc, see Figure 15.4-4. The probability of sites at different distances from the initial ice divide being glaciated at given future times is estimated. We believe that within the limitations of present knowledge, the ice sheet model is able to satisfactory simulate the behaviour of the last ice sheet in Europe. Provided therefore that we are able to generate a climate forcing function for the future, we should be able to predict future ice sheet behaviour.

15.4.6 Geochemistry

General

Geochemical investigations and evaluations have been made mainly within the Äspö project. However, a few general questions, not related especially to Äspö have been delineated, i e *quality classification of groundwater data, natural colloids and regional groundwater conditions.*

The quality classification of groundwater chemistry data has been made in cooperation with the Finnish power company TVO since 1992 /15.4-23/. A thorough examination of different types of classification tools have been tested. As a starting point available data were compiled and documented /15.4-24/. Figure 15.4-5 illustrates the relative weight of the different variables which have been considered in one of the classification systems.

A final phase of the project is to define the relevant methods to improve the quality of the groundwater samples to be collected in site investigations.

An other cooperative study with TVO has involved the analyses of natural colloids in the groundwater sampled within TVOs site investigations at Olkiluoto /15.4-25/. Three different methods were tested, ordinary filtration, filtration in inert atmosphere and ultrafiltration. The results of this particular investigation indicate that the concentration of the natural colloids in the deep groundwater is low and that the procedures used to sample the water create colloids and particles. A careful examination of the material reveals a large proportion of calcite on the filters. This is most likely due to a precipitation caused by degassing of carbon dioxide when the water is pumped to surface. Figure 15.4-6 illustrates the results of the different methods both before and after correction for the amount of calcite precipitated during sampling.

As a part of a regional paleohydrogeochemical study glacial movement along a linear 2D transect path including Stripa to the north and Äspö to the south is being modelled. One aspect of the modelling is the groundwater salinity and density based on the available groundwater data from several sources which lie within or near the transection. These sources include the Swedish Geological Survey's (SGU's) "Brunnsarkiv" database (in conjunction with the Swedish Environmental Protection Board: "Statens Naturvårdsverk"), SKB's site-specific areas (Kråkemåla, Klipperås, Fjällveden and Äspö) the Siljan deep gas holes, the Stripa Mine and other strategic mining areas (e g Zinkgruvan).

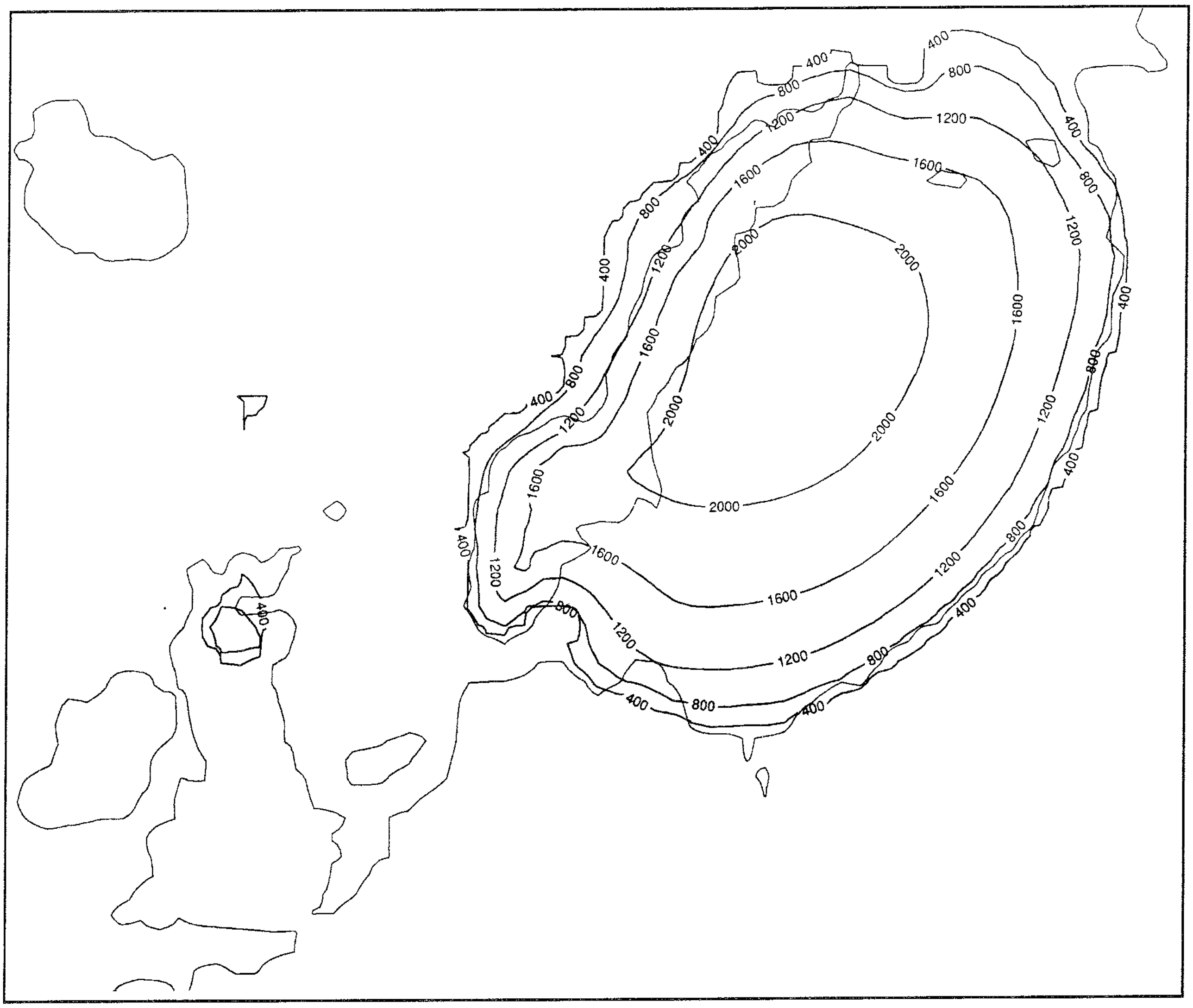


Figure 15.4-4. Maximum extension of ice sheet approx 70 000 years into the future (from 15.4-16).

A simple mixing model was used to predict the groundwater salinities and densities. Since the distribution of the observations and the quality of the measurements vary and the prediction model doesn't take the variability into consideration, the predictions become uncertain. This uncertainty increases with increasing prediction depth. The modelling, in combination with other hydrochemical evidence, points to two regional discharge regions; one centred around the Fjällveden and Zinkgruvan areas, and the second at the southern end of the transect at Äspö and Laxemar. Regional recharge would appear to characterize the northern part of the transect (e g Gravberget) and the area between Äspö and Fjällveden. Isotopic data, indicate residual cold climate precipitation waters to be commonly present in varying mixed proportions in the transect localities studied. There are indications that mixing with younger marine waters or present day precipitation is least apparent in bedrock of low hydraulic conductivity. In areas of higher conductivity, mixing is more common and in some cases the residual cold climate waters have been completely flushed out during isostatic recovery. The upper 2 000 m show most groundwater chemical variation which may reflect more dynamic hydraulic regimes; this may partly conform with the sharp hydraulic conductivity boundary predicted at around 1 500 m, see section 15.4.5. An illustration of the model is given in Figure 15.4-7.

Groundwater chemistry at Äspö

The chemical composition of the groundwater was predicted for the entire tunnel length on the basis of the results of the pre-investigations. During the tunnel construction phase these predictions are compared to the observations made from boreholes drilled every 20 m along the tunnel. The agreement between predictions and

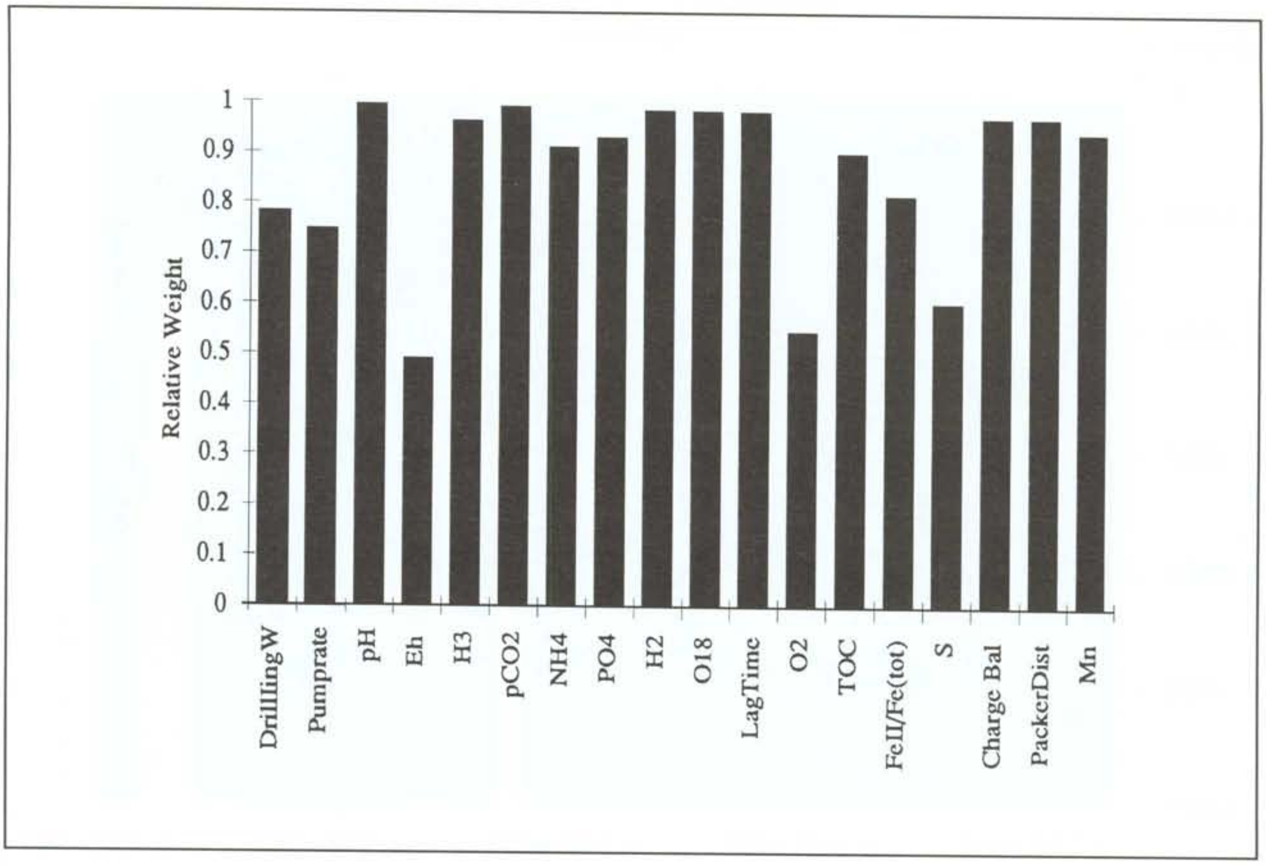


Figure 15.4-5. Relative weights for the different variables used in the model of the scoring system. The higher the relative weight the more importance it has for the total scores of a sample.

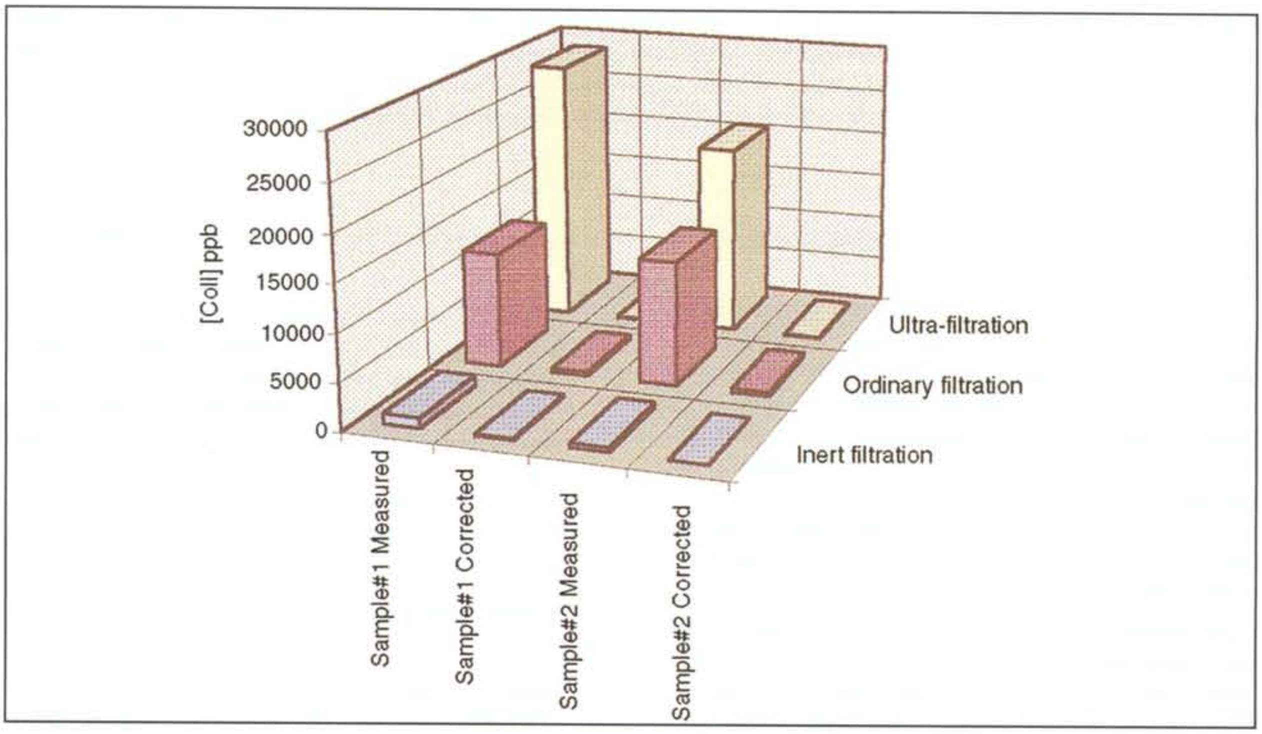


Figure 15.4-6. The concentration of colloids in the groundwater sampled from Olkiluoto borehole KR-1 at a depth of 613-618 m. The results of the measured colloid concentrations for sample#1 and #2 using inert-, ordinary- and ultra-filtration in one borehole in Olkiluoto, Finland. The corrected results show the real value for sample#1 and #2 omitting the calcite contribution which is believed to be a major artefact.

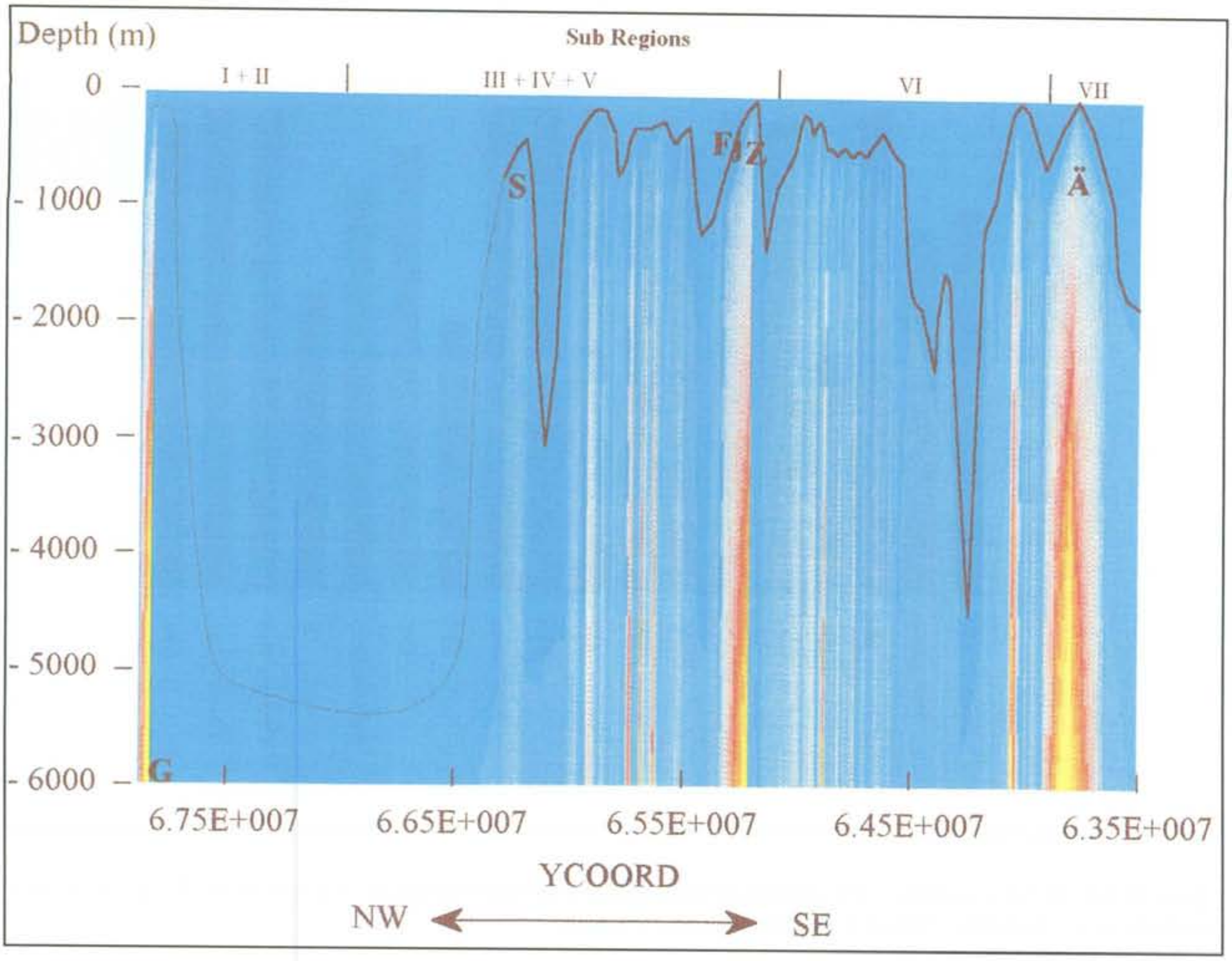


Figure 15.4-7. The results of predicted chloride concentrations of the groundwater in the transect Äspö-Stripa. Yellow colour represents high, red intermediate and blue colour represents low chloride concentrations. The isohaline represents a concentration of roughly 1000 mg/l, dotted with low reliability due to few observations. Roman numbers indicate sub areas discussed by Wallroth and Gustafson /15-4-26/. Ä = Äspö, Z = Zinkgruvan, Fj = Fjällveden, S = Stripa G = Gravberg.

observations is used to assess the suitability of the pre-investigation methods.

The compilation of the data from the documentation work in the tunnel is made in accordance with the procedures set up before the tunnel construction work started. Newly drilled probing holes are sampled in connection to pressure build up tests for determining the initial conditions. On the basis of the results some boreholes are selected for further more careful sampling with an extended analyses programme including major cations and anions, redox sensitive elements, and metal ions. Both types of samples are also analyzed for tritium and O-18.

For practical reasons the predictions were separated into four tunnel sections, 700-1475 m, 1475-2265 m, 2265-3064 m and 3064-3854 m. The outcome of the first two tunnel section 700-1475 m and 1475-2265 m have been reported /15.4-27, 15-4-28/. The third tunnel section will be the last one to follow the predicted tunnel layout strictly. Therefore the comparison between prediction and outcome will end by the tunnel section 2265-3064 m.

Main results from the first tunnel section 700-1475 m are:

- A high and constant salinity of the groundwater as the tunnel passes below the sea between Hålö and Äspö, 50% more saline than the Baltic Sea water.
- An exceptionally high bicarbonate concentration in the tunnel section between Hålö and Äspö, 500-1000 mg/l.
- Tritium concentrations indicating a proportion of 20-50% of present day seawater in the water entering the tunnel.

The major conclusions for the tunnel section 1475-2265 m are:

- Biological sulphate reduction which was encountered in the tunnel section 700-1475 m does not take place at all or to a much less extent in the tunnel below Äspö. The assumption that the bottom sediments of the Baltic Sea are involved in the process therefore seems to be valid.

- Cement grouting of conductive fractures are found to affect the chemistry of the water. pH and potassium concentrations are increasing. However, the pH transient seems to be neutralized quickly while the increase in potassium is seen during a longer time.

- Changes in total salinity in observation boreholes drilled from the surface at Äspö, have been different from what was predicted. High salinity has been observed at depths of 300-400 m. This indicates that there is a good connectivity towards depth in some positions.

Redox experiments at Äspö

The objective of the on-going experiment is to observe the response of an undisturbed water conducting fracture zone when opened during repository construction and operation. Assessment of repository performance includes consideration of molecular oxygen entering the deep groundwater environment and eventually the deposition tunnels during the operating phase.

The purpose of conducting the experiment is to investigate the chemical changes when oxidizing water is penetrating previously reducing fracture systems and to evaluate if complete flow paths can be oxidized from the surface to the repository.

The experiment started in 1991 and will last until 1994. The selected site is at a depth of 70 m in a minor fracture zone which is intersected by the tunnel at 513 m /15.4-29/.

The remaining field work is a tracer test with the purpose of verifying the assumptions of groundwater flow distribution and direction in the investigated fracture zone. The results so far have indicated that most likely the enhanced water circulation in the fracture zone has not caused any significant penetration of oxidizing surface water. The explanation to this is that the high content of organic matter in the infiltrating surface water has been biologically oxidised at the same time as the dissolved oxygen has been reduced. The population of bacteria has increased in order to be able to match the increased water circulation.

Redox experiments concerning the oxygen trapped in the tunnels when the repository is closed are planned to be conducted in the future.

Stagnant groundwater chemistry

As a part of developing detailed investigation methods groundwater has been sampled from low conductive borehole sections. A pilot study to analyze and evaluate trace elements is under way.

15.4.7 The fracture zone project in Finnsjön

A final report has been compiled /15.4-30/. It includes a summary of all the investigations and procedures and reports presented during the project from 1984-1990. Successively the results and experiences have been transformed into the Äspö project and other field activities. The final reporting was accompanied by reports of the radially converging tracer experiment and the dipole tracer experiment /15.4-31, 15-4-32/.

The radially converging tracer experiment formed the basis for the LPT-2 tracer test which was conducted at the end of the pre-investigation phase at Äspö in order to verify the hydrogeological structural model.

The tracer tests in Finnsjön have been one of the test cases in the INTRAVAL project, see section 19.10.3.

15.4.8 Development of instruments and methods

The main goal for Instruments and Methods is to see to it that feasible methods and instruments for geoscientific characterization of rock volumes are available, in special for the siting of SKB deep repository.

Through the years, SKB has given much effort to development of site investigation technique and investment of instruments, resulting in a high level of status in this field. Work in this field were in 1993 organized as follows:

- *under Supporting Research and Development;*
  Development of site investigation technique of basic and general nature and specific support of technique to geoscientific field research project within this area. This work will be described in this chapter.

- *under Äspö Hard Rock Laboratory;*
  Development of Instruments and Methods for ongoing (underground) documentation work during the construction phase and for future experiments during operational phase of the Äspö HRL. This work is described in the Annual Report 1993 of the Äspö HRL /13-5/.

- *under Deep Repository Project;*
  Development, modification and purchase of methods and instruments, as a preparation for the coming site investigations for the Deep repository. This work is described in Chapter 5.

The dominating method and instrument activities under Supporting Research and Development have been

- finalizing the development of the point dilution method,
- development of depth calibration technique for measurements in boreholes,
- instrument modification for hydrochemical characterization in the 1700 m deep Laxemar borehole.

Point dilution probe

The development of the point dilution equipment for in-situ measurement of groundwater flow (the point dilution probe) is now completed. The main components of the system are borehole probe, mobile surface supporting unit, multi-hose and computer system for test operation and data acquisition.

Groundwater flows in the rock are normally calculated from hydraulic conductivity and hydraulic pressure gradients. Groundwater flow values from in-situ measurements in boreholes can be used for calibration of groundwater flow models and controlling results from the modelling.

Point dilution measurements in boreholes mean pulse injection of a tracer, followed by monitoring of the dilution of the tracer, which reflects the flow across the borehole section being tested. This value can be transformed to groundwater flow velocity in the surrounding rock.

Point dilution measurements have earlier been performed in long borehole sections, as an option to the groundwater monitoring programme at Äspö Hard Rock Laboratory, by using surface-based tracer injection and circulation pumping devices. Measurements in short sections have for many years been tested by a prototype dilution probe.

The new point dilution probe is designed for in-situ short section measurement in 56 mm boreholes to depths of 1000 m. Injection of tracer pulses and pumping circulation for mixing the water in the packer isolated section are made by means of the down-hole probe. The dilution of the tracer is measured by two types of detection cells, one for saline tracers and one for coloured tracers. Documentation work of the system is underway.

Depth calibration technique for boreholes

Comparisons of results from different measurements in boreholes, or integrated analysis of collected data, sometimes fail due to incorrect depth data for the measurements. Even with relatively good accuracy of the depth measurements during logging etc, like 0.1-1%, the absolute incorrect may be as much as 1-10 m for a 1000 m borehole. The incorrectness is different for the different borehole equipment, as well as it is a function of the inclination of the borehole, groundwater level etc. The difficulties of calibrating elongation of logging cables, pipes, wires etc for all these conditions, hence, are easy to understand.

To increase the correctness in this matter, SKB has started the development of an in-situ depth calibration technique for measurement in boreholes. The intention is to drill-in markers in the borehole wall at certain depths (for example every 200th or 400th m of the hole length) during or after the drilling of the borehole. Every borehole probe (or at least every logging cable, pipe etc with dummy probes) will be equipped with a sensor for locating the depth markers, making calibration of the depth measurements possible for any type of measurements.

The first step has been to develop a technique to drill-in markers in the borehole wall. A special drill-probe replacing the normal drill-bit and core barrel has been constructed and the technique was successfully tested in a rock-block. A field test in a deep borehole is presently in planning. The next step will be to integrate the sensors to the different measurement probes.

Measurements to depths more than 1000 m

Almost as a standard, SKB borehole equipment is designed for measurements down to 1000 m depths, and 56 mm borehole diameter. As informed in the Annual report 1992 /15.4-33/ a deeper hole, KLX02, was drilled to 1700 m, aiming at testing drilling and measurement techniques to deeper levels and to give information for the understanding of the regional groundwater flow in the vicinity of Äspö HRL.

In order to prepare for logging and measuring in the deep hole some equipment modifications have been made and are planned for. Direct following the completed drilling, the UCM flow-meter probe was stuck during logging at 1430 m depth. The fishing operation ended by loosing the probe for final deposition at the borehole bottom. The calliper method of the following geophysical logging showed a diameter anomaly at that level, resulting in a decision to stop all following geophysical logging and borehole radar above that level. The modification of our borehole-TV for inspecting the calliper anomaly is underway.

