TECHNICAL REPORT

94-33

SKB ANNUAL REPORT 1994

Including Summaries of Technical Reports Issued during 1994

Stockholm, May 1995

SVENSK KÄRNBRÄNSLEHANTERING AB
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Stockholm, May 1995

FOREWORD

The Annual Report on SKB's activities during 1994 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, development and planning activities is well under way. The aim of the programme is to start the permanent disposal of the long lived spent fuel around year 2008. Work is undertaken for the development of encapsulation technology on industrial scale and design of the plant.The siting process for the final repository for spent fuel has started with feasibility studies in a couple of Swedish municipalities to evaluate the potential technical conditions and requirements and influence of the 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 are pleased to note the increasing international interest for international participation in our Äspö Hard Rock Laboratory. We hope this Annual Report will be of interest and that it will enhance the international information exchange.

Stockholm in June 1995

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 1994.

Lectures and publications during 1994 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 post-graduate theses supported by SKB.

Part IV contains the summaries of all technical reports issued during 1994.

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 1994 in total 2 110 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 later. At the end of 1994 a total of 15 500 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 1994 was 185.5 MSEK of which 59.4 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 March 1995 there are 8 foreign organizations participating in the Äspö HRL project.

SKB is planning to build an encapsulation plant for spent nuclear fuel and a deep repository for the encapsulated fuel and other long-lived waste. The encapsulation plant is proposed to be built adjacent to the CLAB facility. In the encapsulation plant the spent fuel will be encapsulated in a copper/steel canister. During 1994 conceptual design work was initiated for the facility. Also development work for the manufacturing and closing of the copper canister was performed. Siting activities for a deep repository included feasibility studies in the municipalities of Storuman and Malå. Technical, geoscientific and socioeconomic studies were performed. Extensive local involvement and discussions is an important part of the siting activities.

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 1994 more than 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 1994 successful public information activities have been carried out using mobile exhibitions in a tailor-made trailer and on the SKB ship M/S Sigyn.

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SKB ANNUAL REPORT 1994

Part I

Overview of SKB Activities

CONTENTS PART I

1 GENERAL BACKGROUND

1.1 THE SWEDISH NUCLEAR POWER PROGRAMME

The nuclear power programme of Sweden consists of 12 nuclear reactors located at four different sites and with a combined capacity of 10 000 MW net electric power. Main data and location of the 12 units are shown in Figure 1-1. The nuclear power plants generated about 51% of the total Swedish electric power produced in 1994.

Swedish reactors

Reactor		Power MWe	Commercial operation	Energy availability in 1994 %
Oskarshamn 1	BWR	445	1972	–
Oskarshamn 2	BWR	605	1974	89
Oskarshamn 3	BWR	1160	1985	89
Barsebäck 1	BWR	600	1975	87
Barsebäck 2	BWR	600	1977	77
Ringhals 1	BWR	795	1976	78
Ringhals 2	PWR	875	1975	84
Ringhals 3	PWR	915	1981	92
Ringhals 4	PWR	915	1983	85
Forsmark 1	BWR	970	1980	92
Forsmark 2	BWR	970	1981	93
Forsmark 3	BWR	1160	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 75 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 700 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.

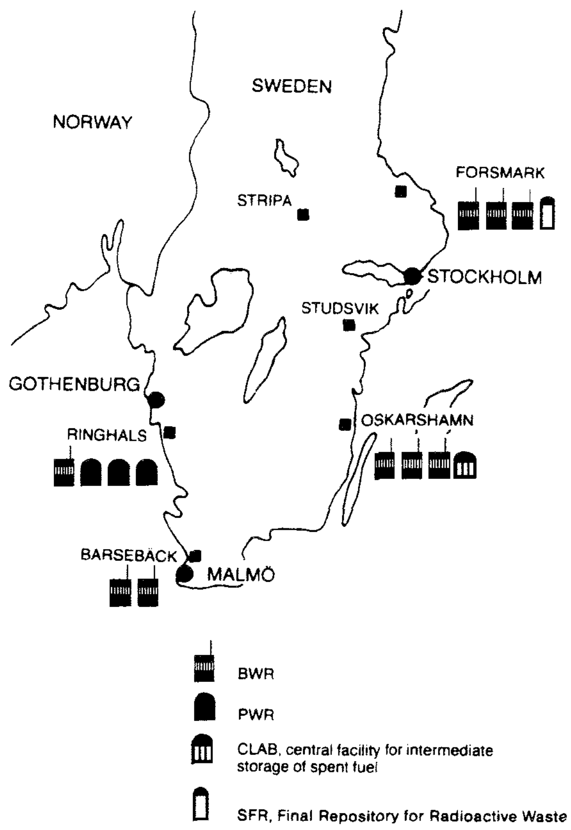


Figure 1-1. The Swedish nuclear power programme.

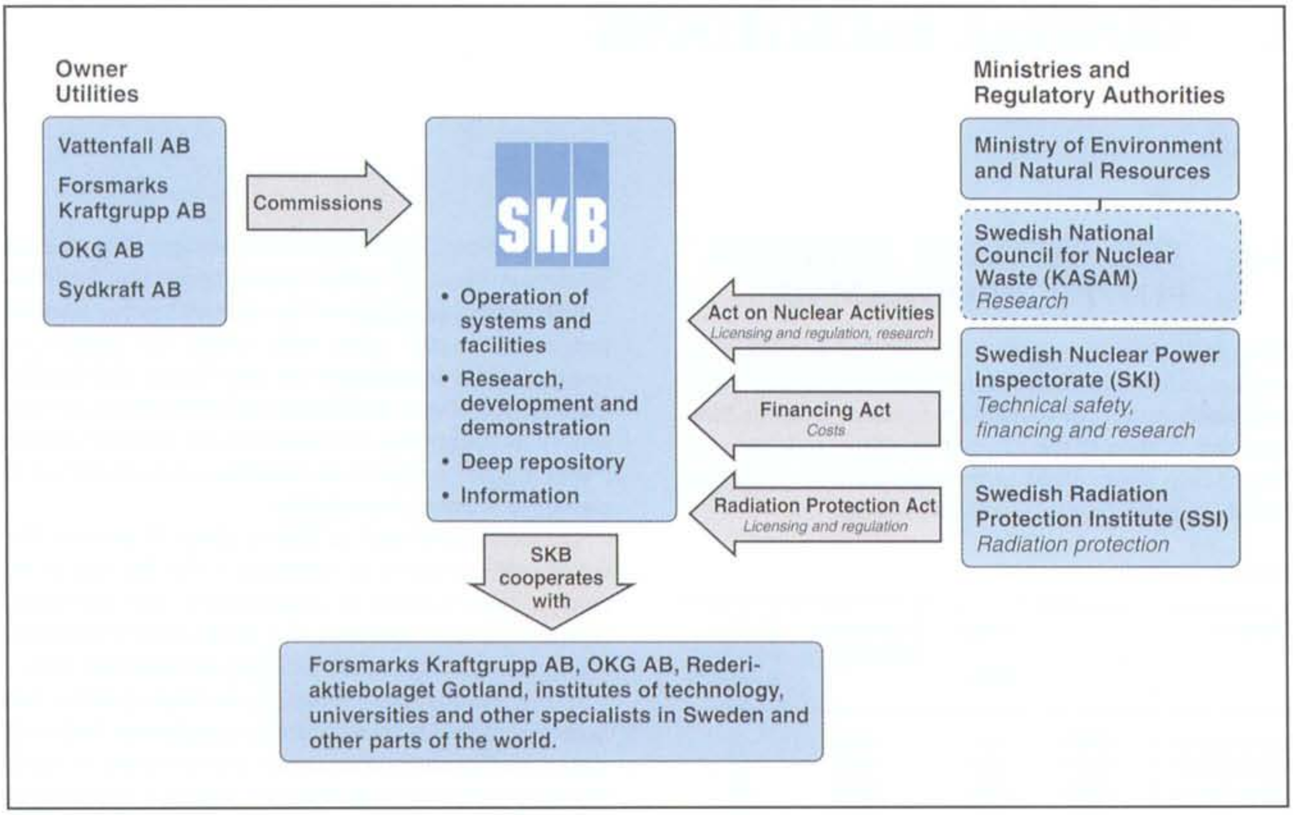


Figure 1-2. *Legal framework for activities of SKB.*

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 Swedish Radiation Protection Institute (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 Radiation Protection Institute (SSI).

The competent authorities have separate funds for the research needed to fulfil their obligations. SKI also sup-

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 (7 800 tU)
2 Transuranic-bearing waste	Waste from the Studsvik research facility	Solidified in concrete	Low- to medium-level. Contains long-lived nuclides	c. 2 000 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.	c. 10 000 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	c. 90 000 m^3
5 Decommissioning waste	From dismantling of nuclear facilities	Untreated for the most part	Low- to medium-level. Short-lived	c. 100 000 – 150 000 m^3 *

* The amount of decommissioning waste to be disposed of will depend on how much material that will be decontaminated.

ports additional waste management research beside the SKB programme.

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.

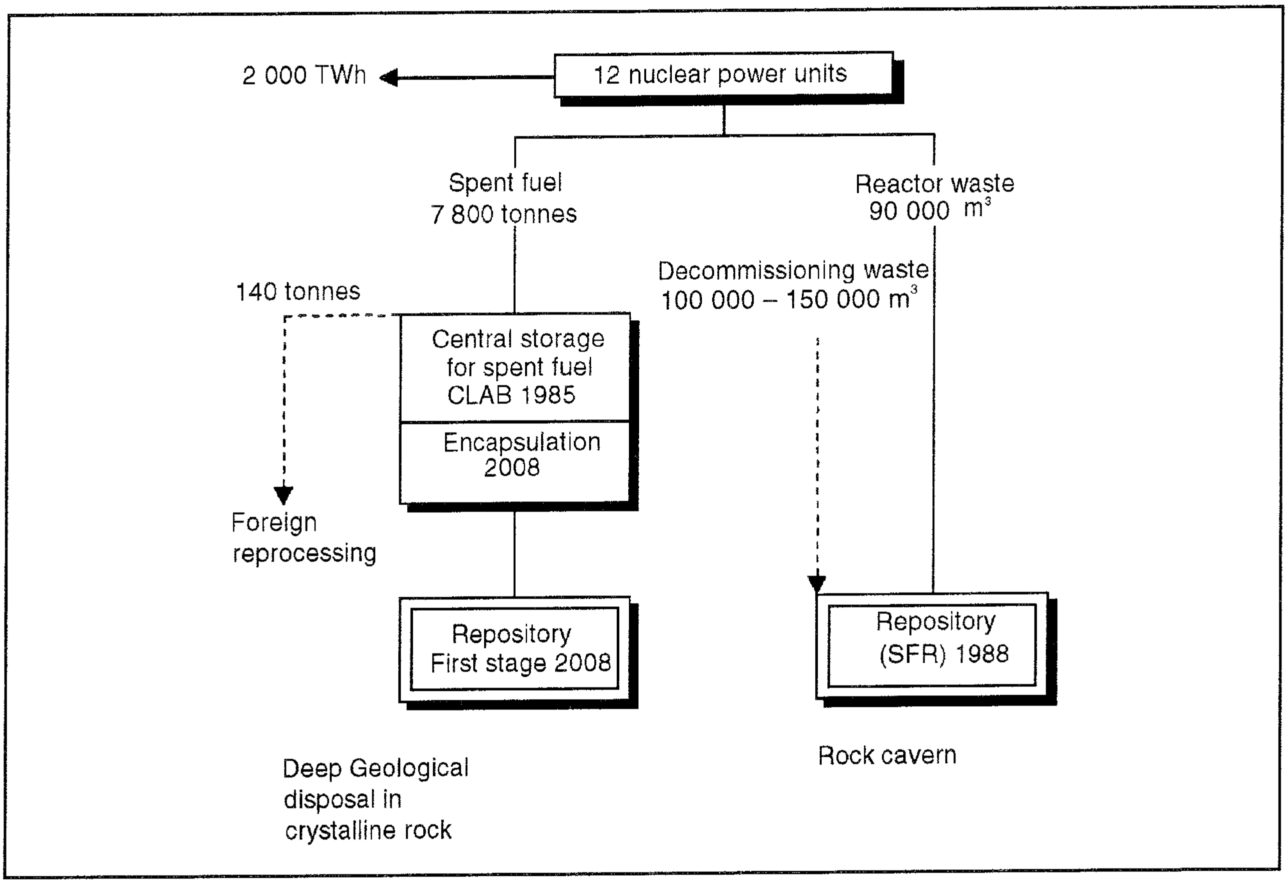


Figure 1-3. Main system for management of radioactive waste in Sweden.

2 INTERIM STORAGE OF SPENT FUEL, CLAB

2.1 GENERAL

The Swedish interim spent 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 Aktiebolag, one of SKB's shareholders, operating three reactors at the site.

2.2 OPERATING EXPERIENCES

By the end of 1994 CLAB has been in operation for 9.5 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 around 2100 tU from the 12 Swedish reactors have been shipped to the facility and placed in storage.

In 1994, 72 casks containing spent fuel assemblies from the Swedish reactors were received together with 16 reactor core component canisters. The total fuel quantity shipped to CLAB during the year amounted to 223 tU. Two 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 64 BWR assemblies and 94 PWR assemblies have been transferred from old canisters to new compact storage canisters in 1994, see section 2.3. By the end of the year about 2/3 of the total PWR fuel amount is stored in the new canisters.

The total occupational dose in 1994 was 103 mmanSv, which is 14 mmanSv less than in 1993 and corresponds to about 40% of the value calculated in the safety assessment made during the design phase.

The release of radioactivity to the environment during 1994 has been negligible, amounting to around 0.01% of

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 permissible release 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 the Studsvik Nuclear Research Centre. The operating procedures and involved equipment have been quite easily adapted to the different casks.

The experiences from more than nine years of operation are continuously used in the project work on the Encapsulation Plant, see section 6, which according to current plans will be built wall to wall with 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 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. *BWR-fuel canister of the old and new types containing 16 respectively 25 fuel assemblies. The octagonal canisters are used for highly radioactive reactor core components.*

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 1994 the ship M/S Sigyn sailed around 37 000 n.m. during 154 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. In total 72 transport casks with spent fuel, 16 transport casks for used core components and 95 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.

During the first half of 1994 one transport cask for spent fuel was repaired at the CLAB facility. Originating from the manufacturing, damages on the inner steel liner of the cask had been found which hindered basket exchanges. The old liner was removed and a new was welded into the cask. This was the first time an extensive work inside a cask, having been in operation, was performed.

The successful decontamination allowed the personal to work inside the cask without special protection clothing. The repair work was finished in August and the cask was taken into operation during autumn 1994.

A new license for the spent fuel cask has been approved by French and Swedish authorities allowing transport of fuel elements with higher enrichment and high burn up. Two casks will be equipped with increased neutron shielding in 1995.

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

Figure 3-2. Loading of a 400 tonnes generator stator on board M/S Sigyn.

When the ordinary transport schedule has permitted, M/S Sigyn has been used on commercial basis for transports of heavy equipment, see Figure 3-2. During 1994 twelve different transports with heavy equipment have been transported with M/S Sigyn

During the summer period M/S Sigyn was used, like earlier years, as a floating exhibition of the Swedish nuclear waste handling system making a voyage along the Swedish coast and visiting 14 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 a repository for low- and intermediate level waste, 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 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 are treated in the same way, if required.

At the end of 1994 a total of 15 500 m^3 of waste have been deposited in SFR. All waste producers have delivered waste. The experience from the operation has been good and the radiation doses to the personnel have been very low.

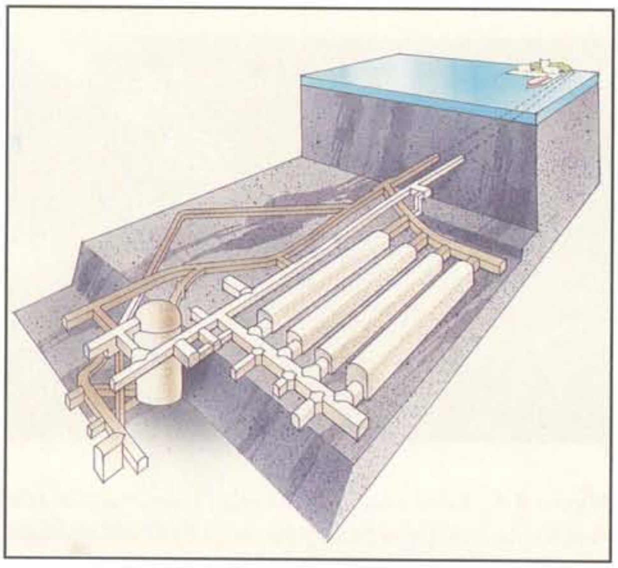


***Figure 4-1.** Overview of tunnels and storage chambers in the first construction stage of SFR.*

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 ground water 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 1994, 36 waste types (of a total of about 50) were accepted for disposal. In 1994 disposal has been carried out in the rock chambers and in the silo.

4.4 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. Up to the end of 1994 a total

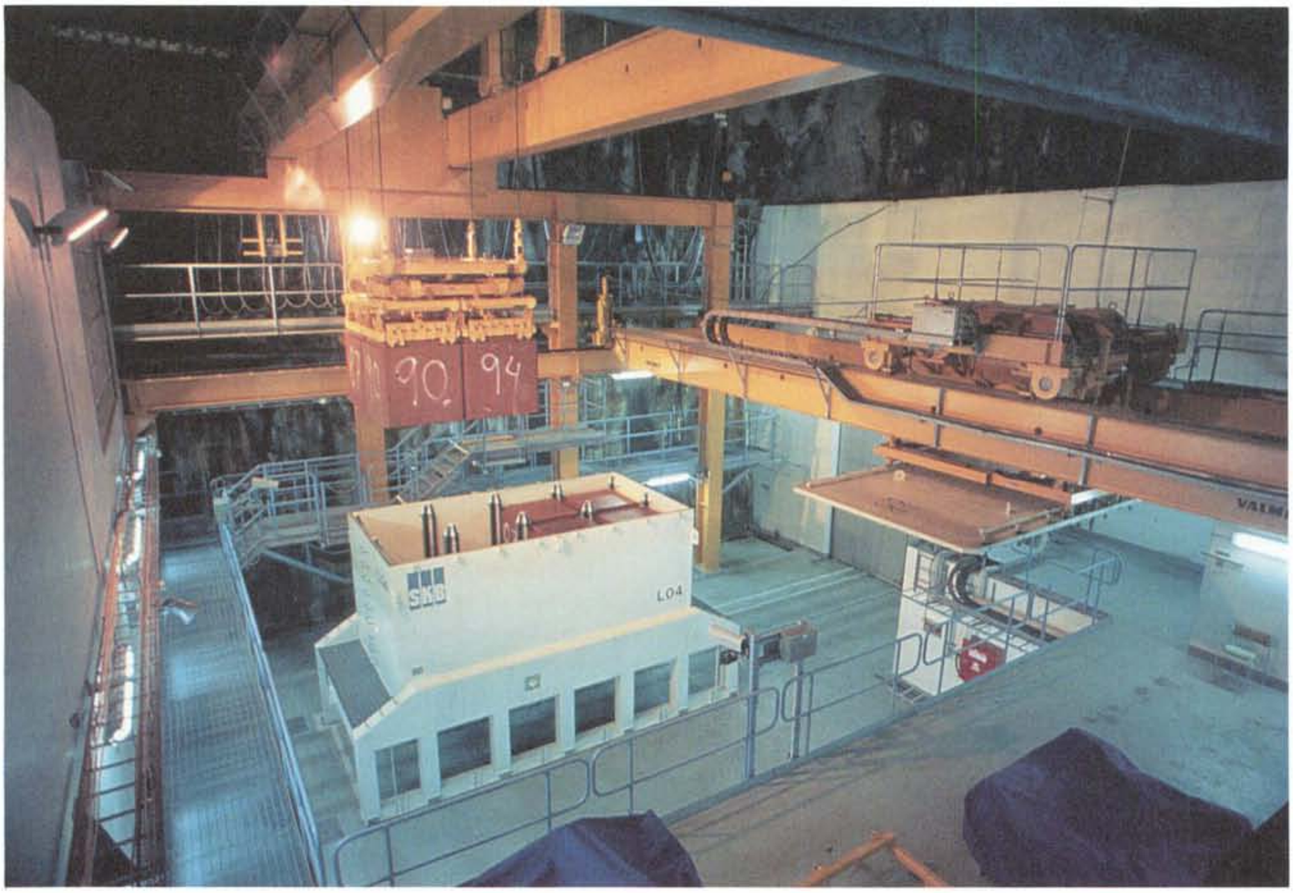


Figure 4-2. The operational waste is transported in special transport containers. In SFR the waste packages are unloaded with remote-controlled handling equipment.

of 15 500 m^3 of waste has been deposited. During 1994, 2470 m^3 was deposited in SFR compared to planned 2500 m^3 according to a firm price agreement which has been established between FKA and SKB.

The same amount is foreseen for 1995.

The operating experience is good both with regard to handling and availability.

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 1994 the system for preparation and handling of the cement grout for the waste package in the silo has been taken into operation. The first grouting in the silo shaft took place during the year.

A new data base system for SFR has been developed and will be taken into operation in 1995.

A 10-year programme for corrosion preventing activities in the facility was started in 1994.

SFR is also an interesting facility for visitors. During 1994 more than 20 000 people including many foreign visitors came to SFR, see Figure 4-3.

***Figure 4-3.** Each year SFR receives more than 20,000 visitors. An exhibition facility has been built underground in a cavern adjacent to the repository caverns.*

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 92 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 1994 the activities have been focused on:

- Further development and description of siting criteria and the siting process.
- Background and national overview studies concerning different aspects of siting a deep repository.
- 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 end up in an application from SKB for detailed site characterisation of one site, including shaft-sinking or tunnel

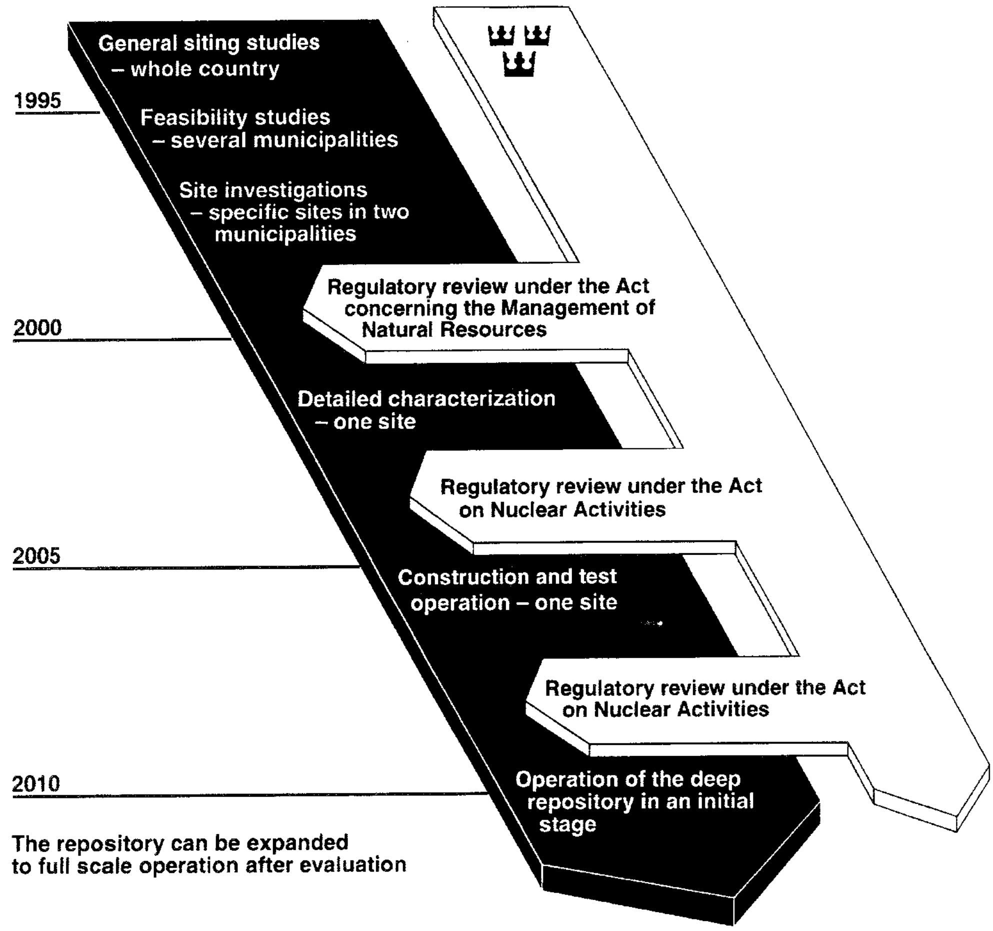


Figure 5-1. Overall plan.

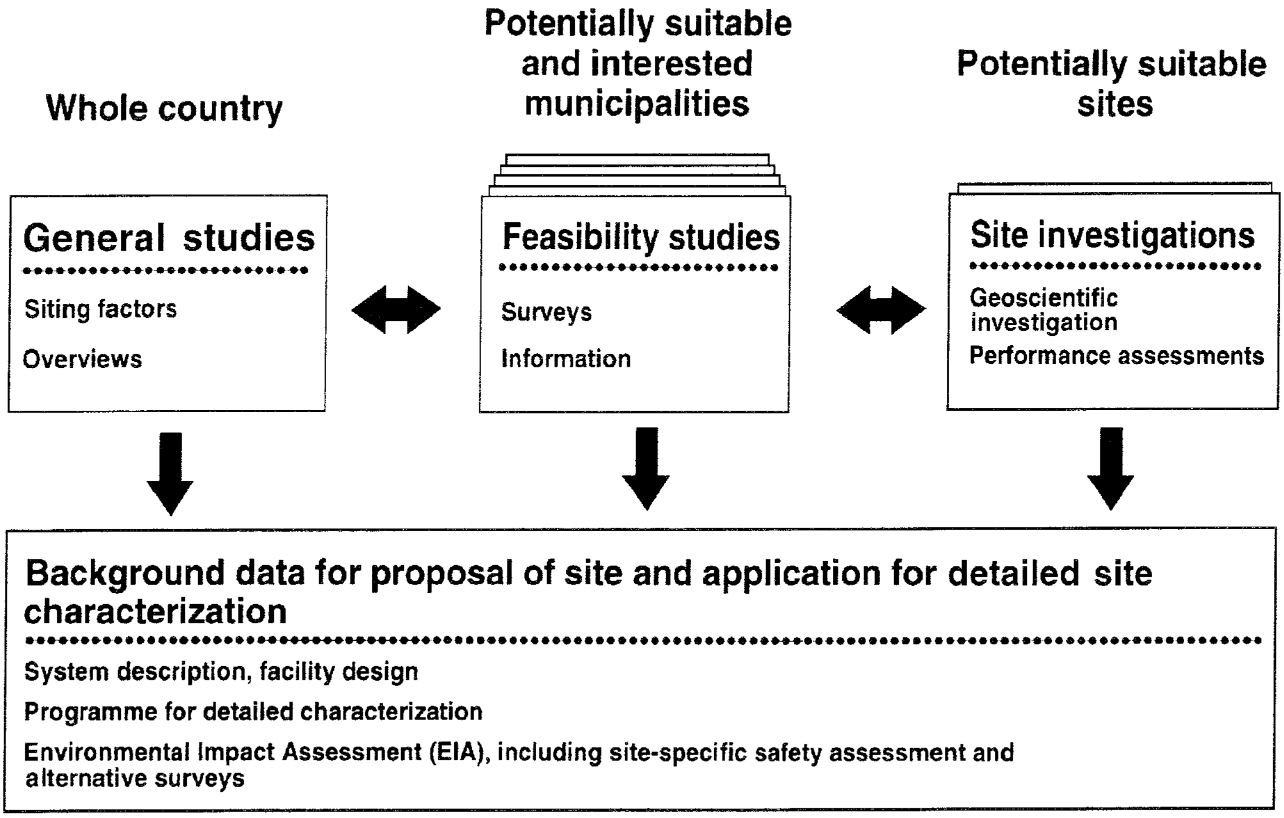


Figure 5-2. *Siting activities, phase 1.*

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 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 are 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 takes about one year and examines 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 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 is 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 been going on since 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 basic site investigation programme, which is scheduled to be finished in 1995.

5.3 SITING ACTIVITIES

During 1994 siting activities have mainly involved the development and presentation of siting criteria, general siting studies of the whole of Sweden and feasibility studies of two municipalities in northern Sweden.