A hydrochemical programme was conducted during the autumn of 1993. The borehole equipment for pumping, in-situ measurement and sampling is hoisted by the umbilical hose of the mobile chemical system. The umbilical hoses are as maximum 1000 m long. Hence, for sampling from deeper levels a tandem arrangement was made of two mobile units with umbilical hoses, see Figure 15.4-8. The pump, chemical Eh-pH probe, and gas/water sampler was then mounted in the connection between the two hoses. This arrangement proved the feasibility of pumping, in-situ measurement and sampling from depths of 1400 m.

Preparation of other methods, hydraulic tests etc, for these depths is going on.

Reverse flushing drilling

Core drilling with reverse flushing of the cooling water for the drill bit was discussed in Annual report 1992 /15.4-33/. The main aim of adopting and testing this technique for SKB core drilling is the need of uncontaminated water samples. By normal drilling, the flushing water to a great amount will be pressed out into the formation, making the water sampling more time-consuming and incorrect. One refinement of the flushing water handling was taken by the development of the telescope-type drilling technique in the Äspö HRL. The entrance of drilling water into the formation was then reduced by means of maintaining airlift pumping from annulus during drilling.

Reverse circulation drilling means that only formation water will be used for cooling the drill bit. The water will be pumped from the formation, through the drill bit and up inside the drill pipe. The presumption for the success of the method is that water conducting fractures with enough water capacities are frequent enough for supplying at least 25 l/min flushing water flow.

The method was tested by drilling a 300 m deep borehole, in which the section 100 to 300 was drilled by the

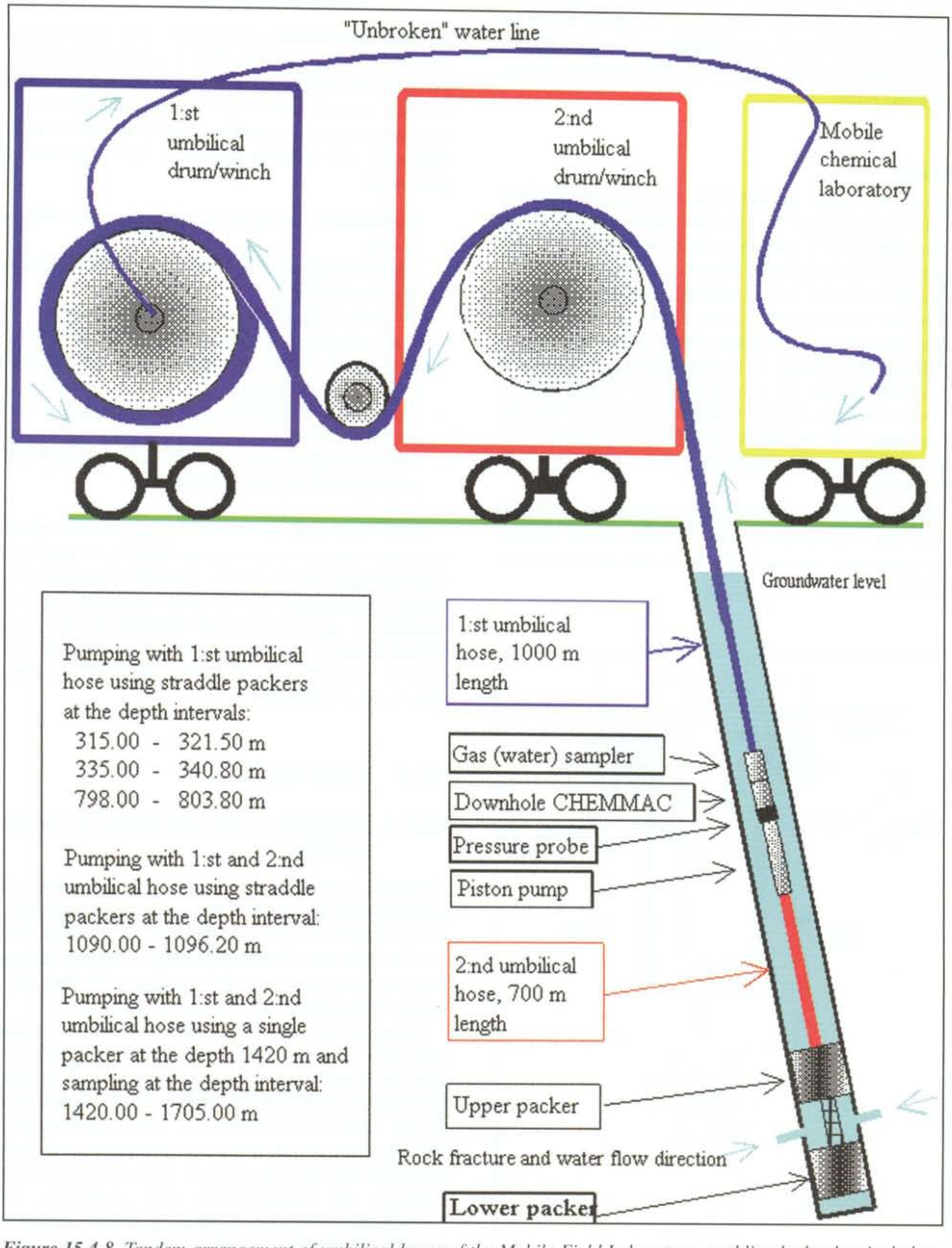


Figure 15.4-8. *Tandem-arrangement of umbilical hoses of the Mobile Field Laboratory, enabling hydrochemical characterization also to deeper levels of the 1700 m borehole KLX02.*

reverse flushing method. The reverse flushing is maintained by means of air-lift pumping in the drill pipe, a reason why the reverse flushing was not started before 100 m depth.

The technique was proven successful, as reported in SKB TR 93-20 /15.4-30/ even if it is more time-consuming than standard drilling, hence to be used when special requirements for uncontaminated water samples are given. The core recovery was at least as good as for standard drilling, with a tendency of slightly better for highly fractured rock. One advantage of the method is that it can easily be switched over to from standard drilling, back and forth.

Others

In order to refine the initial pressure regulation of the water injection tests with the umbilical hose system the development of a prototype of a down-hole pressure regulation valve has been constructed. The potential advantage of a down-hole regulation of the pressure is that it would decrease the injection pressure stabilization time. The main valve function is that constant pressure is maintained by means of a mechanically spring-loaded function. Further, the spring-load can be pre-set by a down-hole screw-motor for different injection pressures. The same motor will also be used for detailed adjustment of the pressure, if needed, by means of a down-hole regulation loop.

Bench tests of the prototype has shown promising results, and will continue before the valve will be adopted for down-hole use and built-in to the umbilical hose system.

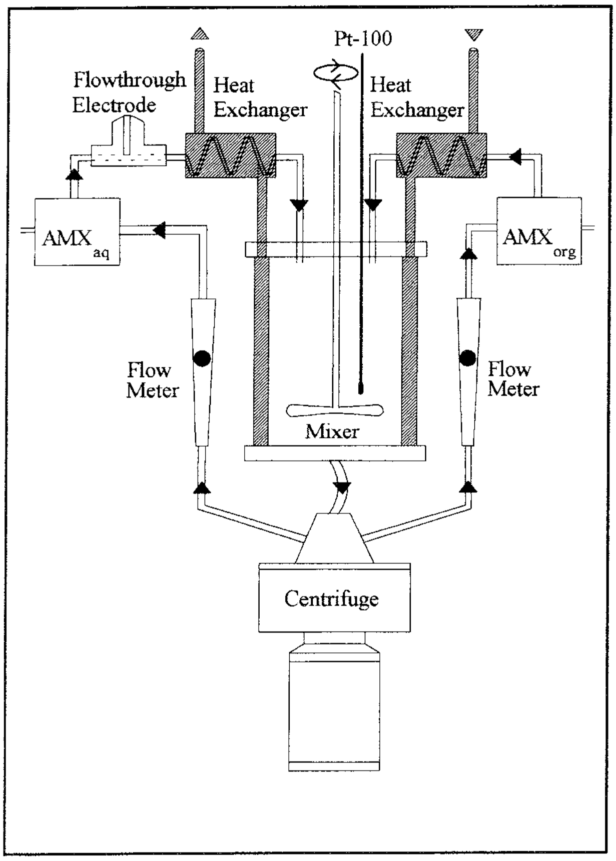


Figure 15.5-1. The AKUFVE-system for measuring complexation with the extraction technique. This equipment has been developed at the dept. of Nuclear Chemistry at Chalmers University, Göteborg.

15.4.9 Miscellaneous activities

The SKB geoscientific programme often deals with interdisciplinary approaches. Thus it is essential to discuss the obtained R&D results in informal manners where different point of views could be ventilated. The following seminars has been arranged with participation of the authorities and different experts in the broad field of geoscience:

- Geoscientific classification within the site selection process.
- Simulation of past and prediction of future glaciations in northern Europe.
- A review of the seismotectonics of Sweden.
- Semi-analytical solutions of coupled Thermo-Hydro-Mechanical Fields for cylindrical and spherical coordinate symmetries.
- The county of Uppland and its environment – an impact structure?
- Fracture mapping and lineament interpretation – presentation and physical properties.

Beside these open discussions it is of great importance to present and assess the ongoing R&D work within the international scientific society. The SKB Geoscience programme encourages the involved consultants and researchers to attend intentional meetings as well as to publish papers in scientific journals. /15.4-12/, /15.4-13/, /15.4-17, /15.4-18/, /15.4-19/, /15.4-20/ (see also Appendices 2 and 7 in part III).

15.5 CHEMISTRY

15.5.1 Solubility and speciation of radionuclides

Constants have been measured which determines the solubility and speciation of the redox sensitive radionuclides technetium and neptunium in deep groundwater /15.5-1/. The data obtained have been compiled and are being implemented in the SKB version of the thermodynamic database used by the code EQ 3/6 /15.5-2/.

Studies on the solubility of ThO_2 in phosphate media have been completed /15.5-3/. Extraction technique was used for the measurements, see Figure 15.5-1. The results demonstrate that phosphate complexation is not important for the speciation of thorium in natural groundwater. Measurements of the strength of phosphate complexes were made already in the sixties by Moskvin et al. /15.5-4/. Although the measurements were suspicious, the corresponding data have spread to a number of databases in current use. If the early data are used, one would expect an increase in solubility of thorium and other tetravalent actinides due to phosphate despite the low concentrations of phosphates in deep groundwater and bentonite pore water. A comparison between the old and new constants of thorium phosphate complexes is presented in Table 15.5-1. The stability constants are many orders of magnitude lower than previously thought and the conclusion is that we do not expect the ambient phosphate concentrations to be of any significance for solubility. However, control experiments are being performed on the influence of phosphate on technetium and neptunium.

Table 15.5-1. Experimentally obtained stability constants (log) for thorium complexes with phosphate /15.5-3/.

Cumulative constant (J = 1 M $Na(H)ClO_4$)

Species	Exp. pH 8.0	Exp. pH 9.0	Literature value[(1)]
$ThHPO_4^{2+}$	$(5 \cdot 10^8)$	$(5 \cdot 10^9)$	$2 \cdot 10^{13}$
$Th(HPO_4)_{2,aq}$	$1 \cdot 10^{15}$	$2 \cdot 10^{17}$	$3 \cdot 10^{26}$
$Th(HPO_4)_3^{2-}$	$1 \cdot 10^{21}$	$1 \cdot 10^{23}$	$8 \cdot 10^{34}$

(1) Moskvin et al. /15.5-4/.

Due to it's importance, experiments with plutonium are given high priority despite the difficulties involved such as difficult chemical properties (different redox states) and that it is difficult to work with. Some preparations have been made to use extraction technique, but it remains to be seen what can be achieved. Experiments of direct measurements of plutonium solubility have been attempted using Pu-239. However, it turned out to be difficult to obtain sensitive enough radiometric detection and the isotope Pu-238 has therefore been acquired.

SKB is continuously supporting international activities in the areas of thermodynamic data compilation, geochemical calculations and validation of geochemical codes. Swedish experts are participating in the OECD/NEA project TDB we are also actively taking part in the CEC project CHEMVAL.

15.5.2 Organic complexes, colloids and microbes

Dissolved organic matter in groundwater, in particular humic substances, are being isolated and characterised. The samples are taken from the study sites, from Äspö Hard Rock Laboratory and from the sites being studied as natural analogues to deep underground disposal, see section 15.6. Attempts have been made to analyze the non-humic organic fraction by the method of capillary electrophoresis.

Formation of complexes between the elements Sr, Eu, Th, U and aquatic fulvic acids have been studied /15.5-5 and 15.5-6/. The methods ion exchange, ultrafiltration and potentiometric titration have been used for that purpose. Efforts to interpret results as due to the intrinsic heterogeneity of the fulvic acids have been successful /15.5-5/. Effects of organic matter on sorption of radionuclides are also being studied /15.5-7 and 15.5-8/.

The influence of colloids and humic substances on the uptake and transport of trace elements has been investigated by A Ledin and presented in her doctoral thesis at the Dept of Environmental Studies at the University of Linköping /15.5-9/. The studies indicate that although colloids and humics are very important for the mobility of trace elements in surface water, they have only minor influence in deep groundwater. This is due to the low concentration of colloids and humic substances in deep groundwater. Within the frame of this study the influence of fulvic acids on colloids has also been tested /15.5-10/. It has been demonstrated that fulvic acids change the electric charge properties of the colloids and thereby their size distribution and their uptake of metals.

In situ measurements of colloids in groundwater using photon correlation spectroscopy has continued /15.5-11/. The possibilities to measure colloids at low concentrations with this technique have been tested using model colloids, see Table 15.5-2. It is necessary to calibrate the instrument against the colloids being measured because of different sensitivity for different minerals. However, despite this complication the technique has the advantage of allowing in-situ on-line measurements. Other methods of sampling and analysis of colloids often fail, because particles are easily generated by for example precipitation due to oxidation, degassing etc.

Table 15.5-2. Properties of different colloids according to Photon Correlation Spectroscopy (PCS) measurements. The colloids have been prepared and are used as "model colloids" to test the PCS sensitivity.

Colloidal Phase	Concentration Interval (mg/l)[a]	Size Distribution (nm)
Fe_2O_3	0.03-2	10-75
$Al(OH)_3$	0.1-2	10-325
SiO_2	0.1-7	50-300
Kaolinite	0.5-10	115-350
Illite	0.5-50	50-400
Humic acid	0.5-75	70-250

[a] Interval in which concentration and count rate are proportional.

Laboratory column experiments have been performed in order to measure the transport of inorganic colloids and their ability to carry radionuclides /15.5-12/. The columns were packed with quartz sand (0.2 mm) and submicron size particles of goethite were used as colloids. The radionuclides used in the experiments were Cs-137, Na-22 and I-131 in the form of iodate (IO_3^-). The parameters pH, flow rate and initial goethite concentration are important for the transport of the goethite colloids. A high pH (pH=10) lowers the retention due to electrostatic repulsion between the colloids and the quartz. Low concentration and low velocity favours the deposition of goethite on the quartz grains. The dependence on flow velocity is due to kinetics. At typical groundwater pH around 8 and normal groundwater composition the goethite colloids are not stable and consequently precipitates. At low pH (pH=4) the goethite colloids are deposited on the quartz. The Goethite colloids have little influence on the transport of cesium and sodium. Iodate is taken up by goethite at low pH (pH=4) but not at high pH (pH=10).

The experiments with bacterial growth in slowly flowing groundwater from a deep borehole in the Stripa mine have been reported /15.5-13, 15.5-14 and 15.5-15/. The bacteria were characterised by using the 16S-rRNA gene sequencing technique. The assimilation rates of carbon dioxide and lactate, and the respiration rate of lactate were also measured. The conditions for bacterial growth were anoxic at pH 9-10. The water came from two sections of the vertical borehole: 812-820 m and 970-1240 m depth. Assimilation of carbon dioxide was indicated, but heterotrophy was found to be the main process for carbon transformation. Different strains of bacteria dominated at the two different levels. The earlier proposed presence of sulphate reducing bacteria could not be confirmed.

Sampling and analysis of microbes in the groundwater at Äspö continues. The Äspö Hard Rock Laboratory facility provides a large number of sampling points in boreholes at different interesting locations and different depths. A total of 9 boreholes have been sampled at depths ranging from 10 down to 600 m. The number of bacteria varies with depth, being relatively numerous in surface water and decreasing at deeper levels, see Figure 15.5-2. The fact that part of the entrance tunnel to the facility passes under the sea makes it possible to compare under-land-conditions with under-sea-conditions. Therefore the sea sediments above the entrance tunnel are also sampled for bacteria. The microbial investigations at Äspö are combined with the other projects and activities there in order to provide additional and complementary information on bacterial influence for the interpretation of the in-situ studies. For example, bacteria appear to be of considerable importance for the mediation of redox processes, see also Chapter 16. Sulphate and iron reducing bacteria (SRB and IRB) are considered important because of their influence on geochemical redox reactions and they are therefore being carefully investigated, see Table 15.5-3. The iron reducing bacteria, IRB, are frequent in groundwater and they may have a considerable influence on redox conditions. Only two strains of IRB have so far been described in the literature: *Geobacter metallireducens* and *Shewanella putrefaciens*.

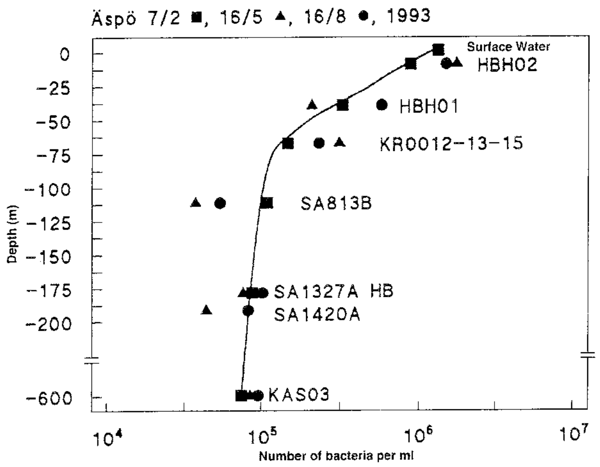


Figure 15.5-2. *The total number of bacteria as a function of depth at Äspö. The samples are taken around the entrance tunnel and out under the Äspö island. The codes refer to sampled boreholes.*

The method of 16S-rRNA-analysis have been extensively used in order to characterise the bacteria sampled at Äspö. Preliminary results indicate the existence of a large number of strains of bacteria. At least 61 different strains have been observed. Differences between populations living at the surface and in the groundwater have been noted. Also there is a considerable variation between different boreholes and between different sampling levels, see Table 15.5-4.

The assumptions that microbes exist in groundwater and that they are geochemically active are supported by the results of the on going investigations /15.5-16/. Bacteria mediated reactions of importance for waste disposal can be envisaged /15.5-17/. This has been discussed in earlier performance assessment studies and these questions are now being revisited in the light of the recent developments in the microbial research area.

15.5.3 Sorption and diffusion

Sorption mechanisms for radionuclides on mineral phases are being investigated. For that purpose sorption experiments have been performed with lanthanides and actinides on iron(III) minerals and amorphous silica. The model of surface complexation is used to interpret the experiments and good agreement has been obtained between sorption and hydrolysis data for each nuclide. It is now easier to discriminate between so called inner- and outer-sphere complexes (notions in surface complexation theory). Chemical explanations can be provided for the fact that some nuclides have high distribution coefficients and others have not. As an example, it has been experimentally demonstrated that the sodium ion Na^+ is taken up as an outer-sphere complex on goethite (FeOOH) /15.5-18/, while the neptunyl ion NpO_2^+ is sorbed according to an inner sphere mechanism and in the form of NpO_2OH /15.5-19/. The sorption mechanisms involved in the uptake of thorium on amorphous silica have also been investigated. In the course of these investigations the method EXAFS (Extended X-ray Absorption Fine Structure Spectroscopy) have been used in order to "see" how thorium is bound to the silicate surface, see Figure 15.5-3. Wet samples can be investigated by this method. The results so far indicate that thorium is bound to the silicon via one oxygen. This is referred to as "sharing a corner". When the surface starts to fill up, the cover resembles structurally amorphous thorium dioxide. The work on thorium sorption will be part of a dissertation by Eric Östhols at the dept. of Inorganic Chemistry at the Royal Institute of Technology.

The reduction of Tc(VII) in the form of pertechnetate (TcO_4^-) in groundwater and on magnetic separated fractions of crushed granite has been studied. The results demonstrate that the reduction of Tc(VII) to Tc(IV) and

Table 15.5-3. Sulphate reducing bacteria, SRB, and iron reducing bacteria, IRB, in samples from different locations in the Äspö tunnel. Included are also measured total number of bacteria on surfaces exposed to flowing groundwater in a biofilm reactor. The codes refer to boreholes at Äspö.

Sample (Depth) Flow ml/min	Total number of bacteria cm^{-2} (Biofilm reactor) 921202–930207	SRB Enriched 921202	Total number of SRB ml^{-1} 930207	IRB Enriched 930207
HBH 02 (10 m) pump	–	no	<20	yes
HBH 01 (40 m) pump	–	no	<5	yes
KR 0012 B (68 m) 500 ml/min	–	–	<10	yes
KR 0013 B (68 m) 605 ml/min	470,000	no	<5	yes
KR 0015 B (68 m) 1460 ml/min	–	–	<5	yes
SA 08 13 B (112 m) *sample 1 (turbid)*			*830,000*	
sample 2 (clear) 220 ml	1,200,000	yes	2,420	yes
SA 0923 A (134 m) 134 ml/min	–	–	<5	yes
SA 1062 B (143 m) (run dry) <10 ml/min	yes	–	–	
SA 1327 A HB (179 m) 200 ml/min	5,600,000	yes	130	yes
SA 1420 A (192 m) 12 ml/min	150,000	no	<5	no
KAS03 (544-626 m)	–	yes	1,390	yes

precipitation as TcO_2nH_2O on the ferrous iron containing mineral surfaces is an important retardation process. The magnetic separated fractions of crushed granite has also been used for experiments with sorption of strontium, Sr^{2+}. This has demonstrated that although the sorption process is rather slow, probably due to diffusion into microfissures, it is completely reversible for strontium, see Figure 15.5-4.

Sorption and diffusion in bentonite are being investigated. The experiments indicate that two different sorption sites exists: "layers" and "edges". The "layers" are sites for ion exchange and consequently the sorption there is insensitive to pH. The sorption on the "edges" on the other hand is pH-dependent and best modelled as surface complexation /15.5-20/. The sorption behaviour of Cs^+ on bentonite have been described in terms of an ion exchange model /15.5-21/. Diffusion and batch sorption experiments were used to derive an ion exchange constant for the Na^+/Cs^+ exchange.

Diffusion in concrete have been studied by experiments /15.5-22/. The elements Cs, Am, Pu and five different types of concrete were investigated. The diffusivity measured for Cs ($Da=10^{-13}$ m^2/s) agreed reasonably well with data found in the literature. However, the diffusivity for Pu and Am is extremely slow. The contact times in the experiments were 2.5 years for Am and 5 years for Pu and

Table 15.5-4. Preliminary grouping of sequenced 16S-rRNA from Äspö samples. Only the most frequent clones are shown. One group corresponds to one strain of bacteria. The methods are described in /15.5-14/. The codes correspond to different boreholes at Äspö.

Borehole, Depth	SRB 5 groups	G+, *Eubacterium* 1 strain isolated	*Acinetobacter* 2 groups	*Pseudomonas* 7 groups	*Gallionella* 3 groups	*Campylobacter* 2 groups	*Bacillus* 1 group	Symbionts 2 groups	The rest, 36 different clone groups,
Similarity	90.1-91.4%	92%	96-98.9%	84.2-98.4%	89.8-94.8%	86.5-87.6%	94.7%	84.3-88.1%	not finished
HBH02, 10 m									12
HBH01, 40 m			6	4					2
KR0012, 70 m			1	1		1			9
KR0013, 70 m			4	3	1				4
KR0013, surface		1			2		9		–
KR0015, 70 m			1						9
SA813, 112 m	11	1							–
SA813, surface	8	4							–
HA1327, 179 m						10		1	1
HA1327, surface						3		6	3
SA1420, 192 m			4	3					5
SA1420, surface						2		8	2
KAS03, 626 m				3	6				3

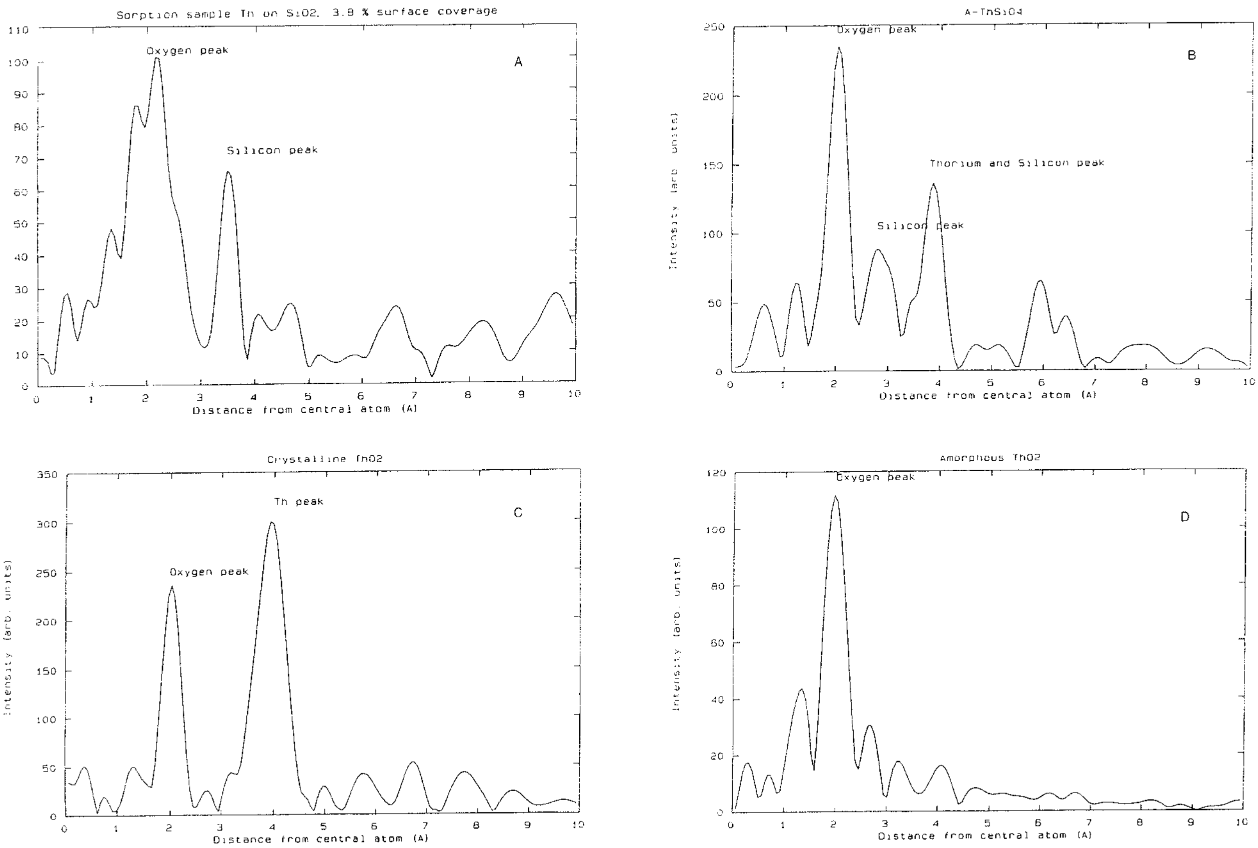


Figure 15.5-3. A. The radial distribution function obtained from EXAFS for Th sorbed on wet amorphous SiO_2 and a 3.8% surface coverage, compared to B. crystalline $ThSiO_4$ (thorite), C. crystalline ThO_2 (thorianite) and D. amorphous ThO_2. The EXAFS measurements were done at the synchrotron in Daresbury, UK and interpreted in cooperation with University of Grenoble, France.