Siting criteria

In RD&D-Programme 92 /5-1/, SKB gave an account of its strategy for the siting of a deep repository for the long-lived radioactive waste, including the spent nuclear fuel. The strategy was accepted in all essential respects by the regulatory authorities and the Government. However, there was some criticism on certain unclear points in the programme that lead to a Government stipulation that SKB shall supplement the above mentioned programme by describing the criteria and methods that can form a basis for the selection of sites suitable for a final repository. Also other supplementary accounts were requested, see Chapter 12.

In August 1994 SKB presented the siting criteria in the RD&D-Programme 92 Supplement /5-2/ A summary of the main groups of siting factors is presented below. For a more complete treatment, see /5-2/.

The question of whether an area is suitable for siting of a deep repository is decided by the following main groups of siting factors:

Safety	Siting factors of importance for the long-term safety of the deep repository.
Technology	Siting factors of importance for the construction, performance and safe operation of the deep repository and its transportation system.
Land and environment	Siting factors of importance for land use and general environmental impact.
Societal aspects	Siting factors connected to societal considerations and community impact.

Figure 5-3 shows how each main group contains a host of criteria and factors that determine the suitability of a site

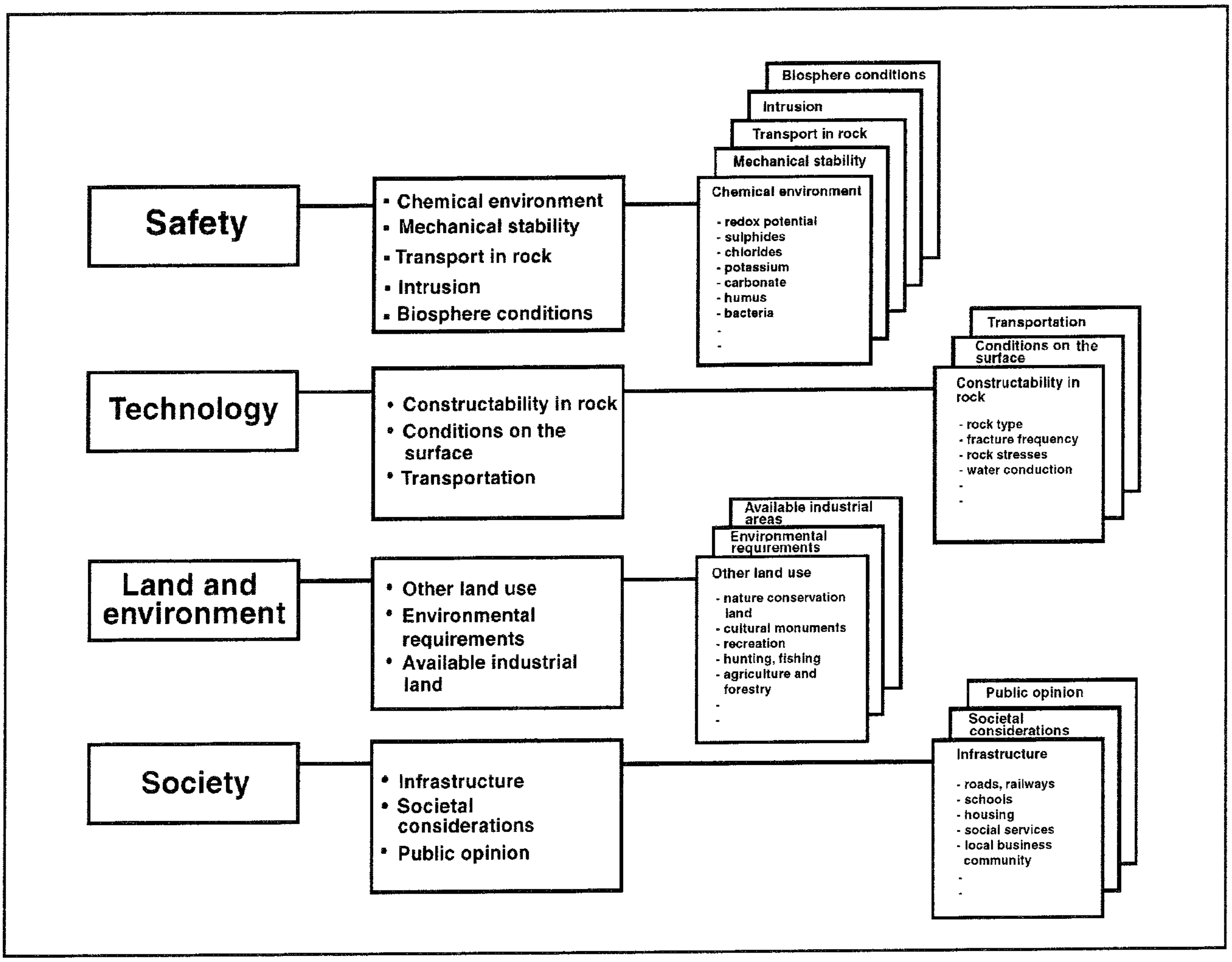


Figure 5-3. Structure for siting factors and criteria.

for a deep repository. Some of the factors are absolute criteria that must be met if a deep repository is to be built on a given site. Examples of such absolute criteria are that the groundwater shall be oxygen-free at repository depth, that mineral deposits may not exist within the deep repository, and that the site may not be situated within a national park.

However, most factors fall along a scale of favourable – unfavourable, which means that they are important in an overall assessment of the suitability of the site, but are not by themselves crucial in deciding whether a site is suitable. Examples of unfavourable conditions are heterogeneous bedrock, long distance to an existing road/railway and competing land-use interests.

The requirements within each of the four main groups can be formulated as follows:

Safety

The fundamental safety principle for the deep disposal system planned by SKB is to completely contain and isolate the spent nuclear fuel in tightly sealed canisters deposited at a depth of about 500 metres at the selected repository site. This isolation shall be achieved and preserved over very long periods of time so that the radioactive materials decay inside the canister and cannot be released. This means that an important safety-related function of the rock is to guarantee stable chemical and mechanical conditions for the engineered barriers over a long period of time.

The safety strategy for a deep repository is based on the multiple-barrier principle. This means that safety must not be solely dependent on the engineered barriers' functioning as planned. Another important safety-related function of the bedrock at a deep repository site is to retain the radionuclides or retard their transport if the engineered barriers should be damaged.

For the sake of long-term safety, the following factors must be taken into consideration when selecting a site:

- chemical environment in the rock for canister, bentonite and fuel,
- mechanical stability of the rock,
- conditions for transport of corrodants and radionuclides in the rock,
- risk of future intrusion, i. e. mainly conceivable utilization of natural resources in the bedrock.

Technology

The requirements that transportation shall be safe can as a rule always be met by the use of appropriate technology and the necessary investments. It is advantageous if an existing infrastructure for sea and land transport can be utilized. It is a disadvantage if extensive new investments are required and if new harbours, roads or railways conflict with other important land-use interests.

The parts of the bedrock where shafts, access tunnels, transport tunnels, deposition tunnels etc. are planned shall possess such properties that the work can be carried out in a safe manner using known technology.

When data from repository depth have been reported, the suitability of an area for construction purposes can be determined based on factors such as rock type, fracture frequency, location and character of fracture zones, hydraulic conductivity, size and orientation of rock stress and mechanical properties of the bedrock.

Land and environment

Site selection and design of the facilities shall be done so that conflicts with competing interests are minimized. Consideration shall thereby be given to the natural, environment, cultural monuments, recreation, hunting, fishing, other outdoor activities, important natural resources, agriculture and forestry, current and planned land use. Facilities and transport routes shall blend in smoothly with the terrain.

To comply with the requirements in the environmental legislation, the facility's environmental impact must be weighed against the specific environmental conditions in the area early in the siting process.

The site for the deep repository shall have:

- few competing interests for land use,
- good prospects for being able to build and operate the facilities in compliance with all environmental protection requirements.

Societal aspects

Socioeconomic considerations are important for both site selection and design of the facilities on the selected site. The establishment and operation of a deep repository will have different impacts on the locality and the region. These include e. g. impact on employment, the local business community and local services. Politically and in terms of public opinion, siting is a sensitive issue. Experience in both Sweden and other countries shows that strong feelings and opinions can be aroused. Opposition to industrial sitings in general is not unusual in modern society. Siting of a deep repository shall be carried out so that:

- the siting process is carried out in stages involving a democratic decision-making process,
- social and socioeconomic consequences are taken into account.

General siting studies

The general studies constitute background facts for the municipality- or site-specific investigations that need to be done. With the aid of the general studies it will be possible to place the relevant sites in their national and regional contexts. Information is entered and stored in SKB's GIS system, which now comprises one of Sweden's largest databases of this type. The general studies will also provide a picture of different areas in the country which are, for different reasons, less suitable for siting of a deep repository. They cannot, on the other hand, provide any specific guidance in the work of finding suitable sites. This requires studies on a more detailed scale and a dialogue with, among others, concerned local and regional politicians and population.

In the general studies, comprehensive background material on geological, technical, environment-related and societal conditions is compiled. These studies have been published continuously as a part of the research and development work which SKB has been conducting since the late 1970s /5-2/. The studies include, among other things:

- General facility description and general background data for future environmental impact assessments.
- General survey of transportation system, including transshipment in harbour and transport by road or rail.
- Compilations of geographically related information on a national and/or regional scale concerning bedrock, topography, nature conservation areas, mineral deposits, major regional fracture zones, earthquake frequencies, etc.
- Surveys, analyses and forecasts of e. g. effects of glaciation on the bedrock and on seismotectonic conditions for different parts of the Swedish bedrock.

Results from geoscientific general siting studies published during 1994 are described in Section 15.3.

An overview study started in 1994 to investigate the prospects for feasibility studies of those municipalities that host the nuclear power plants.

SKB plans to compile a collective account of the general studies by 1995.

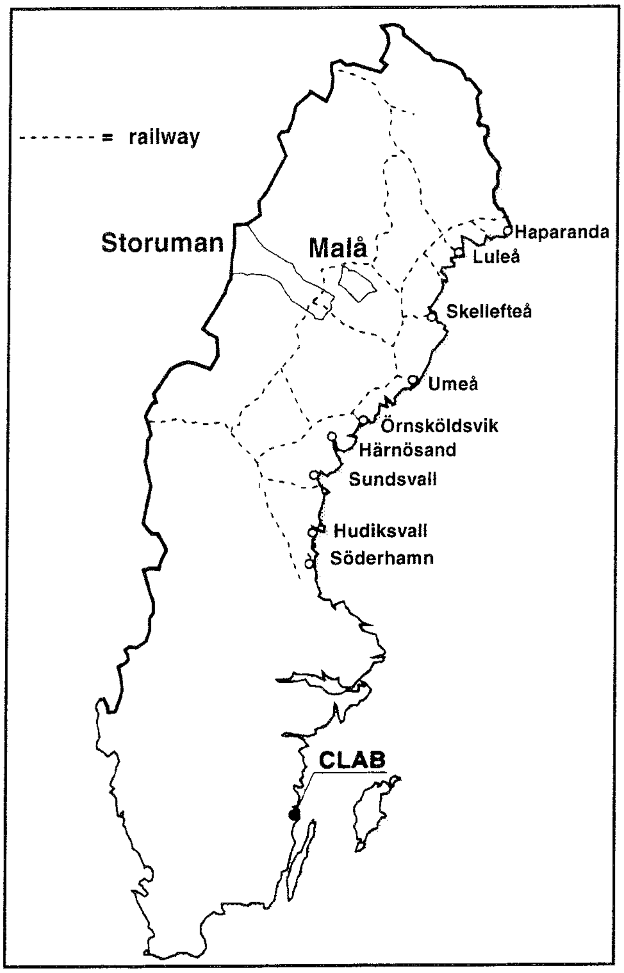


Figure 5-4. *Location of the municipalities Storuman and Malå. The central interim storage facility for spent nuclear fuel is located at CLAB. If the deep repository is located at Storuman or Malå spent fuel will probably be transported by ship to a harbour in the northern part of the Baltic sea and by train to the repository.*

Feasibility studies

An important part of the siting programme involves feasibility studies of municipalities which have expressed a potential interest in hosting a repository facility or are not negative to such studies.

Feasibility studies entail evaluation of siting prospects together with the positive and negative environmental and societal consequences of such a siting. The main purpose is to provide an adequate information basis such that the municipality and SKB can decide whether or not to continue with site investigations. An essential prerequisite to continue further is that there is sufficient interest from both the municipality and SKB.

SKB plans to carry out between five to ten feasibility studies mainly based on existing geoscientific and other data. During 1994 two feasibility studies, Storuman and Malå, were in progress of which the Storuman feasibility study was finalised. Figure 5-4 shows the location of the two municipalities. A summary of the feasibility study of the Storuman municipality is presented below.

Feasibility study of the Storuman municipality

The feasibility study in Storuman is the first to be conducted. It began during the second half of 1993 with the conclusion of an agreement between the municipality and SKB. SKB has been in charge of the execution of the feasibility study. The municipality has had insight into and been able to influence the feasibility study through a steering group with two representatives for the municipality and two for SKB.

Altogether about 30 reports have been published within the framework of the study. They are all in Swedish. A final report published in January 1995 summarizes the results of the various studies and presents the collective evaluation of the results. This report is also available in English /5-3/. The purpose of the studies has been to describe, in as much detail as possible, the prospects for siting a deep repository in the municipality of Storuman, and to shed light on the possible positive and negative consequences of such a siting.

The feasibility study shows that areas exist within Storuman municipality which may offer good prospects for the siting of a deep repository. However, a more detailed assessment of long-term safety requires comprehensive

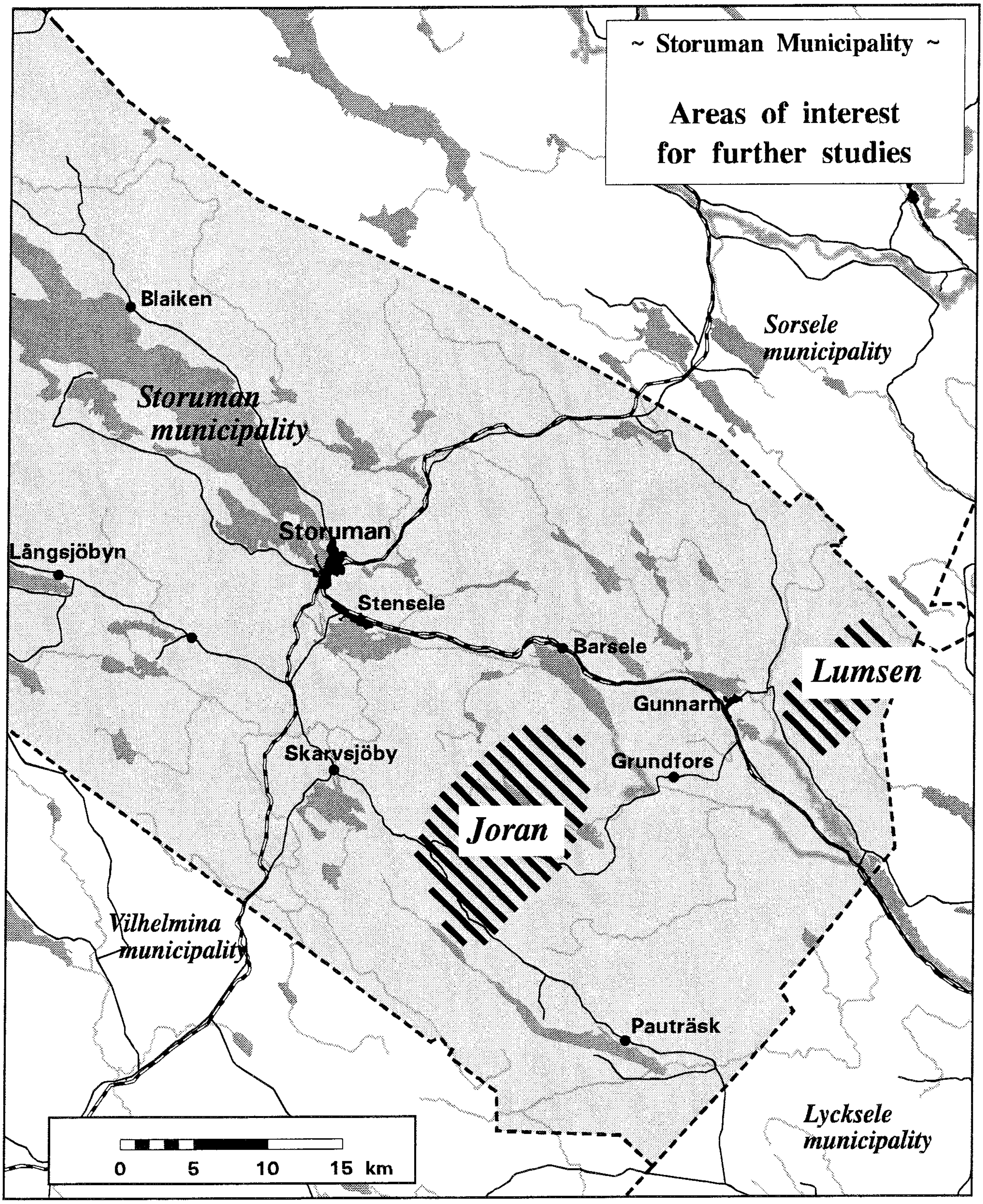


Figure 5-5. *Areas of interest for further studies. The Joran area is given top priority.*

geoscientific investigations and a safety assessment. The top-priority area for further studies is Joran located within a granitic pluton, see Figure 5-5. The area is about 90 km^2 in size, the rock is well-exposed and consists entirely of granite. Available data indicate that the granite is homogeneous, with a low fracture content and relatively few fracture zones. Due to the size of the area it should be possible to locate the facility with a connecting railway and road so that allowance is made for both the suitability of the bedrock conditions and the interests of landowners, nearby residents, reindeer herders and others. Factors that must be given particular attention in further investigations are the depth of the granite and the possible presence of flat-lying fracture zones, elevated rock stresses and radon emission. An area of secondary interest is Lumsen, see Figure 5-5. Here as well are presumable large volumes of homogeneous and fracture-poor granite. The degree of exposure is low, however, and the area is smaller than Joran.

There are railways and roads of good standard close to Joran and Lumsen that can be utilized for shipments to a deep repository. The shipments could, for example, go by rail from Skelleftehamn or Umeå to a deep repository in Storuman, see Figure 5-4.

To shed light on all aspects, the feasibility study has not been limited to geoscientific and technical questions, but has included several enquiries into such aspects as tourism, the future outlook for the municipality, business opportunities and the local economy. This material includes both facts and analyses, as well as the opinions of entrepreneurs and local citizens with different perspectives on the question.

Like any other major industrial facility, the deep repository entails some environmental impact on the site where it is constructed. The feasibility study's environmental study finds that the impact is small compared with what is usual in industrial contexts. This is because there is no real industrial process and chemicals are used sparingly.

The radiological working environment will conform to the standards and requirements that apply to nuclear facilities.The deep repository can be designed so that personnel doses are kept well below existing safety limits. Granites with higher uranium concentrations than usual in Storuman can give rise to high radon concentrations in rock facilities. In a deep repository, the radon must be ventilated away so that levels can be kept under legal limits.

Transport safety will be ensured through a system of transport planning, protective transport casks, physical protection and emergency planning. The shipments to the deep repository are not expected to entail any risks other than those that are usually associated with shipments of heavy goods.

The design of the deep repository and all measures on conjunction with deposition are aimed at containing and isolating all radioactive material. A central part of an environmental impact assessment for the deep repository is the assessment of long-term radiological safety. The feasibility study does not include any such assessment of safety for a deep repository in Storuman, since this requires, among other things, borehole investigations, which cannot be done until a site investigation is undertaken.

The results of the feasibility studies show that the establishment and operation of a deep repository will affect the locality and the region in different ways. The deep repository entails jobs, an increase in population, support for the local infrastructure and new business opportunities for the local entrepreneurs. However, it also entails something unknown and new that can be perceived as a threat and create anxiety.

A deep repository would, when fully operational, provide about 200 direct and 100 or more indirect jobs, which would correspond to nearly 10% of the number of persons employed in the municipality today. Figure 5-6 shows direct and indirect employment effects of the deep repository. As the figure shows, the indirect employment effects

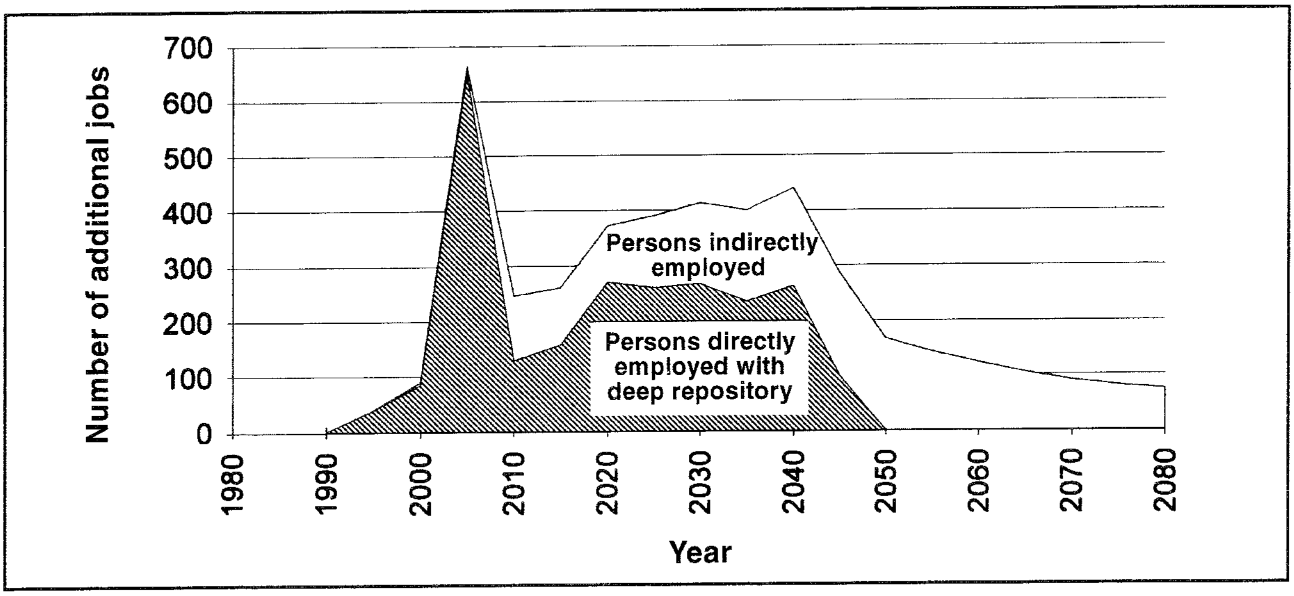


Figure 5-6. *Total number of jobs created by deep repository, directly and indirectly employed with deep repository.*

do not ebb out during the forecast period, but extend even further ahead in time. This means that the employment effects of the deep repository in Storuman span more than a hundred years.

Nearly 500 more persons would live in the municipality between the years 2000 and 2050 with a deep repository than without one. It is estimated that more than 30% or about SEK 5 billion of the total cost of SEK 15 billion could be absorbed locally.

SKB's conclusion is that areas exist in the municipality that may offer good prospects. They will therefore be included in the siting material as being of potential interest for site investigations. Before any further studies can be considered a comparison with the results from other feasibility studies will be made.

5.4 TECHNICAL STUDIES OF A DEEP REPOSITORY SYSTEM

Following the judgement made in 1992 that the KBS-3 design provides the most favourable possibilities in the Swedish crystalline bedrock the more detailed planning of the repository has been based on this design and the first step out of the five defined for the planning prior to construction has been worked through for three alternatives with respect to the system for access to the repository:

- Shafts only.
- Spiral ramp and shafts.
- Straight ramp implying separate locations of surface and underground parts as for the SFR facility.

Each of these studies has been made on the level of detailing that is requested as a base for initiating the second step of the planning process, which may start when site-specific data are available and one preferred access system can be outlined. The preference may very well be different for different sites, but even if the same basic principle, e. g. straight ramp, is chosen the layout at two different places are expected to be different because of the many ways to plan, in detail, for layout, ventilation system, water drainage system etc.

The main feature of the KBS-3 design is the location of the canister in good rock outside the disturbed zone caused by the excavation, and a position vertically downwards below the tunnel bottom is favoured. The merits of a horizontal position are, however, also analyzed such as:

- Self-drainage of holes.
- Less volume of deposition tunnel per canister when positions are located in each wall of the tunnel.
- Weight of canister distributed over larger bentonite surface.
- Less excavated disturbed zone in rock wall.
- Canister sealing weld may be located in the bottom of hole and weld finish can be placed downwards.

In conjunction with the comparison of different repository concepts in the PASS study /5-4/ the economy of the KBS-3 concept was also assumed to be possible to improve by the location of two canisters in each hole, which also is considered. The repository planning strategy is requesting a detailed engineering in accordance with the definitions of the first step before the second step is started. Only the vertical position has so far been studied to that detailed level. During 1994 preparations have started to evaluate the pros and cons with other canister position options in order to provide the basis for comparison, and, in case of a positive outcome, further engineering studies.

The technical studies on deep repository system comprise developing and adapting known technologies, R&D results etc. to the repository conditions and to choose and develop e g underground excavation methods, method and equipment for canister and buffer emplacement, compaction technique for the bentonite blocks, design and application of plugs and seals after disposal. Studies, discussions and planning has taken place on a broad range of topics during 1994. A more detailed presentation of these studies are given in Chapters 13 and 15.

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.

The preparation of the site investigation programme is going on. The aim of the site investigation is to give site specific data for the performance and safety assessment and for the layout and constructability analysis for the deep repository. Areas for site investigations will be selected among possible areas with good prognosis for siting of a deep repository which will be evaluated during ongoing and planned feasibility studies in a number of municipalities in Sweden. The site investigations will start with an initial step, aiming at investigate whether very unfavourable or discriminating geological conditions exist or not. The second step, complete site investigation, will be carried out at two sites, almost in parallel, according to present plans.

The site investigation programme will first of all be based on the siting factors of importance for siting a deep repository. In special those which are related to the geosphere and which are of relevance for the site investigation stage of the siting process. Secondly, the site investigations shall reach a general geoscientific understanding of the site, i. e. the area and the rock volume must be described and understood with regard to existing conditions and ongoing processes.

Preparation of techniques and routines for data management involves development of QA-routines, the geological database and rock modelling and visualization tool. Preparation of instrument and methods involves a new borehole-TV system, depth calibration of borehole measurements, development of high resolution radar etc.

5.6 ENVIRONMENTAL IMPACT ASSESSMENT

SKB plans for the deep repository include the preparation of Environmental Impact Statements. An EIA is formally required for certain facilities in accordance with the Swedish Act on the Management of Natural Resources and the Act on Nuclear Activities. The deep repository is such a facility.

The first, formal EIA has to be presented before licences of the detailed site characterization. In 1994 the SKB continued to prepare 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 content of an EIA should be developed gradually in a process where all parties (SKB, municipality, regional and national authorities etc.) concerned try to agree upon aspects and items to be covered in the EIA.

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 shell 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.

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

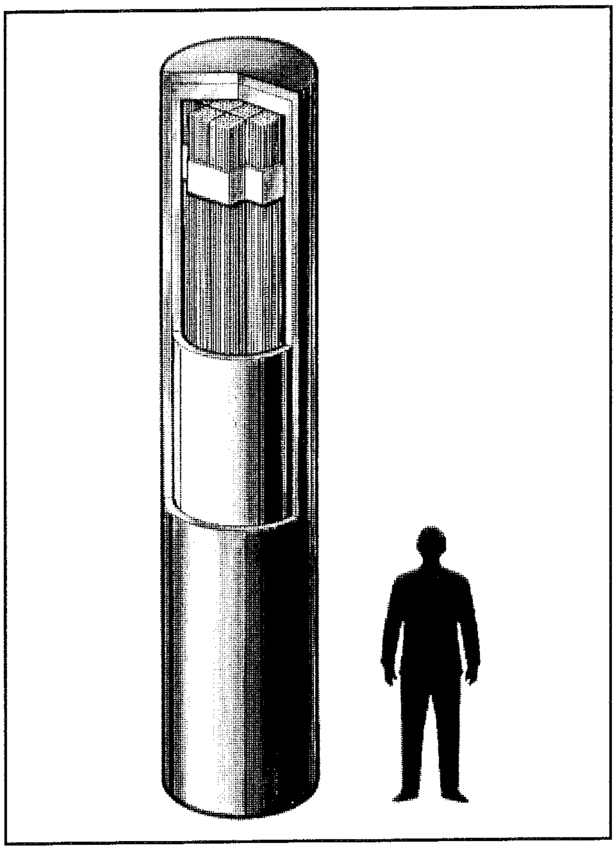


Figure 6-1. *Design of canister for BWR fuel elements.*

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 not affect the other barriers in the repository and 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. Earlier a preliminary design of the steel container was made. The basis for the preliminary design has been that the container shall resist an external uniform pressure of up to 15 MPa with a safety factor of 3. This allows the canister to also withstand the increased pressure foreseen with an ice cover of three kilometres (with safety factor 1). The initial temperature is for the design assumed to be 100°C. After several thousand years the temperature will decrease to an ambient temperature near 20°C.