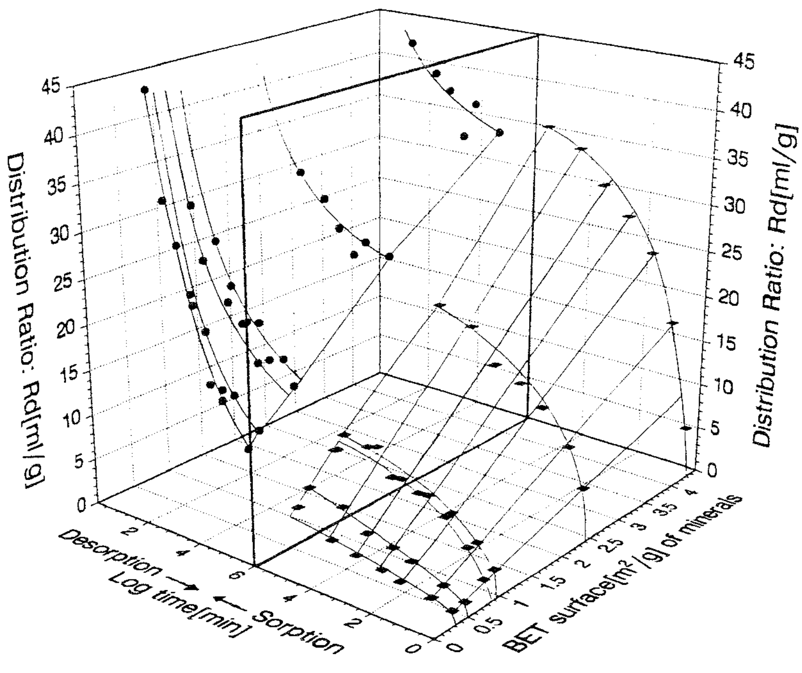


Figure 15.5-4. 3-Dimensional plot of measured sorption and desorption distribution coefficients R_d for strontium (Sr^{2+}) on various mineral fractions of crushed granite. The mineral fractions are represented by their specific surface area. Synthetic groundwater with 10^{-6} M strontium marked with ^{85}Sr was used in the experiments and the solid to liquid ratio was 1/3 g/ml.

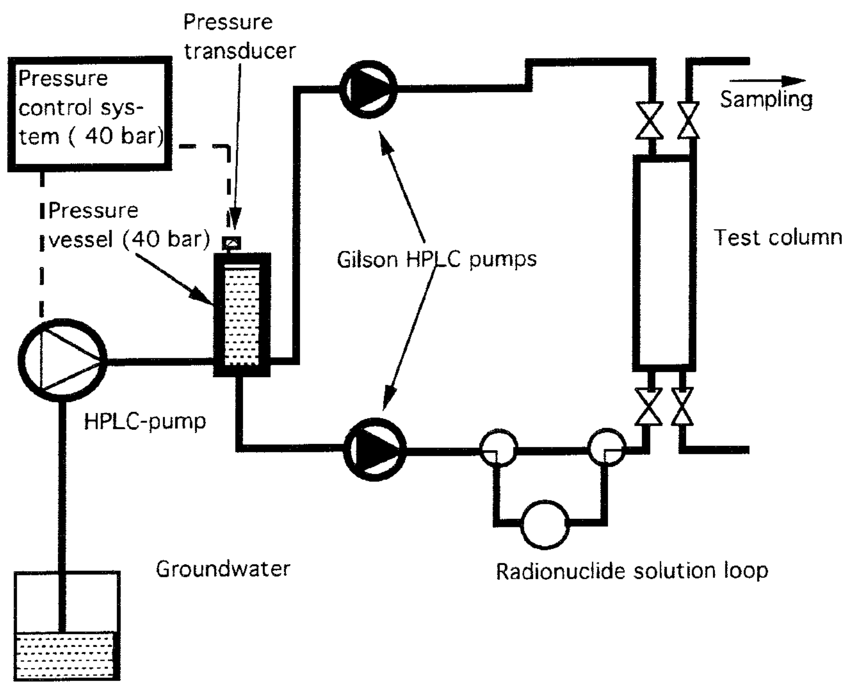


Figure 15.5-5. The schematic drawing of a bench test of an experimental set up intended for later use in-situ.

it was concluded that the diffusivity Da is less than 10^{-17} m^2/s . Such a low value proves that no mobile complexes were formed. For example negative hydroxide complexes which have been predicted earlier are either not formed, or they are being strongly retained by sorption. Carbonate complexes would be another possibility, but they are most probably ruled out by the chemical conditions in concrete that precipitates carbonate ions.

15.5.4 Validation experiments

An overcored natural rock fracture has been arranged in a laboratory setup in such a way that tracer experiments can be carried out at different rock pressures perpendicular to the fracture plane. However, this has taken more time than originally expected due to several technical problems with the first arrangement such as: lack of stiffness (volume changes in the fracture due to variations in the internal hydraulic pressure), formation of bubbles in the water and non linearity in the optical detection system. The status of the experiment now is that the undeformed fracture has been characterised in flow tests with nonsorbing tracers and experiments with Sr^{2+} have been started.

In-situ experiments with radionuclides are being planed for the Äspö Hard Rock Laboratory. The experiments in-situ will be performed at pressure conditions that are much different to what is normally used in laboratory tests. A bench scale model of the in-situ experiment is being constructed to test the functions and the response to pressure and pressure differences, see Figure 15.5-5. The experiment is intended for the CHEMLAB-probe.

Cement is frequently used in underground construction for several reasons, for example concrete structures and pavement, cement grouting of fractures and shotcrete on tunnel walls. Concrete made of Ordinary Portland Cement has a pore water with a high pH due to alkali hydroxides (NaOH and KOH) and portlandite ($Ca(OH)_2$). There are models to calculate the interaction between concrete pore water and the rock, but they need to be tested. Therefore experiments have been started where synthetic cement pore fluids are percolated through columns filled with crushed rock minerals. British Geological Survey is performing the study which is jointly supported by NAGRA, NIREX and SKB. The experiments are carried out as "blind tests" in order to test the capabilities of currently available coupled chemical and flow models to predict product solids and output fluid composition as a function of time.

15.6 NATURAL ANALOGUE STUDIES

15.6.1 The application of analogue studies

A significant volume of data are now available as a result of analogue studies, which can be applied to the prediction of repository performance over long periods of time. These data have been sporadically used in performance assessment notably within the Swedish and Swiss waste management programs. For example, references to natural analogues have been made in all safety performance assessment studies made by SKB, such as KBS-1 on vitrified waste, KBS-2, KBS-3 and SKB 91 on spent fuel, the final safety report, FSR, for SFR and the supplement to the FSR report which is an additional safety assessment. Most of the applications have been made to the conditions in the near-field environment. These and related examples are treated in a recent review entitled "Natural analogue studies in the geological disposal of nuclear waste", which has been published as a book by Elsevier /15.6-1/. The writing of this book have been supported by NAGRA, NIREX and SKB, and emphasis has been given to studies that are relevant to disposal concepts for radioactive waste in Sweden, Switzerland and the UK. In addition to providing a comprehensive review of the state of development of natural analogue studies the second aim of the book is to discuss the potential of natural analogous for presenting the concept of geological disposal to all interested audiences in a coherent, understandable and scientific legitimate manner.

A more detailed review of selected specific analogue applications to performance assessment has also been produced. This study was initiated and ordered by TVO in Finland and also supported by SKB. The report is available both from TVO and SKB /15.6-2/. It was demonstrated that studies of natural analogues and geological systems have provided significant information regarding many issues of importance to repository performance. In several cases the analogues have shown that processes assumed to take place in repositories do actually occur in natural systems under conditions similar to those expected in a future repository. The following subjects, of relevance for radionuclide retention, were treated:

- Groundwater redox, see Figure 15.6-1.
- Radiolysis of groundwater.
- Redox front development.
- Radionuclide solubilities.
- Co-precipitation.
- Near-field transport.
- Colloid transport.
- Matrix diffusion, see Figure 15.6-2.
- Channelling of groundwater flow.
- Microbial influences.

Groundwater redox, radiolysis, near-field transport and microbial activities are important for the chemical stability of the repository components, such as canisters and waste. Other studies specific for near field stability are investigation of material analogues (spent fuel, canister materials, bentonite, concrete and bitumen), high pH-conditions (concrete) and glaciation effects. These issues have also been summarised in the report.

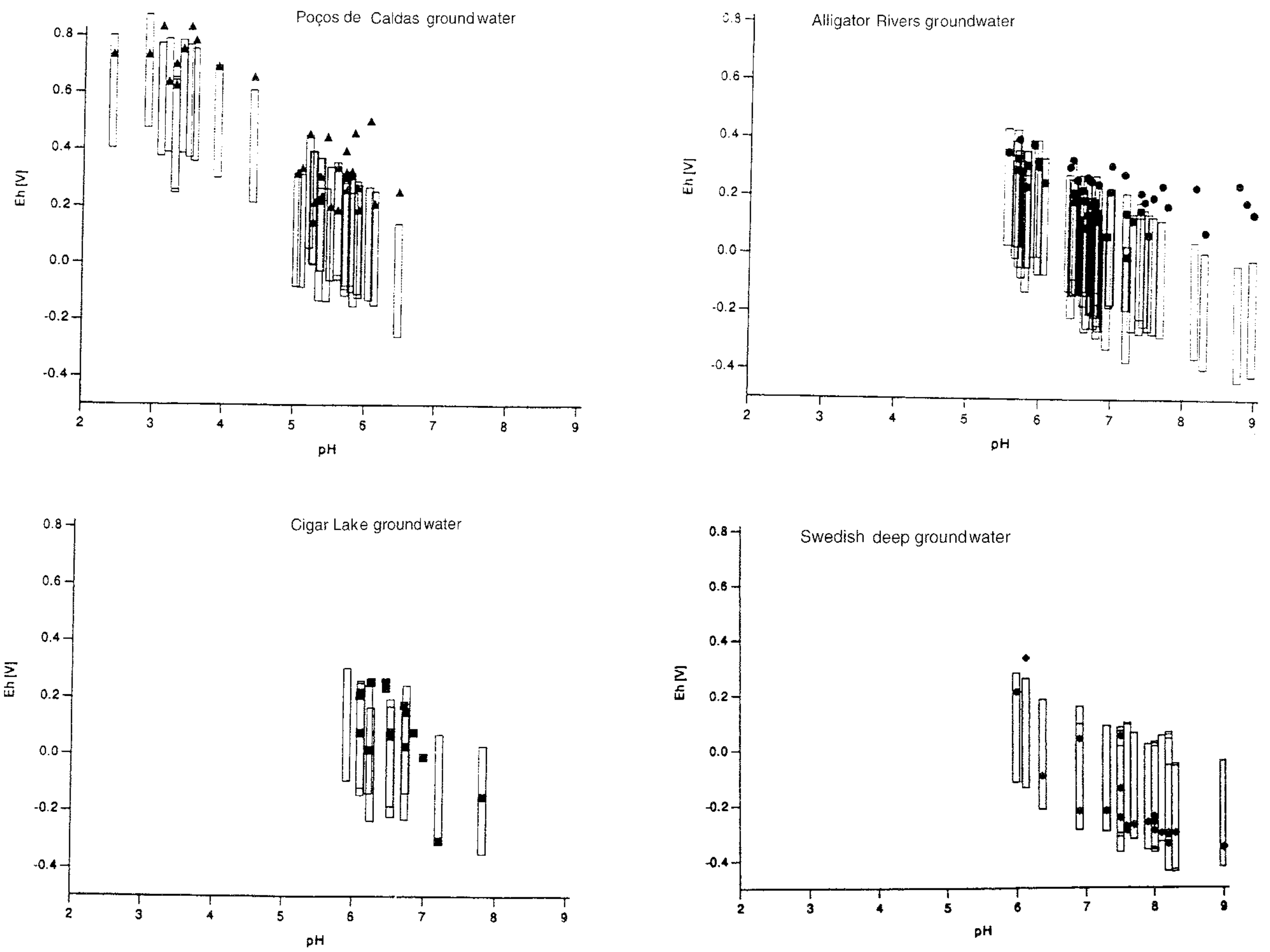


Figure 15.6-1. Measured redox potentials (points) and the calculated redox potentials for different ferric minerals (bars) at three analogue sites and Swedish deep groundwater. The bars show redox span calculated for precipitated $Fe(OH)_3$ (upper) and goethite (lower).

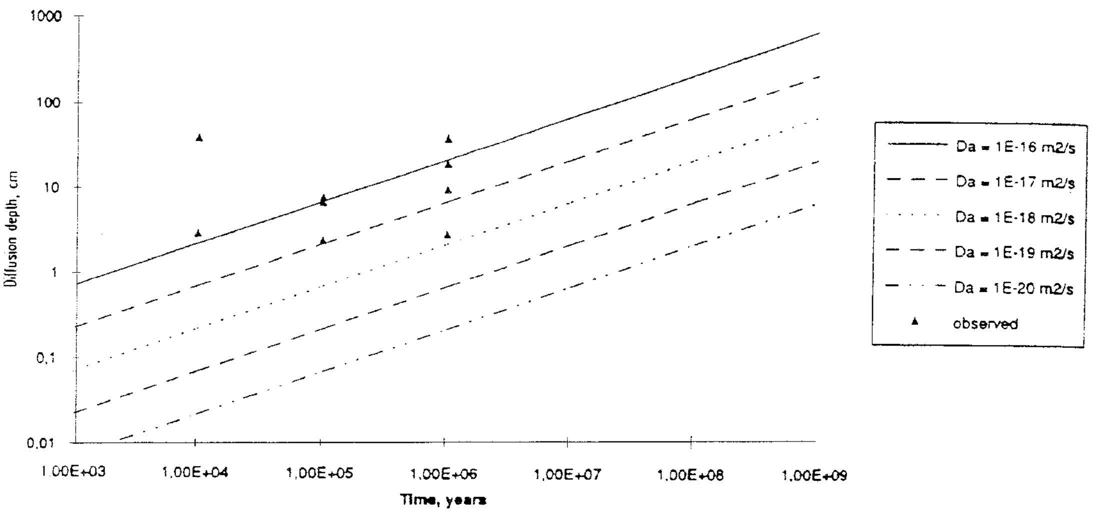


Figure 15.6-2. Calculated diffusion depths versus time and observed depths versus estimated times of movement in rock samples from Finland (Palmottu), Sweden (Kamlunge, Kråkemåla) and Switzerland (Grimsel).

15.6.2 Cigar Lake

The Cigar Lake natural analogue project has investigated a very concentrated uranium mineralisation which is situated in northern Saskatchewan, Canada. It has been studied as an analogue to a spent fuel repository by AECL since 1984. SKB joined the project in 1989 and Los Alamos National Laboratory participates in the study since 1991. The originally decided three year period of SKB engagement in the project was finished in 1992. This period of studies is now in the process of being reported as a final report. A draft copy of the report has been produced and the final version is expected in 1994 /15.6-3/. The general conclusions can be summarised as follows:

UO_2 dissolution and stability;
- long-term stability under reducing conditions,
- little dissolution achievable during 10^8 years,
- congruent dissolution controlled by surface alteration.

Clay sealing;
- clay (in this case illite) can provide effective, long term sealing,
- long term stability of illite,
- clay is an efficient barrier to radionuclide and colloid migration.

Colloids;
- colloid and particle contents in groundwater are generally lowest in competent rock and highest in friable rock,
- only a small fraction of radionuclides in water is attached to colloids,
- colloids can be effectively sealed in by clay rich rocks,
- colloids were not important in radionuclide migration at Cigar Lake, at least on a time scale of 10 000 years.

Organics and microbes;
- low humic-contents in dilute water are unlikely to play significant role in mobilization of radionuclides,
- microbes can survive in radiation fields, and they can mediate in redox control and buffering,
- organics and microbes are unlikely to adversely affect radionuclide migration in the near-field.

Groundwater chemistry;
- interactions with clay minerals control the bulk composition of groundwater,
- redox geochemistry is strongly controlled and buffered by the iron redox couple,
- the evolution of groundwater composition can be predicted by existing geochemical codes.

Radiolysis;
- radiolytic oxidation models for UO_2 dissolution appear overly conservative in SKB's current PA approach (SKB 91),
- dissolved Fe^{2+} is an important scavenger of radiolytic oxidants.

Radionuclide migration;
- natural hydrologic barriers and appropriate geochemical conditions are effective in limiting radionuclide migration,
- clay sealing is an important barrier to radionuclide migration.

A wealth of data have been gathered in the study, so in addition to the general statements above there are also more detailed quantitative performance assessment oriented evaluations being made. An example of that is the near-field mass transport modelling which have been performed /15.6-4 and 15.6-5/. This modelling exercise is based on the fact the generation rate of helium in the ore body, see Table 15.6-1, have to be balanced by the mass transport of helium through the clay halo. This mass transport can be expressed as equivalent flow Q_{eq} by dividing with the difference in measured helium concentration inside and outside the ore body.

$$Q_{eq}=N/(c_0-c_i)$$

Table 15.6-1. Helium generation rate by various nuclear reactions /15.6-6/.

	Helium generation rate in the entire ore body (mol a^{-1})
In U-238 decay series	0.442
In U-235 deacy series	0.0176
In in-situ neutron-capture reactions	Negligible
Total	0.46

The quantity Q_{eq} is conveniently used to express the transport capacity in the near-field of a waste repository. It is calculated from parameters such as geometry, flow, clay barrier thickness and diffusivities. Values of these parameters exist for the Cigar Lake ore body and consequently Q_{eq} can be independently calculated. The result of this comparison is presented in Table 15.6-2. The model was further applied to other constituents in the ore body

Table 15.6-2. Equivalent volume flow rate calculated by two independent approaches /15.6-4/.

	Equivalent volume flow rate for helium release (Q_{eq}) (m^{-3} a^{-1})
Calculated from known helium generation	54
Calculated theoretically by the near-field release model	67

such as uranium and the in situ generated isotopes tritium, C-14 and Cl-36. The observed retention of uranium and tritium could be predicted, but Cl-36 has long enough half-life and high enough mobility to be released according to the model. However, that has not been confirmed by measurements and is still a matter of discussion.

15.6.3 Oklo

The fossil reactor zones in the uranium ore in Oklo, Okelobondo and Bangombe in Gabon are being studied as natural analogues to radioactive waste repositories. The Oklo analogue project is directed by the French CEA and supported by CEC /15.6-7/. SKB and organisations from other countries such as Japan, USA etc are participating in the study.

The first reactor zone was discovered in 1972. A total of about 16 zones of past nuclear criticality has been discovered at present. The U/Pb ratios have been analyzed in order to determine the history of the zones. As an example the zone 10 has the age 1970 Ma, and some of the zones like zone 13 have been hydrothermally influenced by the intrusion of a dolerite dyke with the age of 750 Ma. The dolerite intrusion can be used in order to evaluate the thermal influence on nearby reactor zones.

At the time of criticality of the Oklo reactors the 235/U-238 ratio was 3.68 % which is five times more t
today's normal, 0.725%. This normal ratio of urani
isotopes is depleted in the reactor zones as a result of
nuclear fission processes that took place 2 Ga ago, and
is how the Oklo phenomenon was originally discover
As an example of that the U-235/U-238 ratio of zone
is going down to 0.560%. However, one example has a
been found of an enrichment! Close to the core of
reactor zone 10 (about 30 cm) one sample showed the r
0.7682%. This is explained as a result of plutonium tra
port and decay. The isotope Pu-239 has migrated to
outside of the reactor, become trapped in the clay miner
and decayed to U-235 /15.6-8/.

One of the reactors, the Bangombe zone, see Fig
15.6-3, is relatively far away from the other zones a
situated a few kilometres to the south-east of the to
Moanda which is located about 20 km south fr
Oklo/Okelobondo and the town Mounana. However,
Bangombe reactor is in the same geologic formation as
corresponding zones in Oklo and Okelobondo. The la
scape is dominated by savanna covered plateaus w
grass and brush vegetation grading to more dense r
forest type vegetation along small rivers and brooks a
other low points in the topography. The deposit is locat
at the foot of a plateau at an approximate elevation of 3

Figure 15.6-3. *The Bangombe site. Sampling of groundwater from a packed off section of a vertical borehole.*

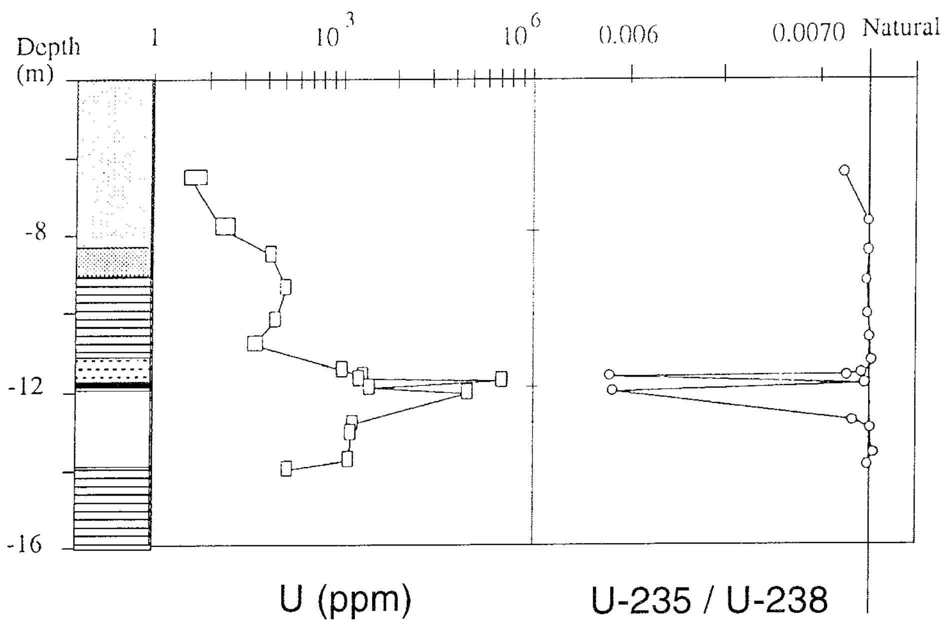


Figure 15.6-4. *Evolution of U contents and U-235/U-238 ratio along BAX 3 drill-hole.*

m asl. The mean annual temperature is 25°C and it is assumed that 40% of the groundwater recharges to produce groundwater. The uranium deposit in Bangombe, like the other zones, occurs in the transition between black shales and sandstone. The hydraulic conductivity ranges from 10^{-8} to 10^{-7} m/s with the sandstone being in general more permeable than the shales.

The Bangombe zone is close to the ground surface (about 12 m) and well preserved due to its position in a recharge area. The oxidative weathering from the surface is close to reaching the reactor zone and it is of interest to compare the Bangombe zone with the deeper ones in Oklo and Okelobondo. In 1992, a total of 7 boreholes were drilled both outside the zone and through it. Cores were taken for analysis and the drillholes were secured for hydraulic testing and sampling of groundwater. An example from these investigations is the mineralogical and isotope geochemical analysis of a the drillcores from the hole BAX 3 /15.6-9/. Results from this study is presented in Figures 15.6-4 and 15.6-5, where the reactor zone is clearly distinguished by the depletion of U-235 relative to U-238, see Figure 15.6-4, and where the distribution of fissiogenic Nd, Sm and Eu can be studied, see Figure 15.6-5.

15.6.4 Cement analogues

Cement is a widely used material in connection with low level waste management. It is being used for repository construction, for manufacturing of waste containers and for conditioning of waste like for instance spent ion exchange resins. In fact concrete and cements are likely to be present in all repository designs including high level waste repositories. Potential uses are underground constructions, shotcrete lining of rock walls and paving of floors, injection and grouting of fractures, and sealing of openings. The stability of concrete and the chemical influence of concrete on the waste and on the underground environment have to be taken into account in the performance assessment of the repository barriers to radionuclide dispersal. Modern concrete is generally

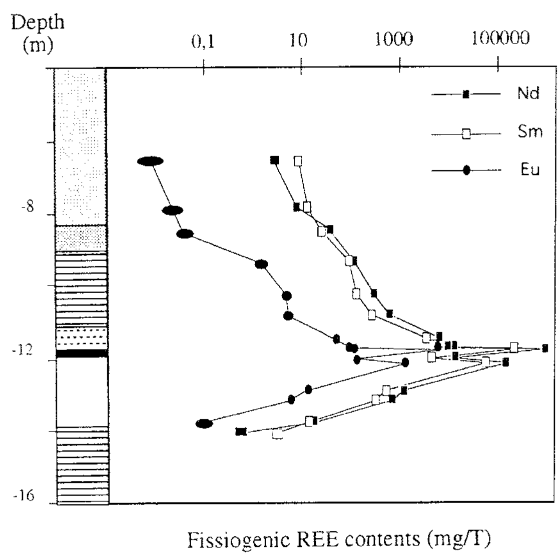


Figure 15.6-5. *Distribution of fissiogenic Nd, Sm and Eu contents along BAX 3 drill-hole.*

based on portland cement. The hardened cement contains portlandite ($Ca(OH)_2$) and relatively small amounts of alkali hydroxides (NaOH and KOH). Consequently the pH of concrete pore water is high and will remain so for a very long time. Other important hydration phases in cement are calcium silicate hydrate compounds, CSH, which are important in binding the aggregate particles together. Ions and chemical compounds can diffuse into the concrete and some of them will react such as carbonates, magnesium, sulphate etc. The slow interaction with the environment and the slow mineralogical processes in the concrete can influence the structural and mechanical properties.

Uppsala

The first portland cement was manufactured in 1824 /15.6-1/. Already the romans used concrete, but their pozzuolana concrete was different to modern portland concrete in that the CSH phases were formed by a reaction between the lime and pozzuolana components rather than hydration of grind cement clinkers. The importance of this difference can of course be discussed. Supposedly it depends on what you want to demonstrate. However, it has to be considered when making a comparison.