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

The final design requirements for the canister will in the next design phase be reviewed and specified.

Welding techniques

Development of electron beam welding as a method for sealing of the copper lid continued during 1994. Earlier work had already demonstrated that high quality welds can be made in thick section copper at reduced pressure (0.5 mbar). In the beginning of the year a demonstration facility for canister lid sealing was commissioned. It is a welding chamber specially built for this purpose at The Welding Institute, TWI, see Figure 6-2. The upper part of the chamber has a rectangular cross-section to which the welding equipment is installed on a sliding seal. In the lower cylindrical part the copper cylinder is placed on a turn-table. The position of the top of the canister is monitored during the welding procedure and the sliding seal as well as the rotary motion is control by a computer. This way the joint can be tracked and followed even if the heat gives a length extension of the copper-cylinder. Once full diameter lids can be welded successfully, this chamber can be extended to welding full length canisters.

The benefits of employing reduced pressure electron beam welding are as follows:

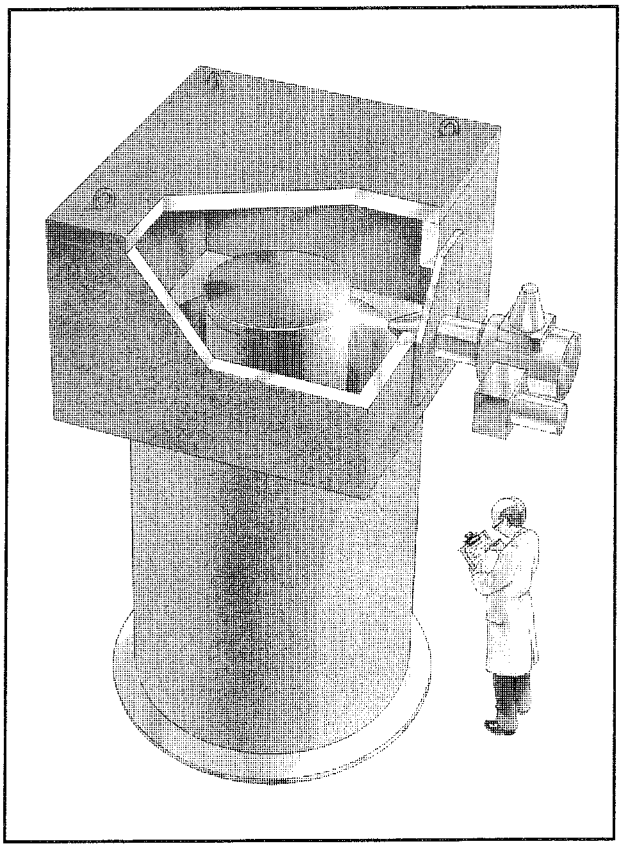


Figure 6-2. *Canister lid sealing demonstration facility.*

- Outgassing from trapped volumes in the canister is not expected to occur and affect the electron beam welding process.
- The integrity of vacuum seals in the chamber does not need to be as great for operation in reduced pressure (0.5-10 mbar range) as for high vacuum (0.005 mbar) systems.
- Maintaining a positive flow of helium out of a small diameter nozzle avoids ingress of metal vapour, ions and gas into the equipment. This reduces discharge events and associated weld defects.

During the year a series of 7 lids was welded to 50 mm thick copper cylinders with 900 mm diameter. The results show that it is feasible to seal the copper canister with electron beam welding technique. The quality of the seals has been tested by ultrasonic tests and radiography. Small defects have been detected and further studied after machining of the sealed area.

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.

As a first step for development of the future equipment for industrial welding of lids a new generation of "high power switch mode inverter" is being developed. A prototype of this electrical supply and control unit will be operational at TWI in the spring 1995.

Manufacturing tests

The feasibility of manufacturing copper canisters of the size needed for the encapsulation of spent fuel will be tested by use of two methods;

- Forming of copperplates to half cylinders to be joined by electron beam welding.
- Extrusion of copper cylinders.

After machining of the copper cylinder a bottom will be welded to it and a steel container will be put inside. The first two half cylinders have been manufactured so far and four canisters are planned to be manufactured until summer 1995.

6.3 DESIGN OF THE ENCAPSULATION PLANT

General plant description

It is planned to extend the CLAB facility with buildings for the encapsulation plant, see Figure 6-3. The encapsu-

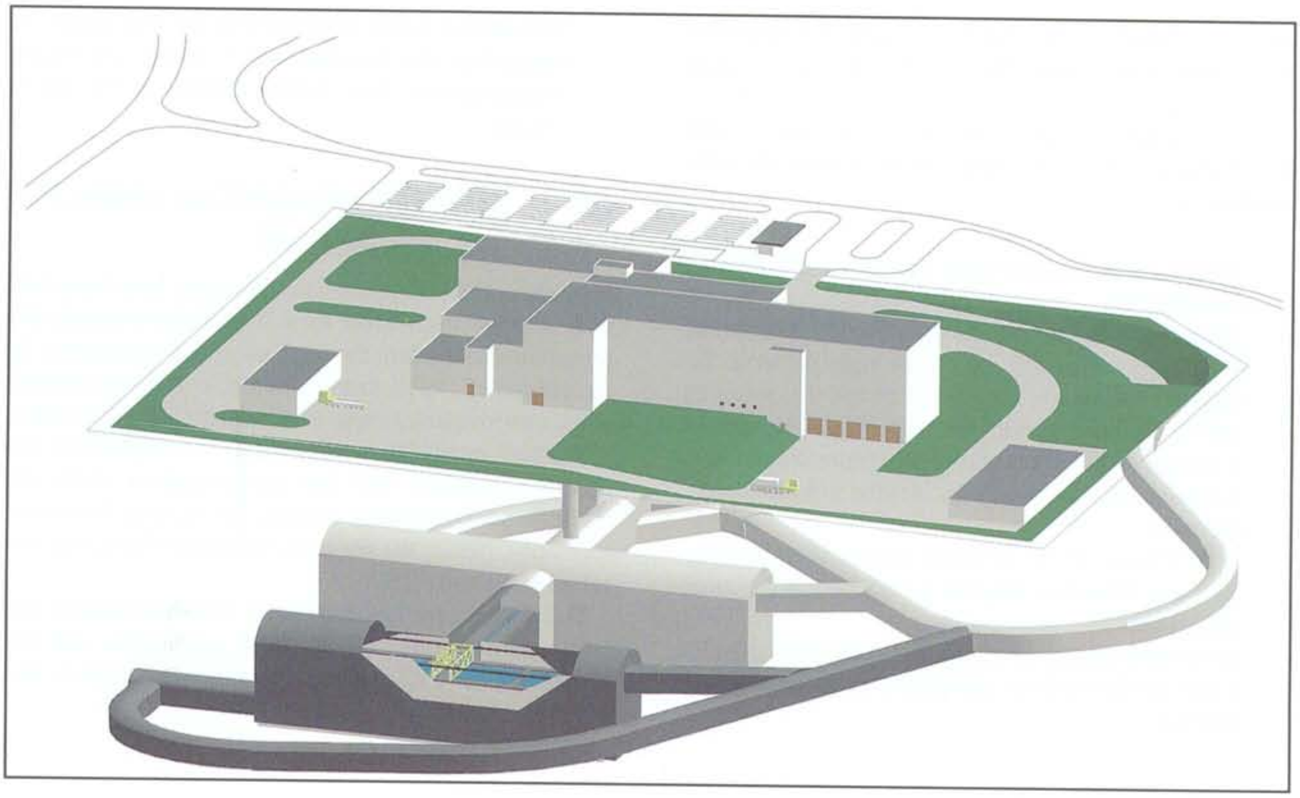


Figure 6-3. Overview of the encapsulation plant adjacent to the CLAB facility.

lation plant shall be designed and constructed mainly for the encapsulation process. Further shall it be possible to extend the facility with a process line also for treatment of core components. In the design work questions regarding operation, safety and maintenance shall be studied.

The encapsulation process starts with transport of the fuel elements from the storage pools in the rock caverns and ends with the fuel encapsulated in copper canisters prepared for transport to the deep repository. In parallel with the encapsulation plant an extension of the spent fuel storage capacity in CLAB is planned by building an additional rock cavern. This is also a part of the project. The design of the new cavern with storage pools and handling equipments is planned to be based mainly on the same technique used for the existing cavern. The cavern is planned to be designed for 1200 storage canisters in four separate storage pools.

Encapsulation process

In order to explore alternative designs and state of the art for the encapsulation process, feasibility studies were performed during 1993. Evaluation of the results was carried out during the winter 1993/94. The studies gave many interesting proposals for technical solutions for the various parts of the encapsulation process based on experiences from reference facilities. For the next design phases – the Conceptual and the Basic Design – an invitation to tender was sent in the spring 1994 to the various European companies who had contributed with studies for the feasibility study phase.

In June 1994 a contract was awarded to BNFL Engineering for the Conceptual Design and optional Basic Design for the encapsulation process. The conceptual design work started in the summer and was reported in preliminary documents at the end of the year. Another contract was in September awarded to ABB Atom for design of service systems and service areas in the encapsulation plant.

The conceptual design work started based on a preliminary general flow diagram for the encapsulation process. This flow diagram showed a preferred process based on the evaluation of the results from the feasibility studies. The diagram showed e.g. that the preparation of the fuel should be performed in water pools before entering the "hot cell" for drying and emplacement in the canister. It also showed that the encapsulation should be carried out in separate work-stations. The work in this first design phase was then focused on "optioneering" for the various parts of the process. For each part of the process alternative technical solutions were identified and evaluated as a base for the conceptual design phase. Preliminary design of the various systems have then been performed and reported in preliminary system descriptions with drawings of major components.

The conceptual design phase can be summarized with the following general description of the steps in the planned process.

- 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 placed in the canister. Before the canister is moved to the next work-station a temporary lid is fitted to avoid contamination.
- In the filling cell the air in the canister is replaced by inert gas. Finally a steel lid is attached to the inner steel container.
- In the next station, the welding station, the copper lid is put on the canister and sealed by electron beam welding.
- The canister is then transferred to the next station for machining and non destructive testing and finally contamination check before transfer to the buffer storage.

6.4 ENVIRONMENTAL IMPACT ASSESSMENT

From the start of the project close contacts have been held with representatives of the local community to explain the project and to explore the requests of the community. In the autumn of 1994 a formal discussion about the contact of the environmental impact assessment (EIA) took place. A working group has been created. It is chaired by the county authorities and has representatives from the Oskarshamn community council, the Nuclear Power Inspectorate (SKI), the Swedish Radiation Protection Institute (SSI) and SKB.

The community has engaged a local coordinator for information transfer to the local population and for knowledge build-up in the community. This work is financed by money from the Waste Funds.

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 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.

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.

The government decision on the programme was given December 16, 1993. 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 was submitted to SKI in August 1994 and then sent for review by SKI to the same reviewers as for the main report. By the end of 1994 SKI submitted their review report to the government. They found that "concerning siting, safety analyses and commitments by different decisions has SKB given the account requested by the government in the decision 1993-12-16. Concerning design premises for the encapsulation plant and the repository the account is, however, partly incomplete".

A summary of the Supplement to RD&D-Programme 92 is given in chapter 12 together with a brief account of the general SKI comments.

The government decision on the supplement is expected to be taken in the spring of 1995.

The work carried out during 1994 has in general followed the 1992 RD&D-programme. The expenditures for research and development within the SKB budget were 185.5 MSEK of which 59.4 MSEK were investments in the Äspö HRL as compared to 180.3 MSEK and 78.2 MSEK respectively during 1993.

This chapter gives a brief overview of some of the main R&D-activities. A more detailed account of the progress of R&D-activities is given in chapters 13 through 20 and in a separate annual report for the Äspö Hard Rock Laboratory.

7.2 SAFETY ANALYSIS

7.2.1 General

As mentioned above the Government decision on RD&D-Programme 92 stipulated that a supplementary account should be submitted. With regard to the safety assessments it was found that *the safety assessment methods that SKB uses should be further developed, especially with regard to how uncertainties are to be clarified and integrated. A strategy for the review of the relevance (validity) of the models should be developed based on the safety requirements of the safety assessments.* It was further required that SKB with regard to the safety assessments shall supplement the RD&D-programme with a programme for the safety assessments that SKB intends to prepare.

In this supplement SKB has declared its intention to give an account of safety and radiation protection matters for both the operating phase and the post-closure phase at all important decision occasions. This will be done

- in the form of (preliminary or final) safety reports (PSR/FSR) for the activities and the processes
  - in the encapsulation plant
  - in connection with transports and
  - in the deep repository, as well as

- in the fcrm of safety reports on integrated assessments of the long term performance of the deep repository after deposition and closure.

The evaluation of operating safety at waste facilities can be done in all essential respects using the same methodology as is used for other nuclear facilities.

In the programme for coming long-term safety assessments, the organization of the work and the methodology for performance and safety assessments for a deep repository are presented.

The programme during the forthcoming six-year period aims at producing:

- background data for sizing and designing the repository with respect to safety;
- a suitable structure for how the safety assessment is to be presented;
- a safety report on the long-term performance of the repository based on general data and preliminary site data prior to construction of the encapsulation plant, and a safety report (PSR) for the encapsulation plant;
- a safety report on the long-term performance of the repository based on data from site investigations prior to detailed characterization for the deep repository and a general safety report (PSR) for the operation of the deep repository.

In their review of the supplement SKI found that the presented plan for future safety assessments is well adapted to its purpose, and the description of how the assessments will be done is a good starting point for a dialogue between the stakeholders on the content and methodologies.

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 first step in the scenario development methodology is to describe the repository system and the relevant processes involved. All the relevant features, event and processes (FEPs) that are found are assigned to either the Process System (a description of the repository system in question) or regarded as external FEPs that might influence the Process System.

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 FEPs databases are under way.

The last step in the scenario methodology is to select the actual scenarios to be subject to quantitative evaluation. The above mentioned scheme seems to be a helpful tool to find the most important and interactive pathways through the Process System and also for finding processes and issues that can be given less priority. All decisions can be documented and put in relation to the schemes and thereby the overview of the decision process and the motivations will become clearer.

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.

7.2.3 Performance assessment of a copper/steel canister

The Swedish system for the final disposal of spent nuclear fuel is based on a copper canister with a very long lifetime. In 1992 different canister designs were compared and ranked. The outcome was that a steel canister with a copper overpack was the most favourable alternative, partly for fabrication-related reasons and partly in view of the assessment of the mechanical integrity of the canister.

The long time performance of this canister has been evaluated earlier, but a more complete assessment was made to clarify if the copper/steel canister meets the same safety standard as the previous reference designs.

The study indicates that the copper/steel canister meets very high safety standards and that the new scenarios pertinent for the new design can be treated in an acceptable way. Main conclusions from the preliminary study were:

- 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 through 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 suggests that there is ample capacity to transport gas away from the repository and up towards the surface.

7.2.4 Modelling of transport in the far field

Development for a Channel Network Model has been focused on improving the dispersion behaviour in the model. One option may be to include ideas from the field of self-similarity and fractals. A few algorithms have been tested. Work has also been devoted to using a system where only the fracture zones are represented. Each fracture zone within the target area would then be modelled as a 3D block consisting of a channel network. Finally, some development has also been focused on how to enable the model to use site specific data.

A series of verification studies have been carried out on HYDRASTAR. In general the agreements were found to be satisfactorily for all cases studied. Together with earlier studies on verification this help to build confidence that the code will produce correct results when applied to realistic cases. Use of hydraulic interference tests will probably improve simulation results by the large scale connectivity information.

Within the Äspö International Task Force a modelling of groundwater flow and transport of solutes is made using the large data base at Äspö.

The Channel Network Model was with comforting results applied to data from the Äspö site as a part of the Äspö Task Force work to model the large scale pumping and tracer test. A region of Äspö was simulated and the calculated drawdowns in boreholes were compared with the actual experimental outcome. The tracer tests were also analysed. Much work was focused on obtaining model parameters using available field information. In the perspective of a Channel Network approach, some parameters are lacking in the Äspö data.

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 has 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 alfa radiolysis and on fuel natural analogues. The experimental programme at Studsvik in progress since 1982 has accumulated contact times of up to 13 years on BWR fuel and 9 years on PWR fuel. Experimental studies of spent fuel fragments in contact with bentonite has indicated that technetium released from the fuel as TcO_4^- is reduced to Tc(IV) and strongly sorbed in the bentonite.

The work on canister materials is now included in the encapsulation project, see chapter 6.

Studies of buffer and backfill include testing and modelling of the physical behaviour and heat conductivity of water saturated and nonsaturated bentonite. Documentation of bentonite longevity has continued as well as the studies of cement-clay interaction. Work on alternative backfill materials to the sand/bentonite mixture has been initiated.

7.3.3 Geoscience

The general geoscientific programme comprises activities which among others attempt to quantify probable impacts of earthquakes, glaciation and land uplift. These activities emphasise long-term geodynamic processes in the Baltic Shield, such as postglacial faulting and glacial impacts on hydrogeology and ground water chemistry.

During 1994 the geoscience programme has focused on coupled processes.

A time dependent glaciation model of Scandinavia was developed during 1992. The ice sheet model reconstructs the ice sheet thickness, the ice sheet temperature, including basal temperature, basal melting pattern and velocity distribution. The model has now been coupled to a subglacial Darcian groundwater flow model which in turn provides boundary conditions for evaluations of long-term hydrogeological evolution at specific sites.

The next phase of this project has the objectives to investigate possible glacially-generated fracturing of bedrock and generating boundary conditions for a detailed study of time-dependent groundwater flow in the Äspö-Laxemar region. A further test of the climate/ice sheet model and an understanding of bedrock conductivity will be based on the chemical variability and the isotopic composition of groundwater recharge including glacier meltwater.

7.3.4 Chemistry

Included in the chemistry program are investigations of radionuclide chemistry and studies of chemical conditions that determine solubility, mobility and retention of radionuclides in a waste repository.

Thermodynamic constants that determine the solubility of radionuclides are measured in the laboratory. The relevant chemical environment is deep groundwater, bentonite pore water and concrete pore water. It is necessary to prove that redox reactions do indeed occur since they are sometimes inhibited. Therefore the kinetics of technetium reduction has been investigated. It was demonstrated how the mobile negative pertechnetate ion is reduced in rock-groundwater to four-valent technetium, which has a low solubility and high sorption.

Humic substances, colloidal particles and microbes exist in groundwater. In principle they can influence radionuclide solubility and mobility. Bacteria can also mediate geochemical reactions which are of importance such as oxygen consumption and sulphate reduction. Sampling of natural organic substances, colloids, and microbes in groundwater is performed at Äspö and Laxemar. Samples for comparison are also collected at the analogue investigation sites. SKB has together with AECL and ANDRA supported the microbial investigation of the bentonite from the buffer mass heater test at URL in Canada.

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 has performed 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 analogue studies

Natural analogue investigations are used in performance assessment to justify the assumptions made and validate the models. The SKB natural analogue program comprises four international projects; Jordan, Oklo, Palmottu and Cigar Lake, and the study of old concrete constructions (Portland concrete).

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 – 13. Typical solid cement phases are occurring as natural minerals and the environment is rich in elements, which also occur as waste nuclides. The first phase of the project was jointly funded by NAGRA, NIREX and Ontario Hydro. SKB participated in the second phase together with NAGRA and NIREX. A third phase is now under way, jointly supported by HMIP (Her Majestys Inspectorate of Pollution), NAGRA, NIREX, and SKB.

The 2 billion years ($2 \cdot 10^9$ 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 EU. Organisations from other countries including SKB are participating in the study. Our involvement has been concentrated 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. A total of 7 boreholes have been core drilled both into the Bangombé zone and outside. These boreholes have been sampled for geochemical investigations and used for hydraulic measurements. The first phase of the project will be finished in 1995. A continuation in a second phase is anticipated. Work completed so far has shown that the Oklo/Okelobondo/ Bangombé reactor zones hold great promise as a natural analog for processes associated with nuclear waste disposal. To date, however, direct use of these data in performance assessment of repository processes has not been undertaken. Plans are currently being formulated to develop a program that will provide a more direct linkage between the analog studies and performance assessment. This program will be proposed as a multinational effort to EU for the next phase of the Oklo project.

The 1.7 to 1.8 billion year old uranium-thorium deposit at lake Palmottu in southwestern Finland has been investigated as a natural analogue to spent fuel in granitic rock since 1988. The discontinuous subvertical ore zone is 1 to 15 m thick and extends from the surface and down to a depth of about 300 m. The uranium mineralisation, which has been investigated by 62 inclined prospection holes is situated in a host rock with the same hydrogeological, hydrochemical and geological conditions that are anticipated for a Finnish (and Swedish) spent fuel repository in the Fennoscandian Shield. The uraninite has chemical properties in common with spent fuel and the fact that the mineralisation extends from the ground surface and downwards makes it possible to study and compare the geochemical reaction of uranium under both oxidising (near the surface) and reducing (at depth) conditions. SKB has participated in the study.

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 was issued in 1994. Conclusions were drawn in repository performance areas such as: UO_2 dissolution and stability, clay sealing efficiency, colloid transport, groundwater chemistry, radiolysis and radionuclide migration. Most of the evaluations were focused on repository near-field issues for which Cigar Lake is a very good analogue. Due to the wealth of data gathered, we decided to continue the evaluation on results that are relevant to the SKB concept of spent fuel disposal. The working group that was set up for this purpose has completed its task.

Old constructions made of Portland cement have been sampled to investigate the development of the cement paste. Samples have been taken from the foundation of an old school built at the end of the 19th century in the Swedish town Gävle, from a dam (tunnel) in Älvkarleby in Sweden built in 1917 and from a 90 year old water tank from the castle in the Swedish town Uppsala. The results points to the benefits of a tight concrete and no hydraulic gradients over the construction. Saturated conditions, a tight concrete and stagnant groundwater will improve the quality of the cement by slow hydration reactions.

7.3.6 Biosphere

The biosphere studies treats the transport of radionuclides from the bedrock via primary receptors (e. g. sediments), redistribution in nature and finally calculates 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 and VAMP. The RES method has proven to be a useful tool in demonstrating process-interactions for different scenarios.

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 how the variations in leached elements from surrounding till is reflected in the strata of the bog sediments.

Site specific data is studied in the Äspö area, and has been studied in the Gideå area since the Tjernobyl 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 WASTE THAN SPENT NUCLEAR FUEL

Long-lived low and intermediate level waste (LLW and ILW) is a third category of waste in addition to spent fuel and short-lived LLW and ILW. The quantities are relatively minor and the main sources are waste from research activities and used components from the power reactors which have been situated inside or near the reactor core (core components and reactor internals). Core components are stored at CLAB and research waste are collected, stored and conditioned at Studsvik. The present concept for disposal of this waste is to build a facility near the repository for spent fuel and at a comparable depth. It will consist of three parts: SFL 3, 4 and 5.

SFL 3 is designed as a cavern with concrete caissons where waste from Studsvik, operational waste from CLAB and the encapsulation plant will be emplaced. SFL 4 consists of tunnels for decommissioning waste from CLAB and the encapsulation plant. SFL 5 consists of caverns for the disposal of reactor core components and internal parts, all packed in concrete containers. Concrete, sand and bentonite will be used as backfill in the various parts of the repository.

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.

At the end of 1992 it was decided to make an inventory of waste for SFL 3-5, to continue work on the design and to compile data for the safety assessments that will become necessary later on. In order to stimulate and direct these efforts it was decided to perform a prestudy that started early 1993 and ended late 1994. The aim of the prestudy was to make a first preliminary assessment of the near-field barriers to radionuclide dispersion. The prestudy has been reported in a series of four reports with the following titles:

- Low and intermediate level waste for SFL 3-5.
- Testing of Influence Diagrams as a tool for scenario development by application on the SFL 3-5 repository concept.
- Radionuclide release from the near-field of SFL 3-5. A preliminary study.
- Prestudy of final disposal of long-lived low and intermediate level waste.

The results of the prestudy indicate that the barriers of the conceptual design are efficient to protect man and the environment from the waste. However, the preliminary nature of the prestudy should be remembered and further work is needed prior to a complete safety assessment. The investigations have therefore been continued in a second phase starting in october 94 with the main aim to prepare for a safety assessment that will begin by mid 96. The second phase of the study of other long-lived waste consists of the following parts:

- Preparation of tables with radionuclide content and waste composition to be used in a safety assessment.
- Preparation of a chemical data base containing information on water chemistry, concrete composition and chemistry, radionuclide sorption, diffusion and solubility, organic complexes and colloids.
- Analysis of alternative scenarios (e. g. ice age), hydraulic influences, the effects of colloids, microbes and gas formation.
- Compilation of barrier properties; waste package, concrete construction, near-field rock, backfill of concrete, bentonite and sand.
- Comparison between different design alternatives.
- Testing and development of transport models.

Disposal of long-lived LLW and ILW is being studied in other countries too. Therefore an informal exchange of experience have been established between SKB and the organisations ANDRA (France), NAGRA (Switzerland) and NIREX (the UK). This is reflected in the prestudy, where references have been made to recently published data from NAGRA and NIREX.

7.5 ÄSPÖ HARD ROCK LABORATORY

The Äspö Hard Rock Laboratory is being constructed as part of the preparations for the deep geological repository of spent nuclear fuel in Sweden. An Annual Report 1994 and Chapter 17 contains more detailed overviews of the work conducted.

The present work is focused on verification of pre-investigation methods and development of detailed investigation methodology which is applied during tunnel construction. Construction of the facility and detailed characterization of the bedrock are performed in parallel. Excavation of the main access tunnel was completed in September 1994 and at the end of the year only minor excavation work remained. The last 400 m of the main tunnel, which has a total length of 3600 m, was excavated with a 5 meter diameter tunnel boring machine (TBM). The tunnel reaches a depth of 450 m below ground.

Office and storage buildings have been completed on the Äspö Island as well as buildings for ventilation equipment and machinery for the hoist. Together, these buildings comprise the "Äspö Research Village", which is designed to look like other small villages in the surrounding archipelago. The village was completed in 1994.

The comprehensive work on data collection for detailed characterization of the underground at Äspö was nearly completed by the end of 1994. These results will be used for a comparison of the predictions made of rock properties and groundwater flow and composition based on surface and borehole data with actual observations in the tunnel. The management of large quantities of data has now been developed to a point where SKB is in possession of a data production methodology that meets rigorous requirements on quality and overview. The final reporting of the experiences and results from the pre-investigation and construction phases is in progress.

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 experiment is performed in two test drifts near the TBM Assembly hall at an approximate depth of 420 m below the ground surface. Measurements of rock properties have been made before, during, and after excavation. The preliminary analysis of the results obtained so far indicates that the measurable changes in properties induced by excavation of the TBM tunnel are small to negligible.

The Redox experiment in Block Scale was completed in 1994. The purpose of the block scale redox experiment was to investigate the chemical changes when oxidizing water is penetrating a 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 lasted until 1994. No oxygen breakthrough was observed and the chemical composition remained constant throughout the experimental time. The explanation for this is that the high content of organic matter in the infiltrating surface water has been biologically oxidized at the same time as the dissolved oxygen has been consumed.

Preparations for the Operating Phase have started and detailed plans have been prepared for several experiments and for a few of them work has already been initiated.

A "Program for Tracer Retention Understanding Experiments" (TRUE) was outlined in 1994. The basic idea is that tracer experiments will be performed in cycles with an approximate duration of 2-3 years. At the end of each tracer test cycle, results and experiences gained will be evaluated and the overall program for TRUE revised accordingly. A test plan which details the work during the First TRUE Stage has been prepared.Investigations with the purpose of identifying a suitable test site within the Äspö Hard Rock Laboratory was started late 1994.

The project Degassing of groundwater and two phase flow has been initiated to improve our understanding of observations of hydraulic conditions made in drifts, interpretation of experiments performed close to drifts, and performance of buffer mass and backfill, particularly during emplacement and repository closure. A pilot test did not show any degassing effects due to a very low gas contents in the hole selected for the test.