Anthropogenic analogues for concrete stability have been studied before in the SKB program and the most notable example is the investigation of the concrete lining of the water tunnel in Porjus /15.6-10/. The wall was cast in 1914. Another example is now being investigated. In 1906 a steel tank for drinking water was constructed in Uppsala with an inner lining of concrete in order to protect the steel from corrosion. Inside a carbonation front of about 5 mm the mortar is remarkably well preserved /15.6-11/. Although it has been in contact with soft water for almost 90 years, there is no clear sign of leaching of portlandite and the steel has also been well protected. We intend to continue this kind of investigations.

Jordan

Hyperalcaline groundwater, similar in composition to concrete pore water, has been found in natural springs of the Maqarin area of northern Jordan, see Figure 15.6-6. This groundwater has been generated by water flowing through natural occurrences of burnt limestone. The heat that burnt the lime was generated by spontaneous combustion of pyrite and bitumen in the marl rock. The reactions with water have not only created high pH groundwater but also a whole series of minerals typically found in portland cement such as portlandite, ettringite, tobermorite etc /15.6-12/. The water contains dissolved alkali and calcium hydroxide and shows pH values of 12.5 typical of portlandite dissolution and even higher than that. Young occurrences which are still burning today can be found in the Maqarin area along with older examples up to thousands of years of age. Much older examples with ages well above 10 000 years can be found in Central Jordan.

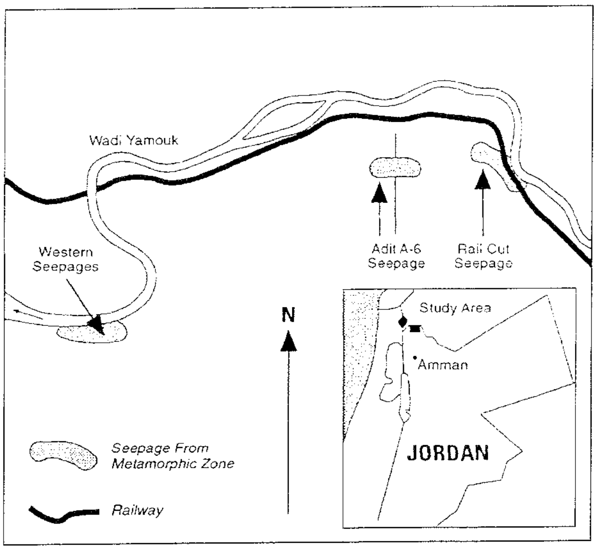


Figure 15.6-6. Location of the Maqarin analogue study site in northern Jordan. The sites of the hyperalkaline springs are shown.

Together with NAGRA and NIREX, SKB has been supporting the investigations as a natural analogue to the use of concrete in a waste repository. A proposal for a third phase of the project is being prepared and, within the frame of that activity, three boreholes have been core drilled in Maqarin to a depth of between 9 and 20 m. Core samples and groundwater samples were collected.

15.6.5 Other analogue studies

In addition to the previously described projects SKB is also following other analogue studies on the international scene. One way of doing that is the active engagement in the CEC Natural Analogue Working Group, NAWG. Another prominent example is our status as observer in the Palmottu analogue project in Finland, where a uranium mineralisation in granite is being investigated /15.6-13/. SKB has participated in the establishment of a 3-dimensional model of the fracture zones of Palmottu. Different methods were applied and our support consisted of radar measurements which performed well in this environment /15.6-14/, see Table 15.6-3. Interesting results have been obtained in the Palmottu study in areas such as: redox chemistry of uranium in groundwater, influence of humic substances, uranium mineralogy, uranium in surfacial deposits and modelling of matrix diffusion /15.6-13/.

Table 15.6-3. Interpreted major structures from radar measurements in five boreholes in Palmottu.

STRUCTURE UNIT	FIVE BOREHOLES 357 (m)	346 (m)	324 (m)	348 (m)	343 (m)	STRUCTURE ORIENTATION (Dip/strike)
V1	203	162	62	116	72	80/140
V2	248	207	113	176	123	70-80/135-160
V3	84	38	Above	8	Above	80/150
V4	134	91	8	71	-14	75-80/150
V5	175	121	31	91	None	80-85/150
V6	315	266	189	242	183	75/140
V7	270	215	135	None	None	70-80/140-160
H1	36	76	126	56	103	15-20/330
V8	122	53	Above	36	Above	70-80/140-160

15.7 THE BIOSPHERE

This subject treats the transport of nuclides from the aquifers above the bedrock, through natural and domestic ecological systems and into different foodstuffs. As usual endpoint, the dose to man is calculated and commonly compared to regulative limits. Dose to (or effect on) biota other than man is also considered.

In short, the contaminants reaching the biosphere are considered to

- enter primary receptors,
- be transported in ecological systems, giving external dose,
- accumulate in foodstuffs like plants animals and fish,
- be consumed and cause internal dose.

The modelling of processes in receptors and ecosystems starts with the outflow of dissolved radionuclides from the bedrock to an aquifer. This aquifer feeds contaminated water into different receptors (well, river or lake) and the contaminants can be transported through different physical compartments like soils, sediments, waters and air. The processes considered, include biological activity such as bioturbation, and human activity as farming.

This part of the modelling is done with compartment models for which volumes and transfer factors between compartments are calculated. Solving the differential equations produces time dependant concentrations for the different compartments.

After this the accumulation in foodstuffs, intake and dose calculations are pure multiplications for each scenario.

15.7.1 Validation of models

The vast number of transport processes involved, can be rationally treated with compartment models. Such models have been extensively used in this area since the 70-ties. General validation of such complex models is really not possible, but some attempts to determine a justified area of application for some models have been made in BIOMOVS, VAMP and PSAC. The numerical performance of a code is easier to validate, and has been done in PSAC.

BIOMOVS

BIOMOVS (BIOspheric MOdel Validation Study) is an international cooperative study initiated in 1985 to test models designed to calculate the environmental transfer and bioaccumulation of radionuclides and other trace substances. To SKB this has been an opportunity to test the widely used modelling tool BIOPATH and the uncertainty tool PRISM in several applications. The first study was run for five years and ended in 1990. BIOMOVS I forcefully demonstrated the shortcomings of our present capabilities for biosphere modelling /15.7-1/.

In 1991 the second phase BIOMOVS II was started at a workshop in Vienna in October. It is jointly managed by five organisations: AECB, AECL, CIEMAT, ENRESA and SSI.

SKB has during 1993 actively taken part in the work with emphasis on the theme "Reference Biosphere Scenario for Long Time Assessment" as we believe it is of great value to get an international consensus how to deal with the modeling and conceptual uncertainties arising with time. Within this working group, a list of FEPs (features events and processes) has been compiled during 1993. The proposed methodology and FEP list will also be used and tested in a related theme "Complementary studies". In this theme a specific site is modelled by 10 different groups and the results and approach compared. The site specific data have been collected from a valley in Wellingen in Switzerland. The results are discussed with emphasis on the processes involved. In a validation scenario for C-14 within the "Validation and Uncertainties" group, we are stochastically testing the model used for the SFR safety assessment with almost all parameters as Probability Distribution Functions (PDFs).

VAMP

SKB has been participating in an IAEA/CEC program "Validation of Models on the transfer of Radionuclides in Terrestrial, Urban and Aquatic Environment and Acquisition of Data for that Purpose" (VAMP). In this programme modelling of Cs-137 in lakes and uncertainty analysis is intercompared between several working groups from several countries. The pathway for Cs-137 via consumption of fish is major in dose calculations.

The lake model and the codes BIOPATH and PRISM are the tools SKB tries to validate in this study. The results have been reported in /15.7-2/ showing that the models give satisfactory results for the five year period studied.

For most of the lakes the predicted to observed ratio (P/O) was within a factor of three for water and fish. Overestimation was most pronounced in a Norwegian lake, probably due to the snow cover during fallout. The main difficulty seams to be the estimate of the water concentrations. If these estimations are close to the measured real concentrations, then the calculated concentration in fish will also be realistic. The uncertainty analysis showed that the source of uncertainty was different between the lakes.

PSAC 1b

This international OECD/NEA exercise "Probabilistic Systems Assessment Code(PSAC) User Group of the OECD Nuclear Energy Agency" PSACOIN level 1b deals with the verification of codes used in biospheric modelling and uncertainty analyses. Most of the work was done during 1991 and a report was published during 1993 /15.7-3/.

The results showed good agreement among the 7 participating codes. The major uncertainty in the results was due to the transport processes and not due to the exposure pathways. The parameters that were most critical for total uncertainty, were not the same ones in the beginning as in the end of the time period studied.

15.7.2 Site specific studies

Äspö

The long term transport from the geosphere to the biosphere has been addressed for a specific site in this project.

Postglacial and glacial sediments and soils have been studied in the archipelago around Äspö, with special interest to the influence of discharging groundwater. Long, 2.5 – 5 m deep sediment profiles have been taken from the strait between Hålö and Äspö and in a peat bog on the island. The chemical composition of pore-water and the solid phase has been investigated, using INAA and ICP spectroscopy for about 30 elements.

The stratigraphy and element concentrations reflected changing sedimentation and weathering conditions. Of special interest is the presence of gravel zones between the clay layers as they may constitute important paths for element transport. They may be analogous to the moraine zone between the clay and the bedrock.

Studying sediments at Äspö, 90 – 99% of the original content of Na, Cl and Br in the pore water were leached, probably into the underlying bedrock /15.7-4/. The total amount of leached ions is considerable and may significantly have contributed to the salinity of the groundwater in the bedrock. /15.7-5/.

Dose factors in the Äspö area

A set of more realistic dose factors was calculated for seven nuclides; C-14, Tc-99, I-129, Cs-135, Np-237, PU-240 and Am-241. An approximately 100 km^2 big area West of Äspö was studied and six types of recipients could be identified. Using pathways identified at the site and current habits a set of dose factors with uncertainty intervals was calculated /15.7-6/.

NATAN

One way of understanding long time transport processes in the biosphere is to study transport of natural occurring elements. In particular, sorption and migration of radionuclides in the interface between biosphere and geosphere is of special interest. This project is in its initial phase and an inventory of good candidate sites was produced 1993 /15.7-7/.

The Chernobyl fallout

In order to utilize the Chernobyl fallout for validation of nuclide migration models in the shallow groundwaters and the upper soil layer, samples have been collected and measurements have been made in two Swedish areas since 1986.

Exposure rate measurements along predefined profiles and gamma spectrometric measurements of soil samples have been made in the Gideå area. The hot spots identified at previous measurements had continued to migrate slightly /15.7-8/.

The levels of radioactivity are now very low, making further analysis difficult. The instrumentation was thus removed during 1993 and activity constrained to theoretical analysis.

The results from this study have been presented at a dissertation monograph /15.7-9/. Of the Cs activity being transported out from the area by the creek water, ~10% is transported as particulates and the rest as cations. After 5 years the major portion of the Cs was found in the upper 5 cm of the soil and predominantly in the silt-clay fractions. Only ~15% of the Cs is considered mobile.

15.7.3 The distribution of radionuclides in soils and sediments

The modelling of transport in soils and sediments has been heavily relying on the sorption assumption expressed as a single K_D-value.

To deepen the knowledge about the teoretical background to K_D-values, available theoretical models for ion-exchange and surface-complexation have been adapted for biospheric conditions The results show that the work with surface complexion model for actinides increases the understanding of both laboratory measurements as well as studies of natural systems. The triple layer surface complexation model could estimate the dependence of K_D as a function of important chemical parameters such as pH and E_H.

The power of the surface complexation model is that equilibrium constants obtained under controlled laboratory conditions on well determined minerals easily can be used to estimate sorbtion under a much wider variety of conditions. K_D-value for Ra could be more precisely determined if the Ca concentration in the environment was known. The elements handled were Cs, Ra, Np, U and Pu. /15.7-10/.

15.7.4 Effects on biota other than man

In the Radiation Protection Act from 1988 it is stated that man and nature should be protected from harmful effects of radiation. It has been suggested that protecting man from stochastic damage also will protect other species from deterministic damage, but for non-radioactive toxic substances this is not necessarily true. A literature survey has been completed during 1993 /15.7-11/ and will be followed by an attempt to estimate the natural and semi-natural levels of radionuclides in nature /15.7-12/. Estimating the doses that some species will get from these natural nuclides and looking for effects may add in understanding the possible effect on ecological health.

16 OTHER LONG-LIVED WASTE THAN SPENT NUCLEAR FUEL

16.1 THE WASTE AND THE REPOSITORY FACILITIES

There are two main categories of nuclear waste being generated in Sweden: spent fuel and short lived low and intermediate level waste (LLW and ILW). Operation of nuclear power plants is the main source of LLW and ILW. A small contribution comes from research, industry and medicine. This category of waste is to be disposed in SFR in Forsmark. Later, the eventual decommissioning of nuclear power plants will generate waste which is going to be disposed in a planned annex to SFR. However, in addition to the two main categories, spent fuel and short-lived LLW and ILW, there will also be a third type of waste: long-lived LLW and ILW. Sweden will have relatively small quantities of such waste and the main sources are waste from research activities and some components from the power reactors in or near the rector core (core components and reactor internals). Core components are being interim stored at CLAB. The research waste is being collected, interim stored and conditioned at Studsvik. Cement is used when conditioning is needed and the waste is packed in containers of steel (e g drums) or reinforced concrete. There may also be some long-lived LLW and ILW from the encapsulation plant.

A deep underground repository (SFL 3-5) is being planned for the long-lived LLW and ILW. A first outline of the design for SFL 3-5 was made in 1982 /16-1/. According to the present concept SFL 2 and SFL 3-5 will be built at roughly the same depth, but separated horizontally by a tunnel of about 1 km length. The SFL 3-5 will consist of three parts: SFL 3, 4 and 5, see Figure 16-1. The repository design is presented in more detail in Plan 93 /16-2/. The total excavated volume for SFL 3-5 will be about 110 000 m^3 and the total volume of waste is estimated to about 25 000 m^3.

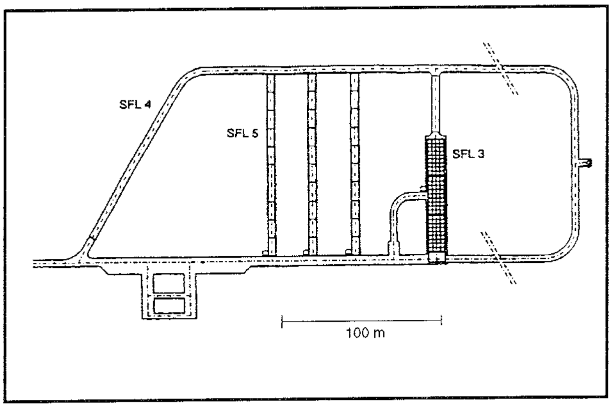


Figure 16-1. *Overview of the SFL 3-5.*

- The SFL 3 is designed for long-lived LLW and ILW from Studsvik, which originates from research, industry and medicine. It shall also receive operational waste from CLAB and the encapsulation plant.
- The SFL 4 is intended for decommissioning waste from CLAB and the encapsulation plant. This part of the repository consists of the transport tunnels and the vaults left after the sealing of SFL 3 and 5.
- The SFL 5 is designed for the disposal of concrete containers with reactor core components and internal parts. This part of the repository consists of rock caverns where the containers are piled up between concrete walls.

The solid and liquid waste are treated at Studsvik. The raw waste consists of for example activated and contaminated scrap metals, precipitations, ashes, ion exchange resins, glove boxes, disused radiation sources and contaminated laboratory outfit and radiation protection equipment. Examples of materials present are cloth, wood, paper, plastics (PVC, plexiglas etc.), rubber, glass, iron, stainless steel, aluminium, some lead and cadmium etc. Sludge from the treatment of liquid waste from Studsvik and universities is immobilised in concrete in 200-litre drums. Solid waste is packaged in drum which are placed in concrete containers, see Figure 16-2. Alpha-active waste from previous research activities that has not yet been conditioned is also kept at Studsvik. It will be treated at Studsvik in the same manner as outlined above.There is also older conditioned waste at Studsvik containing plutonium and uranium.

The strong neutron flux in the reactor core and its immediate vicinity during operation induces radioactivity in the components present there. Most of the nuclides formed are short-lived such as Co-60 and Fe-55, but some long-lived are also generated like Ni-59 and Nd-94. Examples of core components are control rods, neutron detector probes, neutron source probes and boron plates. Examples of internals with high induced activity are core grids and core support plates, see Figure 16-3. The most abundant material is stainless steel. Additional materials are boron steel, boron carbide, hafnium, zircalloy, inconell and boron glass. After a period of interim storage in steel cassettes in CLAB, the intention is to put the waste in concrete containers, backfill with concrete and send the concrete moulds for disposal in SFL 5.

Strictly taken, not all of the waste intended for disposal in SFL 3, 4 and 5 falls into the category of long-lived

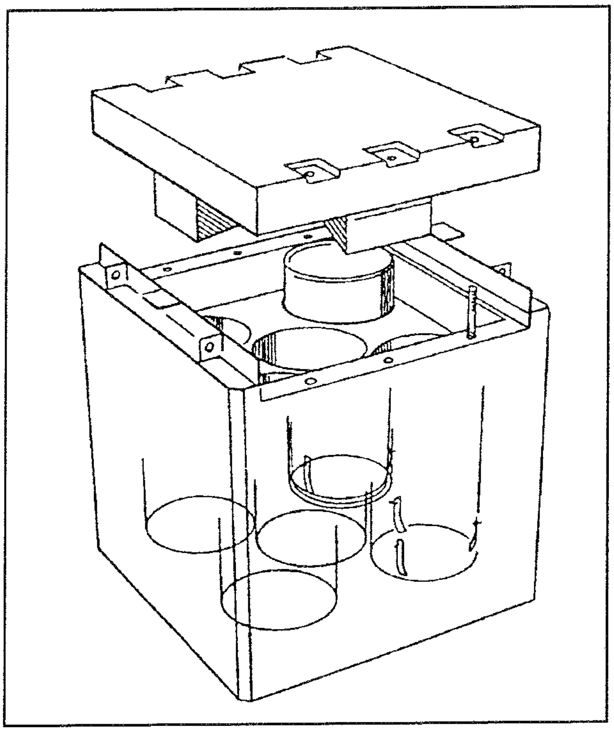


Figure 16-2. Packaging used for solid intermediate level waste at Studsvik. Five double lid steel drums (85 litre drums) are placed in five holes in a reinforced concrete container (1.2 x 1.2 x 1.2 m).

waste. In fact, only the waste that comes from Studsvik, the core components and the reactor internals are long-lived waste. Operational waste and later decommissioning waste from CLAB and the encapsulation plant could in principle be disposed of in SFR. However, SFL 3-5 is intended to receive all LLW and ILW that arise in the post-closure period of SFR.

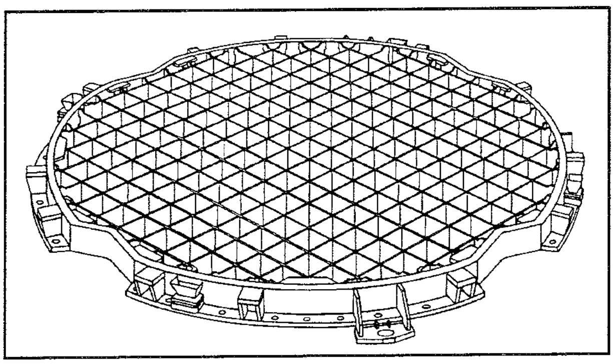


Figure 16-3. Core grid of a BWR. In Oskarshamn 3 the total weight of the core grid is 6 metric tonnes and it is made of stainless steel (SIS 2352). This is an example of a reactor component near the core.

16.2 A PRE-STUDY PROJECT

Design and construction of deep repository facilities beyond those needed for demonstration deposition (SFL 2) will start at the earliest a few years into the 21st century. Therefore, at the end of 1992 /16-3/ it was decided to begin the investigations concerning other long-lived waste than spent fuel by the following aims:

- Make an inventory of existing waste for SFL 3-5 and make a forecast of the waste that is being produced.
- Continue work on the design of the repository for long-lived LLW and ILW.
- Prepare and gather data for the safety assessments that will become necessary at a later stage.

In order to make an inventory and characterise the waste, it is not enough to consider just the radionuclide content. It is also important to know the material composition of the waste, how the waste has been conditioned and packed, etc. Although the hazards of the waste is almost entirely due to its content of radionuclides it is also necessary to get information on issues such as quantity and kind of organic matter, quantities and shape of metals, and amount of chemotoxic substances. The interest in metals and organics is governed by the importance of complexing agents and gas generation (corrosion and decomposition). Records of any toxic substance are simply needed for a complete assessment of disposal safety.

Long-lived LLW and ILW are present in other countries too. Large quantities are obtained in countries that send spent fuel to reprocessing, for example France, the UK, Germany, Japan, USA and Switzerland. During reprocessing, long-lived radionuclides – mainly transuranic elements – are released from the fuel matrix when this is chemically dissolved. Most is reused, e g plutonium and uranium, or ends up in the high-level waste. Many of these countries have well advanced programs for waste management, repository design and studies related to the safety performance. An important task for SKB is therefore to follow the developments in other countries. In an international comparison, Swedish quantities of this waste are small, since Sweden does not intend to reprocess the spent fuel.

An informal exchange of experience has been established between SKB and the organisations ANDRA (France), NAGRA (Switzerland) and NIREX (the UK). This is reflected in this study, were references have been made to recently published data from NAGRA and NIREX.

However, just gathering information on the properties of Swedish long-lived waste and following the international development in the field of performance assessment is not enough to achieve the aims set up in the RD&D-Programme. For example, experimental investigations may be needed which have not been done elsewhere, or if so have to be tested on local conditions. Some of the experiments take a long time to carry out and need to be initiated in time and it is important to know which experiments are relevant and really needed. It was therefore decided to perform a preinvestigation, starting at the beginning of 1993 and intended to end in spring 1994. The main goal of the preinvestigation was the following:

- To make a first preliminary and simplified assessment of the near-field barriers to radionuclide dispersion.

The prerequisites for this investigation was the conceptual design as it is presented in Plan 93 /16-2/ and general assumptions concerning the repository rock conditions. The study has been carried out in the form of a small project, which contained the following parts:

- An inventory and characterisation of the waste. Radionuclide content and other safety relevant components are summarised in an attempt to come as close as possible to the actual content of radionuclides, metals, organic materials, etc. Estimates have been made where hard data are not yet available.
- An inventory of scenarios for radionuclide release, of which one, the base case, will be analyzed within the frame of the prestudy. This is a relatively new approach and the exercise has contributed to the development in this field.
- Laboratory experiments and literature studies of important chemical properties. This includes cellulose degradation, concrete leaching, radionuclide sorption and diffusion in concrete and bentonite.
- Selection of data and calculations of near-field release in the reference case, which was taken from the scenario study.

To make a performance assessment, even in this simplified and preliminary form, is an effective way to focus the search for relevant data and direct the future investigations. This aspect has been promoted by the close cooperation between experimentalists and modellers engaged in the prestudy project. Further, the waste characterisation in combination with performance assessment illustrates what needs to be checked when waste is being conditioned and packed. Experts engaged in this field have been participating in the project.

No attempt has been made to change the conceptual design given in Plan 93 /16-2/, and so far it has proven to be functional. A rough comparison has been made between the present design of SFL 3 and a silo alternative, but they turned out to be fairly equal.

17 THE ÄSPÖ HARD ROCK LABORATORY

The Äspö Annual report /13-5/ is a detailed report on the achievements for 1993 and the reader is referred to this publication for further information.

17.1 BACKGROUND

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

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

In the autumn of 1986, SKB initiated field work for the siting of an underground laboratory in the Simpevarp area in the municipality of Oskarshamn. At the end of 1988, SKB made a decision in principle to site the facility on southern Äspö about 2 km north of the Oskarshamn station, see Figure 17-1. Construction for the Äspö Hard Rock Laboratory started October 1, 1990 after approval was obtained from the concerned authorities.

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

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

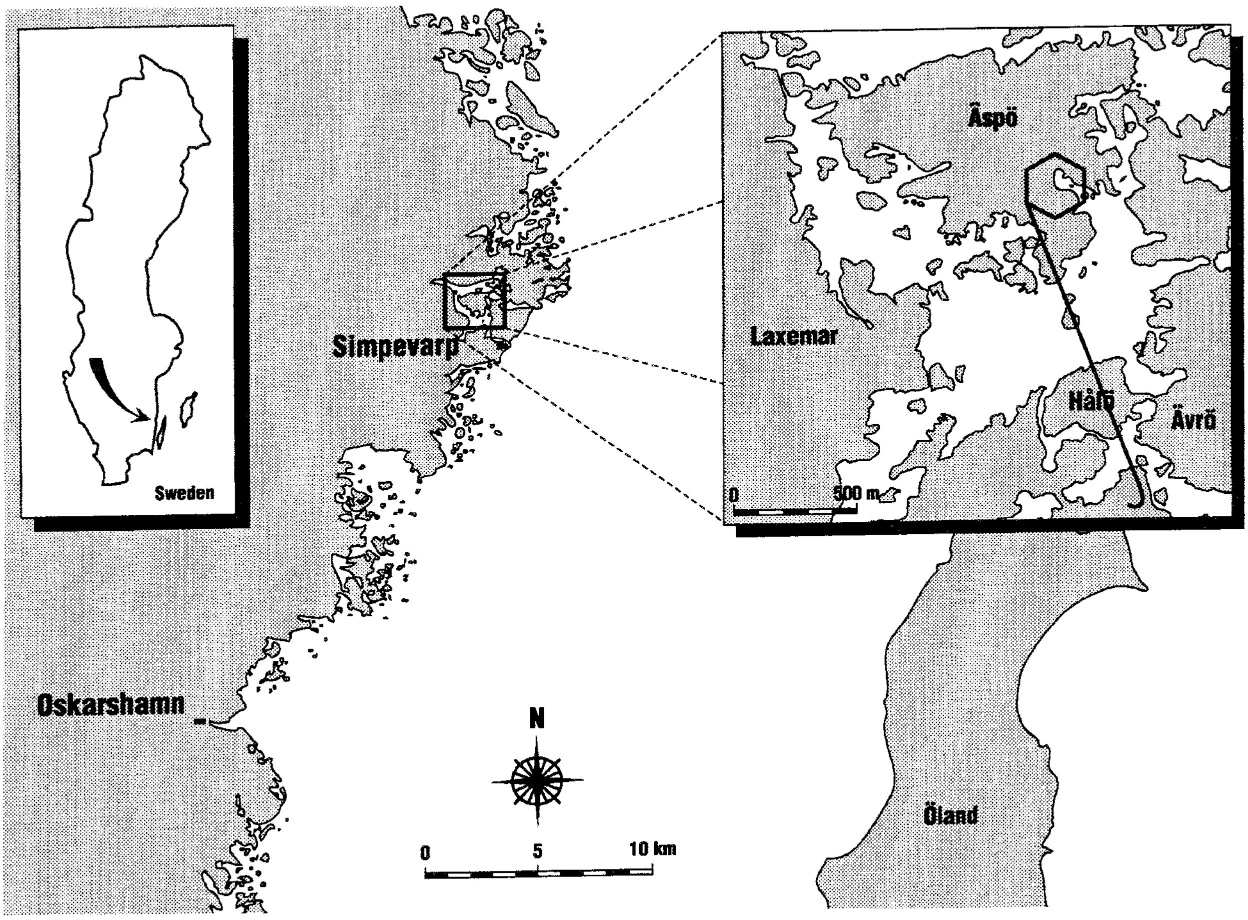


Figure 17-1. Location of the Äspö Hard Rock Laboratory.

construction of the laboratory. The investigations have been summarized in six Technical Reports /17-1 – 17-6/. The construction of the access ramp is used to check the predictive models set up from the pre-investigation phase, to develop methodology for construction/testing integration and to increase the database on the bedrock in order to improve models on groundwater flow and radionuclide migration. A programme for the operating phase has been set up, /17-7/. The operating phase is very much aimed at research and developments of models for transport of groundwater flow and radionuclide migration, tests of methods for construction and handling and pilot-tests of important parts of a repository system.