The CHEMLAB probe is built to conduct validation experiments in situ at undisturbed natural conditions. This is a borehole laboratory built in a probe, in which migration experiments will be carried out under ambient conditions regarding pressure and temperature and with use of the formation groundwater surrounding the probe. The manufacturing of the probe is presently under way.

The Äspö HRL provides an opportunity for demonstrating technology that will be used in the deep repository. The need to integrate existing knowledge and build an (inactive) prototype of a deep repository is recognized within SKB. A part of a deposition tunnel will be built and backfilled at Äspö. In conjunction with planning, design and construction, work descriptions and quality plans are being 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. A programme for the prototype repository was prepared during 1994.

A "Task Force" with representatives of the project's international participants has been formed. The Task Force shall be a forum for the organizations supporting the Äspö Hard Rock Laboratory Project to interact in the area of conceptual and numerical modelling of groundwater flow and solute transport in fractured rock. The evaluation of Task No 1, the LPT2 pumping and tracer tests, is in progress. A wide variety of conceptual as well as numerical models have been used to predict water flow and tracer breakthrough in this rather large scale. Task No 2 on modelling tracer transport in a single fracture was finalized during 1994. The hydraulic impact of the tunnel excavation at Äspö HRL was defined as the 3rd Modelling Task. The objective will be to evaluate how the monitoring and the study of the hydraulic impact of the tunnel excavation may help for site characterization. This will be an exercise in forward as well as inverse modelling.

Presently (April 1995) eight organizations from seven countries participate in the work at the Äspö Hard Rock Laboratory and contribute in several ways to the result obtained. The results of this work are reported in the Äspö International Cooperation Reports.

During autumn 1994 negotiations with Bundesministerium für Forschung und Technologie (BMFT) in Germany has been taken place regarding cooperation in the Äspö Hard Rock Laboratory.

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 of long-lived radionuclides into shorter-lived isotopes (P&T) 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 Gothenburgh. The work at KTH is emphasized on safety related issues and at CTH on processes for partitioning. A status report on the P&T-work is planned for 1995.

SKB is also planning further research work related to the disposal in very deep boreholes.

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 1994 calculations were presented in PLAN 94 /8-1/. The total future electricity production (from 1994) was estimated to be about 1 150 TWh, if all twelve reactors are operated to the year 2010. Up to the end of 1993 about 850 TWh have been produced making a total of about 2 000 TWh in the Swedish programme. For this production a fuel amount of about 7 810 tonnes of U is required.

The total future back-end costs were estimated to be about GSEK 47.6 (price level of January 1994) 1 GSEK = 10^9 SEK $\approx 0.14 \cdot 10^9$ US\$. Up to and including 1994 already GSEK 9.7 have been spent. The total cost for the back-end of the nuclear fuel cycle is thus about GSEK 57.3. 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 1995 shall be SEK 0.019 per kWh on an average. This is the same fee as for the last twelve 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 1994 about GSEK 15.4, an increase by GSEK 2.1 during 1994.

In 1994 a review of the financing system and the management of the funds was made by a Government Commission. The conclusions of the Commission were that the financing system has worked well, but could be improved in the following ways:

- the funds that are at present put in interest bearing accounts in the Bank of Sweden should be invested with the aim of attaining a higher return than is currently possible, while still having a high security,
- the responsibility of the utilities to pay all the costs for the radioactive waste management should be made more apparent by the introduction of formal guarantees from the utilities,
- with the introduction of guarantees, the contingencies normally included in the fees could be removed so that the fees in the future should reflect the probable costs.

The proposal is now studied by the Government and a proposal to Parliament to change the Financing Act along these lines is expected in 1995.

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

In 1994 a comprehensive study of the technology and costs for decommissioning the Swedish nuclear reactors was completed /8-2/. The study was focused on two reference plants, the boiling water reactor (BWR) Oskarshamn 3 and the pressurized water reactor (PWR) Ringhals 2. Subsequently the result from these plants have been translated to the other Swedish plants.

The study gives an account of the procedures, costs, waste quantities and occupational doses associated with the decommissioning. Dismantling is assumed to start immediately after removal of the spent fuel, i. e. one – two years after final power production and the site is restored after decommissioning so that it can be used without restriction for other industrial activities.

The study shows that a reactor can be dismantled in a radiologically safe manner. Most of the equipment that is required is already available and is used routinely for maintenance and refurbishment at nuclear power plants. Some special equipment will be needed, in particular for the cutting of the reactor pressure vessel.

The dismantling of one reactor unit can be accomplished in about five years, with an average labour force of about 150 persons, with a maximum of 300 persons during a shorter period in the beginning of the dismantling works.

The cost of decommissioning Oskarshamn 3 was estimated to be about MSEK 940 in January 1994 prices. The estimate for Ringhals 2 was MSEK 640. In total for all twelve reactors the cost of dismantling will be MSEK 8 800.

Additional costs are incurred for the period from shutdown to start of dismantling. These are dependant on the length of this period, and will at a minimum amount to MSEK 3000.

From the decommissioning of all twelve Swedish reactors a total of about 140 000 m^3 of radioactive waste will be generated (the exact amount of waste depends on how much material that will be decontaminated). Most of this will be transported to the SFR final repository at Forsmark. The cost for transportation and disposal is estimated to MSEK 980.

SKB's engagement in the OECD/NEA international cooperative programme on decommissioning has continued during 1994. SKB is responsible for the programme coordinator function. The programme comprises 29 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 Shipping port reactor in the USA where the dismantling was completed in 1988, the Japanese JPDR reactor and the German Niederaichbach reactor where the dismantling has been almost completed.

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 uranium and certain purchases of enriched uranium.

9.1 NATURAL URANIUM

The Swedish nuclear power plants have annual requirements of about 1 600 tonnes of natural uranium. These requirements are met by producers from Australia, Canada, Kazakstan, Uzbekistan and the Russian Federation. The uranium is mined mainly in modern mines, mostly open-pit mines. Production from Kazakstan and Uzbekistan is mined by in-situ leaching, ISL, which is a method that gives small impact on 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. En-

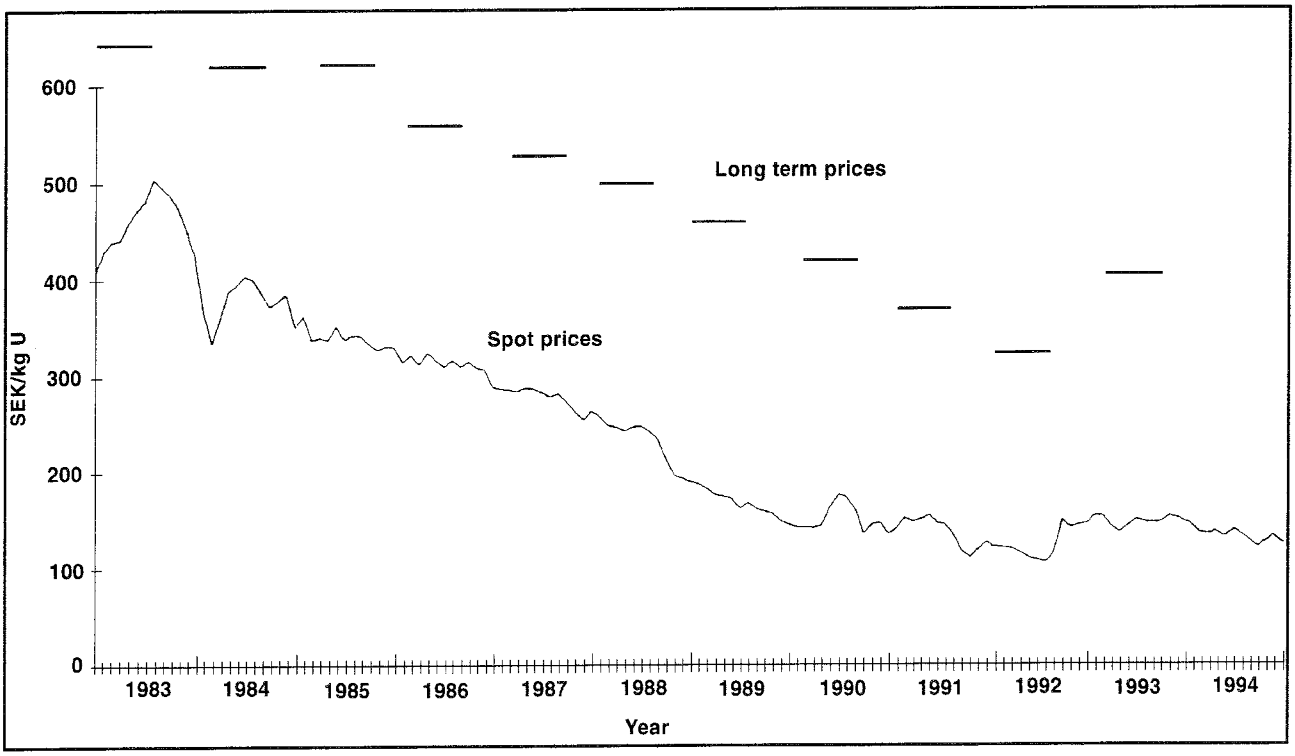


Figure 9-1. *Long term and spot prices for uranium.*

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.

richment is a process to increase this content up to 3-5% of uranium-235. This low enriched uranium is a suitable fuel for light water reactors which are used in Sweden.

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 in Novouralsk, 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 to ABB Atom, but also orders to 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 210 tonnes of UO_2 for nuclear fuel during 1994. Of this volume about 90 tonnes were exported to Belgium, Finland, France, Germany and Switzerland. The fuel assembly design SVEA 96/100 where the fuel rods are divided into four minibundles with 5 x 5 rods separated by a water cross, is now the dominating BWR fuel manufactures in Sweden.

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 1994.

	SEK/kWh	Million SEK in 1994
Natural uranium	0.007	490
Conversion	0.001	70
Isotope enrichment	0.007	490
Fuel fabrication	0.009	630
Strategic stockpile	0.001	70
Total nuclear fuel	**0.025**	**1 750**

9.5 COSTS

The costs for front end supply of nuclear fuel in 1994 in Sweden are shown in Table 9-1 (the production of nuclear electricity was 70.2 TWh in 1994).

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.

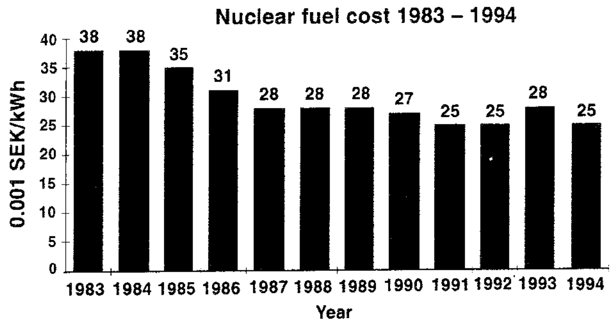


Figure 9-3. Nuclear fuel costs 1983-1994.

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 cooperation 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 more than 100 assignments have been accomplished for organizations in Australia, Belgium, Canada, Czech Republic, Finland, Hungary, Japan, Lithuania, Estonia, South Korea, Spain, Switzerland, Taiwan,

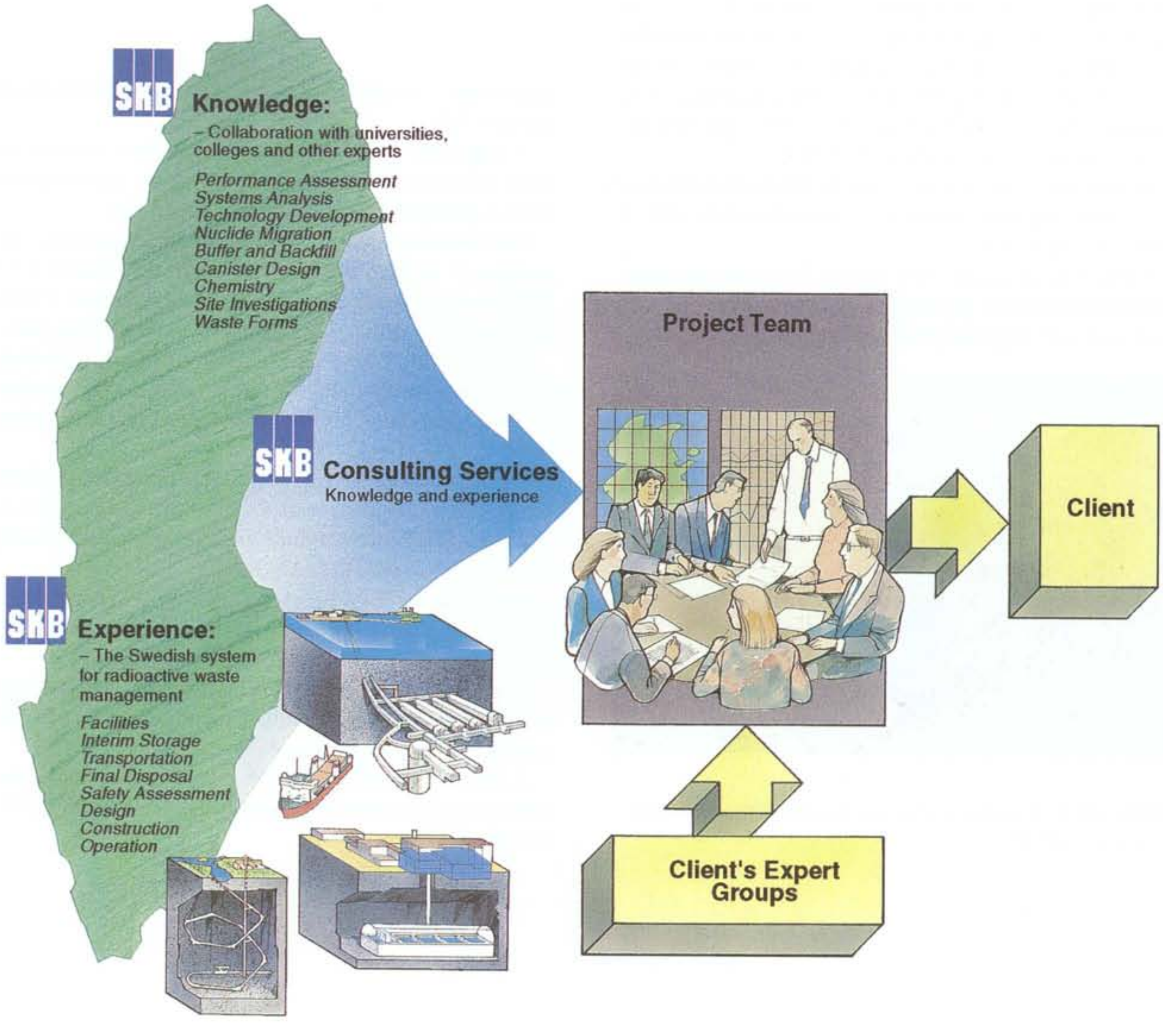


Figure 10-1. The SKB Consulting Services.

United Kingdom and USA. The assignments have dealt with long-term safety, overall planning, canister and buffer materials, transports, field investigations, site selection, decommissioning and facility design.

10.2 NWM WORK DURING 1994

During 1994 SKB was contracted by organizations in United Kingdom, Estonia, Lithuania, Finland, Japan, Spain, Canada and Taiwan. Marketing activities have been going on in a number of countries among them the Russian Federation, China, Republic of Korea, Taiwan and Hungary. In all, some fifteen assignments have been concluded, distributed over eight countries.

The marketing has as in the past year been focused on East Asia and Eastern Europe. The Republic of Korea become at the end of the year of special interest, since the government made publicly known the site for the planned radioactive waste management center, which among other will host a rock cavern type repository for short lived waste.

The activities in Lithuania had high priority during whole the year. Unfortunately the project start for the intermediate spent fuel storage was delayed for a number of months because of financial difficulties. However, the project finally started at the end of 1994 and storage casks manufacturing is scheduled to April 1995 with first delivery to Ignalina NPP at the end of 1995.

A compactor for low level waste has been manufactured in Sweden and was delivered to Ignalina at the end of 1994, see Figure 10-2.

A tendering procedure was started for a cement immobilization facility for spent resins. Seven tenders have been evaluated and negotiations have started with the shortlisted ones. A contract is planned to be awarded during spring 1995.

Figure 10-2. *Compactor for low level waste, delivered to Ignalina NPP.*

Figure 10-3. *Interior picture from one of the two shorebased submarines at Paldiski in Estonia.*

A long-term waste management plan for Lithuania has been prepared. Implementation of given recommendations is planned to start in the course of 1995.

Decommissioning of the two shorebased nuclear submarines is of high priority in Estonia, see Figure 10-3. SKB is commissioned by the Swedish Radiation Protection Institute, SSI, to work out a decommissioning plan.

In cooperation with the Spanish geological company, ITGE, SKB has continued to give support in the development of instruments for hydrogeological borehole instruments.

Japan Nuclear Fuel Ltd, JNFL, has through Mitsubishi Corporation commissioned SKB to develop a report regarding a R&D program for high level waste with priority given to geoscientifical questions.

On behalf of Toyo Engineering Corporation in Japan transfer of know-how and operation experiences from certain process system in CLAB has taken place.

Experiences from the SFR licensing procedure has been compiled for the Radwaste Administration in Taiwan and presented in the form of a seminar in Taipei.

A number of radar reflection measurements have been carried out in deep boreholes in Finland on behalf of TVO as well as IVO.

11 PUBLIC AFFAIRS AND MEDIA RELATIONS

11.1 GENERAL

According to Swedish law, the nuclear power utilities are obliged to take whatever measures are needed to manage and dispose of the nuclear waste in a safe manner. It is SKB who bears 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.

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 that exists today, and the fact that it will pose a risk in the future if it is not dealt with properly. The necessary knowledge on different ways to build safe repositories exists internationally. SKB participates actively in the international research.
- 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 work that SKB has now begun of siting a deep repository for spent nuclear fuel. In 20 years there will be a method, a site, a started facility and money to continue along the chosen path. But freedom must also exist to choose other solutions.

11.2 SKB's 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. Visits to schools, municipalities and expos/fairs of various kinds are made throughout the year.

Figure 11-1. 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.

In the summertime, SKB's personnel host an exhibition on board the waste transport ship M/S Sigyn. In this way SKB meets the public, associations and community leaders face-to-face, see Figure 11-1.

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. At the localities where SKB is initiating or conducting feasibility studies, site offices are opened with their own exhibitions. Interested persons can come into direct contact with representatives of SKB there.

During 1994 SKB's exhibition trailer visited 11 expos/fairs and 26 schools. In addition, SKB visited some municipalities that particularly wanted to have more information on the deep repository for spent nuclear fuel. Visits

Figure 11-2. SKB conducts extensive information activities in Sweden's schools.

were made to 203 school classes with a total of 5,082 pupils during the year, see Figure 11-2. SKB's instructional material *På djupet* ("At Depth") was used by many teachers in the classroom. During the summer, 14 ports were called at by the transport ship M/S Sigyn, which served as a floating exhibition hall.

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 equipment used in the handling of the waste, such as transport casks, as well as models of the planned deep repository and the canister that is intended to be used. The exhibitions were visited by about 61,000 people from the general public, school classes, local community and government leaders, and associations.

SKB's facilities were visited by more than 27,000 people from 32 countries during 1994.

In Malå, where SKB is conducting a feasibility study, a site office was opened with its own exhibition, see Figure 11-3. There is a similar office with exhibition in the feasibility study municipality of Storuman.

Figure 11-3. SKB's site office in Malå.

11.3 SKB's INFORMATION MATERIAL

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

To make it easier for the public to obtain information, SKB offers *Frisvar* ("Free response"), whereby people can write to the company postage-free, and a toll-free 020 number, where information can be ordered round the clock for the cost of a local call (both these offers are available in Sweden only).

The basic philosophy is that everyone who wants to should be able to find out about the facts, principles and future plans for the radioactive waste, and also discuss this with representatives of SKB.

A new video was produced during the year. It is called "Deep repository for spent nuclear fuel" and is about the planned deep repository. The film makes heavy use of computer-graphic animation. It has been widely distributed and is available at all the audiovisual centres in the country. Another film has also been produced about natural analogues, examples of how nature has isolated various materials over long periods of time. It is a co-production with Belgium, Canada, Switzerland, Spain, the UK and the USA.

Lagerbladet, SKB's newsletter, was distributed with four issues during 1994. The newsletter has more than 25,000 subscribers.

REFERENCES PART I

Chapter 1

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

5-1 RD&D-Programme 92. Treatment and final disposal of nuclear waste. Programme for research, development, demonstration and other measures. Main report plus three background reports.
SKB September 1992

5-2 RD&D-Programme 92, Supplement. Treatment and final disposal of nuclear waste. Supplement to the 1992 programme in response to the Government decision of December 16, 1993
SKB August 1994

5-3 Feasibility study for siting of a deep repository within the Storuman municipality.
January 1995
SKB Technical Report TR 95-08, Stockholm

5-4 Project on Alternative Systems Study (PASS). Final report
1992
SKB Technical Report TR 93-04, Stockholm

Chapter 6

6-1 PLAN 94
Costs for management of the radioactive waste from nuclear power production.
SKB Technical Report TR 94-23, Stockholm

Chapter 8

8-1 See 6-1.

8-2 Technology and costs for decommissioning the Swedish nuclear power plants.
1994
SKB Technical Report TR 94-20, Stockholm

SKB ANNUAL REPORT 1994

Part I

Overview of SKB Activities

CONTENTS PART II

Page

12 SUPPLEMENT TO 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 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 safety-boards, 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/.

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/.

The government decision on the programme /12-6/ was given in December 1993. The government decided that the programme should be supplemented by SKB 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 supplement thus requested by the government was submitted by SKB to the Nuclear Power Inspectorate in August 1994 /12-7/. A summary of the supplement is given in section 12.2.

The inspectorate sent the supplement for comments to the essentially same reviewers as for the main programme. Based on the comments thus received and their own review submitted a review report to the government in December 1994 /12-8/. SKI's main comments are summarized in section 12.3.

12.2 SUMMARY OF SKB's SUPPLEMENT

BACKGROUND

In RD&D-Programme 92, SKB gave an account of its – and thereby the concerned power industry's – planning for deep disposal of the long-lived radioactive waste, including the spent nuclear fuel, that arises in connection with the operation of the Swedish nuclear power plants:

> The goal is to begin deposition in a deep repository of a small portion (5-10%) of the spent nuclear fuel in 2008, in compliance with all environmental and safety requirements. For this an encapsulation plant and a deep repository are required. Furthermore, additions to the existing transportation system are needed to ship the encapsulated fuel from the encapsulation plant to the deep repository. The basic scheme is encapsulation in copper canisters and deep disposal in accordance with the KBS 3 concept or a closely-related optimized version at a depth of about 500 m in the crystalline bedrock. The encapsulation plant shall be built as an extension of CLAB. The deep repository shall be built on a suitable site in Sweden that both enables the stringent safety requirements to be met and allows the necessary work to be carried out in consensus with the concerned municipality and the local populace. The safety and radiation protection aspects will be thoroughly penetrated and satisfactorily accounted for before a decision on essential binding measures is taken.

The main strategy described in RD&D-Programme 92 has been accepted in all essential respects by the regulatory authorities and the Government.

The regulatory authorities also level criticism at certain unclear points in the programme. With reference to this criticism, the Government decision stipulates that a supplementary account be submitted to SKI as follows:

SKB shall supplement RD&D-Programme 92 by describing

- *the criteria and methods that can form a basis for selection of sites suitable for a final repository,*
- *a programme for description of the specifications for the design of an encapsulation plant and final repository,*
- *programme for the safety assessments which SKB intends to prepare,*

- *an analysis of how different measures and decisions influence later decisions within the final repository programme.*

The recommendations made by SKI and KASAM in their statements of comment should be taken into consideration in the supplementary account to the RD&D-Programme.

SKB sees this supplementary account as a natural step in the continued planning of the measures required to implement the approved main alternative. A number of important consequential decisions regarding environmental impact assessments, siting, safety reporting, investments, permits under various laws etc. must be made on the way up to completed final disposal. Background information of varying scope is required for these decisions and will be provided by the work now begun. Naturally, such information can also occasion re-evaluation and changes in the chosen main alternative and thereby also affect the schedule.

Some fundamental premises presented in RD&D-Programme 92 are that:

- in SKB's judgement, the current level of knowledge makes it possible to proceed from research and development to implementation,
- the need for further information on geological conditions is chiefly site-related,
- project-oriented work with clear goals is necessary to maintain the level of quality in the work.

The following report first presents an analysis of different measures and decisions in response to the last point in the Government's stipulations on a supplementary account. The reason is that such an analysis provides an overview of the entire process, while the other points deal with more specific programmes.

ANALYSIS OF DIFFERENT MEASURES AND DECISIONS

The requirement for *"an analysis of how different measures and decisions influence later decisions within the final repository programme"* concerns both overall measures and more short-term measures within the decided programme. The overall measures are discussed in this section, while the more short-term measures come under consideration in the specific programmes. Construction of an encapsulation plant and a deep repository, encapsulation of spent fuel and deposition of encapsulated fuel in the deep repository embrace a large number of measures regarding which decisions are made step by step. Measures that concern the deep repository embrace a time span of sixty years or more from the start of feasibility studies up to completed closure of the repository.

Decisions regarding different measures always entail certain commitments in different respects. In this context it may be purely physical commitments, i. e. the measure entails changing the physical state or properties of the waste in a way that makes it difficult or impossible to return to previous states or to choose an alternative path later on. It may also be that a decision on a certain measure ties up large resources, which in turn means that switching to an alternative path is more difficult due to a lack of resources.

In the plan presented by SKB, physical measures that directly affect the waste will not be carried out until encapsulation has begun after the necessary development, design and construction work has been carried out and the necessary permits have been obtained from the authorities. This will not occur until 2007 at the earliest. However, large resources will be committed earlier – especially when the construction work for the encapsulation plant is begun and when detailed characterization starts for the deep repository.

In the initial construction stage for the deep repository, approximately 10% of the spent fuel will be deposited. This will be followed by thorough evaluation and a new permit will be required to continue along the same path. SKB's judgement is, as was asserted in RD&D-Programme 92, that the deep repository will be expanded to full scale.

The approximately 400 fuel canisters that are deposited can, however, be retrieved if this should be deemed desirable. The cost of such retrieval is estimated at SEK 600 million. The investments that will then have been made in the encapsulation plant and in the deep repository are considerable – a total of about SEK 5,000 million, of which SEK 4,000 million will be invested prior to the first encapsulation of nuclear fuel.

One reason for retrieval could be, for example, that (international) technological developments in the field have led to a situation where other handling and/or treatment methods for the spent fuel are found to be very attractive. Another possible reason could be that it has been decided not to continue on the selected site.

The option of interrupting the deposition work and retrieving deposited waste will exist throughout the construction and operating periods for the deep repository, but naturally at progressively increasing costs. Before the repository is closed and sealed, it can be kept under surveillance for as long as desired.

Information on the repository will be filed and the site of the repository will be marked in an appropriate fashion. Even after closure of the repository, this information will make it technically possible for a long period of time to retrieve the waste, if desired. After closure, each generation will have to decide what kind of surveillance and monitoring they wish to have on the site.

An important principle for the encapsulation and deep repository projects is that each new step shall be based on an adequate body of technical data. Regulatory authorities, municipalities and other concerned bodies shall be given sufficient time to review the material thoroughly before making important decisions. At the same time, it must be borne in mind that it is important to keep the process moving forward at a certain pace, not least for the quality of the work. SKB believes that fifteen years is sufficient to complete the first construction stage in the deep repository programme. The necessary facilities are of neither such a size nor such a complexity that more time is needed.

Another important aspect is the interaction between supportive research, development, design and construction of the planned facilities. The development work within the framework of RD&D-Programme 92 is therefore being planned with the needs of the encapsulation and deep repository projects in mind. An example is the Äspö Hard Rock Laboratory (HRL), where the first phase with geological investigations and construction will be concluded during 1995. It is yielding important material for the design of site investigations and later detailed characterization for the deep repository. The next phase of experiments and investigations at Äspö will similarly yield material for safety assessments and for the final design of the deep repository and its barrier systems.

CRITERIA AND METHODS FOR SITE SELECTION

Criteria for siting

Of greatest importance for siting of the deep repository is to choose a site where the safety-related conditions are very good. Since the mid-1970s, SKB has carried out extensive study site investigations and other studies of geological conditions at depth in the Swedish bedrock. Furthermore, SKB and other organizations have conducted a number of detailed safety assessments for final disposal in the environment existing in the Swedish bedrock. Considerable knowledge also exists from siting and construction of underground rock facilities for mines, power plants, oil storage and defence purposes in most parts of the country. Based on this knowledge and experience, many municipalities are judged to have sites with very good conditions from a safety viewpoint. It is therefore reasonable and realistic to start with municipalities who actively wish to participate or otherwise show an interest and investigate the prospects for siting of a deep repository there. The possibilities in municipalities that already have nuclear activities will also be examined. Among municipalities with good safety conditions and with an expressed interest in a deep repository, siting will proceed on the basis of the results of a closer assessment of safety and environmental impact, transportation situation, experience of industrial activity and existing infrastructure in other respects.