17.2 INVESTIGATIONS AND EXPERIMENTS – NEW RESULTS 1993

Stage goal 1 – Verification of pre-investigation methods

Some of the main results from the documentation of tunnel section 1475 – 2265 m (depth 200 – 300 m) are:

- On the site scale (500 m) it seems possible to make a useful prediction of the distribution of the main rock types Småland granite, Äspö diorite and finegrained granite but it seems to be more difficult to predict the distribution of greenstone.
- Based on general information about a rock mass and local cored boreholes it seems to be rather difficult to make useful predictions – on the block scale (50 m) – of the distribution of the main rock types at depth in a relatively inhomogeneous rock mass.
- It also seems possible to predict the distribution and mean number of rock boundaries to rock types.
- It seems possible to make a rather good fracture frequency and fracture density prediction on the assumption that a general model of the structural geology is established.

During 1993 several coreholes have been drilled from the tunnel with the main purpose to investigate fracture zones around the tunnel.

The major fracture zone NE-2 – which was predicted to be "major" has been demonstrated underground as 0.5 – 3 m wide strongly foliated mylonites in two sections in the tunnel. NE-2 probably comprise of two instead of one zone.

The gently dipping zone EW-5 – which was predicted as "possible" has not been possible to confirm underground.

A "swarm" of minor NNW-NNE striking fracture zones were predicted to be hydraulically important and penetrate southern Äspö area and a number of narrow fracture zones – a few metres wide – have also been mapped in the tunnel and pre-grouted sections confirm hydraulic conductors.

The water levels on southern Äspö started to decrease autumn 1991 and are decreasing during 1992 and 1993. The groundwater levels have also decreased in the surroundings. The levels on Laxemar seem to be undisturbed by the tunnel excavation. There is correspondence between the prediction and outcome. However, the predicted level is lower than the outcome. This is due, at least partly, to the measured inflow rate being lower than the predicted for the spiral but higher for tunnel section 700 – 1475 m (depth 100 – 200 m.). The outcome of the inflow to the tunnel section 1450 – 2245 m was approximately $12 \cdot 10^{-3}$ m^3/s and the predicted inflow was 150% of the outcome.

Groundwater samples have been collected from 32 different locations in the tunnel between 1475 and 2265 m. The sampling points are 25 probing holes 20 m deep at an angle of 20 – 45 degree out from the tunnel, two core drilled investigation boreholes and two water conducting spots on the tunnel wall.

In most of these sampling points the composition has been stable without any systematic change. In those cases where there has been a change it has been towards more saline water, indicating a withdrawal of more saline water from deeper levels.

Only a few of the samples have been analyzed for ferrous and ferric iron. These samples clearly show that the iron is in ferrous form and that reducing conditions prevail.

Two thirds of all samples had a bicarbonate concentration of less than 80 mg/l and the maximum concentration was 237 mg/l. For tunnel section 700 – 1475 m half of the samples had more than 500 mg/l with a maximum value of 1200 mg/l.

For sulphate the situation is the opposite. For this section the concentrations are above 150 mg/l whereas only a few samples from the preceding section reached that high. The special importance for studying the sulphate reduction is that the sulphide which is produced is a corroding agent to the copper canister. It is therefore important to know the amount of sulphide that can be produced in order to be able to estimate and calculate the rate of degradation of a copper canister. The results show that biological sulphate reduction is taking place in the tunnel section 700 – 1475 m. The quite different data from this tunnel section indicate that this process is not occurring in the tunnel section 1475 – 2265 m. Therefore the assumption that the sulphate reduction is related to the bottom sediments of the Baltic Sea seems to be appropriate.

The access tunnel has a great impact on the flow conditions and groundwater chemical composition at Äspö. Out of the five studied borehole sections three had been measured for groundwater flow rate also at undisturbed, natural gradient conditions. Already when the tunnel face was close to the major fracture zone NE-1 groundwater flow rates through these borehole sections changed markedly. The chemical composition changes slower than do flow rates and the impact on chemistry from the tunnel drainage is not clearly seen until tunnel face has breached and passed zone NE-1 at position 1450 metres. The transport of solutes is clearly increased in the system of interconnected fracture zones at Äspö when the access tunnel breaches the fracture zone NE-1.

During the Pre-investigation phase, stress measurements were conducted in some of the deep surface boreholes. Based on these early results, stress conditions at a number of locations along the access ramp were predicted.

Further stress measurements are conducted in short holes drilled from selected locations along the access ramp. The CSIRO Hollow Inclusion overcoring technique is used, and 3-5 overcoring tests are made in each borehole at a distance from the ramp sufficient to ensure that data are not influenced by excavation-induced stresses. Measurements have been completed in a total of nine boreholes distributed along the tunnel section 1050-2510 m. This corresponds vertical depths of 140 m to 330 m. In summary, measured stresses are somewhat more scattered than predicted. Possible correlations between stress variations and local geological conditions have however not yet been studied in any detail. The maximum principal stress at 300 m depth is 20-25 MPa, which is the high range as compared to background data from Scandinavia. Measured stress orientations show a very consistent, near-horizontal and NW-SE orientation of the maximum principal stress. This is in accordance with results from the surface boreholes and appears to apply for the entire site.

The evaluation of the predictions and outcomes will be used to assess pre-investigation methodology prior to the site characterization of the sites for the Swedish deep repository. To evaluate all experiences gained so far a special experience report is under way.

Stage goal 2 – Finalize detailed investigation methodology

The detailed characterizations will encompass investigations during construction of shafts/tunnels to repository depth. Finalizing the detailed investigation methodology is stage goal 2 of the Äspö project.

The management of the large quantities of data has been developed to the point where SKB is now in possession of a data production methodology that meets exacting requirements on quality and overview. This methodology is directly applicable to the planned detailed characterization work for a deep repository. The methodology has been developed for conventional tunnelling.

When the deep repository is built a few years after the turn of the century, TBM will undoubtedly be the dominant method for underground rock construction. There are currently also technical means for boring downward-inclined tunnels. This means that the technology will also be of interest in connection with detailed characterization work, which is planned to start in 1998 at the earliest. In view of the above, it has been judged urgent to investigate the possibilities of TBM boring in the Äspö Hard Rock Laboratory right away.

Testing of TBM entails considerable added value for achieving this stage goal of the project. The methodology of coordinating TBM tunnelling and investigations will be tested under realistic conditions, in addition to the methodology that has already been tested in conjunction with the conventional blasting.

Several studies will be performed in conjunction with the TBM- excavation. To obtain a better understanding of the properties of the disturbed zone and its dependence on the method of excavation ANDRA, UK Nirex, and SKB have decided to perform a joint study of disturbed zone effects. The project is named ZEDEX (Zone of Excavation Disturbance EXperiment). The objectives of ZEDEX are:

- to understand the mechanical behavior of the Excavation Disturbed Zone (EDZ) with respect to its origin, character, magnitude of property change, extent, and dependence on excavation method,
- to perform supporting studies to increase understanding of the hydraulic significance of the EDZ, and
- to test equipment and methodology for quantifying the EDZ.

The ZEDEX project will be performed in conjunction with the change of excavation method from drill & blast to tunnel boring that will take place during the summer of 1994. The experiment is expected to provide a better understanding of the EDZ that will contribute to the basis for selecting or optimizing construction methods for a deep repository and its subsequent sealing.

Stage goal 3 – Tests of models for groundwater flow and radionuclide migration

It is necessary to demonstrate the safety of the deep repository over long spans of time. Important phenomena that must be taken into account in the safety assessment are:

- transport of corrodants up to the canister,
- possible transport of radioactive materials away from a defective canister.

These phenomena are in turn highly dependent on groundwater flow and chemistry.

There are today several fundamentally different models for describing groundwater flow and radionuclide transport. Great uncertainty exists regarding the accuracy, precision and reliability of the models. This uncertainty includes the theory, the ability to collect realistic data over an entire repository area, and the ability to carry out realistic calculations. It is urgent to test and demonstrate different approaches in practice in preparation for the licensing process.

A "Task Force" with representatives of the project's international participants has been formed for numerical modelling of groundwater flow and solute transport. This offers excellent opportunities for trying out alternative models in a way that would not have been possible without international cooperation. After remodelling the combined long-time pumping and radioactive tracer test LPT-2 several groups have performed scoping calculations for

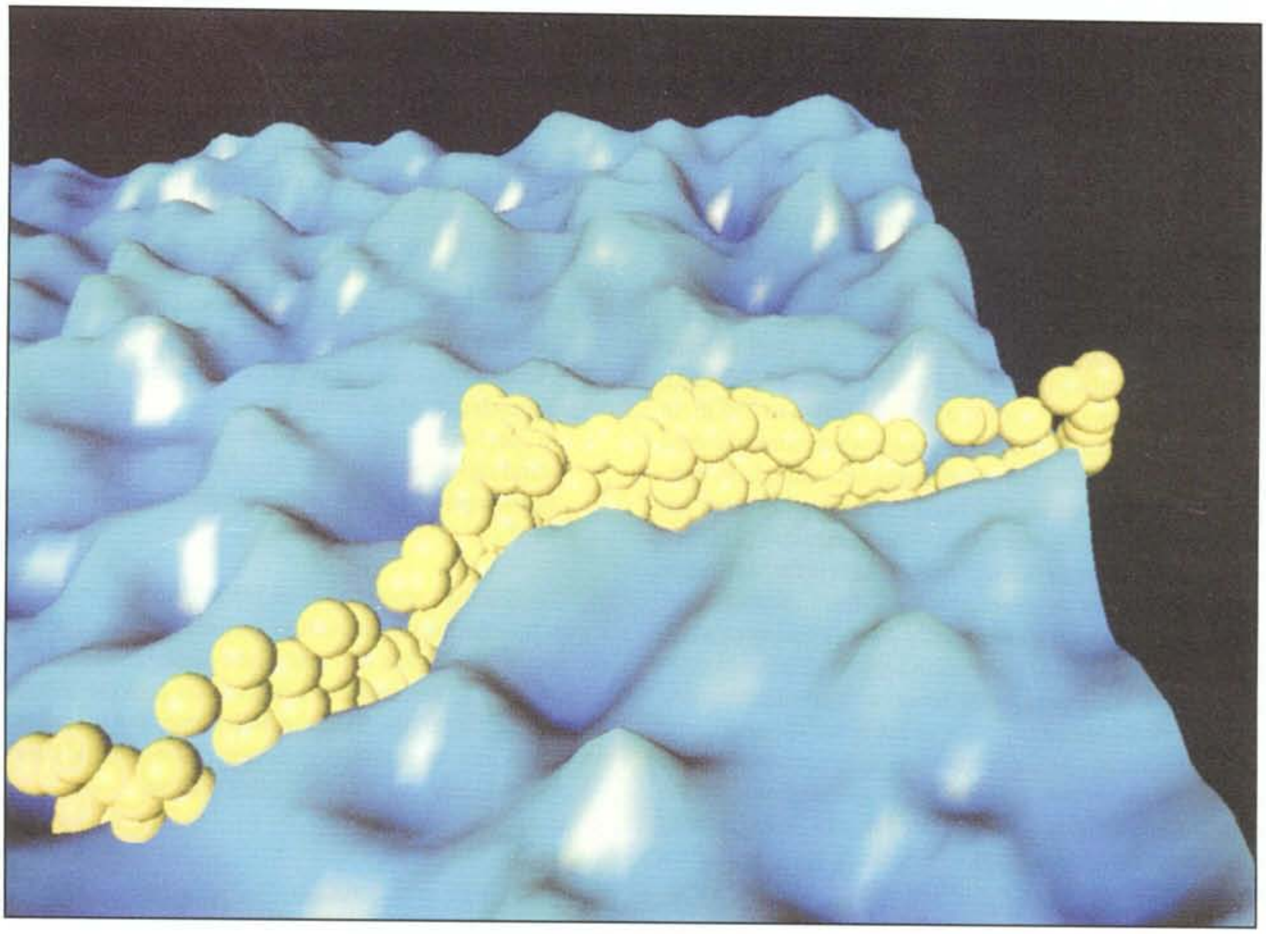


Figure 17-2. Scoping calculation for the MWTE-experiment by Urban Svensson. Tracers are injected in a three-dimensionla fracture with given aperture distribution. The flow model accounts even for molecular diffusion.

the Matrix Diffusion Experiment and the Multiple Well Tracer Experiment.

Figure 17-2 shows a simulation of tracer transport in a three-dimensional fracture accounting even for molecular diffusion.

The planning for a Degassing/Two-Phase Flow Experiment has proceeded as well as the planning for a Radionuclide Retention Experiment.

The monitoring phase of the on-going Redox Experiment continued during 1993. During this three years' period emphasis has been put on describing the chemical processes in the investigated fracture zone. The most important processes have been identified to be microbial activity and mixing. No redox break-through has been observed and the chemical composition is fairly constant. The results so far have indicated that most likely the enhanced water circulation in the fracture zone has not caused any significant penetration of oxidizing surface water. The explanation to this is that the high content of organic matter in the infiltrating surface water has been biologically oxidised at the same rate as the dissolved oxygen has been reduced. The population of bacteria has increased in order to be able to match the increased water circulation.

The objective of the Pore Volume Experiment is to provide data on the pore aperture distribution in selected fractures. The aperture distribution should provide insight on the heterogeneity and connectivity of flow paths within fractures. Such data are obtained by drilling core samples from a previously grouted fracture. Five 200 mm-diameter boreholes were drilled along the fracture plane to a depth of about 1 m. and aperture distributions have been collected. A large spatial aperture variation of the fracture can be observed from the longer profiles from the boreholes. The large variation in aperture is also reflected in the difference in ratio between average aperture and standard deviation between the smaller cores and the longer profiles.

Stage goal 4, 5 – Development of construction and handling methods, pilot test

The safety of a repository is determined by:
- the properties of the site,
- the design of the barriers,
- the quality of execution of the deep repository.

A KBS-3-type deep repository is supposed to hold about 4500 canisters in rock caverns at a depth of about 500 m. The different barriers (canister, buffer, rock) work together to isolate the waste. Backfilling/plugging of tunnels, shafts and boreholes limits the flow of groundwater via the potential flow paths opened up by the construction and investigation work, thereby making it more difficult for corrodents and any escaping radionuclides to be transported up to or away from the canisters/waste. All of this work with barriers, plugs etc. must be executed with a given minimum quality.

The Äspö HRL provides an opportunity for demonstrating technology that will provide this necessary quality. Plans for construction of an initial stage of a deep repository were presented in RD&D-92. By and large, these plans have been received positively by the reviewing bodies. The need to integrate existing knowledge and build an (inactive) prototype of a deep repository is currently being discussed within SKB. For example: A 100 m long deposition tunnel is built and backfilled on Äspö. In conjunction with planning, design and construction, work descriptions and quality plans are prepared which can later be used for the deep repository. The objectives include translating scientific knowledge into engineering practice, testing and demonstrating the feasibility of the various techniques, and demonstrating that it is possible to build with adequate quality. In conjunction with construction of the prototype proposed above, different types of models will be used to describe the performance of the prototype in conjunction with water absorption and restoration of groundwater pressures, etc. The prototype will then be monitored via a large number of measurement points for a period of 5-15 years. Following this there will be an opportunity to study in detail any chemical and physical changes in e.g. the bentonite surrounding the canisters. A pilot-study has been initiated to explore the concept further.

17.3 ENGINEERING AND CONSTRUCTION WORK 1993

The Äspö HRL facility comprises several construction parts and phases. A tunnel ramp has been excavated from the Simpevarp peninsula 1.5 km out under the Äspö island. The tunnel reaches Äspö at a depth of 200 m. The tunnel then continues in a hexagonal spiral under Äspö. The first turn of the spiral was completed in the summer of 1993. The tunnelling of this part was done by means of conventional drill and blast technique.

For the final part of the second spiral (from 430 to 450 m level), fullface boring with a 5 m diameter Tunnel Boring Machine, TBM, will be tested. The first part of the second spiral will follow a hexagonal shape and also be done by drilling and blasting. A rock cavern will be excavated at the end of this part for assembly of the TBM. The tunnel will then go down to the 450 m level close to the shafts and continue horizontally westward to an experimental rock volume.

Three shafts are being built for communication and supply to the experimental levels. Two shafts are being built for ventilation, one for fresh air and one for exhaust air. The diameter of these shafts is 1.5 m. A bigger cylindrical shaft (3.8 m) is being built for the hoist. The shafts are excavated with raise-boring technique.

Office and storage buildings for the future research work are being constructed at Äspö over the tunnel-spiral. As well as buildings for ventilation equipment and machinery for the hoist. Together, these buildings form the "Äspö Research Village", which is designed to resemble other small villages in the surrounding archipelago, see Figure 17-3. The village is under construction and will be finished in June 1994.

Excavation of the tunnel phase 2 started at the section 2600 m on level -340 m in the end of October. Contractor for the second phase is Skanska AB. Excavation with the TBM starts in June 1994, see Figure 17-4. All excavation work will be completed 1994.

17.4 INTERNATIONAL PARTICIPATION

The construction of the Äspö Hard Rock Laboratory (HRL) has attracted significant international attention. The experience being gained at Äspö concerning, for instance, site investigation methodologies, rock excavation and characterization techniques and collection of data of importance to safety assessments, will be of interest to most countries that have their own plans for deep geological disposal of nuclear waste. SKB is open to and welcomes international participation in the project. Presently (May 1994) eight organizations from seven countries participate. They are:

- Atomic Energy of Canada Limited (AECL), Canada.
- The Power Reactor and Nuclear Fuel Development Co (PNC), Japan.
- The Central Research Institute of the Electric Power Industry (CRIEPI), Japan.
- Teollisuuden Voima Oy (TVO), Finland.
- Agence Nationale pour la Gestion des Dechets Radioactifs (ANDRA), France.
- United Kingdom Nirex Limited (NIREX), Great Britain.
- National Cooperative for the Disposal of Radioactive Waste (NAGRA), Switzerland.
- United States Department of Energy (USDOE), USA.

An important part of the collaboration is groundwater flow modelling and radionuclide migration. The results of the work are reported in Äspö International Cooperation Reports.

Figure 17-3. Äspö Research Village.

Figure 17-4. The 5m diameter TBM-machine is an ATLAS COPCO Mk 15 with special features for the Äspö application.

18 ALTERNATIVE METHODS

The main direction of the SKB RD&D-programme is towards completing the first step with deposition of some 5-10% of the spent fuel in a repository within about 20 years time. In parallel the work on alternative treatment and disposal methods is followed and supported in a limited scale.

During the last few years the possibility for partitioning and transmutation has attracted renewed interest. SKB supports some work in this area at the Royal Institute of Technology (KTH) in Stockholm and at Chalmers Institute of Technology (CTH) in Gothenburg. The work at KTH is emphasized on safety related issues and at CTH on processes for partitioning.

During 1993 the KTH group completed an introductory study of accelerator transmutation of wastes (ATW) /18-1/. A brief account of the work conducted by the CTH group is given in the following sections.

SKB is also planning further research work related to the disposal in very deep boreholes. During 1993 a unique compilation of data from drilling of very deep boreholes in the former Soviet Union was published on initiative from SKB /18-2/. The report summarizes data from three holes – Kola 12260 m deep; Krivoy Rog about 5000 m deep; Tyrnauz about 4000 m deep.

18.1 CTH WORK ON PARTITIONING – INTRODUCTION

In 1991 SKB initiated a project at the Department of Nuclear Chemistry, CTH, with the aim to summarize the current state of knowledge about partitioning and transmutation (P-T). The results have been presented in the SKB Technical Report series /18-3/ and in an article in the Nuclear Engineering International /18-4/. The goal of P-T is to reduce the long-term amount (and potential risk) of actinides and long-lived radionuclides in a geologic repository.

The Department of Nuclear Chemistry, CTH, was involved in an earlier separation and transmutation project during the time period 1976-1982. This project resulted in a separation process for separation of actinides from high level liquid waste (HLLW), the so called CTH-process /18-5/. There has been a new interest in this process and the Los Alamos National Laboratory (LANL) is considering to use a similar process as part of their baseline actinide blanket processing for the accelerator transmutation of waste /18-6/.

18.2 CTH – RESEARCH PROGRAMME 1993

In 1993 a R&D project was initiated at the Department of Nuclear Chemistry, CTH, with the objective to evaluate solvent extraction processes for separation of radionuclides intended for transmutation. The project is formulated as a basic research project in solution chemistry and solvent extraction chemistry. The project is performed in international collaboration with other laboratories involved in different P-T research programmes. In 1993 one PhD student was engaged in the project, with the objective to evaluate the baseline actinide blanket separation process proposed by LANL. In the beginning of 1994 one additional PhD student will be engaged in the project with the research objective connected to the Japanese OMEGA-programme (Option Making Extra Gain of the Actinides). The PhD students will perform basic research to gain knowledge about the solution chemistry and extraction mechanisms for important elements that will be present in the partitioning processes.

18.2.1 Experimental work 1993

An experimental programme was initiated in order to investigate the extraction of various elements from nitric acid using Aliquat-336 (tricapryl-methyl-ammonium nitrate) as extraction agent. Aliquat-336 is a liquid anion exchanger consisting of a quaternary ammonium salt, where the nitrogen atom is bound to one methyl- and three alkyl-groups with 8-10 carbon atoms. The extraction of metal ions from nitrate solutions using Aliquat-336 can schematically be expressed as,

$$M^{\mu+} + nNO_3^- + (n-\mu)R_4N(NO_3)^{org} \rightleftarrows (R_4N)_{(n-\mu)}M(NO_3)_n^{org} + (n-\mu)NO_3^-$$

where $n>\mu$, $M^{\mu+}$ is a metal ion with the charge $\mu+$ and $R_4N(NO_3)$ is Aliquat-336 in the nitrate form.

The use of Aliquat-336 was proposed by LANL in their baseline separation process /18-6/. In the LANL process design plutonium, neptunium, technetium and palladium are extracted from 2 M nitric acid using 0.2 M Aliquat-336 dissolved in di-isopropyl-benzene. Plutonium and neptunium are proposed to be backextracted with 0.1 M nitric acid and technetium and palladium will be backextracted with 1 M ammonia.

There is a considerable lack of extraction data for Aliquat-336 in the literature, which motivated an ex-

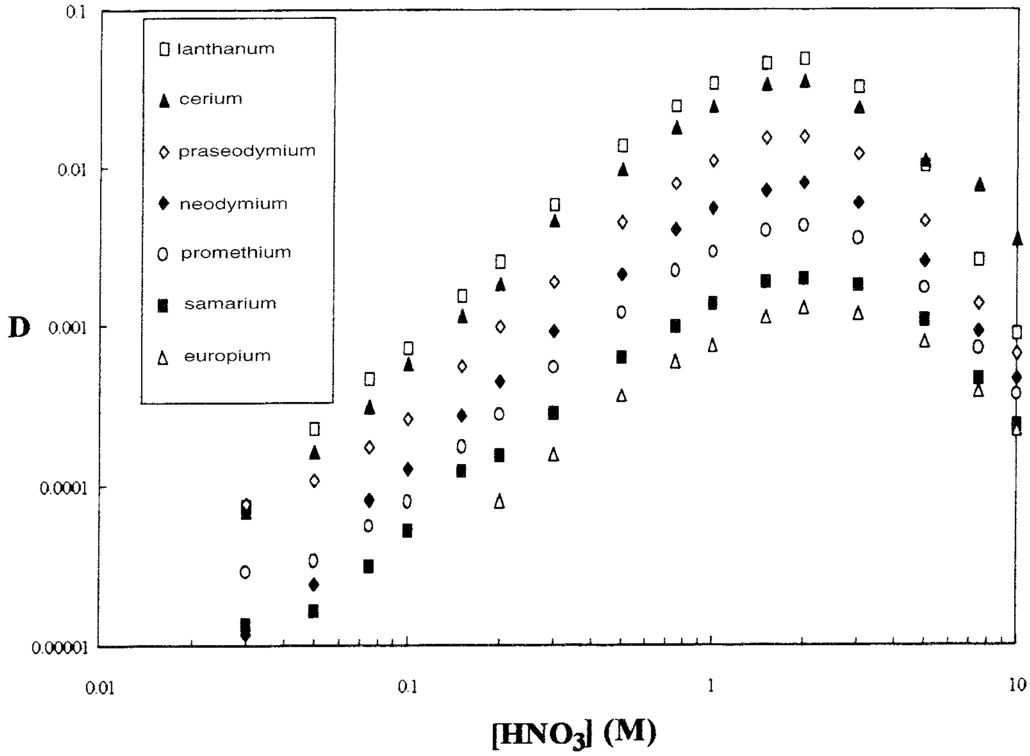


Figure 18-1. Extraction of La, Ce, Pr, Nd, Pm, Sm and Eu as a function of the initial nitric acid concentration using 0.2 M Aliquat-336 dissolved in di-isopropyl-benzene.