This means that the organization of the siting work is based on a conviction that it is necessary and possible to find a site that meets high environmental and safety standards at the same time as a local understanding for the establishment of a deep repository is sought. This approach is well in agreement with the intentions underlying the applicable legislation in, for example, the Act on the Management of Natural Resources and the Act on Nuclear Activities. It also complies closely with the recommendations issued by the Nordic countries' radiation protection and safety authorities. The existing Swedish system with interim storage in CLAB also provides ample time and opportunity to consider the possibilities for executing deep disposal in collaboration.

Siting factors and criteria

Siting of the deep repository must take place in consideration of a number of factors (data, properties, conditions). The criteria which these factors must fulfil (or be evaluated against) for a deep repository site can be grouped under the following headings:

Safety	Siting factors of importance for the long-term safety of the deep repository.
Technology	Siting factors of importance for the construction, performance and safe operation of the deep repository.
Land and environment	Siting factors of importance for land use and general environmental impact.
Societal aspects	Siting factors connected to political considerations and community impact.

Fulfilment of the safety requirements is of primary importance, as already pointed out. Certain of the construction-related requirements are closely linked to safety. The most important requirements in this respect concern:

- the chemical environment in the rock for canister, bentonite and fuel;
- the mechanical stability of the rock;
- conditions for transport of corrodants and radionuclides in the rock;
- the risk of future intrusion, mainly for utilization of natural resources in the bedrock.

In an initial siting phase, the availability of data on the bedrock in areas judged to be of interest for siting is very limited. Many factors that are important for assessing long-term safety and construction-related aspects can only be clarified after comprehensive investigations on the site. Until then it is necessary to rely on general knowledge as a basis for selection of study sites. Since surveying general land and environmental factors as well as societal aspects is simpler to do at an early phase, these siting factors can be clarified more completely to begin with.

Key questions in the initial siting phase are:

- Which sites have particularly good chances of meeting the requirements with regard to safety, technology, land and environment as well as societal aspects?
- Which of these sites offer good opportunities for later carrying out a reliable characterization of, above all, the important environmental and safety factors?
- How can these sites be identified based on existing material?

The following conditions are thereby particularly favourable for the selection of study sites:

- A common rock type without interest for other utilization of natural resources.
- A large site with few major fracture zones.
- Few opposing land-use and environmental interests.

Secondarily, the following conditions are also favourable:

- Local positive interest.
- Availability of necessary infrastructure. Good means of transportation.

In the initial siting phase, i. e. without data from field investigations, the evaluation of the geoscientific material is focused on identifying unsuitable or unfavourable conditions based on publicly available information. Conditions that should be avoided are firstly:

- abnormal (for Swedish bedrock) groundwater chemistry;
- highly heterogeneous and difficult-to-interpret bedrock;
- known deformation zones and postglacial faults;
- pronounced discharge areas for groundwater;
- rock types that might be of interest for prospecting.

In subsequent phases (during execution of site investigations and, eventually, also detailed characterization — see below) efforts are directed at firstly clarifying the conditions that will prevail for the repository as a whole, secondly for the different repository parts, and finally for the individual canister positions. The following conditions are particularly favourable:

- reducing groundwater chemistry;
- normal (for Swedish bedrock) groundwater chemistry in other respects;
- homogeneous and easy-to-interpret bedrock;
- few fracture zones and low to moderate fracture density;
- low groundwater discharge;
- normal (for Swedish bedrock) rock stresses, strength properties and thermal conductivity.

Conditions which can lead to a site being abandoned in a site investigation and/or detailed characterization phase are above all:

- extreme groundwater chemistry, e.g. oxidizing groundwater;
- valuable ores or minerals in the repository area;
- several closely-spaced water-bearing fracture zones;
- extreme rock-mechanical properties.

Siting studies

The purpose of the siting studies is to gather all the background information that is needed to be able to select a site and obtain permission for detailed characterization. For this, SKB is carrying out or plans to carry out:

General studies that provide a general background and general conditions. They cover the entire country or major regions. A collected account is planned for 1995. An overview and exemplification of the material that exists now within the general studies is provided in Appendix A.

Feasibility studies that examine the prospects for a deep repository in potentially suitable and interested municipalities. The general land and environmental factors and the societal aspects are scrutinized in the feasibility studies. Judgements of siting factors for safety and technology are based on general knowledge and data. A feasibility study results in a judgement regarding if and where sites exist with good potential from both a geoscientific and planning viewpoint. It also provides a basis for judgements of impact on local industry and the local community. Two feasibility studies are currently being carried out. SKB plans to conduct feasibility studies for 5-10 municipalities.

Site investigations primarily comprise geoscientific surveys from the ground surface and in boreholes of a specific site. The safety-related and technical siting factors are clarified as far as possible. Some further investigation of local land and environmental factors in particular is also done. The purpose is to gather material to permit a preliminary determination of whether it is possible on the site to build a deep repository that can meet all environmental and safety requirements. Selection of sites is made based on a combined assessment of the results of feasibility studies and general studies. The results of the general studies will be reported before the first site is selected so that this site can be placed in its regional and national context. The results of all feasibility studies will have been reported before the second site is selected.

A site investigation is carried out in a number of stages. If it is found in the initial stages that a site has characteristics that would have a negative impact on the safety of a deep repository, the investigation is naturally interrupted and an alternative site chosen. The results of a complete site investigation are compiled in a site-specific environmental impact assessment (EIA), including an assessment of long-term safety.

When two complete site investigations have been carried out, all relevant material from the siting work is compiled in an application for permission to carry out detailed characterization on one of the two sites. The reasons for the choice of site are described, along with all background material in the form of data, analyses, surveys, appraisals and judgements.

Public insight, local collaboration and EIA process

An extensive programme for collaboration and information is required throughout the siting process. It embraces the municipal, county and regulatory authorities as well as the local inhabitants, local non-governmental organizations, concerned neighbouring municipalities and the general public. Regular information will also be furnished to scientists and other qualified experts with a particular interest in the field of nuclear waste.

In conjunction with the start of the site investigations, a local safety committee or similar body should, in SKB's opinion, be established in concerned municipalities and be given resources to follow the work in a qualified way.

It is essential that clear forms be established at an early stage for producing an environmental impact assessment (EIA process). For the siting of the deep repository, this should be done before site investigations are begun in a municipality. Principles must thereby be stipulated for how the process is to be organized and documented. Important parties are above all those in whose jurisdiction the facility may be built (the municipality), those who will build and operate the facility (SKB), the regulatory authorities and the county administrative board.

Concerned municipalities should be given resources to follow and participate in the siting work in a qualified way. It is important that clear forms be established for such support, for example via funds from the waste reserves administered by SKI. It is also important to establish forms at an early stage for scientific/technical support to concerned municipalities from the regulatory authorities for safety and radiation protection.

PROGRAMME FOR DESCRIPTION OF DESIGN SPECIFICATIONS

The design specifications are described for each step in the design process. The specifications are determined gradually as different kinds of material become available. The major facilities are designed in layout steps. In its work, SKB follows the design model that has been developed during the past two decades and applied with good results in, for example, the power industry for important civil engineering projects.

The geometric layout of the deep repository for spent nuclear fuel is being planned by and large in accordance with the KBS-3 concept. This consists of a number of deposition tunnels in the bottom of which holes are bored for placement of canisters with spent nuclear fuel and surrounding bentonite buffer. The deposition tunnels are interconnected by tunnels for transport and communication, which are also connected to a central service area and ramp/shaft to the ground surface. The exact placement of the deposition tunnels and deposition holes is adapted to local rock conditions. The repository depth is about 500 m in the normal case, but local adaptation will take place within the range 400 to 700 m.

The deep repository is planned to be constructed in two stages. The first stage is estimated to accommodate about 10% of the total quantity of spent fuel. The second stage includes deposition of the remaining quantity of spent fuel and other long-lived waste. Parts of the construction work for the deep repository will be commenced at the start of detailed characterization.

In the design process, known technology or known methods will be adapted to the special conditions and requirements of the deep repository. A number of methods that will be used will be based on know-how obtained from ongoing R&D programmes. Important technology areas for the deep repository are:

- Construction method for tunnels and rock caverns, including boring of deposition holes.
- Grouting for sealing of water inflow.
- Compaction of bentonite blocks.
- Deposition procedure.
- Options for retrieval.
- Backfilling and closure.

The first two areas will be of importance already during the detailed characterization phase, while the others will not be applied until operating phase 1. The activities within supportive R&D and at the Äspö HRL are aimed at carrying out the necessary work in time for rational application during detailed characterization and during the first construction phase of the deep repository. Full-scale tests with certain special mechanical equipment, e. g. machines for compaction of bentonite blocks, are not planned to be done until during construction of the deep repository.

Before the spent fuel is placed in the deep repository it will be encapsulated in a durable canister. The most important requirement on the canister is that it shall remain intact for a very long time in the environment that will prevail in the deep repository. Accordingly it shall have a high corrosion resistance in the groundwater present in the rock and have a capacity to withstand by the mechanical stresses to which it is subjected in the deep repository.

The canister is planned to be constructed with an inner cylinder of steel, which provides mechanical strength, and an outer shell of copper, which provides corrosion resistance. Copper corrodes very slowly in the oxygen-free groundwater found at depth in Swedish bedrock. Completed studies show that the canister will probably remain intact for millions of years, providing a considerable margin of safety.

To determine dimensions for tunnels, deposition holes and radiation shields and requirements on mechanical equipment in the deep repository, the dimensions and properties of the canister must be known. Important parameters are weight, overall dimensions and maximum radiation level. These data need to be determined before the detailed investigation is begun.

Encapsulation is planned to take place in a new encapsulation plant connected to CLAB. There the fuel will be received from CLAB's storage pools and placed in the canister after being checked and dried. Before the lid on the inner steel container is put on, the air in the canister will be replaced with inert gas and the void filled with e. g. boron glass beads. Then the copper canister will be sealed with a copper lid fastened by means of electron beam welding. Very stringent requirements are made on the leaktightness of this weld and the capability to test this leaktightness. In designing the encapsulation plant, great emphasis will be placed on radiation protection for the personnel and the environment. This means, for example, that the actual encapsulation procedure will be performed by remote control from heavily radiation-shielded compartments called "hot cells". A large part of the handling of canisters will also be done by remote control. Experience from CLAB and SFR, as well as from various foreign facilities, will be drawn upon.

The work of fuel encapsulation is divided in the programme into canister design, sealing method and plant design.

Key issues for canister design are: functional requirements, material selection and tests for both copper and steel components, sizing of canister and steel components, inserts and possible backfilling in canister, detailed design of the lid with regard to lifting and non-destructive testing, and fabrication and inspection methods.

To meet the high requirements on sealing of the copper canister, a method for sealing by means of electron beam welding to industrial scale is currently being developed, along with methods for non-destructive testing. The latter will be used to verify that the seal meets the specified requirements.

The work on development of the sealing method includes the following steps: development and testing of inspection methods, trial welding of lids on copper cylinders, welding of prototype canisters and manufacture of prototype plant for testing of welding equipment and welding chamber before they are incorporated into the plant.

PROGRAMME FOR SAFETY ASSESSMENTS

SKB intends to give an account of safety and radiation protection matters for both the operating phase and the post-closure phase at all important decision occasions. This will be done

- in the form of (preliminary or final) safety reports (PSR/FSR) for the operational activities;
  - in the encapsulation plant,
  - in connection with transports and
  - in the deep repository, as well as
- in the form of safety reports on integrated assessments of the performance of the passive storage of the deep repository after deposition and closure.

The evaluation of operational safety at waste facilities can be done in all essential respects using the same methodology as is used for other nuclear facilities. It is therefore not discussed further here.

In the present programme for coming long-term safety assessments, the organization of the work and the methodology for performance and safety assessments for a deep repository are presented.

The programme during the coming sex-year period aims at producing:

- assessments for sizing and designing the repository with respect to safety;
- a suitable structure for how the integrated safety assessment is to be presented;
- a safety report on the long-term performance of the repository based on generic geologic information and preliminary site data prior to construction of the encapsulation plant, and a safety report (PSR) for the encapsulation plant;
- a safety report on the long-term performance of the repository based on data from site investigations prior to detailed characterization for the deep repository and a general safety report (PSR) for the operation of the deep repository.

The continued assessment work for subsequent safety reports will be carried out in basically the same way as for those mentioned above, but with progressively more detailed background data.

Regardless of whether the assessments constitute performance assessments of barriers or sub-systems, or whether they are safety assessments of the total performance of the entire disposal system, the work is carried out as follows:

- Definition of the purpose of the assessment.
- Definition of given assumptions for the assessment.
- Clarification of the conditions for which the system is to be assessed (scenarios).
- Clarification of the processes that are essential to the performance of the system.
- Definition of calculation models for quantifying the performance of the system.
- Quantification of the performance of the system and essential changes in performance.
- Discussion of uncertainties and of the validity of the assessment with respect to its purpose.

The programme describes how the studies of barriers and sub-systems are compiled into integrated safety assessments, and how uncertainties and validity will be handled.

12.3 SKI's REVIEW AND COMMENTS TO THE SUPPLEMENT

The following is an excerpt from the SKI statement to the government December 22, 1994 concerning the Supplement to the RD&D-Programme 92 from SKB:

"General statement

SKI finds that concerning siting, safety analyses and commitments by different decisions SKB has given the account requested by the government in the decision 1993-12-16. Concerning delineation of prerequisites for the encapsulation plant and the repository the account is, however, partly incomplete.

The general overview studies that SKB currently makes should be reported before the start of additional feasibility studies and not later than in RD&D-Programme 95. The siting factors and criteria given by SKB are a suitable basis for the continued siting work but the criteria should be successively amended and quantified. A programme for site investigations should be presented before they are started. The programme should show the safety related site properties which actually can be measured and how they will be measured. SKB should also address these issues in the R&D-Programme 1995.

SKI would like to emphasize that SKB must clarify the prerequisites for the design and construction of the canisters. SKI considers that SKB at the latest in R&D-Programme 1995 shall describe the plans for establishment of design criteria which at first hand but not only are based on the role of the canister in the repository system evaluated from performance and safety analyses, plans for development of technique in industrial scale for fabrication and closure of canisters and plans for qualification of canisters for final disposal. A plan for development of safety analysis of operation of the encapsulation plant and of the repository should also be described in the R&D-Programme 1995 at the latest. These plans should be well coordinated with SKB's plans for design of the encapsulation plant."

SKI also presents proposals and comments concerning guidelines for the licensing of the remaining waste management facilities in Sweden. The proposals concern

- coordinated review and evaluation with respect to different laws,
- independent review,
- insight and participation in preparations for an Environmental Impact Statement,
- financial support to municipalities,
- responsibility for repository closure,
- prerequisites for licensing of facilities.

The last of these points are mainly directed to the licensing of the encapsulation plant where SKI argues that the application for a siting and construction permit must be supported by an analysis and evaluation of alternatives including a "zeroalternative" and by a complete safety analysis of the whole repository system. Further SKI considers that SKB must show that canisters of required and verifiable quality can be fabricated in series production and by site investigations show that there exist a site which meets the demands according to the safety analysis on the site specific properties that can be measured at site investigations.

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

The preparation of the site investigation programme is going on. The aim of the site investigation is to give site specific data for the performance and safety assessment and for the layout and construction analysis for the deep repository. Areas for site investigations will be selected among possible areas with good prognosis for siting of a deep repository which will be evaluated during ongoing and planned feasibility studies in a number of municipalities in Sweden, see Chapter 5. The site investigations will start with an initial, relatively comprehensive step, aiming at investigate whether very unfavourable or discriminating geological conditions exist or not. The second step, complete site investigation, will be carried out at two sites, almost in parallel, according to present plans.

The site investigation programme will first of all be based on the siting factors of importance for siting a deep repository /13-1/. In special those which are related to the geosphere and which are of relevance for the site investigation stage of the siting process. These siting factors will be specified in the programme and favourable and/or unfavourable conditions will be discussed.

Secondly, the site investigations shall reach a general geoscientific understanding of the site, i. e. the area and the rock volume must be described and understood with regard to existing conditions and ongoing processes.

The site investigation programme shall be goal-oriented rather than specifying how the investigations will be performed in detail. Main goals and sub-goals for different tasks and steps of the site investigations are general and non site-specific. How to perform the investigations, on the other hand, are to some degree site-specific. Hence, the written programmes will be structured as follows:

- general programme for site investigations. Will present the general goals, strategies etc of the site investigations,
- site-specific programmes for initial site investigations, and
- site-specific programmes for complete site investigations.

These site-specific programmes will not be finished until the areas for site investigations have been selected. Site specific goals and site-specific plans of the performance will be presented in these programmes.

One major experience base for the site investigation programme is the Äspö HRL, pre-investigation phase. An evaluation report on the feasibility and usefulness of site investigation methods was published in 1994 /13-2/.

Experiences from similar site investigation programmes abroad will also be of value for SKB. For that purpose experience reports from site investigations in Canada (AECL) and in Finland (TVO) have been compiled /13-3/, /13-4/.

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. All investigations will be carried out according to QA-plans which in turn refer to manuals or other specifying documents. Some of these manuals will be adopted more or less directly from the Äspö HRL, while other manuals must be written separately. Routines for the QA procedures are under preparation.

A central database for the site investigations will be used. The intention is that the database will be used as

QA-tool for the ongoing investigation as well as an archive for the long-term storage of all data from the site investigations. Based on experiences of the previous geological database GEOTAB and an activity database SADB, developed in the Äspö HRL, a new database is under development, se further description in section 20.4.7.

As a tool for modelling and visualization of structures, rock type bodies, etc in the rock volume, a "Rock Visualization System" (RVS) is under development. Based on the Microstation CAD system various application programme modules will be developed for different tasks of the modelling work. Major goals for the integrated RVS are:

- to simulate the main rock elements; rock types and structures,
- 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.

For further details of the development work, see the Äspö Annual Report /13-5/.

13.1.4 Instruments and methods

BIP-1500 borehole-TV System

For geological documentation of boreholes, in special for orientation of fractures and other structures, TV inspection of the borehole wall is the most promising method. As discussed in the last annual report SKB was testing a borehole-TV system from Japan. After a second demonstration measurement in our KLX02 borehole SKB decided to purchase the BIP System from RaaX Co, Japan. However, the system had to be modified in order to fulfil some additional requirements of SKB:

- measurements down to 1500 m in 56 mm diameter borehole,
- automatic orientation of the TV-probe.

An upgraded version of the system, BIPS-1500, was delivered in December, 1994, after a development cooperation between RaaX and Malå GeoScience. The fiber-optical data communication system and power supply technique, developed for the borehole radar, RAMAC, was adopted also to the BIP System. This resulted in increased resolution of the images and moreover in the advantage of having the same logging cable for the two system.

At the delivery test TV-logging was performed down to 1400 m in the KLX02 borehole. Examples of 0-360^{o} images of the borehole wall are presented in Figure 13-1. Images can be presented in different ways and in different scales. Analyses of fracture orientations are semi-automatic, i. e. the fracture is defined by the geologist with a set of points on the computer screen and the computer will calculate the strike and dip of the fracture.

In conjunction with the delivery of the BIPS a documentation survey of a part of the TBM tunnel in the Äspö HRL was demonstrated. Only a special camera module had to be added to the borehole BIP System /13-5/.

High resolution borehole radar

The borehole radar system RAMAC is working in two different frequencies of the electromagnetical waves, 22 MHz and 60 MHz. Separate antennas are used for the two frequencies and for the 60 MHz frequency also directional antenna (receiver antenna) are used for the true orientation of reflectors from single hole reflection measurements.

The range and resolution of the method are dependent on the frequency and on the electrical conditions of the rock, i. e. resistivity of rock and pore water. The blind window around the hole, i. e. where no reflectors can be seen is also dependent on the frequency. Higher frequencies generally result in a shorter range but in a better resolution and a smaller blind window. In low resistivity rock the range becomes smaller.

The development of antennas, control electronics, etc, for an additional, higher frequency for the borehole radar is going on. The center frequency will be 250 MHz and this will result in better resolution and smaller blind window, but the range will be somewhat shorter. In special for low resistivity conditions the smaller blind window is supposed to increase the usefulness of the radar method.

Depth calibration technique

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 developed a depth calibration technique for borehole measurements. After the drilling of a borehole is completed, diamond-impregnated copper rings are drilled in as markers in the borehole wall, for example every 200 m along the hole. These markers will then be detected by sensors attached to every logging probe or other borehole measurement tool, hence calibrating the depth measurements for the ongoing measurement, see Figure 13-2.

The in-drilling of a number of markers has been made in a test borehole. The way of attaching sensors to the different measurement systems has been prestudied, and this work will continue in 1995.

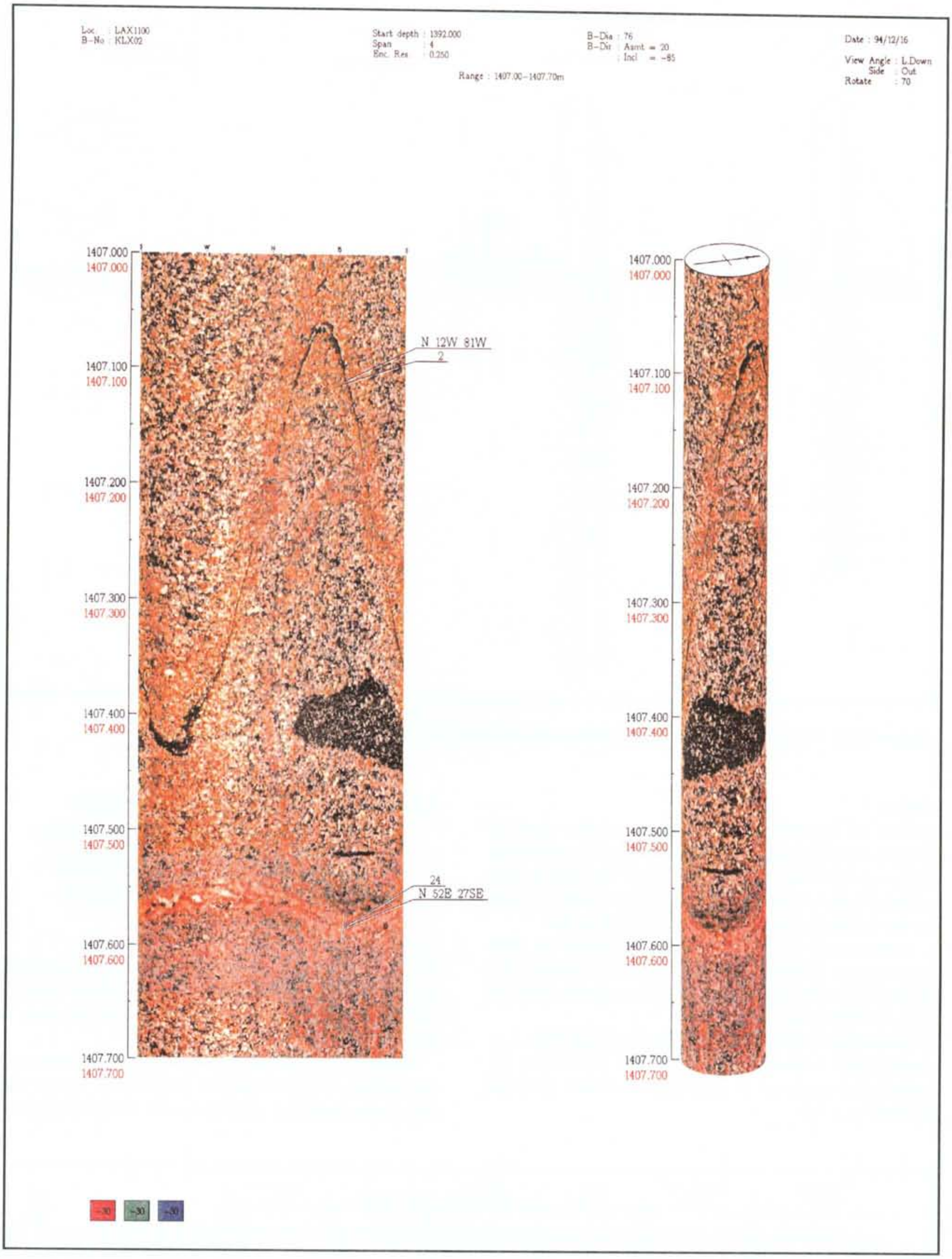


Figure 13-1. Borehole wall images from borehole KLX02, produced by BIPS-1500 borehole TV.

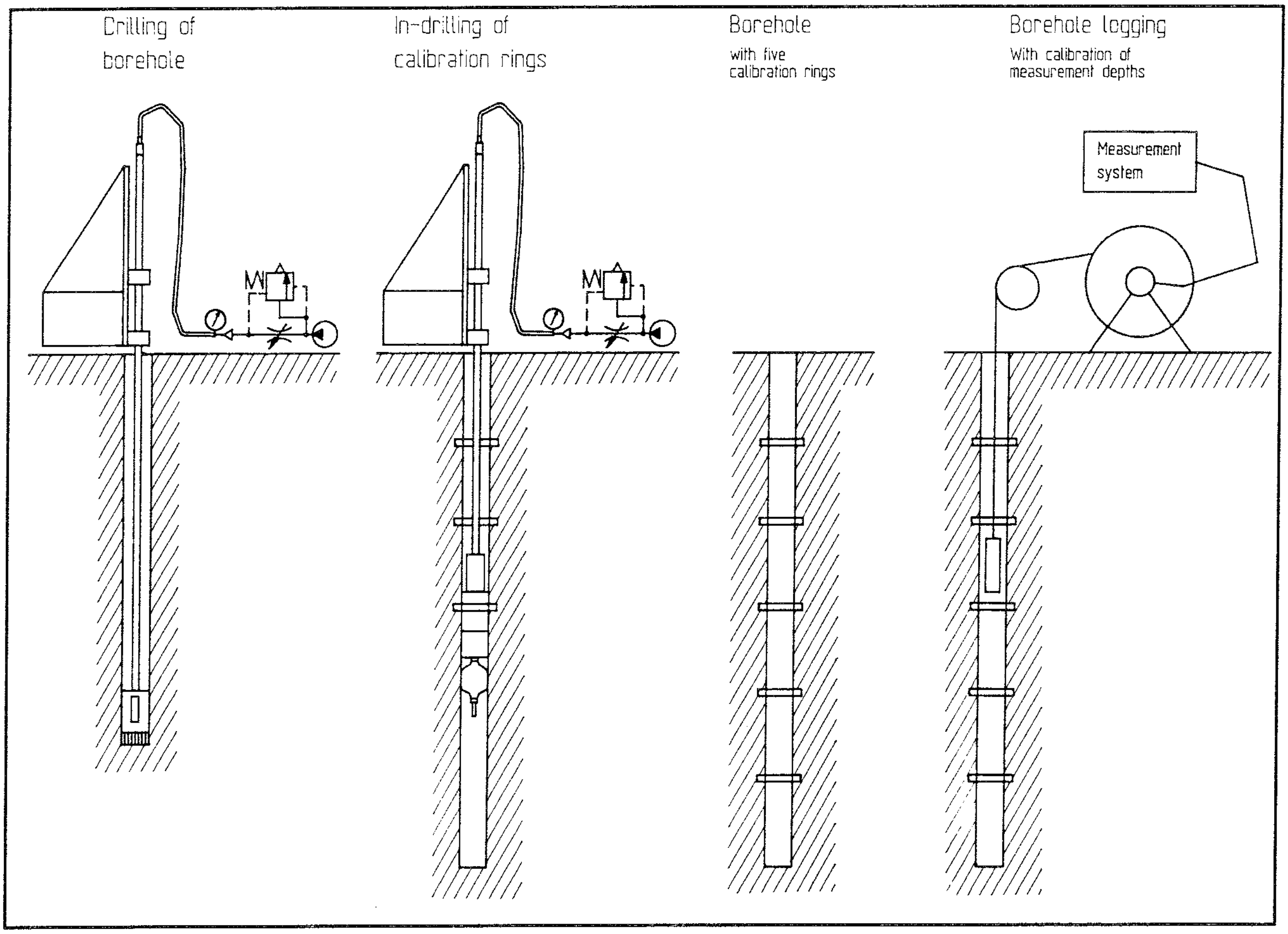


Figure 13-2. The principle of the depth calibration technique for boreholes and borehole measurements.