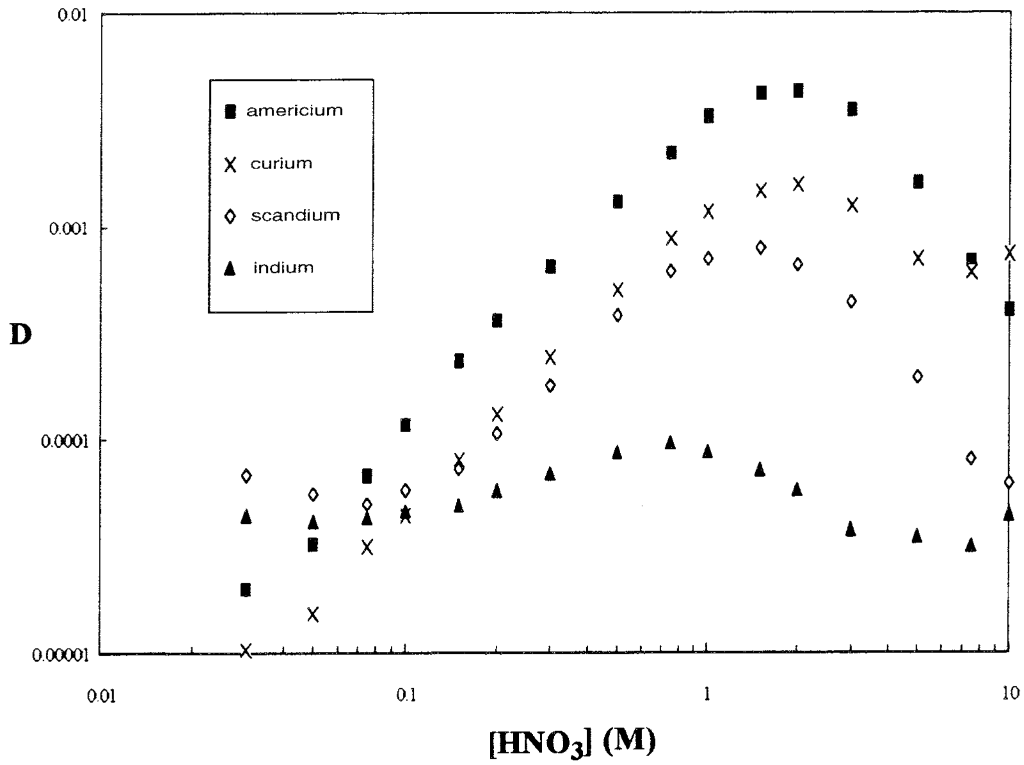


Figure 18-2. Extraction of Am, Cm, Sc and In as a function of the initial nitric acid concentration using 0.2 M Aliquat-336 dissolved in di-isopropyl-benzene.

perimental programme in order to investigate the Aliquat-336/nitric acid system. Initial process calculations of the LANL process and some preliminary experiments showed that the backextraction of plutonium and technetium from the process may not work /18-7/. Plutonium and technetium may both be accumulated in the process.

There is also extraction data missing for other elements that will be present in the process. Elements that are extracted with low yield in a single step extraction can cause problems if the process is based on multistage extraction or when high organic to aqueous flow rate ratios are used. This motivated the first phase of the experimental programme, to investigate the extraction behaviour of trivalent elements with Aliquat-336. Trivalent elements are present in the process as fission products (e g lanthanides) and some minor actinides (e g americium and curium). Some extraction results of trivalent elements as a function of the nitric acid concentration are shown in Figures 18-1 och 18-2. The results are presented as distribution ratios (D-values), i e the total concentration of the element M in the organic phase divided by the total concentration in the aqueous phase. The low extraction of trivalent elements is due to the difficulties for these elements to form anionic complexes with nitrate ions and the competing extraction of nitric acid with Aliquat-336. Initial process calculation shows that the investigated elements will not cause any problems in the LANL process.

One of the most important parameters needed, in order to evaluate the extraction mechanisms using Aliquat-336, is the extraction of nitric acid. An experimental programme to investigate the extraction of nitric acid has therefore been initiated.

During 1993 an experimental programme was also started to study the extraction of actinides in the tetravalent oxidation state. Several of the actinides will be present in different oxidation states, at the same time, if no action is taken to control the oxidation states. An experimental programme using thorium as a tetravalent reference element was therefore initiated. This programme will later be completed with extraction studies of tetravalent plutonium and neptunium.

The experimental results from the project in 1993 are summarized in a progress report /18-8/ and in a diploma thesis /18-9/.

The experimental programme using Aliquat-336 will continue during 1994. The programme will include extraction of actinides and a search for elements that can interfere in the separation process. Furthermore it is important to complete the extraction study of nitric acid, to study the reversibility of the extraction and to find suitable stripping reagents.

The experimental programme will be expanded during 1994 with investigations of acidic organo phosphorus and organo nitrogen compounds that may have the potential to be used as extraction agents for partitioning.

18.3 CTH – COLLABORATION

This CTH-project is performed in international collaboration with laboratories involved in different P-T research programmes:

- Japan Atomic Energy Research Institute, Department of Fuel Cycle Safety Research.
- Los Alamos National Laboratory, USA.
- A Swedish coordination group for P-T research at universities and research institute.

19 INTERNATIONAL COOPERATION

An important part of SKBs programme is to follow the corresponding research and development work conducted in other countries and to participate in international projects within the field of nuclear waste management.

These efforts give positive results in many ways e g:

- contributions to method– and model development,
- broadened and strengthened databases,
- exploration of alternatives for repository and barrier design, material selection etc.,
- insights in programmes to broaden the public confidence in waste management systems.

The international work gives a perspective to the domestic programme and is an aid to the SKB strive for maintaining state-of-the art in relevant scientific areas of nuclear waste management.

19.1 SKBs BILATERAL AGREEMENTS WITH FOREIGN ORGANIZATIONS

SKB has signed formal bilateral agreements with the following organizations in other countries:

- USA – US DOE (Department of Energy),
- Canada – AECL (Atomic Energy of Canada Ltd) and ONTARIO HYDRO,
- Switzerland – NAGRA (Nationale Genossenschaft für die Lagerung Radioaktiver Abfälle),
- France – CEA (Commissariat à l'Energie Atomique), ANDRA, DCC and IPSN,
- EC – EURATOM,
- Finland – TVO and IVO,
- Russia – MINATOM
- Japan – JNFL (Japan Nuclear Fuel Ltd.).

The formal agreements are similar in their construction and cover information exchange and cooperation within handling, treatment, storage and final disposal of radioactive waste. Exchange of up-to-date information (reports), as well as results and methods obtained from research and development, are main points in the agreements. Arranging joint seminars and short visits of specialists to other signatories' facilities are other examples of what is included within the framework of the agreements. General reviews of the signatories' waste programmes and activity planning are held at approximately one-year intervals.

In the case of exchanges of personnel of long duration or extensive direct project cooperation, special agreements are generally concluded within the framework of the general agreement.

SKB also has information exchange without formal agreements with organizations in the other Nordic countries, Germany, Belgium and Great Britain.

19.2 COOPERATION WITH DOE, USA

The cooperation between USDOE and SKB during 1993 has mainly been focused on activities lined out in the joint project agreement concerning the Äspö Hard Rock Laboratory, see section 19.13.

19.3 COOPERATION WITH AECL, CANADA

During 1993 SKB has reviewed parts of the draft of the AECL Environmental Impact Statement document. AECL has taken part in the Äspö Hard Rock Laboratory international meetings.

19.3.1 Natural analogues

Concerning the joint AECL/SKB work at Cigar Lake see section 15.6.2.

19.4 COOPERATION WITH NAGRA, SWITZERLAND

SKB has during 1993 had an extensive cooperation with NAGRA. Some of the items involved have been

- safety analysis and performance assessment,
- natural analogue studies, see section 15.6.1,
- underground construction material performance, see section 15.5.4.

19.5 COOPERATION WITH CEA, FRANCE

19.5.1 Natural analogues

SKB is engaged in the CEC sponsored natural analogue project in Oklo which CEA is managing, see section 15.6.3

19.5.2 Instruments

IPSN/CEA in Cadarache, France, has performed development work on a borehole probe (CHEMLAB)

19.6 COOPERATION WITH EURATOM, CEC

19.6.1 COCO

The working group COCO (Colloids and Complexes) was formed by CEC to explore the importance of colloids and organic complexes for the migration of radionuclides. An important part of the cooperation is comparative experiments with different methods used at different laboratories. SKB is supporting the participation of a Swedish specialist active within the field.

19.6.2 CHEMVAL

The first phase of the CEC project CHEMVAL for verification and validation of chemical equilibrium calculation programs and coupled models for geochemistry transport was finalized and reported during 1990. A new phase of the CHEMVAL project called CHEMVAL2 started up during 1991 with participants from the EC countries, Sweden, Finland and Switzerland. The project will run from 1991–1994 and will comprise temperature effects, ion strength effects, organic complexes, sorption, coprecipitation and coupled geochemical transport, see section 15.5.1.

19.6.3 Natural Analogue Working Group

Natural Analogue Working Group (NAWG) is an international group working with natural analogues and their use in the safety assessment modelling. It's organized by CEC.

SKB has been represented in this group since its start in 1985. Presently one of SKB consultants, Dr John Smellie, is the chairman of the group.

19.7 COOPERATION WITH TVO, FINLAND

SKB has a very close cooperation with TVO in many fields of the research on nuclear waste management. Following areas have during 1993 been the most active cooperation items:

- Safety analysis.
- Exchange of experience and technology for site investigation. Finnish representatives are included in the reference group for the Hard Rock Laboratory.
- Waste canisters.
- SKB is following the investigations at a uranium mineralization in Palmottu as an observer.

SKB and TVO scientists have during 1993 had numerous meetings where information and experience exchange have been carried out.

19.8 COOPERATION WITH RUSSIA

The formal cooperation set up with the former organization SCUAE in 1988 has during 1993 been inactive. The present situation in Russia has blocked the financial possibilities from the Russian side to perform necessary meetings and seminars to fulfil the intended cooperation.

During 1993 SKB has cooperated with a Russian company involved in deep drilling activities. The cooperation has resulted in very interesting scientific data relating to the deep borehole repository concept, see Chapter 18.

19.9 COOPERATION WITH JNFL, JAPAN

During 1993 the cooperation has been carried out through study visits at SKB facilities and through informal information exchange meetings.

19.10 COOPERATION WITHIN OECD NUCLEAR ENERGY AGENCY

19.10.1 RWMC

One of OECD/NEA's principal areas of cooperation is radioactive waste management in the member countries. These questions are dealt with by the **Radioactive Waste Management Committee (RWMC)**, where SKB is represented through Per-Eric Ahlström. Some work is carried out in joint international projects, and working groups are formed to facilitate information exchange or prepare material as a basis for joint opinions or coordination.

Seminars and workshops are arranged within important areas to document and discuss the state of development and the direction of future work.

The groups and projects within the area of radioactive waste management where SKB during 1993 was providing personnel or funding are listed below.

PAAG (Performance Assessment Advisory Group) functions in an advisory capacity to RWMC in matters pertaining to cooperation on means and methods for performance and safety analyses of final disposal systems.
Member from SKB: Tönis Papp

SEDE (Site evaluation and design of Experiments for Radioactive Waste Disposal) functions in an advisory capacity to RWMC in matters pertaining to the activities of experimental work in the member countries.
Member from SKB: Lars-Olof Ericsson

PSAG (Probabilistic Safety Assessment Group) is a cooperation group between those who develop and those who use mathematical models for probabilistic analyses of repository systems. The emphasis lies on coordinating the development and comparing the quality of the models.
Member from SKB: Nils Kjellbert

Cooperative Programme for the Exchange of Scientific and Technical Information Concerning Nuclear Installation Decommissioning Projects is a forum for information exchange and cooperation on various decommissioning projects all over the world.
Member from SKB: Hans Forsström. SKB is also sponsoring a programme coordinator, Shankar Menon, Studsvik Energiteknik AB.

Expert Group on Geochemical Modelling and Data deals with matters of common interest within geochemistry, including the buildup of a common thermodynamic database TDB and augmentation of the database for sorption data, SDB.
Member from SKB: Fred Karlsson

Working Group on the Assessment of Future Human Actions at Radioactive Waste Disposal Sites deals with different aspects on human intrusion into waste repositories. The group was initiated in 1990.
Member from SKB: Torsten Eng.

19.10.2 TDB

The TDB Project (Thermochemical Data Base) is under the direction of OECD/NEA. The goal is to develop a chemical thermodynamic database for a number of elements that are of importance for the safety assessment of the final disposal of radioactive waste. The development of the database entails not only collecting and storing published data, but also critical review. Review is carried out by a group of international experts selected for each element. At present the work is concentrated on neptunium, plutonium, americium and technetium. The uranium database was the first to be completed.

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

19.10.3 INTRAVAL

INTRAVAL is an international project whose purpose is to validate calculation models for radionuclide transport in the geosphere. The project is a follow-up of the previous projects HYDROCOIN and INTRACOIN. All of these projects were initiated by SKI, which also appointed the secretariat that coordinates the work within INTRAVAL.

A total of 14 test cases were included in the project phase I, which involved evaluation of results of selected laboratory tests, field tests and studies of natural analogues. In many of the cases, it was possible for different model groups to perform predictive modelling before the measurement results had become available.

Five of the fourteen test cases were SKB-linked:

- laboratory tests of migration in overcored fractures/KTH,
- tracer tests at Finnsjön within the fracture zone project/SGAB,
- Stripa 3D migration/KTH,
- Poços de Caldas Project,
- colloid transport/BGS,
- redox front/KTH.

The detailed results of INTRAVAL phase I were published during 1991.

Phase II of INTRAVAL started in 1990. This phase emphasizes on validation efforts based on field studies and natural analogues. The number of test cases are less than in phase I and cover validation issues like scale dependency, heterogeneity and coupled processes. SKB is supplying data for this study.

19.11 COOPERATION WITHIN IAEA

Cooperation has during 1993 also been conducted within the International Atomic Energy Agency, IAEA, concerning the management of radioactive waste.

The cooperation is conducted in different ways, including the publication of reports consisting of:

- proceedings from international symposia,
- guidelines and standards within established areas of activity,
- status reports and methodology descriptions within important areas undergoing rapid development.

IAEA has an expert advisory group for its waste management programme (the International Waste Management Advisory Committee, INWAG) and arranges for information exchanges within different special areas through Joint Research Programmes. IAEA publishes an annual catalogue on current research projects within the waste management field in the member countries.

An important new IAEA initiative is the RADWASS programme to work out international safety standards and guidelines. SKB will participate in the Standing Technical Committee for Disposal within the RADWASS programme.

19.11.1 VAMP

SKB is participating in an IAEA/CEC program on "Validation of Models on the Transfer of Radionuclides in Terrestrial, Urban and Aquatic Environment and Acquisition of Data for that Purpose" (VAMP), see section 15.7.

19.12 OTHER INTERNATIONAL COOPERATION

19.12.1 BIOMOVS

As indicated in section 15.7 SKB is participating in an international cooperative study BIOMOVS II (BIOspheric MOdel Validation Study) to test models for calculation of environmental transfer and accumulation of radionuclides in the biosphere. SKB has during 1993 taken active part in the reference scenario definition work as well as a validation study concerning C-14 in lakes.

19.12.2 DECOVALEX

Interest in developing coupled models has increased in recent years. The purpose is to be able to describe conditions in the near field of a repository in particular with greater realism. Within the framework of the DECOVALEX project (international cooperative project for the DEvelopment of COupled models and their VALidation against EXperiments in nuclear waste isolation), development and verification of coupled thermo-hydro-mechanical models is being conducted. SKI initiated the project during 1992 and is also the organization in charge of its execution. Nine countries are participating in the project which will run up to 1995, see section 15.4.5 .
Member from SKB: Lars-Olof Ericsson.

19.13 INTERNATIONAL COOPERATION IN THE ÄSPÖ HARD ROCK LABORATORY

As is mentioned in Chapter 19 the Äspö HRL has gained great international interest. The following organizations have up to the end of May 1994 signed agreements to cooperate in joint work at the Äspö HRL:

- AECL, Canada,
- PNC, Japan,
- CRIEPI, Japan,
- ANDRA, France,
- TVO, Finland,
- UK NIREX, UK,
- USDOE, USA,
- NAGRA, Switzerland.

Most of the participating organisations have one or several groups working on models for groundwater flow and radionuclide migration. To coordinate this work a special Task Force has been formed.

For further information, see the Äspö Hard Rock Laboratory Annual Report 1993 /13-5/.

20 DOCUMENTATION

The scientific work in the SKB programme is documented at different levels:

- in reports requested by law and submitted to the Swedish Government or its authorities such as KBS-3, RD&D-Programme 92 and Plan 92,
- in the series of SKB Technical Reports, in contributions to scientific journals, symposia and conferences in different subject areas, see Appendix 2,
- in SKB Arbetsrapporter,
- in internal SKB memos,
- in technical memos and notes.

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

20.1 TECHNICAL REPORTS

SKB Technical Reports and many main reports, like for instance the KBS-3 report, are written in or translated to English. They are given a broad distribution to the scientific community in the nuclear waste management field in order to get feedback to the program by the comments, discussions and contacts between specialists that they may give rise to. SKB Technical reports are filed as microfiche at IAEA in Vienna and are available through them. Abstracts of the 1993 Technical Reports are included in part IV of this Annual Report.

20.2 CONTRIBUTIONS TO PUBLICATIONS, SEMINARS ETC

The contributions to conferences, symposia and scientific journals have been extensive during 1993, see Appendix 2.

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

20.4 LONGEVITY OF INFORMATION

A working group of the Nordisk Kärnsäkerhet (NKS) presented in 1993 a report on the possibilities for long-term conservation and retrieval of information about nuclear waste repositories /20-1/. Two main strategies were identified for long-term information transfer, one which links information through successive transfers of archived material and other forms of knowledge in society and one relying on a direct link from the present to the distant future – such as use of markers of different kinds at the repository site. Both strategies may be used, depending on site-specific circumstances.

The Nordic countries have a long tradition and good experience in archiving. If high quality paper is used together with appropriate writing media the estimated lifetime of documents can be several hundreds of years. The same order of estimated lifetime is applicable to microfilm. Digital methods of storing information in a long time perspective (> 10 years) are not recommended since the technical development in this area is rapid and readability of old information can not be guaranteed more than a few years. For structuring and summarizing valuable information and as a tool to produce information documents with long lifetime (on paper or microfilm), the digital media is excellent.

To ensure that information regarding the radioactive waste repositories will be available for a very long time ahead, the duplication principle can also be applied. If the most valuable parts of the information bulk (the primary information) are summarized and duplicated (second, third ... level information) and then placed in regional, national and/or international archives, the probability of loosing essential parts of the information is minimized.

20.5 SKB BIBLIOGRAPHICAL DATABASE

SKB has built up a database containing bibliographical data and abstracts on all reports currently available in the SKB library. The database, called BIBAS, contained by the end of 1993 about 9 000 references. The software used to manage the database is AskSam which has a powerful free-text search capability.

20.6 THE GEOLOGICAL DATABASE SYSTEM – GEOTAB

The data from the geological site investigations, including the Äspö hard rock laboratory, is managed by and brought together in GEOTAB, a common database system. The aim of this database system is threefold, namely to

- facilitate retrieval and combination of data from different disciplines,
- provide an archive, independent of the different data collecting contractors,

– assure the quality of measurements and calculations performed.

20.6.1 Technical

GEOTAB is a so called relational database, giving the investigator the possibility to freely select and combine information. The stored data can be kept at the high initial quality due to the implied data structure. In 1993 the database was ported from a VAX system running the database manager MIMER to a SUN (UNIX) workstation running INGRES. This port meant better response times, better integration with other programs (PC and UNIX), better consistency control and better auditing and logging. The codes are generally written in the either the language C, using 3-GL calls to the database manager, or in the 4-GL languages VISION or WINDOWS-4GL (INGRES). Typical response times are 1 to 20 seconds for a selected retrieval from two combined tables with 1.000 records in each.

20.6.2 Structure

Like all relational databases the data tables in GEOTAB are free tables that each contains a set of information. In this database there is many tables though – about 500. To facilitate retrieval they are also hierarchically structured in "sciences", "subjects" and "methods". The set of tables making up a "method" are normally one or two "flyleaf" tables, a comment table, some data tables and possibly some calculated data tables. The "flyleaf" tables contain information about who, when, equipment and other features of the measurement. A set of "methods" makes a "subject" and a set of "subjects" and "methods" makes a "science".

20.6.3 Documentation

The data acquisition techniques are documented in technical reports /20-2, 3, 4, 5, 6/. As new measuring methods and data acquisition techniques are applied, new methods and tables are created and the documentation is completed with working reports. Overview /20-7/ and Users Guide /20-8/ are of course important documents for the occasional user. All documentation is in English.

20.6.4 Content

The data stored in the database are of course limited to what can be captured in letters and digits. The open concept however allows other programs to directly interact with the database thus extending the use of the database to geometrical or graphical information used in CAD (Computer Aided Design) and GIS (Graphical Information System) systems.

The database now contains surface data from 43 sites and data from 489 boreholes in many of these. Total borehole length that is investigated is about 150 km.

20.6.5 Statistics

Data are as mentioned above structured in "sciences", "subjects" and "methods" and tables. Currently there are about 500 tables containing 4932 columns and about 4.1 millions of tupels (lines). In addition there is one log table corresponding to each data table and some 50 tables containing system and meta data (information about the hierarchical structure, units, formats), totalling to more than 1000 tables. The integrity of the data is maintained with a system of insert and update rules, currently about 1700 rules and 1250 procedures.

Total data volume is about 1.5 Gbyte.

20.6.6 QA routines

The system is designed to have new data continuously fed into it with a time lag varying between one day and some weeks, depending on which quality-assurance routines that must be applied. Due to the difficulties with primary data collected in dBase format at the Äspö laboratory and validation of these data, this time lag is now more than one year for some data. A special application (SADB) has been designed to solve this problem using an ingres database with a user friendly graphical user interface (GUI). After entry in GEOTAB the stored data is checked again by the investigator and signed off.

20.7 COMPUTER SYSTEM AT SKB

An overview of the network and the computers at SKB is shown in Figure 20-1.

20.7.1 Computer network – LAN and WAN

The computers owned by SKB are placed in four physical locations; the office at Brahegatan, the computer room at Birger-Jarlsgatan (both in Stockholm), the office of Äspö Hard Rock Laboratory, north of Oskarshamn and the office in Storuman 800 km north of Stockholm.

The computers at all sites are connected to a local area network (LAN type "thin wire ethernet"). The LANs are connected via two pairs of ethernet bridges, operating over leased 64 kbps lines, SUN workstations routing the traffic via ISDN connections, making the segments appear as one.

Only one standard protocol is used in the network – TCP/IP. TCP/IP is used by all connected computers (nodes) and also used for PC networking, terminal sessions, NIS, DNS, mail and file transfer.

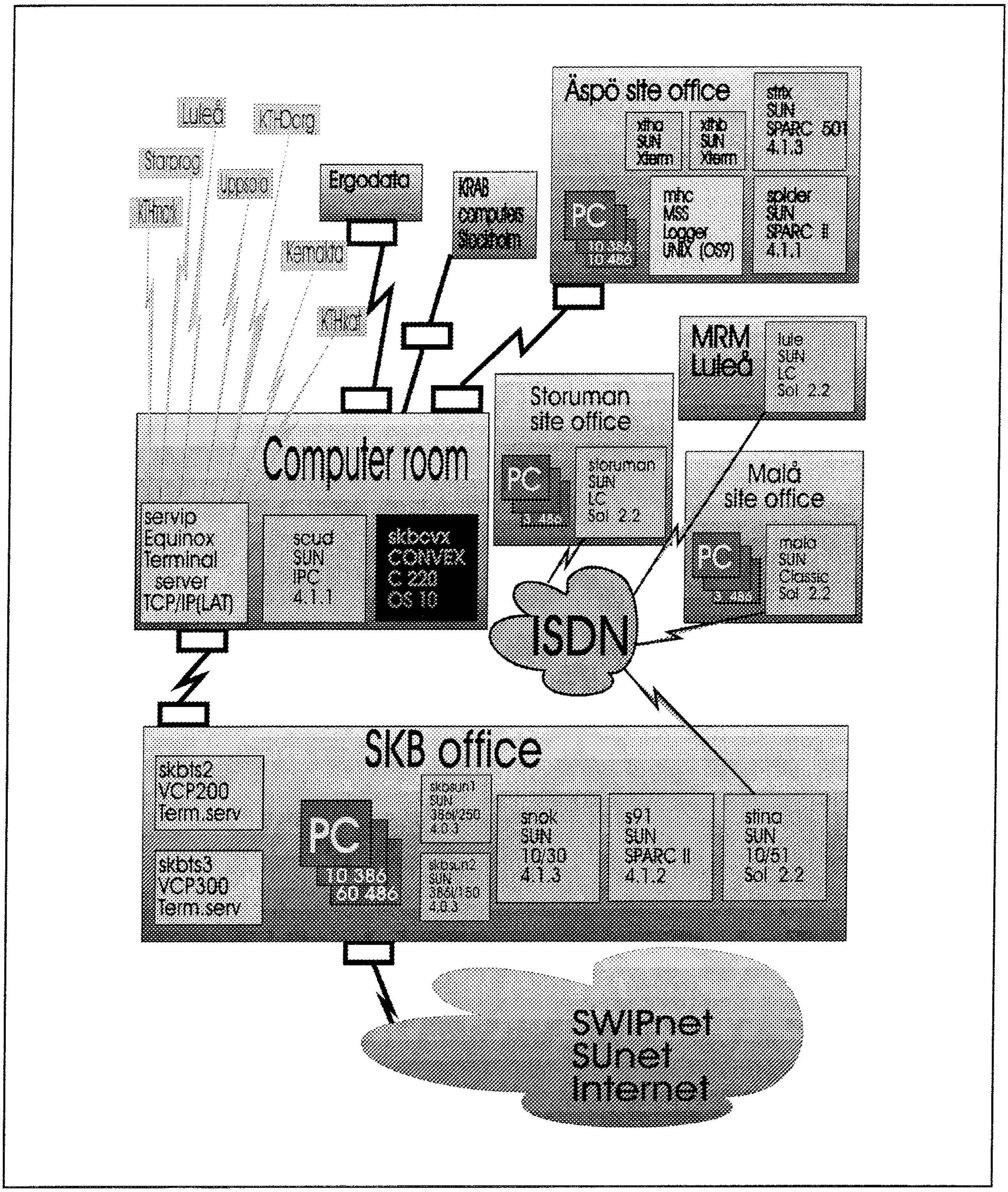


Figure 20-1. *The SKB computer network.*

The SKB network is very open in the sense that a user at any node can log into any other node (except PCs), depending on his rights. Most filesystems are shared throughout the whole SKB network.

The connection to the Internet is used for incoming terminal and file transfer sessions, making it possible for contractors at the Swedish universities as well as in UK and US, to work interactively with our computers and browse our databases. This incoming access is limited to a few identified hosts and to certain types of traffic but outgoing access is unlimited.

As SKB is contracting several companies for different work in the computer system a wide area network (WAN) for terminal lines has emerged during the years. Currently

40 lines are connected to the computers in the computer room. Of these, 9 are used as dialup lines (2 in Gothenburg) and the rest connected via multiplexors and leased lines to 9 different sites in Stockholm and to Uppsala, Luleå and Gothenburg.

20.7.2 Electronic mail

The mail systems in all multi user machines are integrated and externally connected to the E-mail international mailing system, covering 90% of all UNIX machines worldwide. All UNIX and PC users have a worldwide E-mail address on the form skbsn@skb.se where "sn" is the person's initials, the preceding "skb" identifies the organization and "skb.se" identifies the SKB network domain. During 1994 mail applications for PCs are planned.

20.7.3 Minisupercomputer

The CONVEX C220 is a 2-processor vector computer. It has been very easy to operate, running 24 hours a day with no major problems and with the expected vector capacity of about 24 Mflops (floating point operations per second). The operating system is a BSD UNIX 4.3 system with system V extensions. The current hardware configuration is 128 Mbyte main memory, 6 Gbyte on 6 disks, a 6250 bpi tape drive, 2 ethernet transceivers and 16 asyncronous ports.