Others

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

A programme for service and maintenance of SKB equipment is running. Even if not in use at present, the accessibility and functionality of all instruments must be high for field measurements.

Instruments and methods related to the Äspö HRL, i. e. underground investigation methods and instruments for experiments (planned or ongoing) of various kind are reported in /13-5/.

13.2 TECHNICAL STUDIES CONCERNING THE CONSTRUCTION OF A DEEP REPOSITORY SYSTEM

Planning

The design process introduced in the Deep repository project comprises a step-by-step approach with more detailed engineering of selected solutions in each step, as illustrated in Figure 13-3 /13-1/.

During 1994 the planning on the E-phase continued with the analysis of two alternatives to the access system with only shafts, featuring spiral ramp and straight ramp. The

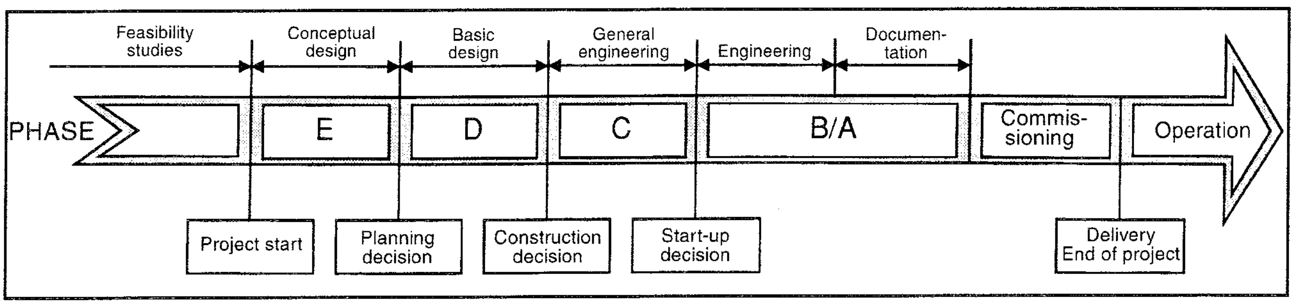


Figure 13-3. Schematic illustration of the repository design process.

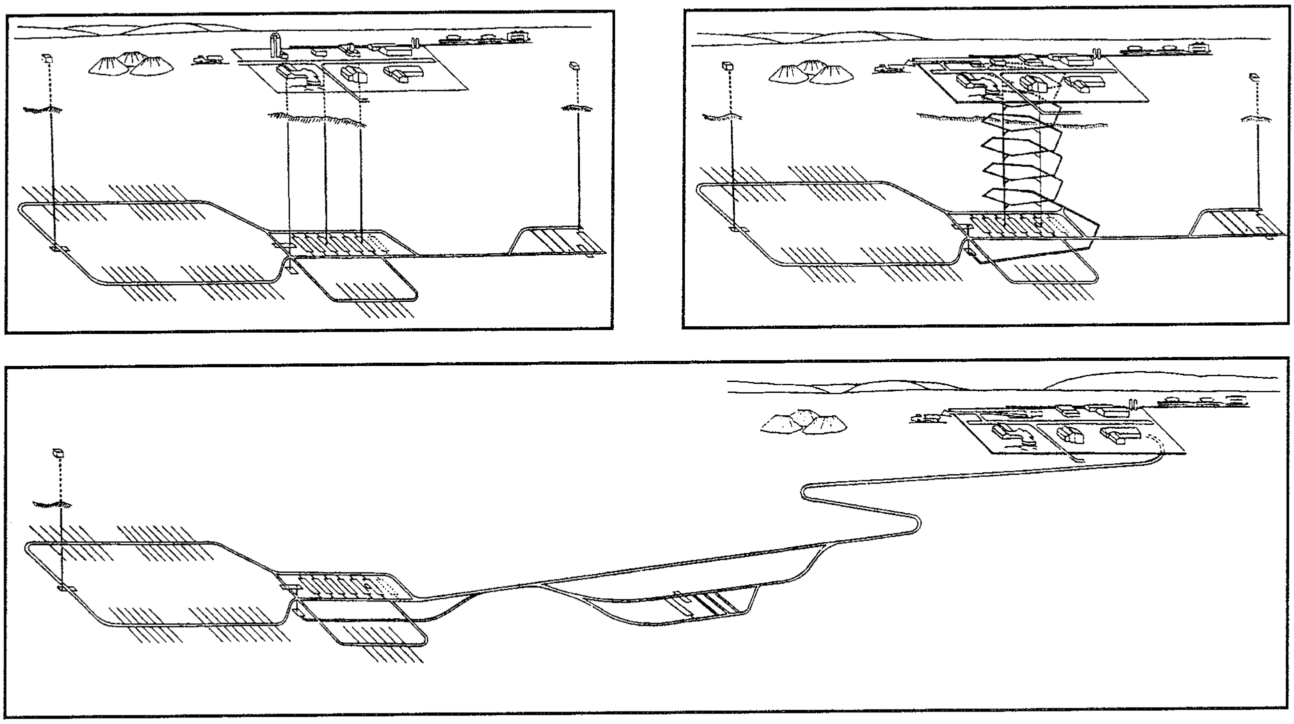


Figure 13-4. Schematic illustration of three alternative access systems.

difference between these three access systems is illustrated in Figure 13-4.

Several different analyses were launched during the year with the objectives of eventually providing information on questions related to design and layout so that evaluation and comparison of different alternatives can be made and engineering in the E-phase be made of favourable solutions. As no investigations on any candidate site has started the work has to rely on general data only. The aim with the E-phase, therefore, is to generate solutions in such detail that only site-specific data are needed in order to make the final choice among the studied solutions. The initiated studies concern:

- Repository depth.
- Layout of deposition tunnels if it would be excavated by mechanical means (TBM).
- Pros and cons of the three studied access systems.
- Deposition method with respect to vertical or horizontal positioning of canisters and with respect to separate or combined deposition of canister and buffer.
- Transport systems in shafts and in ramp.
- Transport system on repository level.

Test of boring full-scale vertical deposition holes

The high degree of proven technology in the proposed methods for excavation of shafts, tunnels and caverns is referring to work that has been carried out in different underground constructions, while the specific task of excavating the deposition holes has been referring to adaptation of proven technology only, as no need has been raised in underground construction for excavation of blind holes with the KBS-3 dimensions. The most efficient boring technique for the job is a reversed raise-boring technique with the head pushed downwards instead of pulled upwards as in raise-boring. The removal of the cuttings can be solved in many ways and existing systems favour flushing or pumping as they are used in deeper holes than 10 m. Air suction also has been tried and is more favourable in a repository because no handling of large quantities of water is required.

In order to verify the feasibility of adapting efficient boring technology to the task a project was set up by SKB in cooperation with TVO of Finland that comprised the boring of three full-scale deposition holes in the research tunnel of the Finnish repository for final disposal of LLW and MLW in Olkiluoto. This tunnel is situated at a depth of 60 m in tonalite gneiss. Drillcon Contracting AB was contracted for the job and furnished the boring machine including vacuum suction unit and carried out the boring. They subcontracted AB Sandvik Rock Tool for delivery of the head with vacuum suction nozzles, and Kroll-Disab AB for modifying the vacuum suction unit.

A standard small size raise-boring machine – Subterranean 005 – was used for creating the torque and thrust force. The machine was placed on a frame so that ample space was left below it for mounting the head. A used Sandvik head was redesigned and equipped with eight roller button cutters and four gauge rollers. The cuttings

Figure 13-5. *Test of boring full-scale vertical deposition holes. The boring machine was placed on a frame in order to provide space for mounting the cutterhead.*

was sucked through the cutterhead and drillstring, and collected in a filter unit in the tunnel. The test set-up is shown in Figure 13-5.

The work comprised boring of three holes to a depth of 7.5 m and the diameter of the hole was made with the size of the available cutterhead of 5 feet (1.524 m). The head is shown in Figure 13-6.

During the boring tests were carried out in order to study the impact of major operating parameters for the performance of the equipment and the quality of the hole. Most important was the penetration rate and the efficiency of the vacuum suction system. The quality of the hole was investigated with respect to the roughness of the walls and the mechanically induced disturbance in the rock walls. The hole during boring is shown in Figure 13-7.

In all three holes a pilot hole was made first, whereafter the head was mounted and the hole reamed to full width. In one hole the pilot hole ended above the final bottom and boring without a pilot hole was tested. Cutting samples were taken during the boring to find out the effect of

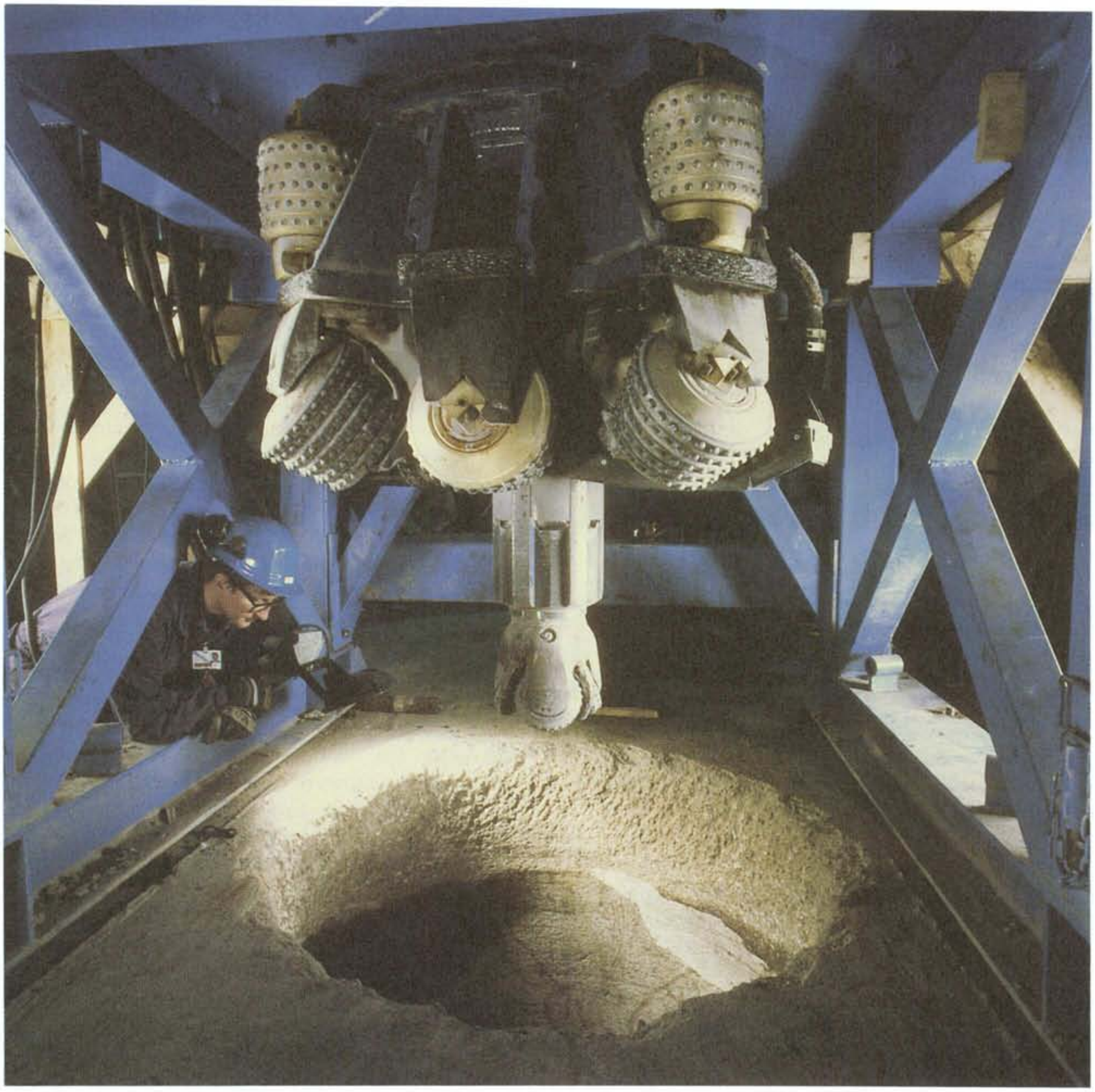


Figure 13-6. The cutterhead.

different thrust forces and rotation speeds. And the temperature of the cutters was monitored as well as the dust content of the air in the tunnel.

The analysis of the test is still in progress but some preliminary results can be presented. One conclusion is that deposition holes can be bored effectively by using a boring technique which is based on fullface rotary crushing and removal of the cuttings by air vacuum suction. No pilot hole is needed and the deposition hole can be made to full width in one step. The highest rate of penetration achieved during the test was about 1 m/h with a total maximum thrust of 73 tonnes and a rotation speed of 8 rpm. Test with different rotation speeds resulted in a decreased depth of cut per rotation when the speed was higher than 8 rpm but maintained the same below that value. This implies that the ceiling capacity of the vacuum suction system was reached at this point and that improved design of the nozzles in the head need to be made in order to meet the capacity of a more powerful boring machine. The measured correlation between rate of penetration and thrust force was linear which is in agreement with the model. This model predicts a theoretical capacity of up to

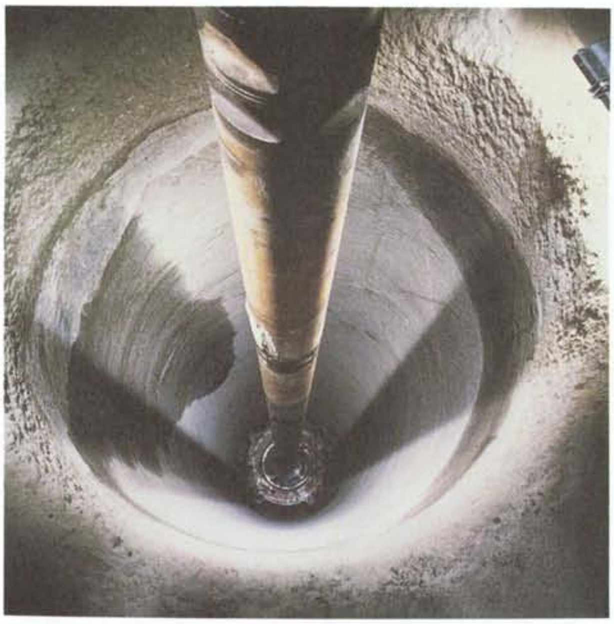


Figure 13-7. Borehole close to being completed.

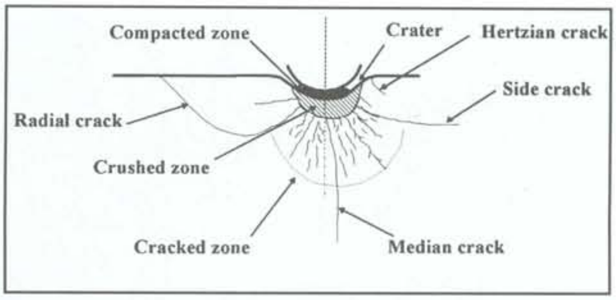


Figure 13-8. Conceptual view of cracks in rock caused by mechanical excavation.

3 m/h if the total load the cutters can take is applied. In practice, however, the plausible rate of penetration is expected to be significantly lower than that.

Cracks in rock caused by mechanical excavation

Rock indentation by a bit is the fundamental mechanism in disc cutting and most drilling methods. The bit is forced into the rock and the rock near the bit is crushed into small or large fragments and further away penetrated by different sets of surface cracks. An efficient creation of cracks in the front are of importance for a high rate of penetration in drilling. But cracks will also be formed that penetrate into the wall of the tunnel or borehole and cause a remaining disturbance. These cracks may help to distribute groundwater around the buffer and backfill in deposition holes and in TBM-excavated deposition tunnels so that water sorption and swelling take place evenly in the bentonite. In order to outline the possibility of modelling the remaining disturbance in the rock wall and to estimate the possible impact different mechanical applications may give a study on cracks in rock caused by mechanical excavation has been initiated.

From numerous experimental results a general picture of fractures in rock under indentation can be summarized as shown i Figure 13-8 /13-6, 13-7/. Underneath the indenter there is a compacted zone, a crushed zone and a cracked zone. Outside the cracked zone three kinds of cracks may develop: median cracks, radial cracks and side cracks. In some cases so called Hertian cracks have also been observed. The size of the crushed or the cracked zone and the length of various kinds of cracks are mainly dependent on the load magnitude and the macro mechanical properties of rock, but they are also influenced by the geometry of the indenter. The micro structure of the rock has less influence on the fracture process and the crack pattern compared to the macro mechanical properties if the characteristic size of the micro structure is smaller than the indenter.

Conclusions drawn from laboratory work indicates among other things that the crushed zone and part of the cracked zone will only develop in the front and not in the side walls. The most important cracks concerning the hydraulic conductivity in the near field rock are radial and median cracks. These have for TBM-excavations been judged to have a maximum penetration depth of 100 mm into the wall in semi-infinite granite /13-6/.

Grouting

Grouting operations may play a major role in the construction of the deep repository for preventing groundwater inflow to tunnels and caverns and for providing mechanically stable conditions in very fractured rock. In order to be able to prescribe correct methods to meet the needs and predict the outcome in the actual construction a deeper theoretical understanding of methods and materials is required than is at hand today. Under special conditions such as high water pressure and transmissive discontinuities also strategies and methods have to be developed. During 1994 a compilation of present knowledge and estimated demands were initiated with the objective to outline specific repository related topics which need to be addressed. The major conditions to consider are the transmissive discontinuities with high piezometric pressure. But also fine fractures are of concern following the results of grout and grouting developed in the Stripa project. Data collected during the construction of the ramp in the Äspö Hard Rock laboratory are unique in that respect that they can be used to evaluate the lessons learned in analysis of information available prior to grouting and after passing the grouted part of a discontinuity or rock zone.

14 SAFETY ANALYSIS

14.1 GENERAL

During 1993 the SKB RD&D-Programme 92 was reviewed by the Swedish Nuclear Power Inspectorate and KASAM. In the Government decision /14-1/ it found that the programme fulfilled the requirements of the Act on Nuclear activities. The regulatory authorities also levelled criticism at certain points in the programme. Thus the Government decision stipulated that a supplementary account should be submitted (cf Chapter 12) /14-2/.

With regard to the safety assessments it was found that the safety assessment methods that SKB uses should be further developed, especially with regard to how uncertainties are to be clarified and integrated. A strategy for the review of the relevance (validity) of the models should be developed based on the safety requirements of the safety assessments. It was further required that SKB with regard to the safety assessments shall supplement the RD&D-programme with a programme for the safety assessments that SKB intends to prepare.

In this supplement, chapter 6 – "Programme for safety assessments" – SKB has declared its intention to give an account of safety and radiation protection matters for both the operating phase and the post-closure phase at all important decision occasions. This will be done

- in the form of (preliminary or final) safety reports (PSR/FSR) for the activities and the processes;
  - in the encapsulation plant,
  - in connection with transports, and
  - in the deep repository, as well as
- in the form of safety reports on integrated assessments of the long term performance of the deep repository after deposition and closure.

The evaluation of operating safety at waste facilities can be done in all essential respects using the same methodology as is used for other nuclear facilities.

In the present programme for coming long-term safety assessments, the organization of the work and the methodology for performance and safety assessments for a deep repository are presented.

The programme during the coming sex-year period, see Figure 14-1, aims at producing:

- background data for sizing and designing the repository with respect to safety;
- a suitable structure for how the safety assessment is to be presented;
- a safety report on the long-term performance of the repository based on general data and preliminary site data prior to construction of the encapsulation plant, and a safety report (PSR) for the encapsulation plant;
- a safety report on the long-term performance of the repository based on data from site investigations prior to detailed characterization for the deep repository and a general safety report (PSR) for the operation of the deep repository.

The continued assessment work for subsequent safety reports will be carried out in basically the same way as for those mentioned above, but with progressively more detailed background data.

Regardless of whether the assessments constitute performance assessments of barriers or sub-systems, or whether they are safety assessments of the total performance of the entire disposal system, the work is carried out as follows:

- Definition of the purpose of the assessment.
- Definition of given assumptions for the assessment.
- Clarification of the conditions for which the system is to be assessed (scenarios).
- Clarification of the processes that are essential to the performance of the system.
- Definition of calculation models for quantifying the performance of the system.
- Quantification of the performance of the system and essential changes in performance.
- Discussion of uncertainties and of the validity of the assessment with respect to its purpose.

The programme describes how the studies of barriers and sub-systems are compiled into integrated safety assessments, and how uncertainties and validity checking will be handled.

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.

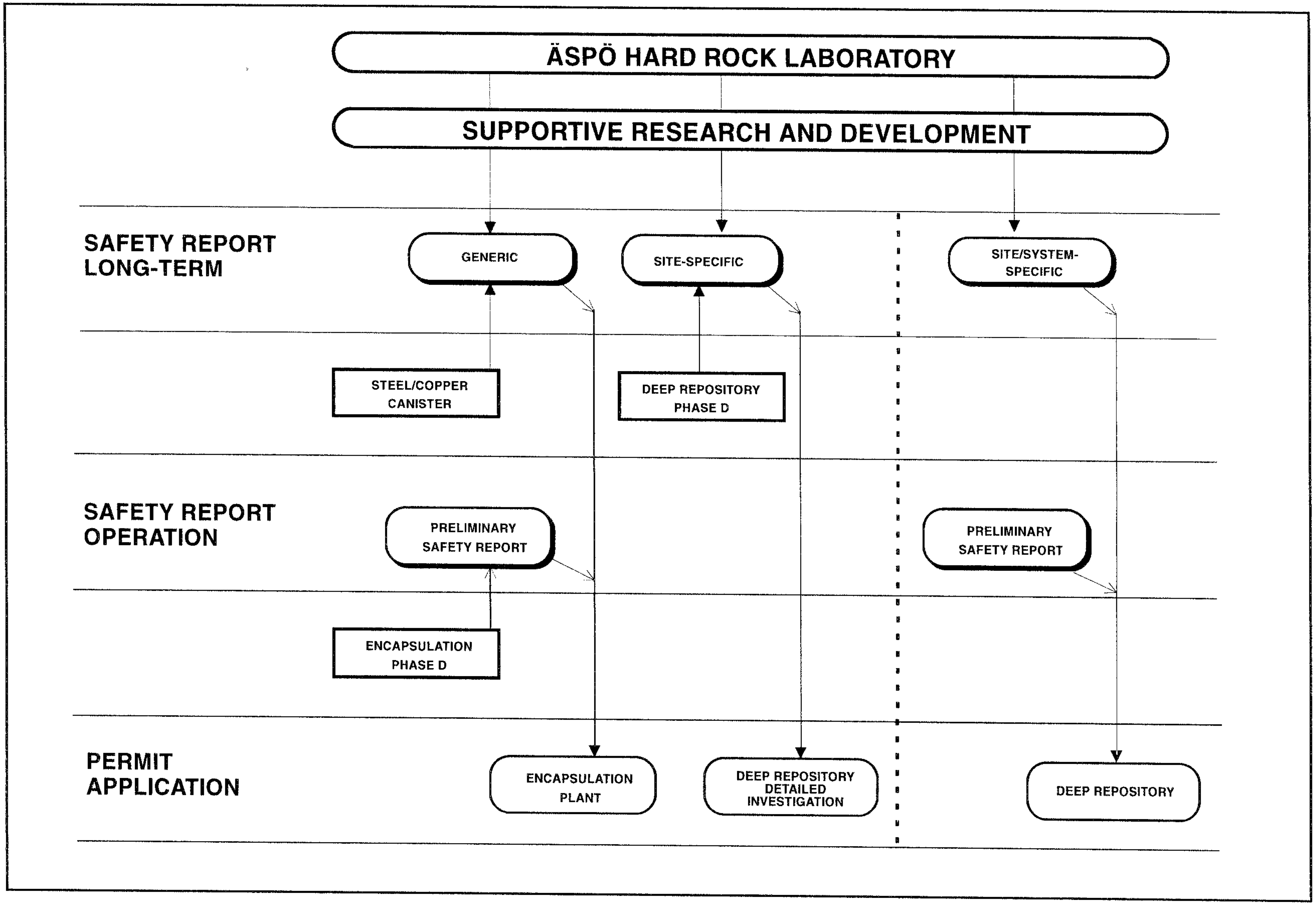


Figure 14-1. *Logic diagram of upcoming safety assessments for deep disposal of spent nuclear fuel.*

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 /14-3/ 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 1991-1994 attempts have been made with several different methods 1) visualization of the FEPs in a tree structure, /14-4/, 2) using Influence diagrams and 3) using the Rock Engineering Systems (RES) approach /14-5/.

A description of each of these approaches as well as a comparison between them can be found in SKB TR 94-28 /14-6/.

The influence diagram methodology research was in 1994 mainly driven by SKI but was also used by SKB in a study concerning other longlived wastes than spent nuclear fuel /14-7/.

The RES methodology have 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. The total repository system is presented in a few smaller submatrices as indicated in Figure 14-2. Further development and use of the methodology together with a linking to FEPs databases are under way. A typical example of one of the submatrices can be seen in Figure 14-3.

The second step in the scenario methodology is to select the actual scenarios to be subjected to numerical evaluation. The above mentioned schemes seems to be helpful tools to find the most important and interactive 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 and thereby the overview of the decision process and the motivations will become clearer.

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.

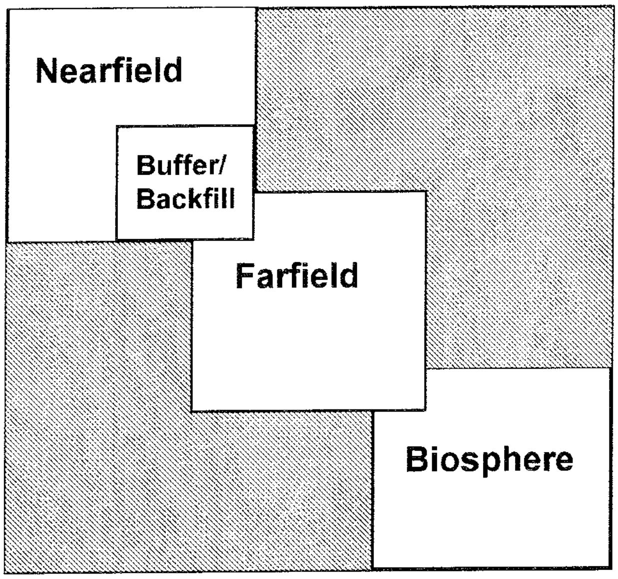


Figure 14-2. The RES-matrices applied for visualizing the total repository system.

14.3 MONITOR 2000

A need for a more user friendly system for managing complex model calculations has been identified during previous work on safety assessments at SKB. Therefore, preliminary studies of a graphic user interface were carried out during 1994. This "Graphic System for Managing Complex Model Calculations" has been named Monitor 2000.

Compared to the present system which is based on text-files, the use of a graphic interface would result in improved quality assurance, better documentation, independence of specialist competence for managing complex calculations and considerable time savings in the set-up and documentation steps of the calculations.

The results of the preliminary studies will form the basis for the construction of a graphic user interface in 1995.