20.7.4 Workstations and measuring system

Currently 11 SUN workstations are mainly used as PC network servers and communication servers, but they are of course also used as personal workstations and for presentation purposes (CAD at Äspö).

The different data media coped with are Exabyte tapes (2 and 5 Gb), QIC tapes (0.15 and 0.3 Gb), CDs, 1/2-inch tapes and diskettes.

The main machine in the automatic measuring system at Äspö is also a UNIX-like system, connected to the network, sharing disk and backup device with a SUN workstation and accessible from the all other nodes in the WAN.

20.7.5 PC network

The networking software used for PC networking is PCNFS from SUN Microsystems. The main use is to keep a common secure file system, making document transfer very easy and the common software and standards consistent throughout the company. A PC in this LAN is served by several file servers simultaneously, to improve performance, at least one server has been sited at each site. A typical PC is nowadays a 486/66 with at least 200 Mb disk running DOS 5 Windows 3.1, WordPerfect 5.2 and others.

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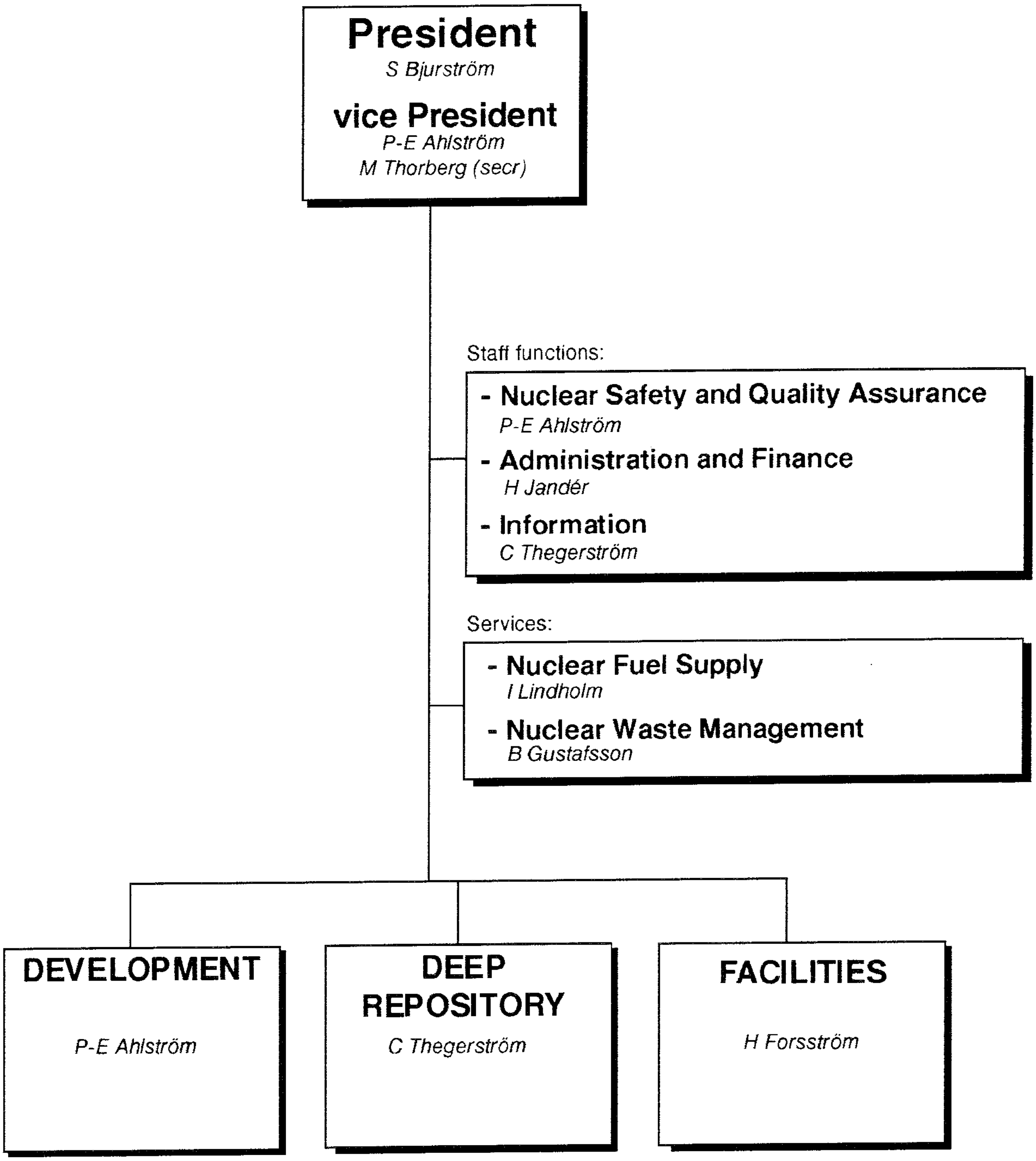

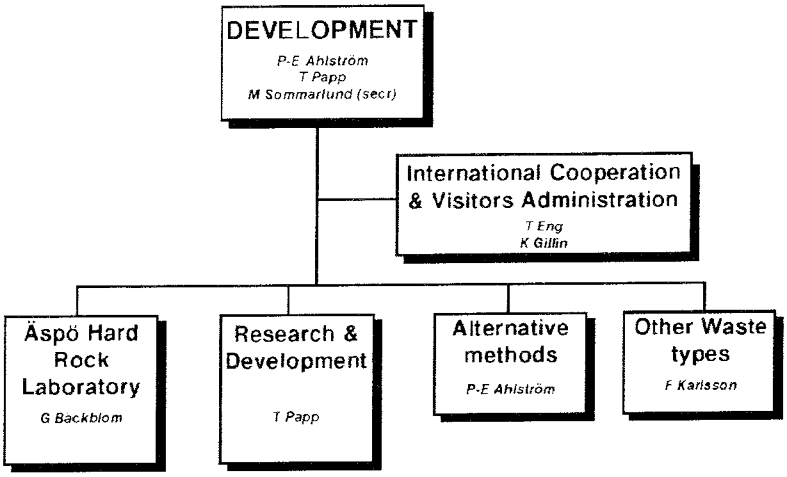
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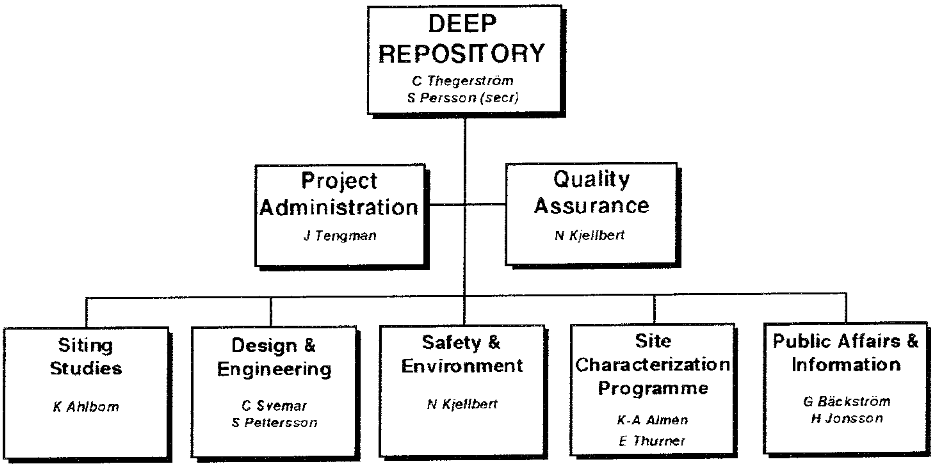
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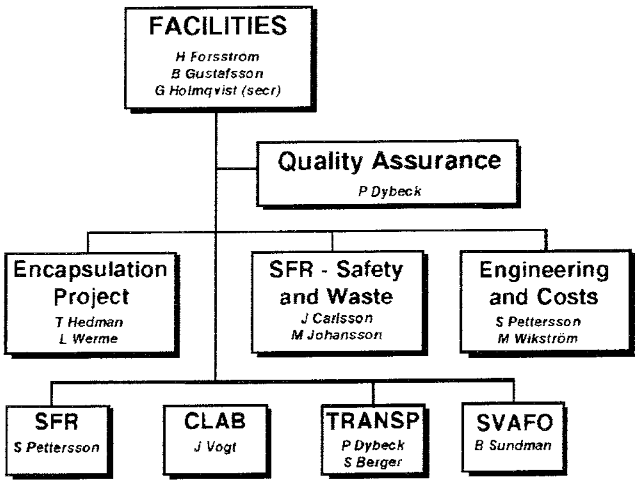
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Part IV

Summaries of Technical Reports Issued during 1993

SKB Technical Report 93-01

Stress redistribution and void growth in butt-welded canisters for spent nuclear fuel

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February 1993

ABSTRACT
The stress redistribution in Cu-Fe canisters for spent nuclear fuel during waiting for deposition and after final deposition is calculated numerically. The constitutive equation modelling creep deformation during this time period employs values on materials parameters determined within the SKB-project on "Mechanical integrity of canisters for spent nuclear fuel". The welding residual stresses are redistributed without lowering maximum values during the waiting period. A very low amount of void growth is predicted for this type of copper during the deposition period. This leads to an estimated very large rupture time.

SKB Technical Report 93-02

Hydrothermal field test with French candidate clay embedding steel heater in the Stripa mine

Pusch, R 1); Karnland, O 1); Lajudie, A 2); Lechelle, J 2); Bouchet, A 3)

Clay Technology AB, Sweden 1); CEA, France 2); Etude Recherche Materiaux (ERM), France 3)

December 1992

ABSTRACT
Field experiments with French kaolinite/smectite clay heated up to 170°C in boreholes in granite were conducted for 8 months and 4 years. The clay heated for 8 months had a considerably higher water content and it had undergone much less changes in mineralogy and physical properties than the clay exposed to heating for 4 years. The drying of the latter clay was probably caused by hydrogen gas from corrosion of the heater. The clay next to the heater turned into clay-stone despite conversion of the kaolinite component to smectite.

SKB Technical Report 93-03

MX 80 clay exposed to high temperatures and gamma radiation

Pusch, R 1); Karnland, O 1); Lajudie, A 2); Decarreau, A 3)

Clay Technology AB, Sweden 1); CEA, France 2); Univ. de Poitiers, France 3)

December 1992

ABSTRACT
MX-80 bentonite saturated with pressurized weakly brackish water, was heated up to 130°C with and without gamma-radiation for 1 year. The smectite content remained largely intact while accessory minerals like feldspars were strongly affected. The hydraulic conductivity was not altered but slight cementation by precipitated silica took place.

SKB Technical Report 93-04

Project on Alternative Systems Study (PASS). Final report

October 1992

ABSTRACT
Alternative repository systems for deep disposal of spent fuel and different types of canisters are studied regarding technical aspects in Project on Alternative Systems Study (PASS). The objective is to present a ranking of repository systems as well as of canister types for each system.

The studies and compared systems are: KBS-3, Medium Long Tunnels (MLH), Long Tunnels (VLH) and Deep Boreholes (VDH). For KBS-3 and MLH five canister types are compared (copper/steel, copper/lead, copper (HIP), steel/lead and steel), for VLH two types (copper/steel and steel), and for VDH three types (titanium concrete with non-consolidated fuel assemblies, titanium concrete with consolidated assemblies, and copper (HIP) with non-consolidated assemblies).

The comparison is separated into three sub-comparisons (Technology, Long-term performance and safety, and Costs), which eventually are merged into one ranking.

With respect to canister alternatives the result is that the copper/steel canister is ranked first for KBS-3, MLH and VLH, while the titanium/concrete canister is ranked first for VDH (non-consolidated as well as consolidated assemblies). With these canister alternatives the merged ranking of repository systems results in placing KBS-3 slightly in front of MLH. VLH comes thereafter and VDH last.

SKB Technical Report 93-05

Studies of natural analogues and geological systems. Their importance to performance assessment

Brandberg, Fredrik 1); Grundfelt, Bertil 1); Höglund, Lars Olof 1); Karlsson, Fred 2); Skagius, Kristina 1); Smellie, John 3)

Kemakta Konsult AB 1); SKB 2); Conterra AB 3)

April 1993

ABSTRACT

This review has involved studies of natural analogues and natural geological systems leading to the identification and quantification of processes and features of importance to the performance and safety of repositories for radioactive waste. The features and processes selected for the study comprise general geochemical issues related to the performance of the near- and the far-field, the performance and durability of construction materials and the effects of glaciation. For each of these areas a number of potentially important processes for repository performance have been described, and evidence for their existence, as well as quantification of parameters of models describing the processes, have been sought from major natural analogue studies and site investigations. The review has aimed at covering a relatively broad range of issues at the expense of in-depth analysis. The quantitative data presented are in most cases compilations of data from the literature; in a few cases results of evaluations made within the current project are included.

The results of the study show that studies of natural analogues and natural geological systems have provided significant information regarding many issues of importance to repository performance. In several cases the evidence from natural analogues has demonstrated that processes assumed to take place in repositories actually occur in natural systems or under conditions similar to those predicted to prevail in a future repository. One example of such a process is coprecipitation of fission products and ferric oxyhydroxides as an analogue to corrosion products from a steel canister. In addition, the study of concentration gradients of uranium and other trace substances in the rock surrounding groundwater conduits confirm that matrix diffusion occurs in nature and that the diffusivities in the rock matrix measured in the laboratory are consistent with the observations in nature. Furthermore, observations within natural analogue studies of colloids associated with uranium, thorium and rare-earth elements indicate that colloids do not appear to transport significant amounts of these' trace elements. This would suggest that either the sorption of the trace elements onto the colloids is reversible or the mobility of the colloids is low due to filtration effects or other phenomena.

Observations from natural systems and archaeological artefacts have been used to demonstrate the durability of the different materials comprising the near-field multibarrier system. Studies of copper and steel, bentonite and various types of cement and concrete strongly support the credibility of predicting long-term stability of these materials under repository conditions.

Increasingly, natural analogue studies are providing the opportunity to test the thermodynamic solubility and speciation codes and associated data bases used in performance assessment. This has been carried out with some success. However, in situ speciation measurements are necessary to rectify the large uncertainties which still exist for some elements in the data bases.

In general, natural analogue studies are progressively making their impact felt on repository performance assessment, in particular studying processes which have been occurring over time scales compatible with those predicted for long-term radioactive waste disposal.

SKB Technical Report 93-06

Mineralogy, geochemistry and petrophysics of red coloured granite adjacent to fractures

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March 1993

ABSTRACT

Mineralogical, geochemical and petrophysical investigations were conducted of red-coloured alteration rims and of the neighbouring unaltered equivalents along fractures within granite from Äspö. An investigation was made also of a weak to rather strong, red-coloured granite from the Stripa mine, as well as a weak brownish-red colouration, definitely not hydrothermal in origin, of weathered rinds at a glacial polished rock surface in the Bohus granite.

When approaching the fracture planes in the Äspö granite, the most diagnostic alteration features are 1) the saussuritisation and Fe-oxyhydroxide staining of plagioclase, 2) the crystallisation chlorite pseudomorphs after biotite and 3) the hematisation of magnetite. The porosity within the alteration zones increases generally 2 to 3 times compared with the protolith rock, whereas the densities decrease by some 5 to 10 %. The oxidation of magnetite gives as much as a tenfold lowering of the magnetic susceptibility.

The red colouration of the Stripa granite is caused by hematite ± Fe-oxyhydroxide formation along microfractures, grain boundaries and, subordinately, the main minerals. Oxidisation and re-precipitated of iron liberated

during a retrograde muscovitisation of principally chlorite is interpreted to be the cause of the formation of the ferric oxides. The rather homogeneous density and porosity values of the grey and of the red-coloured granites reflect the minor, change in the mineralogy when going from fresh into altered granite.

Weathering and whitening of plagioclase in the bleached, outer zone and precipitation of small quantities of Fe-oxyhydroxides/hydroxides in the brownish-red zone cause the macroscopic colouration of the weathering rind below the glacial polished rock surface of Bohus granite. There is a marked increase in porosity from the interior fresh (c. 0.4-0.5%) towards the exterior bleached zone (c. 1.5-2%) of the subaerialy, weathered Bohus granite surface. The incipient decomposition of magnetite is shown as a slight lowering of the magnetic susceptibility of the outermost bleached zone.

SKB Technical Report 93-07

Modelling the redox front movement in a KBS-3 nuclear waste repository

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May 1993

ABSTRACT

In a KBS-3 repository for spent nuclear fuel, radiolysis can occur if canisters are breached and water comes into contact with the fuel. The oxidants produced by radiolysis may migrate into the clay surrounding the canister and change the redox conditions from reducing to oxidizing. If much oxidants are produced, they can migrate to the water flowing in the fractures in the rock. Some of the oxidants also may oxidize the uranium and other nuclides in the fuel and make them more soluble. The nuclides will then migrate out in a higher oxidation state and may precipitate at the redox front.

Calculations were done for a production of 144 moles of oxidants in one million years. A higher and a much lower production were also considered. It was assumed that the canister is either totally or locally corroded. The results show that, for the most probable production rate, a large fraction of oxidants would be consumed in the clay. If the corrosion is local and there is a fracture opposite the damage, the amount of oxidant transported into the fracture would be significant. Here the advance of the redox front in the fracture would be some tens of metres. For the lowest production rate, the oxidants never reach the fractures in the rock. Only with improbably high production rates could the tips of the redox front move very long distances, in isolated channels that are not part of a network.

SKB Technical Report 93-08

Äspö Hard Rock Laboratory Annual Report 1992

SKB

April 1993

ABSTRACT

The Äspö Hard Rock Laboratory is being constructed in preparation for the deep geological repository of spent fuel in Sweden. This Annual Report 1992 for the Äspö Hard Rock Laboratory contains an overview of the work conducted.

Present work is focused on verification of pre-investigation methods and development of the detailed investigation methodology. Construction of the facility and investigation of the bedrock are being carried out in parallel. December 1992, 1925 m of the tunnel had been excavated to a depth of 255 m below surface.

An important and integrated part of the work is further refinement of conceptual and numerical models for groundwater flow and radionuclide migration. This work is carried out in cooperation with seven organizations from six countries that participate in the project.

SKB Technical Report 93-09

Verification of the geostatistical inference code INFERENS, Version 1.1, and demonstration using data from Finnsjön

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June 1993

ABSTRACT

This report describes preliminary verification and demonstration of the geostatistical inference code, INFERENS Version 1.1. This code performs regularization of packer test conductivities, and iterative generalized least-squares estimation (IGLSE) of nested covariance models and spa-

tial trends for the regularized data. Cross-validation is used to assess the quality of the estimated models in terms of statistics for the kriging errors. The code includes a capability to generate synthetic datasets for a given configuration of packer tests; this capability can be used for verification exercises and numerical experiments to aid in the design of packer testing programs.

The report presents the results of a set of verification test cases. The test cases were designed to test the ability of INFERENS 1.1 to estimate the parameters of a variety of covariance models, with or without trends. This was done using synthetic datasets.

The verification exercises confirmed the functionality of the fitting algorithms, for intrinsic models with simple isotropic, simple horizontally isotropic, or nested isotropic covariances. The code also was successful in estimating models with spatial trends and simple isotropic or horizontally isotropic covariance. The more general forms of statistical anisotropy which are supported by INFERENS 1.1 were not adequately tested.

Verification of the fitting of more complex models, with nested anisotropic covariances, was not successful, primarily because the configuration and quantity of measurements in the synthetic datasets were not adequate for definition of the more complex models.

This report also describes an application of INFERENS 1.1 to the dataset from the Finnsjön site. The results are roughly similar to those obtained previously by Norman (1992a) using INFERENS 1.0, for the comparable cases. The actual numerical results are different, which may be due to changes in the fitting algorithms, and differences in how the lag pairs are divided into lag classes.

The demonstrations confirm the result previously obtained by Norman, that the fitted horizontally isotropic models are less good, in terms of their cross-validation statistics, than the corresponding isotropic models. The use of nested covariance models is demonstrated to give visually improved fits to the sample semivariograms, at both short and long lag distances. However, despite the good match to the semivariograms, the nested models obtained are not better than the simple models, in terms of cross-validation statistics.

These seemingly paradoxical results are explainable by the fact that the model fitting is performed by minimizing a weighted sum of the squared differences between the model covariance and the sample covariance, while the cross-validation statistics are calculated from the kriging errors using the fitted models. The optimum model in terms of cross-validation statistics is not necessarily coincident with the least-squares match to the sample covariance.

The use of direct fitting to the data pairs, rather than binned estimates (lag-class) of the semivariogram, in general is seen to yield poorer fits, as measured by the cross-validation statistics. This is interpreted as indicating that the direct-fitting approach is less robust. The relatively poor results achieved by direct fitting are problematic, since geostatistical inference using lag classes has been demonstrated to be highly sensitive to the arbitrary choice of lag classes.

SKB Technical Report 93-10

Mechanisms and consequences of creep in the nearfield rock of a KBS-3 repository

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December 1992

ABSTRACT

Creep in rock depends on the structure as well as on the stress and temperature. Log time creep is often observed and can be explained on the basis of statistical mechanics. Simple Kelvin behavior can be used as an approximation. The code FLAC is concluded to be useful for predicting creep strain, assuming that the rock obeys the Kelvin law.

SKB Technical Report 93-11

Post-glacial faulting in the Lansjärv area, Northern Sweden. Comments from the expert group on a field visit at the Molberget post-glacial fault area, 1991

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May 1993

ABSTRACT

Post-glacial faults have been recognized in the northern Baltic shield for several decades.

It is important to evaluate whether such neotectonic movements can lead to new fracturing or decisively alter the geohydrological or geohydrochemical situation around a final repository for spent nuclear fuel.

The post-glacial Lansjärv fault was chosen for a interdisciplinary study because of its relative accessibility.

The goals of the study were to assess the mechanisms that caused present day scarps, to clarify the extent of any recent fracturing and to clarify the extent of any ongoing movements. All these objectives were reasonably met through a series of studies, which have been performed by SKB during 1986-1992 in two phases.

This report gives a summary of the first phase of the Lansjärv study (1986-1989) and describes achievements that have been gained during the second phase of the study.

As a final of the field-work in the Lansjärv area a meeting combined with a field excursion was arranged by SKB in June 1991 for a group of international experts. Comments from the expert group on the excursion and the overall Lansjärv Project are presented.

One of the major conclusions is that the Lansjärv post-glacial fault reactivated pre-existing old structures and that the causes of the post-glacial movement is a combination of plate tectonics and deglaciation.

SKB Technical Report 93-12

Possible strategies for geoscientific classification for high-level waste repository site selection

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June 1993

ABSTRACT

This work was performed to suggest possible strategies for geoscientific classifications in the siting process of a high-level repository. To develop a feasible method for geoscientific classifications, a number of factors of a philosophical character, related to the purpose of the classifications, need to be accounted for. Many different approaches can be visualized, and this report was not intended to present a complete classification methodology. The purpose was rather to suggest some strategies for handling geoscientific factors that may be included and integrated in a functional classification methodology in the siting procedure. In this work it was assumed that geoscientific classifications will primarily be of interest with respect to the geoscientific aspects on the safety of the repository.

Before any geoscientific classifications can be performed, the following questions need to be addressed: what areas should be classified?; what methodology should be used?; and what parameters are of interest? To address these issues, the following parts are included in this report.

First, a strategy based on simple set theory was suggested to select areas suitable for geoscientific classifications. The areas are chosen with respect to the costs for the decisions related to each factor that is considered to be important. Possible factors are political, demographical, and economical factors.

Second, a strategy for classification of the geoscientific conditions was suggested based on the basic concepts of an American system for classification of groundwater vulnerability, DRASTIC. The suggested classification strategy has a so-called Bayesian approach, i e the classifications of the critical parameters are based on a combination of professional judgments and existing data. Due to limited economical resources, detailed investigations can never be performed to cover all areas that have to be included in the classification process and therefore the classifications have to some extent to be based on professional judgments. In the suggested strategy the critical parameters are treated stochastically and the classifications are updated as new data are collected.

Third, a selection of critical parameters to be included in the geoscientific classification was suggested, based on a literature review of geoscientific factors of importance to the safety of a repository. The parameters are related to the mechanical stability, transport of solutes, groundwater chemistry, groundwater flow, and the geological-structural setting.

Fourth, a simple test of handling a critical parameter in a Bayesian context was performed. RQD was used as the critical parameter. This approach allows for getting optimum value on a parameter from professional judgment and existing data. It also allows for estimations of where and to what extent new data should be collected, i e it allows for decisions based on optimal use of the available information and knowledge at every stage of the siting process.

SKB Technical Report 93-13

A review of the seismotectonics of Sweden

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April 1993

ABSTRACT

A study has been undertaken of data relating to the seismotectonic state of Sweden, both under current conditions and also through the glaciation/deglaciation cycle. The focus of the study has been to explore primary data on all the separate sources of information bearing on seismotectonics including: a) regional tectonics; b) neotectonic surface faulting; c) geodetic and tide-gauge observations of land-level changes; d) the horizontal strain field; e) Holocene land-level changes; f) historical and instrumental seismicity; g) palaeoseismicity; h) stress determinations, and i) geothermal observations. These data have then been

combined into a regional seismotectonic model, relating the distribution, style and rates of seismicity to the seismogenic properties of the crust and the continuing crustal deformation.

From the evidence of the modelled and observed horizontal strainfield and the diversity of focal mechanisms, all the current seismicity of the region appears to be a response to postglacial rebound. Through an understanding of the interaction between the pre-existing tectonic strainfield, and the strainfield resulting from glacial loading and unloading it is possible to make testable predictions about the localisation of deformation and seismicity in Fennoscandia at different stages of the glacial cycle. Immediately following glacial unloading intense deformation was concentrated on the northwestern flank of the downwarped crustal bowl. Currently low-level deformation and associated seismicity is most pronounced around the western margins of the dome of postglacial rebound. While the rebound dome is primarily extensional relieving the high levels of compression that accompanied crustal downwarping, there are also areas of compression and extension associated with flexures in the rebound surface that appear to affect the distribution and style of seismicity. The study shows how the significance and localisation of deformation and seismicity may be predicted both under present conditions and at other stages of the glacial cycle. Strain changes that accompany glacial loading and unloading are likely to have had a pronounced impact on hydrogeology.

SKB Technical Report 93-14

Simulation of the European ice sheet through the last glacial cycle and prediction of future glaciation

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December 1992

ABSTRACT

Global climates of the recent past appear to correlate with patterns of variation in the earths orbit round the sun. As such orbital changes can be predicted into the future, it is argued that the pattern of natural long-term future change can also be estimated. From this, future trends of glaciation can be inferred.