14.4 PERFORMANCE ASSESSMENT OF A COPPER / STEEL CANISTER

The Swedish system for the final disposal of spent nuclear fuel is based on a copper canister with a very long lifetime. Originally, in the KBS-3 /14-8/, there were two different canister designs, a hot isostatically pressed pure copper canister and a lead filled copper canister. In the PASS /14-9/, different canister designs were compared and

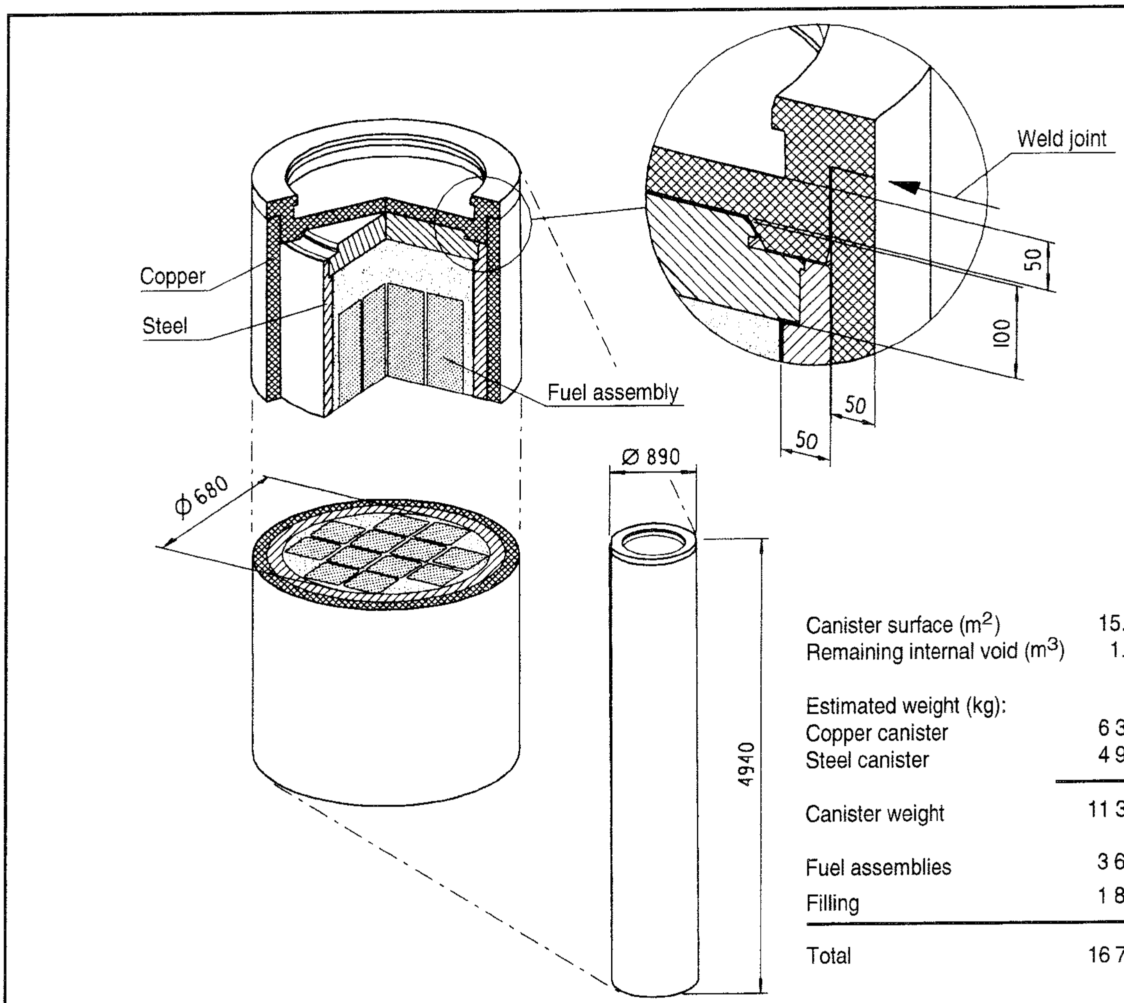
FAR FIELD

process system - far field 1

- Interaction which should be part of the model chain, i e assessment modelling of radionuclide transport
- Important interaction - can give effects on other parameters, should be well documented
- Interaction present - influences on other parts of the process system in a limited way and/or under special circumstances
- Interaction present - influences on other parts of the process system can be neglected

CONSTRUCTION/ LAYOUT	1.2 Excavation method	1.3 Tunnel dimension Excavation Grouting Reinforcement	1.4	1.5 Displacement effects	1.6 Construction materials Stray materials	1.7	1.8 Drawdown effects	1.9 Repository depth Ventilation	1.10 Tunnel dimension Plastic deformation	1.11 Ventilation Blasting gas Gas source	1.12	1.13 Industrial facility Dumps
2.1 Swelling ability Heat	**BUFFER/ BACKFILL/ SOURCE**	2.3 Buffer/backfill penetration into EDZ	2.4	2.5 Buffer into intersecting fractures	2.6 Radiolysis Colloids Na/Ca ratio pH, $[SO_4^{2-}]$, $[HCO_3^-]$	2.7 Reduced flow in holes Changed flow in tunnels	2.8 Resaturation	2.9 Heat generation	2.10 Swelling pressure	2.11 Gas source	2.12 Source term	2.13
3.1 Excavation method Amount of reinforcement	3.2 Volume for buffer swelling Rock fallout	**EDZ**	3.4	3.5	3.6 Changed [illegible] and a_w Dissolution and precipitation of fracture minerals	3.7 Changed permeability	3.8	3.9 Modified thermal diffusivity	3.10 Fractures affected	3.11 Indiffusion of air Transport path for gas	3.12 Changed [illegible] and a_w, K_d	3.13
4.1 Layout Construction method	4.2	4.3 Geometrical extent	**ROCK MATRIX/ MINERALOGY**	4.5 Fracture characteristics Infilling mineralisation	4.6 Fe, pH, Eh, TDS Colloid generation	4.7 Matrix K Rock compressibility	4.8	4.9 Geothermal gradient Thermal properties	4.10 Genesis, tectonic history and rock type	4.11 Radon generation	4.12 Sorption capacity Porosity	4.13 Land-use Potential human intrusion
5.1 Avoid major zones Constructability	5.2	5.3 Mechanical properties and fracture frequency	5.4	**NATURAL FRACTURE SYSTEM**	5.6 Dissolution of fracture minerals Colloid generation	5.7 Flow paths Connectivity Fracture aperture Storage caps	5.8	5.9	5.10 Stress magnitude and orientation	5.11 Transport path for gas	5.12 Pathway & Sorption capacity	5.13 Wells Land-use
6.1 Depth affected by redoxpot. Construction materials	6.2 TDS Ion exchange Illitisation	6.3 Calcite precipitation Fe/Mn-bacteria	6.4 Groundwater rock interaction: alteration precipitation	6.5 Precipitation and dissolution of fracture minerals	**GROUNDWATER CHEMISTRY**	6.7 Density, Viscosity	6.8 Density affects groundwater head	6.9	6.10	6.11 Gas generation reactions	6.12 Sorption and solubility ability Colloids and bacteria	6.13 Water-use Biotopes
7.1 Canister positioning Construction problems	7.2 Bentonite erosion Homogenisation	7.3 Erosion	7.4	7.5 Erosion and sedimentation	7.6 Mixing and dilution	**GROUNDWATER MOVEMENT**	7.8 Equalisation of pressures	7.9 Forced heat convection	7.10	7.11 Transport of dissolved gas Two-phase flow	7.12 Sorbing & non-sorbing species Hydrodynamic dispersion	7.13 Recharge and discharge
8.1 Construction problems	8.2	8.3	8.4	8.5	8.6	8.7 Driving force due to pressure gradient	**GROUNDWATER PRESSURE**	8.9 Change in freezing point of water	8.10 Effective stress	8.11 Degassing Dissolution of gases	8.12	8.13 Potential effect on vegetation
9.1	9.2 Thermal expansion	9.3 Fracture characteristics	9.4 Thermal expansion Permafrost λ(T)	9.5 Permafrost	9.6 Dissolution and precipitation of minerals	9.7 Density, viscosity	9.8 Density changed	**TEMPERATURE/HEAT**	9.10 Thermal expansion	9.11 Gas solubility	9.12 K_d, D_e (kinetic effects)	9.13
10.1 Design/layout Construction methods	10.2 Reaction force on swelling pressure	10.3 Mechanical stability Fracture aperture changes	10.4 Mechanical stability	10.5 Mechanical stability Fracture aperture	10.6	10.7	10.8	10.9	**ROCK STRESSES**	10.11	10.12	10.13 Mechanical stability
11.1 Ventilation problems	11.2	11.3 Opening of fractures Changes T 2-phase flow conditions	11.4 Fracturing at high pressures Changed thermal properties	11.5 Opening of fractures at high pressures	11.6 pH, Eh affected	11.7 Creation of 2-phase flow conditions	11.8 Capillary forces	11.9 (Gas law)	11.10	**GAS**	11.12 Colloid sorption on gas bubbles	11.13
12.1 Design/ layout	12.2	12.3	12.4	12.5	12.6 Changed concentrations	12.7	12.8	12.9	12.10	12.11	**TRANSPORT OF SOLUTES**	12.13 Contamination
13.1 Siting Design/ layout	13.2	13.3	13.4	13.5	13.6 Infiltrating water Infiltration of corrodants	13.7 Surface water recharge & percolation	13.8 [illegible]	13.9 Climatically driving forces	13.10 Iceload Erosion	13.11 Gas infiltration	13.12	**BIOSPHERE**

Figure 14-3. A first attempt regarding the RES-matrix for the far-field.



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 14-4. *Copper/steel canister with BWR assemblies.*

ranked. The outcome of this project was that a steel canister with a copper overpack, see Figure 14-4, was the most favourable alternative, partly for fabrication-related reasons and partly in view of the assessment of the mechanical integrity of the canister. The copper/steel canister was chosen as the reference canister alternative for the future. This meant that a new performance/safety analysis has to be done to evaluate the new canister concept.

The long time performance of this canister has been evaluated earlier /14-10/, but a more complete assessment is required to demonstrate that the copper/steel canister meets the same safety standard as the previous ones. This presentation will focus on the areas which are considered the most important for the time being:

- *A as far as possible complete assessment.* The "Rock Engineering Systems /14-11/" scenario analysis methodology has been used to ensure that all interactions are treated.
  The copper/steel canister is, in principle, identical with the previous canisters. The difference shows up when there is a defect in the corrosion protective copper overpack of one or more canisters. The following topics are only important when there is such a defect.
- *A more detailed release model.* This canister lacks the extra protection, that was given by the lead, in the lead filled canister. Therefore, a more detailed description of the behaviour of the canister internals and void, in the case of a defect canister, is useful to ensure that the release calculations are given a reasonable degree of conservatism.
- *The effect of the steel corrosion products.* If there is a defect (small) in the copper overpack, the steel will start to corrode. The expansion of the corrosion product may widen the defect in the copper. The magnitude of this process has to be evaluated, since a limited defect is an important mass-transfer resistance.
- *The gas migration from the canister.* It is important to ensure that the hydrogen gas, created by the corrosion of the steel, does not jeopardize the function of the repository.

These processes have been studied in detail.

The Rock Engineering Systems (RES) approach is used to identify scenarios in order to ensure that all aspects of the problem are being covered. The method is objective based, and thus proceeds always bearing the objective in mind. The basic device used is the interaction matrix, in which the main parameters are identified and listed along the leading diagonal of a square matrix. The interactions between the parameters occur in the off-diagonal terms. When more than two parameters are involved, the interaction is a pathway through the matrix, and then the order of parameter sequence is important. Using the RES approach the system parameters were listed along the leading diagonal of a 11x11 matrix. All the binary interactions were identified. Events, like an initial failure, were imposed on the matrix and the interaction pathways were identified. The final result showed that the RES approach is an excellent tool to get a complete and transparent picture of the scenarios that are affecting the canister, see Section 14.2.

The development of a more detailed release model has focused on the effect of the canister internals. The most likely scenario is that all canisters in the repository are intact for a very long time. However, in a performance assessment it is important to illustrate the effect of an early canister failure and to demonstrate the robustness of the system. Release calculations has been done with a compartment model in witch many of the mass-transfer resistances in the near field are included /14-12/.

In the reference failure scenario, a 5 mm^2 defect in the copper overpack is assumed (a result of a unsuccessful welding and quality control). It is also assumed that the steel canister will lose its mechanical integrity after 5000 years and all mass-transfer resistance in the canister wall will than be lost. The result of the release calculations for some of the most important radionuclides are shown in Figure 14-5. To investigate the sensitivity for some of the model parameters on the release of radionuclides the following variations have also been studied:

V1 Glaciation at 50 000 years with rock movement resulting in a large breach in an initially intact canister and doubled water flow in the host rock.

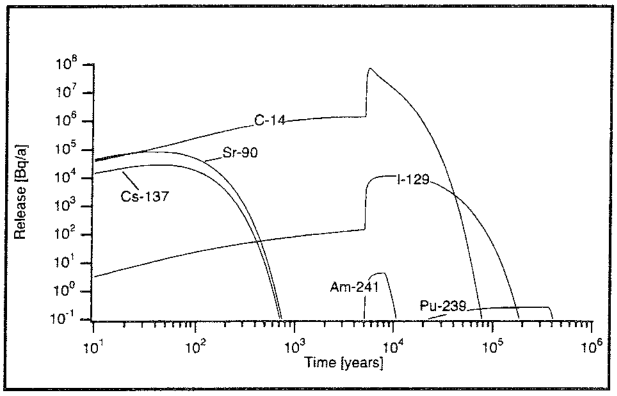


Figure 14-5. Reference scenario release from the near field.

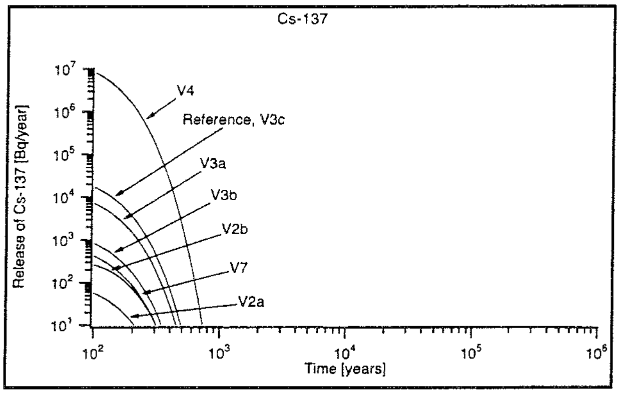


Figure 14-6. Release of Cs-137.

V2a Only 1 zirkaloy tube damaged up to 5000 years.

V2b 1% of the tubes damaged up to 5000 years.

V3a No filling material in the canister.

V3b A stabilizing filling material that will maintain the mechanical stability of the canister.

V3c A filling material with ability to sorb Cs and Sr.

V4 Large breach in the canister immediately after deposition.

V5 Lower sorption for Pu.

The results for the release calculations of Cs-137 and Pu-239 are shown in Figures 14-6 and 14-7.

Calculations have been done to estimate the effect of swelling corrosion products, assuming that there is a circumferential crack in the copper overpack. The calculations /14-13/ suggests that a typical stress on the copper overpack is in the form:

$$\frac{d\sigma_\theta}{dt} = 3x10^{11}\frac{d\delta}{dt}$$

where

$$\frac{d\sigma}{dt}$$

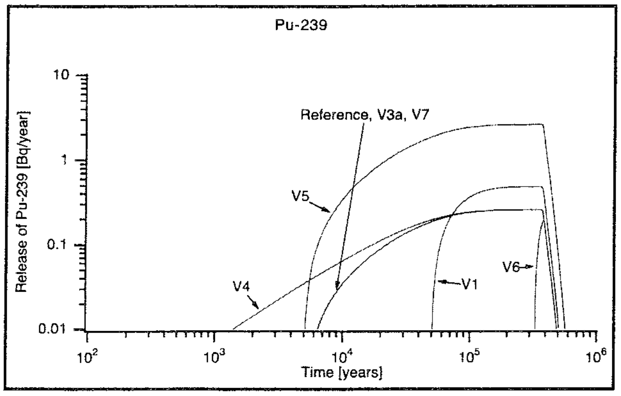


Figure 14-7. Release of Pu-239.

is the rate of increase in thickness of the corrosion residue in the annulus. A diffusion calculation implies that under most repository conditions, corrosion will continue to take place over a significant fraction of the steel surface, and therefore the crack in the copper overpack is unlikely to "yawn". The only scenario that could lead to a widening of the crack occurs if the repository is saturated with groundwater and the corrosion is aerobic. Such conditions exist, if at all, only for a short time in the lifetime of the repository.

The hydrogen gas produced by the corrosion of the steel canister can not escape through the buffer material by aqueous diffusion, at least not if a conservative corrosion rate is used in the calculation. This means that the establishment of gas phase flow paths must represent a significant gas transport mechanism. Models have been considered to investigate the displacement of clay aggregates by the penetrating gas. Some calculations have been undertaken to assess the sensitivity of the models to the input data and to try to estimate the pressure increase in the canister required to support the necessary gas flux.

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 /14-14/ has addressed the potential overpressurization of the canister and the possible effects of the gas on water movement around the repository. The principal objectives of this preliminary programme of work were 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 through 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 suggests that there is ample capacity to transport gas away from the repository and up towards the surface.

This study indicates that the copper/steel canister meets very high safety standards and that the new scenarios can be treated in an acceptable way.

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 also 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. A Modelling Task Force was initiated in 1992 as a part of the international cooperation at Äspö HRL. The work will increase our understanding of the fundamental processes involved as well as give an opportunity to test our models with site-specific data.

1994 has been a year of further development which may be seen when comparing the sections below.

14.5.2 Development of models

The Channel 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.

Development has been focused on improving the dispersion behaviour in the model. One option may be to include ideas from the field of self-similarity and fractals. A few algorithms have been tested. Work has also been devoted to using a system where only the fracture zones are represented. Each fracture zone within the target area would then be modelled as a 3D block consisting of a channel network. Finally, some development has also been focused on how to enable the model to use site specific data.

HYDRASTAR is a tool for Stochastic Continuum modelling of groundwater flow. 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 1.4 is provided with a user-friendly input data interface as well as a transient solver. Furthermore the documentation has been improved /14-15/, /14-16/.

A series of verification studies have been carried out on HYDRASTAR. The studies concern the accuracy of the implementation of the Turning Bands algorithm and the transport and dispersion of fluid particles in two and three dimensions. In general the agreements were found to be satisfactorily for all cases studied /14-17/. Together with earlier studies on verification this help to build confidence that the code will produce correct results when applied to realistic cases. It may also be mentioned that the verification work was performed by AEA Technology, England, using the SKB CONVEX computer via Internet. This way of communication worked out extremely well.

The methodology in HYDRASTAR will be further developed. Use of hydraulic interference tests will probably improve simulation results by the large scale connectivity information. Calibration procedures for taking account of both steady-state and transient groundwater head data have been examined /14-18/. The study involved development of a 2D simulator for method evaluation and what-if simulations in MATLAB. An inverse modelling procedure, the pilot point method /14-19/, was found to have the greatest potential for development. Large uncertainties are obtained for geosphere performance measures given few data. The methodology has a great potential for variance reduction. Significant improvement in variance by further conditioning will be obtained as the number of data becomes much larger. However, inverse modelling procedures are a structured way of utilising available site groundwater head information as opposed to manual calibration.

An investigation regarding performance assessments requirements on radionuclide transport modelling has been carried out /14-20/. Specifically, the methodologies for performance assessment specific models have been discussed in an international perspective. Possible development and alternative methods have been identified in relation to the existing methods /14-21/.

The PHOENICS/PARTRACK groundwater flow and transport modelling tool utilised in the Äspö HRL project has been the focus for a study evaluating the possibility of using the tool for performance assessment purposes /14-22/. The PARTRACK algorithm does implicitly treat the processes influencing radionuclide migration in fractured media. A few lacking features were identified such as no radioactive chain decay included and that additional work is needed in order to relate PARTRACK input parameters to actual field data available.

14.5.3 Application of models

The Channel Network Model has been applied to data from the Äspö site as a part of the Äspö Task Force work /14-23/. The task in question is the large scale pumping and tracer test LPT2. The Äspö International Task Force will focus on modelling of groundwater flow and transport of solutes using the available large data base at Äspö.

The Channel Network approach was applied for the first time using site data. A 1000 m by 700 m by 700 m region of Äspö was simulated and the drawdowns in boreholes could be compared with the actual experimental outcome. The tracer tests were also analysed. Mainly, this was a feasibility study with comforting results. Much work was focused on obtaining model parameters using available field information /14-24/. Some parameters are lacking from Äspö in the perspective of a Channel Network approach.

In the Äspö Task Force group the modelling activities will be further evaluated.

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.

Further work will be headed towards alternative stochastic approaches for groundwater flow simulation and the effect on transport predictions. The aforementioned inverse modelling technique has to be applied using site specific data.

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, Buffer and Backfill, Geoscience, Chemistry, Natural Analogue Studies, and The Biosphere.

The canister research has been presented together with the development work on canister design and production in Chapter 6.

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 experimental programme in the hot-cells at Studsvik Nuclear has been in progress since 1982. Two specimens of BWR fuel from this first series are still being corroded using a sequential corrosion scheme, where the corrosion solution is replaced with fresh solution after predetermined contact periods. These specimens have now reached an accumulated contact time of over 13 years. Other ongoing long term experiments are a series of PWR specimens, started in 1986, also with sequential exposure to water.

The cooperation with other groups in the world performing similar studies has continued during 1994, through the spent fuel workshop that was held in Montebello, Quebec, Canada, and arranged by AECL Research, Canada. More direct cooperative work has also been performed with AECL Research.

15.1.1 Fuel characterization

Since alpha and beta radiolysis are probable driving forces for oxidation and dissolution of spent fuel under reducing conditions, high-magnification scanning electron microscopy studies of corroded fuel specimens have been performed during the past few years. Particular attention has been paid to the pellet periphery, which has a higher burnup and alpha activity than the bulk pellet. Although a few specimens appeared to show evidence of corrosive attack at the periphery, examination of other specimens, which would be expected to show a similar effect, did not confirm these results.

This was discussed in a previous report /15.1-1/, together with a presentation of an indirect method for determining the locations in the pellet, where the uranium is dissolved during corrosive attack. Direct measurements of the $^{236}U/^{235}U$ ratio of the uranium in solution from corrosion tests were compared with calculated values for bulk fuel and pellet peripheries, determined from quantitative measurements of the radial burnup at three locations in the rod, and a series of ORIGEN calculations, which were used to establish a relationship between the $^{236}U/^{235}U$ ratio and burnup. It had tentatively been expected that the experimental values would fall somewhere between the calculated bulk fuel and the periphery, indicating some selective attack at the high alpha dose periphery. It was found that the ratios in solution were grouped around the bulk fuel values.

The use of ORIGEN calculations to predict actinide compositions at the pellet rim is, of course, subject to uncertainty. Experimental evidence for the existence and size of the change in $^{236}U/^{235}U$ ratios at or near the rim would be very useful. Measurement of the radial variation in a high burnup PWR fuel pellet by means of laser ablation and ICP-MS has been reported /15.1-2/. However, the size of the laser-sampled crater, about 0.5 mm, gave inadequate spatial resolution for the rim zone, and the reported change in isotopic ratio was only about 20%.

In order to obtain more experimental data, a few tentative attempts have been made to analyse very small fuel fragments from a fuel that shows pronounced rim effect with respect to radial profiles for burnup and alpha activity. Eleven randomly chosen fuel particles showed a $^{236}U/^{235}U$ ratio of 1.13 ± 0.09. These were compared with analyses of three scrapings from the pellet periphery, which suggested that there is a radial variation of about 30% in this specimen. The values of the $^{236}U/^{235}U$ ratio obtained in the last two contact periods of corrosion on the specimen were, in each case, 1.11 ± 0.02, which also suggests bulk corrosion rather than preferential corrosion at the fuel rim.

15.1.2 Spent fuel corrosion

In March 1990, a corrosion test was started of fuel from a stringer rod with variable burnup along its length. The burnup ranged from 21.2 to 49.0 MWd/kgU (Series 11). Since the local linear heat-rating was proportional to the burnup, the rod was well suited for investigating the effects on corrosion of migrational effects during reactor operation. Sixteen sections of fuel/clad were used for the corrosion tests and two shorter sections for burnup and inventory determination. So far, the tests have consisted of 8 completed contact periods; the 9th is still in progress. Ten of the 16 fuel specimens were corroded in synthetic bicarbonate groundwater under oxic conditions, while the remaining 6 were corroded in the same groundwater under nominally anoxic conditions produced by flowing 5%H_2/Ar over the solution surface.

Since 1992, the ICP-MS technique has been used for analysis of the solutions. The analyses have been performed directly, without employing separations or isotope dilution techniques. The potential and limitations of direct analyses of actinides from oxic and anoxic corrosion experiments were studied in conjunction with the analyses of the solutions from the 8th contact period of Series 11 /15.1-3/.

A complication in using ICP-MS on samples containing fission products and actinide is that the isotopic composition departs significantly from those in the lithosphere, and can also vary from sample to sample depending on enrichment of the original fuel, the irradiation conditions, burnup and decay time. A consequence of this is that the pattern of isobaric interferences will differ from lithospheric material, and will not be predictable other than by calculations performed external to the instrument. Corrections for isobaric interferences, however, were found to be relatively straightforward for fission products. For actinides, total inventories and isotopic compositions are strongly dependent on both irradiation conditions, fuel burnup and radioactive decay, and their accurate calculation is difficult. This is a particular problem in Series 11, where the burnup varies along the length of the fuel rod.

An illustration of the results from the ICP-MS analysis is shown in Figure 15.1-1, which presents the mass spectra of the actinides in fuel specimens from the high-burnup end of the fuel rod. The upper spectrum is the dissolved inventory fuel specimen. The lower spectrum is of the corrosion solution from a fuel specimen close to the inventory specimen and, therefore, with very similar actinide inventories and isotopic composition.

The determination of uranium from tests performed under oxic conditions presents few problems, since the concentrations are in the range of 10^{-5} mol/dm^3. Under anoxic conditions the uranium solubility decreases sharply to about 10^{-7} mol/dm^3, but poses no difficulties in the analyses.

For the transuranic actinides, Np, Pu, Am and Cm, the concentrations in solution depend both on the dissolution of the UO_2 fuel matrix in which they are in solid solution and on their own solubilities. Under oxic conditions, the concentrations of Am and Cm are always low, while Np and Pu are typically at the levels of $8 \cdot 10^{-10}$ mol/dm^3 and $1.6 \cdot 10^{-9}$ mol/dm^3, respectively. Under anoxic conditions, their concentration decrease to about $1.6 \cdot 10^{-11}$ mol/dm^3 and $5 \cdot 10^{-11}$ mol/dm^3, respectively. For americium and curium, it was found that the low levels in solution made it unfeasible to directly determine the concentrations.

In conclusion, it can be stated that under oxic conditions, concentrations of both Np and Pu can be directly measured with satisfactory accuracy and precision if multiple analyses are performed. Under anoxic conditions, their concentrations can be determined at least to within one order of magnitude.

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 mixed with the clay. The experimental design and earlier results are described Skålberg et al. /15.1-4/ and by Albinsson et al. /15.1-5/. A schematic view of the diffusion cell is shown in Figure 15.1-2. During 1994, the release and migration of ^{90}Sr in the clay after contact times of 101, 197, 386, and 2213 days have been published /15.1-6/. From the distribution of ^{90}Sr from the fuel after 101 days an apparent diffusivity of $6.3 \cdot 10^{-12}$ m^2/s was determined, see Figure 15.1-3.

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

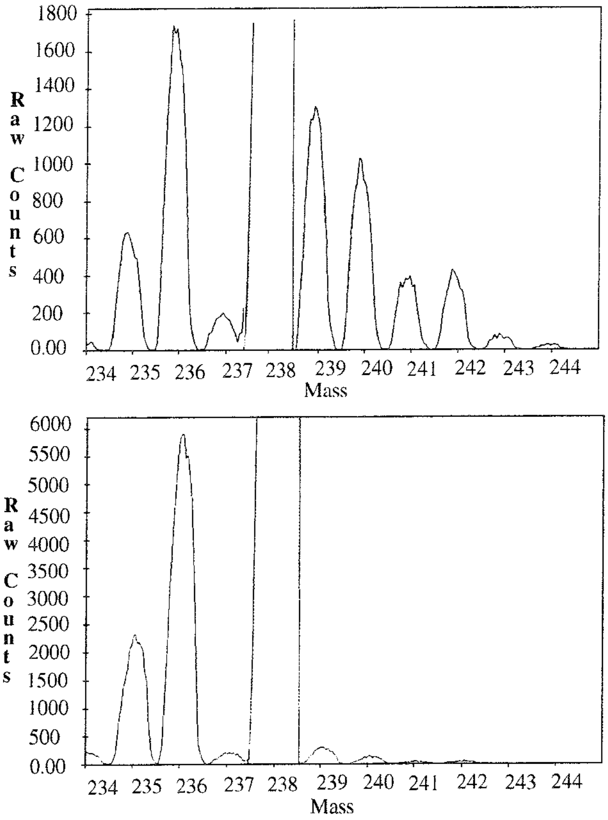


Figure 15.1-1. *Actinide spectra from specimens from the high burnup end of the stringer fuel rod.*

Upper; Dissolved fuel from the inventory specimen. Lower; Solution sample from 8th contact period of a fuel specimen close the inventory specimen.