The physical and mathematical basis of a time-dependent, thermomechanically coupled, three dimensional ice sheet model is described. The model is driven by changes in the equilibrium line altitude (ELA) on its surface. This causes flexure of the underlying lithosphere. The model is tuned to the maximum extension of the last (Weichselian) ice sheet and driven by an ELA fluctuation which reflects the NE Atlantic sea surface temperature fluctuation pattern during the last glacial cycle in such a way that the model reproduces the ice sheet margin at the glacial maximum. The distribution of internal ice sheet velocity, temperature, basal, melting rate and subglacial permafrost penetration are all computed.

The model is then tested against its predictions of the areal pattern of ice sheet expansion and decay, the pattern of crustal flexure and relative sea level change, and the distribution of till produced by the last European ice sheet.

The tested model is then driven by predictions of future climate change to produce simulations of future ice sheet glaciation in northern Europe.

SKB Technical Report 93-15

Analysis of the regional groundwater flow in the Finnsjön area

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June 1993

ABSTRACT

The present study on regional groundwater flow in the Finnsjön area was performed by Kemakta Consultant Co. under contract from the Swedish Nuclear Fuel and Waste Management Company (SKB). The study was initiated by the discussions following the SKB 91 study. In the present report, the large scale regional groundwater flow situation in a vertical cross section through the Finnsjön site is analysed using two-dimensional finite-element modelling assuming the rock can be described as a porous media.

The analysis is focused on the effect of the position of the upstream lateral boundary and to what degree different fracture zone patterns influence the flow situation around the area that was used as an example repository site in SKB 91. It is of special interest to investigate if any of the chosen variations can result in an upward flow of water in the repository area with shorter groundwater travel times as a consequence.

The potential effects of the following were studied:

- three different sizes of the modelled domain: 43 km, 26 km and 18 km,
- a number of different generic fracture zone patterns and

- a number of different combinations of rock matrix and fracture zone hydraulic conductivity.

In all, 19 model cases were performed.

The modelling was performed using the finite element code NAMMU together with the program package HYPAC for pre- and post processing. Topographical data for the region were taken from the SKB GIS database.

SKB Technical Report 93-16

Kinetic modelling of bentonite – canister interaction. Implications for Cu, Fe, and Pb corrosion in a repository for spent nuclear fuel

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June 1993

ABSTRACT

The chemical corrosion of three potential canister materials, Fe, Cu, and Pb is reviewed in terms of their thermodynamic and kinetic behavior in a repository. Thermodynamic predictions which are compatible with sedimentological observations indicate that for all three metals, chemical corrosion is expected at any time in a repository. From the kinetic information obtained by experimental and archeological data, long-term corrosion rates are assessed. In the case of Fe, the selected data allow extrapolation to repository conditions with a tolerable degree of uncertainty except for the possible effect of local corrosion in the initial oxic phase. For the other two metals, the scarcity of consistent experimental and archeological data limits the feasibility of this approach. In view of this shortcoming, a kinetic, single-box model, based on the STEADYQL code, is presented for quantitative prediction of long-term canister-bentonite interaction. The model is applied to the corrosion of Cu under anoxic conditions and upper and lower limits of corrosion rates are derived. The possibilities of extending this single-box model to a multi-box, diffusion-extended version are discussed. Finally, further potentials of STEADYQL for future applications of near field modelling are highlighted.

SKB Technical Report 93-17

Oxidation of uraninite

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June 1993

ABSTRACT

Samples of uraninite and pitchblende annealed at 1200°C in H_2, and untreated pitchblende were sequentially oxidized in air at 180-190°C, 230°C, and 300°C. Uraninite and untreated pitchblende oxidized to the U_4O_9-type oxide, and their x-ray symmetry remained isometric up to 300°C. Reduced pitchblende, after oxidation to UO_{2+x} and U_4O_9-type oxides, transformed into α-U_3O_8 at 300°C. Two major mechanisms control uraninite and untreated pitchblende stability during oxidation: 1) Th and/or lanthanide elements maintain charge balance and block oxygen interstitials near impurity cations; 2) the uraninite structure saturates with respect to excess oxygen and radiation-induced oxygen interstitials. Untreated pitchblende during oxidation behaved similarly to irradiated UO_2 in spent nuclear fuel; whereas, reduced pitchblende resembled non-irradiated UO_2.

An analysis of the data in the literature, as well as our own efforts (XRD, EMPA, SEM, AEM) to identify U_3O_7 in samples from Cigar Lake, Canada, failed to provide conclusive evidence of the natural occurrence of tetragonal α-U_3O_7. Most probably, reported occurrences of U_3O_7 are mixtures of isometric uraninites of slightly different compositions.

SKB Technical Report 93-18

Solubility of the redox-sensitive radionuclides ^{99}Tc and ^{237}Np under reducing conditions in neutral to alkaline solutions. Effect of carbonate.

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September 1993

ABSTRACT

We have studied the solubility of Tc(IV) and Np(IV) hydrous oxides in aqueous solution as a function of pH and carbonate concentration. The solid phases used were prepared by electro-reduction and precipitation on platinum electrodes. The experimental data are explained by the following equilibria and equilibrium constants,

Equilibrium	log K
Hydrolytic equilibria	
$TcO_2 \cdot nH_2O(s) = TcO(OH)_2(aq)$	-8.17 ± 0.05
$TcO_2 \cdot nH_2O(s) = TcO(OH)_3-$	19.06 ± 0.24
$Np(OH)_4(s) = Np(OH)_4(aq)$	-8.28 ± 0.23
$Np(OH)_4(s) = NpO_2+ + e^- + 2H_2O$	-9.40 ± 0.5
Carbonate complexes	
$TcO_2 \cdot nH_2O(s) + CO_2(g) = Tc(OH)_2CO_3(aq)$	-7.09 ± 0.08
$TcO_2 \cdot nH_2O(s) + CO_2(g) = Tc(OH)_3CO_3-$	-15.35 ± 0.07
$Np(OH)_4(aq) + CO_32- = Np(OH)_4CO_32-$	3.00 ± 0.12
$Np(OH)_4(aq) + HCO_32- = Np(OH)_3CO_3-$	3.23 ± 0.12

The implications on the speciation and mobility of Tc(IV) and Np(IV) in groundwater, as well as those of U(IV) and Pu(IV), are discussed.

SKB Technical Report 93-19

Mechanical properties of fracture zones

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May 1993

ABSTRACT

Available data on mechanical characteristics of fracture zones are compiled and discussed. The aim is to improve the basis for adequate representation of fracture zones in geomechanical models. The sources of data researched are primarily borehole investigations and case studies in rock engineering, involving observations of fracture zones subjected to artificial load changes. Boreholes only yield local information about the components of fracture zones, i e intact rock, fractures and various low-strength materials. Difficulties are therefore encountered in evaluating morphological and mechanical properties of fracture zones from borehole data. Although often thought of as macroscopically planar features, available field data consistently show that fracture zones are characterized by geometrical irregularities such as thickness variations, surface undulation and jogs. These irregularities prevail on all scales. As a result, fracture zones are on all scales characterized by large, in-plane variations of strength- and deformational properties. This has important mechanical consequences in terms of non-uniform stress transfer and complex mechanisms of shear deformation. Field evidence for these findings, in particular results from the Underground Research Laboratory in Canada and from studies of induced fault slip in deep mines, is summarized and discussed.

SKB Technical Report 93-20

The Fracture Zone Project – Final report

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September 1993

ABSTRACT

This report summarizes the work and the experiences gained during the Fracture Zone Project at the Finnsjön study site. The project is probably the biggest effort, so far, to characterize a major fracture zone in crystalline bedrock. The project was running between 1984-1990 involving a large number of geological, geohydrological, geochemical, and geomechanical investigations.

The methods used for identification and characterization are reviewed and discussed in terms of applicability and possible improvements for future investigations. The discussion is exemplified with results from the investigations within the project.

Flow and transport properties of the zone determined from hydraulic tests and tracer tests are discussed. A large number of numerical modelling efforts performed within the Fracture Zone Project, the INTRAVAL Project, and the SKB 91-study are summarized and reviewed.

Finally, occurrence of similar zones and the relevance of major low angle fracture zones in connection to the siting of an underground repository is addressed.

SKB Technical Report 93-21

Development of "CHEMFRONTS", a coupled transport and geochemical program to handle reaction fronts

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October 1993

ABSTRACT

A computer program to calculate coupled mass transport and fluid rock interactions has been developed. The program, CHEMFRONTS, is based on the quasi-stationary state approximation and uses a kinetic expression for the mineral dissolution and precipitation coupled to a transport model. It is adapted to handle sharp reaction fronts. Such fronts evolve in the ground and typical examples are redox fronts and dissolution and precipitation fronts.

CHEMFRONTS calculates the chemical reactions for one-dimensional advective flow through a porous medium. Reactions between the water and the solid phase such as dissolution and precipitation are included in the model. In the water phase, complexation and redox reactions are also computed.

To verify the program, comparisons have been made with results obtained with other computer programs, CHEQMATE, PHASEQL/FLOW, and DYNAMIX. Natural analogues, such as Poços de Caldas and Cigar Lake, are also studied. The results from the simulations and comparisons are encouraging.

SKB Technical Report 93-22

Carbon transformations in deep granitic groundwater by attached bacterial populations characterized with 16S-rRNA gene sequencing technique and scanning electron microscopy

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October 1993

ABSTRACT

This report presents molecular characterization of attached bacterial populations growing in slowly flowing (1-3 mm s^{-1}) artesian groundwater from deep crystalline bed-rock of the Stripa research mine, south central Sweden. The assimilation rates of CO_2 and lactate, and the lactate respiration rates were also determined. The bacteria studied grew in anoxic, high pH, 9-10, and low redox artesian groundwater flowing up through tubings from two levels of a borehole designated V2, 812-820 m and 970-1240 m below ground.

Bacteria were allowed to attach to and grow on sterile microscope glass slides in laminar flow reactors connected to the flowing groundwater. Total numbers of bacteria were counted with acridine orange direct counts. The bacteria grew slowly with doubling times of 34 days for the 812-820 m population, 23 days for the 970-1240 m population in 10°C and 16 days in 20°C. Numbers of attached bacteria reached between 10^6 and 10^7 bacteria cm^{-2} after at most 160 days of exposure.

The glass slides were collected, the bacterial DNA was extracted and the 16S-rRNA genes amplified with PCR using primers matching universally conserved positions 519-536 and 1392-1405. The resulting PCR fragments were subsequently cloned and sequenced. The sequences were compared with each other and with 16S-rRNA sequences in the EMBL database.

Three major groups of bacteria were found. Signature bases placed them in the appropriate systematic groups. All belonged to the Proteobacterial groups beta and gamma. One group was found only at the 812-820 m level, where it constituted 63% of the sequenced clones, whereas the second group existed almost exclusively and constituted 83% of the sequenced clones at the 970-1240 m level. The third group was equally distributed between the levels. A few other bacteria were also found. None of the 16S-rRNA genes from the dominating bacteria resembled any of the other by more than 90% similarity, and none of them resembled anything in the database by more than 96%. Temperature did not seem to have any effect on species composition at the deeper level. SEM images showed rods appearing in microcolonies. The difference in population diversity between the two levels studied presumably reflect the different environments. The earlier proposed presence of sulphate reducing bacteria could not be confirmed.

The CO_2 assimilation rates (as mole CO_2 cm^{-2} h^{-1}, using liquid scintillation techniques) increased with depth and temperature. The quotients calculated for inorganic/organic carbon utilization were between 0.07 and 0.25, indicating that autotrophy could not support the levels of growth observed and that heterotrophy was the dominating carbon transformation process for growth of the studied populations. The Stripa bacteria could further be seen not only to assimilate but also to catabolize lactate and release CO_2 from lactate, which adds to the indications of a heterotrophic dominance in the Stripa environment.

The influence these populations have on the carbon content in rock fractures is considered. The populations at the two levels of the borehole were different in physiology as well as in phylogeny and reflected the heterogeneity between the sampling levels. Available electron acceptors and possible present bacterial groups are discussed in relation to these results and the results from 16S-rRNA gene sequencing studies. The molecular techniques used and the combined studies of physiology, morphology and

16S-rRNA gene sequences in polyphasic taxonomy are also discussed.

SKB Technical Report 93-23

Accelerator transmutation of wastes (ATW) – Prospects and safety

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November 1993

ABSTRACT

Accelerator transmutation of nuclear waste – ATW – has during last years gained interest as a technologically possible method to transform radioactive wastes into short-lived or stable isotopes. Different ATW-projects are described from the physical and technical point of view. The principal sketch of the safety analysis of the ATW-idea is given. Due to the very limited technical data for existing ATW-projects the safety analysis can be performed only qualitatively. Difficulties related to chemistry and material problems can cause some risks for the health and environmental safety for the closest environment. General public should not be effected.

SKB Technical Report 93-24

Direct fault dating trials at the Äspö Hard Rock Laboratory

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November 1993

ABSTRACT

Over seventy rock samples were collected from fault and fracture zones in the Äspö Hard Rock Laboratory tunnel for a study of direct fault dating techniques. Following microstructural and mineralogical analysis, isotopic, palaeomagnetic and electron spin resonance (ESR) methods were employed in an attempt to determine the age of the most recent movements on the sampled faults.

The larger fracture zones contain faultrock assemblages and microstructures which are consistent with a prolonged and polyphase movement history, although the cumulative displacement is difficult to quantify. For the important fracture zones NE-4 and NE-3, the most recent shear displacements involved formation of fault gouge cemented by authigenic 'illite'. Dating studies were targeted particularly at the gouge but also at older fault-rock and vein phases.

ESR dating of quartz grains, separated from gouge from fracture zones NE-4 and NE-3, strongly indicates that the ESR signals have not been reset by fault movements for a minimum time period of several hundred thousand to one million years. These minimum ages are inherently limited by the dating technique.

Palaeomagnetic dating of gouge from Fracture Zone NE-4 shows that a stable component of magnetisation overlaps both Precambrian (c.1350Ma) and Permo-Triassic (c.270-190Ma) parts of the apparent polar wander curve. The younger age of magnetisation is preferred on geological grounds and by comparison with the isotopic dating results. The magnetisation may correspond to a diagenetic event following fault movement. Palaeomagnetic ages determined on countryrock and epidote vein samples are largely consistent with independent age constraints.

K-Ar dating of clay fractions (<2 to <0.05 μm) separated from gouge from four faults, including fracture zones NE-4 and NE-3, gave model ages in the range 706-301Ma. Accounting for the effects of contamination by potassium-bearing porphyroclasts, it is likely that authigenic 'illite' was formed at least 250 million years ago, after the most recent significant fault movements. Oxygen and hydrogen isotope analyses of the dated clay fractions show that they are not in equilibrium with present-day groundwaters at Äspö. It is possible that the clays were precipitated from an isotopically-heavier brine.

This multi-disciplinary trial of fault dating techniques has been successful in showing the potential for fault dating studies to become a standard component of investigations on the long-term stability of bedrock.

SKB Technical Report 93-25

Radially converging tracer test in a low-angle fracture zone at the Finnsjön site, central Sweden. The Fracture Zone Project – Phase 3

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October 1993

ABSTRACT

The performance and results of a radially converging tracer test in a low-angle major fracture zone in crystalline rock are described. The extensive, about 100 m thick, Zone 2 was encountered by means of borehole investigations at depths ranging from 100 to 250 metres at the Finnsjön site, central eastern Sweden. The zone studied (Zone 2) consists of highly conductive, metre thick interconnected minor shear and fracture zones (sub-zones) with low conductive rock in between.

The objective of the tracer test was primarily to determine flow and transport characteristics in a major fracture zone. Secondly new equipment, experimental design and methods of interpretation were developed, tested and improved.

The converging flow field was created by pumping in a central borehole from a packed-off interval enclosing the whole thickness of Zone 2. The pumped flow rate was 120 litres/minute and pumping lasted for about 6 months after beginning of tracer injections. Injections of 11 different tracers were made in totally 9 borehole sections straddling highly conductive sub-zones in three peripheral boreholes, located in different directions from the pumped tracer withdrawal borehole. The tracers used were rare earth metal-DTPA and EDTA complexes, ions and fluorescent dyes. Eight tracers were continuously injected for 5-7 weeks and three were injected as pulses. The distances ranged from 155 to 200 metres and the average hydraulic gradient during the test was low, about 0.005 in the tracer flow paths.

Interpretation of the tracer breakthrough curves was strongly helped by independent supporting measurements, such as tracer mass release per time unit into the fracture system. These data could be calculated due to the injection techniques developed; passive continuous injection and decaying pulse injection. Further, possible interconnections between sub-zones were checked by sampling major hydraulic conductors in the withdrawal borehole. Groundwater flow rates, hydraulic heads and delay and dispersion in the withdrawal borehole were also measured. The evaluation and interpretation of the tracer breakthrough curves was made with one-dimensional models. Several solutions were applied, depending on injection technique used. Also described is two-dimensional modelling, based on hydraulic test results, performed as prediction and subsequent evaluation/re-calibration.

Tracer breakthrough was registered from all nine injection points, with first arrivals ranging from 24 to 3200 hours. Evaluated flow and transport parameters included; flow porosity, dispersivity, flow wetted surface, fracture aperture and hydraulic conductivity in fracture flow paths.

Directional variations were found in the flow and transport parameters determined, which is concluded to be due to heterogeneity and/or anisotropy. This condition is more pronounced at depth in Zone 2. The results from the tracer test also clearly show that the upper boundary of Zone 2 is highly conductive and consistent over hundreds of metres. Within Zone 2, and between upper and lower margins, interconnected discrete minor shear and fracture zones (sub-zones) constitute flow paths of considerable variable residence times. The dispersion within the sub-zones of Zone 2, expressed as Peclet numbers ranged from 16 to 40. Flow porosity was determined to be 0.001 - 0.05 in the upper sub-zone and 0.01 - 0.1 in the intermediate and lower ones and flow wetted surface area per volume of rock was calculated to be within 1 – 92 m^2/m^3.

SKB Technical Report 93-26

Dipole tracer experiment in a low-angle fracture zone at Finnsjön – results and interpretation. The fracture zone project – Phase 3

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November 1993

ABSTRACT

This report describes a large scale tracer experiment performed in a dipole flow geometry in the upper highly transmissive part of a low angle fracture zone, called Zone 2, at the Finnsjön study site. The experiment was performed as a part of Phase 3 of the Fracture Zone Project aiming to characterize a major fracture zone. The purpose of the experiment was to determine transport parameters for Zone 2 and to test the applicability of the experimental method for characterization of major fracture zones. The dipole experiment involved a total of 15 tracer injections including 14 short-lived radionuclides and 5 inactive tracers. Both sorbing and non-sorbing tracers were injected and some of them several times.

Tracer breakthrough was monitored both in the pumping hole at a distance of 168 m and in two observation holes inside the flow field at distances 157 and 223 m, respectively.

The evaluation of the results included both 1-D modelling of individual flow paths as well as 2-D modelling of the entire flow system. Inverse modelling technique was applied for both models including regression statistics. The statistics were used to assess the uniqueness and goodness of the model fits. The 1-D modelling was used to study effects of multiple flow paths and to determine transport parameters such as mean travel times and dispersivity. The purpose of the 2-D modelling was to study effects of the magnitude and direction of the natural gradient, anisotropy, and leakage. Comparison with previous predictions was also made with the 2-D model.

The report also contains a comparison of all three tracer experiments performed in the upper part of Zone 2.

SKB Technical Report 93-27

An approach to quality classification of deep groundwaters in Sweden and Finland

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ABSTRACT

The quality and representativeness of groundwaters sampled in the Swedish SKB and the Finnish TVO nuclear waste disposal site investigations have been evaluated. By definition a high quality sample is considered to be the one which best reflects the undisturbed hydrological and geochemical in situ conditions for the sampled section. Manual (expert judgement), statistical multivariate, mixing models and quality scoring system have been used to classify the waters regarding representativity. The constructed scoring system is best suited for quality classification, although the expert judgement is always needed as a complement. The observations are scored on a continuous scale based on the response of selected quality indicating parameters. Less representative samples are not rejected but given a value indicating the confidence of the observation. Finnish data obtained 45% of the possible scores compared to 55% for the Swedish data. The quality is generally 10% higher in the Swedish samples compared to the Finnish samples. The difference in sampling procedure is the probable reason for this.

SKB Technical Report 93-28

Plan 93. Costs for management of the radioactive waste from nuclear power production

Swedish Nuclear Fuel and Waste Management Co

June 1993

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 have commissioned SKB, the Swedish Nuclear Fuel and Waste Management Co, to plan, build and operate the necessary facilities and systems.

This report presents a calculation of the costs for implementing all of these measures. The cost calculations are based on a scenario for management and disposal of the radioactive waste products. This scenario has been prepared by SKB and is described in this report.

The facilities and systems that exist are:

- Transportation system for radioactive waste products.
- Central interim storage facility for spent nuclear fuel, CLAB.
- Final repository for radioactive operational waste, SFR 1.

Future facilities under planning are:

- Encapsulation plant for spent nuclear fuel, EP.
- Deep repository for spent fuel and other long-lived waste.
- Final repository for decommissioning waste.

The cost calculations also include costs for research and development, including the Äspö Hard Rock Laboratory, and for decommissioning and dismantling of the reactor plants etc.

The amounts of waste to be handled are dependent upon the total operating time of the nuclear power plants. In order to illustrate some variations, the calculations given in this report are based on three scenarios: 1) operation of all reactors up to and including the year 2010, 2) operation of all reactors for 25 years, and 3) operation of all reactors for 40 years.

The total future costs of the Swedish waste management system, commencing from 1994, have been calculated to be SEK 48.3 billion in January 1993 prices considering operation of all reactors up to and including the year 2010. These costs will be incurred over a period of about 60 years. SEK 9.2 billion has been spent up to the end of 1993. In case of 25 or 40 years of reactor operation the total future costs will be SEK 45.9 or 55.5 billion respectively.

This cost calculation is presented annually to SKI, the Swedish Nuclear Power Inspectorate, which uses it as a basis to propose a fee on the nuclear electricity production to cover all future expenses. The fee for 1993 is on average 1.9 öre/kWh (0.019 SEK/kWh).

SKB Technical Report 93-29

Diffusion of radionuclides in concrete/bentonite systems

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ABSTRACT

In a repository for nuclear waste, different construction materials will be used. Two important materials among these are concrete and bentonite clay. These will act as mechanical barriers, preventing convective water flow, and also retard transport due to diffusion of dissolved radionuclides by a combination of mechanical constraints and chemical interactions with the solid.

An important issue is the possible change of the initial sodium bentonite into the calcium form due to ion exchange with calcium from the cement. The initial leaching of the concrete has been studied using radioactive spiked concrete in contact with compacted bentonite.

The diffusion of Cs, Am and Pu into 5 different types of concrete in contact with porewater have been measured. The measured diffusivity for Cs agrees reasonable well with data found in literature. For Am and Pu no movement could be measured (less than 0.2 mm) even though the contact times were extremely long (2.5 y and 5 y, respectively).

This report gives also a summary of the previously published results about sorption and diffusion of radionuclides in cement performed in Prav/KBS/SKB projects 1980 - 1990.

SKB Technical Report 93-30

Core drilling by reverse flushing – a new drilling concept for small diameter boreholes

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ABSTRACT

In order to minimise the contamination of the groundwater and the preexisting fractures during drilling, SKB's first step in early 1980's was to use specific water wells to provide the water supply for the drilling operation. The next step toward cleaner boreholes was taken as the technique of telescope-type core drilling was introduced. The present report describes the latest improvement toward cleaner boreholes; the development of a core drilling technique using reverse flushing in small diameter boreholes. Reverse flushing is based on the principle of only using formation water, which flows into the borehole, as media to cool off the drill bit and transport the drill cuttings to the surface. The construction of the equipment is described, as well as performance results from a pilot drilling test. Furthermore, factors affecting the reverse flush drilling is discussed. It is concluded that reverse flushing works satisfactory, even under circumstances of only moderate water inflows to the borehole. For good drilling performance, comparable with conventional core drilling, it is required that the borehole penetrates water-bearing zones/fractures every 50-70 m. Due to initial pressure losses in the equipment system for reverse flushing, the technique is not recommended at depths less than 100 m.

SKB Technical Report 93-31

A preliminary assessment of gas migration from the Copper/Steel Canister

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ABSTRACT

A preliminary assessment has been carried out of the consequences of hydrogen gas generation in the Copper/Steel Canister, a new concept that is being considered by SKB, Sweden, for the encapsulation of spent fuel for geological disposal. The principal aims of the study were as follows:

(a) to determine the mechanisms by which gas generated by anaerobic corrosion will migrate from a canister;

(b) to identify the possible consequences of gas generation, for example overpressurization of the canisters and effects on water movement;

(c) to carry out studies to assess the magnitudes of the consequences of gas generation and the way in which they are influenced by the mechanisms and ease of gas migration;

(d) to determine the likely fate of the gas produced in the repository; for example whether the gas will eventually be dissolved in the groundwater as it moves away from the canister or whether it will collect as free gas in the tunnel or elsewhere;

(e) to identify the potential benefits of using computer modelling techniques for estimating hydrogen generation rates within disposal canisters during the post-emplacement period.

SKB Technical Report 93-32

Colloids or artefacts? A TVO/SKB co-operation project in Olkiluoto, Finland

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ABSTRACT

TVO (Teollisuuden Voima Oy, Finland) initiated a co-operative task with SKB (Swedish Nuclear Fuel and Waste Management Co.) to critically evaluate colloid sampling methods at the test site in Olkiluoto, SW Finland. Three different colloid sampling methods were compared when sampling borehole OL-KR1 at 613-618m depth. One possible way to make a conservative in-situ colloid estimation is to omit the contribution from calcite precipitation which is considered to be the main artefact. When this is made the inorganic colloid content (size 1 – 1000 nm) in Olkiluoto is 184 ± 177 ppb consisting of clay minerals, silica, pyrite, goethite and magnesium oxide; the concentration of organic substances are around 10 ppb. The in-situ colloid concentration seems to be low which is in good agreement with experiences from years of sampling in similar environments and depths. The exercise shows the many difficulties encountered when sampling colloids. Small errors in the planning, pump-rate selection, a lack of precautionary measures, artefact sensitivity of the method etc. have a tendency to affect significantly the results on the measured ppb colloid level.

SKB Technical Report 93-33

Evolution of models for conversion of smectite to non-expandable minerals

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ABSTRACT

Hydrothermal alteration of smectite has long been regarded as conversion to illite and chlorite as concluded from investigations of Gulf sediments. As manifested by statements given earlier at various international scientific meetings and in the literature, smectite-to-illite conversion (S→I) has been assumed to be a solid-state reaction with layer-by-layer alteration via mixed layer I/S to illite. In the last 10 years this opinion has successively changed and in recent years the concept of dissolution of smectite and accessory minerals and precipitation of illite and possibly I/S has been favored by many investigators. The present report reports laboratory and field investigations on bentonite and also calculations based on geochemical codes, which all support the dissolution/precipitation process. Applying Pytte's model for calculating the rate of conversion to illite, one finds good agreement with a number of experiments and field data, and this model is therefore recommended for practical use.