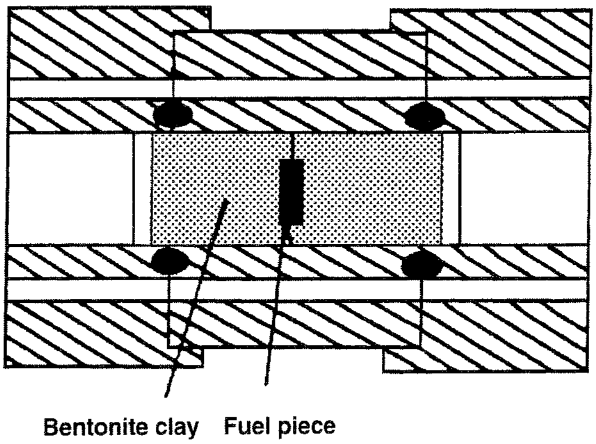


Figure 15.1-2. Schematic view of the diffusion cell.

conditions show a ^{90}Sr release fraction of 0.02% after one year /15.1-7/. Thus, the present experiment shows release rates more indicative of anoxic conditions.

The apparent diffusivity of technetium has measured in the fuel-leaching/diffusion experiments. Previously, the 101 days experiments have been evaluated, using radiometric methods /15.1-5/. In the present study, the analysis was made using ICP-MS /15.1-8/. With this technique, a detection limit of 0.45 pg/ml was achieved. The apparent diffusivity of technetium after 101 days was found to be $9.9 \cdot 10^{-13}$ m^2/s, which is in agreement with what was reported in /15.1-5/. However, a lower apparent diffusivity ($3.1 \cdot 10^{-13}$ m^2/s) was observed after 386 days of diffusion time and an even lower after six years of diffusion time ($6.1 \cdot 10^{-14}$ m^2/s).

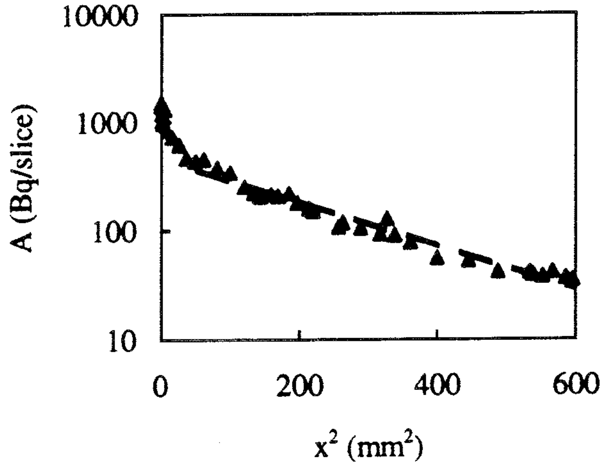


Figure 15.1-3. Diffusion profile of ^{90}Sr in compacted bentonite, ρd=2100 kg/m^3. The dotted line represents an apparent diffusivity of $6.3 \cdot 10^{-12}$ m^2/s.

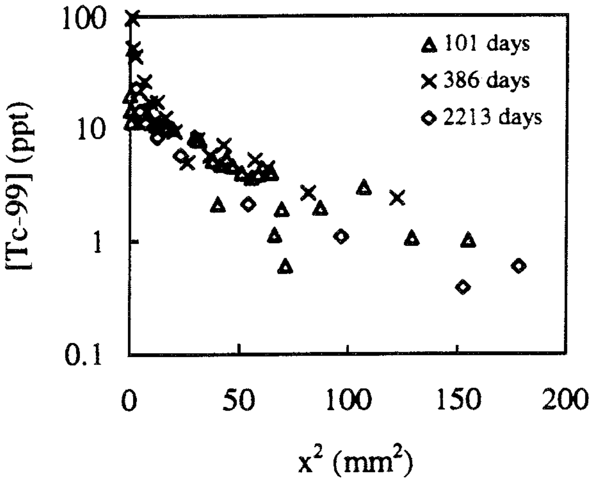


Figure 15.1-4. Diffusion profile of ^{99}Tc in compacted bentonite, ρd=2100 kg/m^3 after different contact times.

The apparent diffusivity seems to differ by a factor corresponding to the diffusion time used in the evaluation. If the apparent diffusivity is calculated from the concentration profile obtained after 2213 days, but using a diffusion time of 101 days, almost the same apparent diffusivity is obtained as in the 101 days experiment. The diffusion profiles after different diffusion times are shown in Figure 15.1-4. An explanation is that technetium is released from the fuel as TcO_4^- and diffused into the bentonite clay, whereafter it is reduced to Tc(IV), probably TcO_2 or $TcO(OH)_2$, which will be sorbed strongly in the clay. The total amount of released Tc was about two orders of magnitude lower than in fuel corrosion experiments performed under oxic conditions.

15.1.3 Alpha radiolysis

The production of H_2, O_2 and H_2O_2 by radiolysis of the leach solution have been studied in a closed system containing fragments of irradiated PWR fuel and argon purged distilled water /15.1-9/.

The radiolysis of water produces equivalent amounts of oxidising and reducing species. Oxidation of used fuel by radiolytically formed oxidants results in a net production of reducing species, primarily as H_2. However, it is not clear to which extent the radiolytically produced oxidants effect the dissolution behaviour of the UO_2 fuel matrix. In /15.1-9/, the mass balance for radiolytically produced oxidants, reductants and dissolved uranium was studied in a closed system initially containing fragments of used fuel and oxygen free distilled water.

During a first contact, H_2 and O_2 concentrations initially increased in the gas phase above the leach solution. The increase in H_2 reached at steady state within about a week. The O_2 concentration, however, increased to maximum value in about the same time, whereafter it decreased with time, see Figure 15.1-5. In a second contact, H_2 behaviour

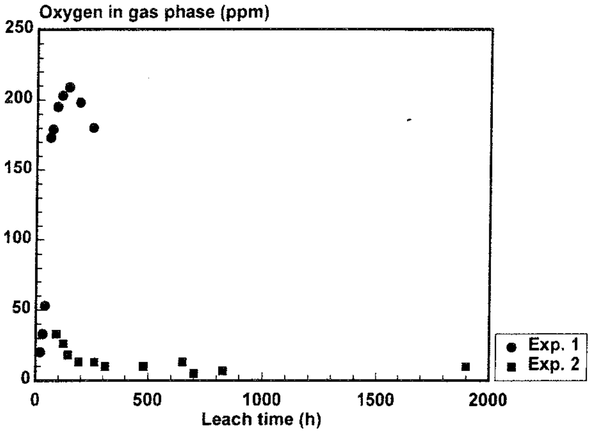


Figure 15.1-5. Oxygen concentration in gas phase plotted versus leach time. (1.88 g fuel, 14 cm³ distilled water, 50 cm³ Ar).

was the same, while only a very low O_2 concentration was observed. Very low concentrations of H_2O_2 and dissolved uranium were observed in the aqueous phase at the end of the experiments.

After these two contacts, the fuel was leached in an anaerobic solution of 10 mmol/dm^3 of carbonate solution in order to dissolve any U(VI) on the fuel surface. It was found that there was a clear deficiency of oxidants in the overall redox system. The concentrations of uranium in the experiments performed in distilled water were in the range 0.6-1.7 $\cdot$ 10^{-6} mole/dm^3, in close agreement with the expected concentrations in equilibrium with $UO_3 \cdot xH_2O$. However, in the presence of carbonate, the observed steady state uranium concentrations (6 $\cdot$ 10^{-6} mole/dm^3) were far from what is expected if the surface oxidation had proceeded up to U(VI). The observed uranium concentrations were close to the ones expected in equilibrium with a UO_{2+x} surface oxide. The findings of this preliminary work indicate that redox buffering by the UO_2 oxidation to UO_{2+x} may be a mechanism of critical importance to assess the effects of radiolytic oxidation.

Additional experiments of this kind with controlled chemical conditions should indicate the overall effect on master variables like pH and pe, as well as on the release of minor nuclides. From this more realistic models to describe the radiolytic oxidation of spent fuel could be derived. Such experiments are currently in progress.

15.1.4 Natural analogues

The dissolution behaviour of uraninite, becquerelite, schoepite and uranophane has been studied /15.1-10/. The information obtained under a variety of experimental conditions has been combined with extensive solid phase characterizations, performed under both leached and unleached samples. The overall objective is to construct a thermodynamic and kinetic model for the long-term oxidation alteration of $UO_2(s)$, as an analogy of the spent nuclear fuel matrix.

The dissolution of bequerelite under anoxic conditions in distilled water gave solubilities much lower than calculated by the solubility constant found in the literature. A solubility product of 32.7 ± 1.3 has been proposed based on the results of the dissolution experiments. The solubility product of uranophane was determined to be 7.8 ± 0.8. In some experiments, the reaction progress showed initial dissolution of uranophane followed by precipitation of a solid phase, characterized as soddyite. With the data obtained, a solubility product for soddyite of 3.0 ± 2.9 was suggested.

The kinetics of dissolution of uraninite, uranophane and schoepite have been studied under oxidizing conditions conditions in synthetic groundwater. The normalized rates of dissolution of uraninite and uranophane were calculated, referring to uranium release, as 1.97 $\cdot$ 10^{-8} mole/h $\cdot$ m^{-2} and 4 $\cdot$ 10^{-9} mole/h $\cdot$ m^{-2}, respectively. For schoepite, no measurement of surface area was performed, due to the lack of sufficient amount of sample. However, for schoepite the dissolution process showed two different stages, with a relatively fast initial rate of 1.97 $\cdot$ 10^{-8} mole/h followed, after approximately 1000 hours by a slower one of 1.4 $\cdot$ 10^{-9} mole/h. No formation of secondary phases were observed in those experiments, although final uranium concentrations have in all cases exceeded the solubility of uranophane, the thermodynamically more stable phase under the experimental conditions.

It was concluded that further work should be concentrated in establishing the thermodynamics and kinetics of uranophane and soddyite synthetic samples to ascertain the final pathway for the long-term bahaviour of spent nuclear fuel under oxic repository conditions.

15.2 BUFFER AND BACKFILL

15.2.1 Buffer and backfill encyklopdia

The more than 15 years of research and investigation of smectite-based buffer materials have developed a broad know-how of the behaviour of the material under repository conditions as well as laboratory experience of how to prepare samples and measure the properties. In the future phase of designing a repository there is a need for a compilation of the relevant information summarizing unified definitions of physical and chemical terms, standardized and recommended laboratory and field test methods, and mathematical models for describing and predicting practically important processes and bulk behaviours. Such documentation has started and is intended to consist of three parts of which the first one has been completed in a preliminary version within the frame of current cooperation between TVO and SKB.

This first part deals with units and definitions, soil characterization, contents, consistency, physical and chemical properties, and routine methods for quality assurance of large quantities of buffer material. The second part is planned to be a material handbook with description of practically important parameter data, and with recommended methods for preparation of buffers and backfill in bulk and block forms. The third part will contain a compilation of models for predicting major transport processes and rheological behaviours.

15.2.2 General microstructural model for bentonite

The practically important transport and rheological properties of smectite-based buffers and backfills depend on the microstructural constitution. Thus the hydraulic conductivity and diffusive transport capacity, expandability and compressibility, shear strength and creep behaviour are controlled by the arrangement and physical and chemical interaction of the mineral constituents and solutes. An understanding of the microstructure has been shown helpful in the interpretation of measured data obtained from various testing of buffer and backfill in the laboratory /15.2-1/.

Based on an early developed conceptual model further improvements have been made. Information on the microstructural constitution, especially concerning the distribution of immobile and mobile porewater, has been derived by use of electron microscopy and application of fundamental physical models that are based on the ratio of these two porewater types and that yield microstructural patterns of the sort depicted in Figure 15.2-1. This figure shows that the voids between the clay particles, that are filled with clay gels, are not developing a homogeneous density after saturation but a density that is dependent on the size of the void. The softer parts of the smectite gel serve as the most permeable passage for flowing water and diffusive transport of ions as well as for gas. The gas may expand the passages and make them permanent.

In order to quantify the properties of the buffer and backfill the conceptual model has to be supplemented with a numerical model and such work has started. An improved physical model has been adapted to the general rheological model /15.2-3/ working with the ABAQUS code. Its first form in 2D for pure bentonite particles as well as for mixtures of bentonite granules and ballast grains verifies that large inhomogeneities may prevail even after complete maturation as illustrated by Figure 15.2-2 /15.2-4/.

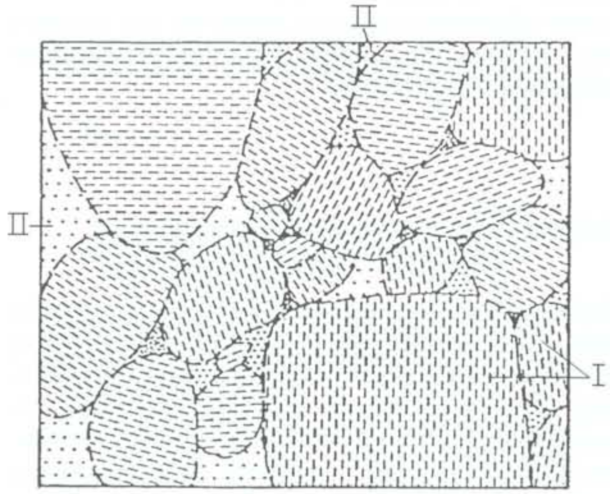


Figure 15.2-1. *Basic pattern of granules in highly compacted bentonite clay:*

I) Expanded powder grains.
II) "External" voids filled with clay gels with a density that is related to the void size. /15.2-2/

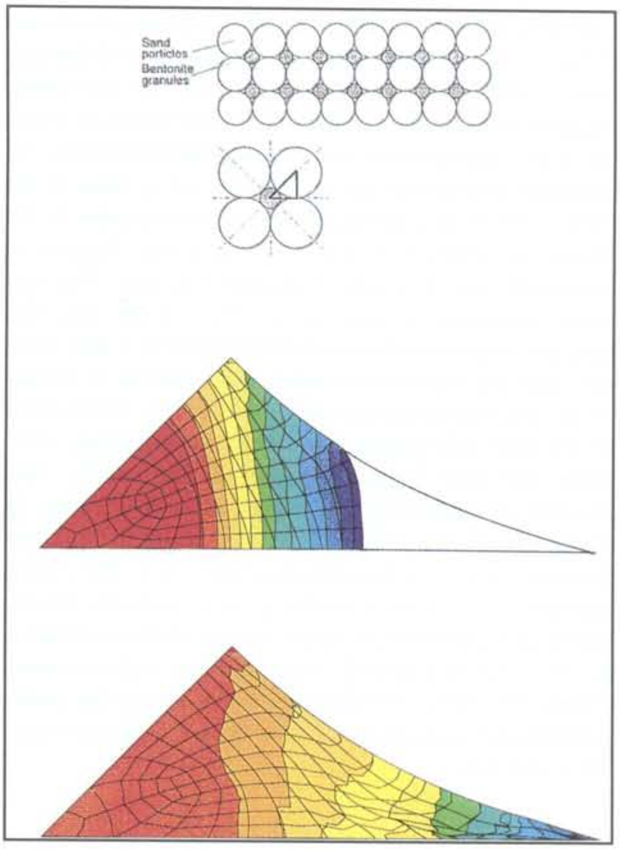


Figure 15.2-2. *Preliminary material calculation of the maturation rate of bentonite granule assemblage in bentonite/ballast mixture. Upper: Schematic microstructure. Centre: Early stage with a large part of voids still unfilled. Lower: Late stage with a small part of voids unfilled. Red is high density, yellow intermediate density and blue very low density.*

15.2.3 Modelling of degradation process

A technique for modelling buffer degradation processes that require transport of one reaction component from the near field or from the buffer boundary has been developed /15.2-5/. The technique is based on the finite difference code FLAC, using FLAC thermal logic for simulating transport to the buffer boundary as well as transport within the buffer, and the FLAC built-in programming facility for implementing the reaction mechanism taking place in the buffer. The modelling technique has been applied to the process of smectite-to-illite conversion with fixation of potassium ions in cation exchange positions. The dissolved potassium is assumed to diffuse in the clay. The reaction mechanism has been represented by a rate equation and the conversion reaction is assumed to follow Pyttes and Huangs models /15.2-6/. For cases which could be checked with analytical solutions the modelling technique has been found to give accurate results. One example of application is the deposition hole model, in which potassium is assumed to be supplied from the tunnel floor and the rock walls of the deposition hole. The results indicate that even for very conservative estimates regarding the rate of potassium supply and the effective diffusivity in the clay at least 50% of the bentonite buffer remains unconverted after 100 000 years, and thus that the buffer performance still is dominated by the properties of smectite at that time.

15.2.4 Cements impact on bentonite

The work concerns possible mineral alteration in construction with bentonite in close contact to cement and is carried out as a joint project between NAGRA and SKB. The investigation comprises 1, 4 /15.2-7/ and 16 months test series with hydrothermal cell tests, percolation tests and diffusion tests. The MX-80 bentonite quality from American Colloid Ltd has been used in all tests after conversion to a monoionic sodium state. Two types of artificial cement pore water solutions were used, one dominated by alkali hydroxides which consequently has a high pH (approximately 13.5), and the other dominated by calcium hydroxide and thereby with a more moderate pH (approximately 12.5). The clay density is 1.8 g/cm^3 after saturation with distilled water and the temperature has been held at 40°C in all tests. The swelling pressure and the 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. The most important findings concern the samples contacted to the most reactive cement solution, in which e. g. small but significant increases in 10 Å minerals were found. However, the preliminary results from the 16 months tests indicate a retarding rate of the reaction which produces this mineralogical change.

15.2.5 Testing and modelling of physical behaviour of bentonite in unsaturated form

The work up till now has been focused on saturated conditions but has now also been expanded into unsaturated conditions. During the water uptake the buffer will be exposed to a thermal gradient that induces mechanical and hydraulical as well as chemical processes. During 1994 thermo-hydro-mechanical properties have been investigated by laboratory tests, material modelling and adaptation of the coupled model to the ABAQUS code /15.2-8/. This preliminary model includes several submodels as follows.

- Heat conduction.
- Effect of the evaporation-condensation process on the heat flux.
- Effective stress theory corrected for the degree of saturation controlled by the mechanical properties of the pore water and the particles.
- Porous elasticity model.
- Drucker-Prager plasticity model.
- Darcys law for water flux.
- A negative pore pressure directly related to the degree of saturation.
- Vapour flux driven by a thermal gradient.
- Thermal expansion of the pore water and the particles.

The model is a compromise between the available function of the latest version of ABAQUS and a tentative material model based on the latest knowledge of the behaviour of unsaturated buffer material. Some additional functions like the vapour flux have been coded and incorporated in the program. The code has been used in calculations for evaluating its validity. This has shown that the model often yields acceptable results but does not apply to all investigated cases. Especially the mechanical modelling is lacking accuracy.

15.2.6 Salt accumulation in bentonite exposed to a thermal gradient

During the saturation process, after emplacement of buffer and canister, the clay takes water from the surrounding rock as a wetting front moves towards the hot canister. At high temperature gradients, which may be present in the repository, enrichment of ions can take place. Two different processes of possible importance have been noticed both in pilot laboratory tests and in field experiments /15.2-9/, i. e. the transport of ions from easily dissolved impurities in the buffer or from the surrounding ground water to the wetting front in the clay, and precipitation of compounds that have a lower solubility at higher temperatures. Series of tests have been performed in order to further develop the understanding of the processes, although with exceeded temperature and salt gradients. The performed laboratory results validate the hypothesis of accumulation of cementing compounds at the warmer part of a buffer but the processes observed under laboratory conditions may be much slower and less obvious under true repository conditions.

15.2.7 Precompaction of bentonite blocks

The emplacement of the bentonite buffer around the canister in the deposition hole is planned to be made with precompacted blocks, which during the saturation phase swell and fill the hole yielding a final density of approximately 2 g/cm^3. The feasibility of precompacting bentonite blocks was demonstrated in the Stripa project in conjunction with block manufacturing for the buffer mass tests carried out in underground experiments. The technique used was isostatic compaction of bentonite with its natural water content. The blocks were then cut to suitable shapes by sawing.

However, the sawing is a time-consuming operation and a good geometrical precision is difficult to obtain. An improved way of compaction is therefore desired. Furthermore, the strong influence of the degree of water saturation on the thermal conductivity of the buffer makes it also desirable to compact blocks with a high initial water content. The development work during 1994 has been focused on uniaxial compression, and a production process for blocks of a size that is possible to handle by man, i. e. 10-20 kg, has been outlined /15.2-10/.

If such blocks would be used in the repository some 1000-2000 would be required in each deposition hole and the production of each block consequently has to be fast. One industry in Sweden using a suitable method is the brick factory of Höganäs Bjuf AB in Bjuv in southern Sweden, and SKB's knowledge of bentonite and Höganäs Bjuf AB's experience in brick production has been combined to yield a feasible technique. This development includes series of tests in the Bjuv production equipment.

Production under industrial conditions puts special demands on the technique like a very high compaction rate, and several practical problems have been identified and addressed with proper solutions. One main problem was cracking of the blocks, and several different types of cracks with different origins were discovered, such as:

- Expansion of the block at extraction from the form.
- Friction against the form walls during compaction.
- Entrapped air in the block.
- Brittle edges with low strength.

These problems were overcome by using the following techniques:

- Addition of water to yield a water ratio of 18% in the bentonite from the naturally occurring 10%.
- Granulated bentonite with a well defined grain size distribution.
- Decrease of the gap between the form and the piston.
- Lubrication of the walls of the form.
- Stepwise compaction.

Figure 15.2-3 shows an example of a block compacted with this technique.

The work has also started with respect to compaction of magnum blocks with the aim of fabricating blocks with a diameter of about 1.5 m in one piece, which would fit in the deposition hole with a diameter of about 1.6 m. The compaction technique for such blocks differs in many respects from the one developed for manually manageable blocks. The large form needed is difficult to combine with the very high stiffness, and a more advanced technique is required in order to get a high quality of the blocks. Tests in a small scale form with a diameter of 0.25 m have indicated similar problems with cracking as were encountered in the Bjuv factory, but they were solved in a slightly different way by applying:

- Low compaction rate.
- Vacuum suction during compaction.
- Sealing rings of copper in the bentonite in contact with the piston.
- Slightly conical shape of the form.

The coming step is to apply the technique on an almost full scale with a form for blocks with a diameter of 1.0 m and a height of 0.4 m in a press with a capacity of 30 000 tonnes. This press is situated in a plant in Ystad in the southern part of Sweden. Also uniaxial compaction of full scale blocks is possible to test in this press.

Figure 15.2-3. *Bentonite block compacted in the Höganäs Bjuf AB brick plant for production of fireclay bricks before sintering.*

15.3 GEOSCIENCE

15.3.1 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.

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. Unoxic (=reducing) conditions of the groundwater are 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 interaction between the minerals of the rock and the groundwater and is consequently 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 the different 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 none or weakly 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 are being conducted within:

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

The overall objectives and main activities of the 1994 geoscience programme are expressed in the SKB RD&D-Programme that was released in September 1992. During 1994 the geoscience programme has involved the following main tasks:

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

15.3.2 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 nonsorbing 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.

During 1994 laboratory experiments were accomplished by means of a biaxial cell.

The lengths of the samples in the tests were about 400 mm and the core diameters approximately 190 mm. The drilled core samples had fractures parallel to the core axis and were placed inside the biaxial cell during the tests. The water pressure gradients and the compression stresses were varied and tracers were also added to the flow. After the flow tests on a sample, the aperture distribution was measured for a certain compression by injecting an epoxy resin into the fracture. The thickness of the resin layer was studied in saw cut sections by an image processing system. The results from the experiments will be used to select relevant stochastic models for aperture distributions and to confirm mathematical models for flow and transport simulations according to those aperture distributions /15.3-1/.

Overview of in-situ hydraulic testing

During 1994 an ad hoc-group on the knowledge of hydraulic testing and interpretation was created. The overall objective of the group (HYDRIS) 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. A report is foreseen during 1995.

15.3.3 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,
- process, evaluate and increase knowledge concerning the geodynamic processes in the Baltic Shield.

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

A compilation work about tectonic regimes of southern Sweden was reported last year. The compilation has now been extended to the whole Baltic shield. The 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 /15.3-2/.

The review is focused on tectonics and palaeostress regimes in 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 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 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 immediate 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.

First order shear zones

The Fennoscandia rock basement is a cratonic region, stabilised more than 1000 million years ago from the lithological point of view. Regarding structural geology in a regional perspective different conceptualisations are assessed for the present. One theory says that Sweden is divided by NW-directed shear zone regions into large blocks (approx 200 kms). A compilation work summarizes the interpretation of these first order shear zones /15.3-3/.

Tectonic framework of the Hanö Bay area

The Hanö Bay is located offshore southeastern Sweden along the southwestern border of the East European Platform. The sedimentary bedrock ranges in age from Early Palaeozoic to Late Cretaceous. Minor remnants of Tertiary sedimentary deposits may be present. The Quaternary sediment cover includes deposits from at least two glaciations followed by postglacial clays and muds.

A separate project /15.3-4/ has analysed the post-Palaeozoic tectonic development of the Hanö Bay and the geodynamic relation of this area to the Tornquist Zone. The tectonic framework and structural outline presented have been based on seismic stratigraphy, and therefore no absolute timing of the separate tectonic events has been possible. However, a special emphasis has been made to separate post-Tertiary (neotectonic) movements from older tectonic phases.

The results are largely obtained from single channel seismic reflection profiles recorded during the period 1975-1982. This seismic data set contains about 5000 km of seismic reflection profiles in the Hanö Bay displayed in 0.5 s. TWT. Two additional seismic data sets, used for this study, contain about 1200 km of unmigrated multi-channel seismic reflection profiles displayed normally in 2-3 s. TWT. These latter data sets were recorded by Oljeprospektering AB (OPAB) between 1971 and 1973 and by Dansk Boreselskab AS between 1975 and 1976.

The Hanö Bay has been interpretated as subdivided into four areas of different geologic settings. These are: 1) The Hanö Bay slope, which forms a southward dipping continuation of the rigid Blekinge coastal plain. 2) The eastward dipping Kalmarsund Slope which southwards from Öland forms the western part of the Palaeozoic Baltic Syneclise. 3) The Mesozoic Hanö Bay Halfgraben, which forms the central and southern parts of the Hanö Bay. The subsidence of the Halfgraben has been estimated to be in the order of 20-60 m during the Quaternary. 4) The Yoldia Structural Element which forms a deformed, tilted and possibly rotated block of Palaeozoic bedrock located east of the Hanö Bay Halfgraben.

Two tectonic phases dominate the postPalaeozoic development of the Hanö Bay these are: 1) The Early Kimmerian phase, which initiated subsidence and reactivated older faults. 2) The Late Cretaceous phase, which is the main subsidence phase of the Hanö Bay Halfgraben.

Fracture mechanisms

Some R&D-activities at SKB are aiming at developing a numerical model which ca be used to study generic rock fracture mechanisms. The modelling concept has been based on an initially unfractured volume of rock which has been subjected to a tectonic stress which induces subsequent fracturing. In order to make recommendations for the numerical modelling of the joint initiation and propagation a separate literature compilation project was set up. Issues like joint set patterns, joint kinematics, joint fracture mechanisms and classification have been compiled /15.3-5/.

Constructability

During 1993 an ad hoc-group on "bedrock moveability," formulated state of the art in general terms and identified future R&D-activities in the subject for SKB on the basis of a structured overview. According to this activity special interest was also devoted the constructability issues. The design and lay-out aspects have been compiled in a separate progress report /15.3-6/. Among the recommendations one may note the need for further studying the effect of the repository as a possible indication of mechanical weakness in the regional scale perspective.

15.3.4 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.

Thermal-Hydro-Mechanical modelling

Development and verification of coupled thermo-hydromechanical models is taking place in the DECOVALEX project, (international cooperative project for de DEvelopment of COupled models and their VALidation against EXperiments in nuclear waste isolation). DECOVALEX was initiated by SKI and SKB is a member of the Steering Committee for the project. 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.

On behalf of SKB the so called Test Case 3 within the DECOVALEX programme has been modelled with the finite element code ABAQUS /15.3-7/. The test concerns a full scale laboratory experiment of a deposition hole. This so called Big Ben experiment has been conducted by PNC to study the Japanese concept for nuclear waste disposal. The calculations resulted in a complete prediction of the temperature, void ratio, degree of water saturation, pore water pressure and effective stress in the buffer material.

Another modelling exercise has calculated a thermomechanical large scale test, Test Case 2, in the French uranium mine Fanay Augères at a depth of 100 m./15.3-8/

The Test Case 6 of DECOVALEX has addressed the hydro-mechanical behavior of fractured crystalline rocks submitted to high pressure testing between double-packers. Special interest has been devoted to the behavior of a single horizontal fracture when pulse testing, jacking testing and constant pressure testing. In some high-pressure response tests, the flow of water into the rock increases with time. The conclusion of an analysis says that in such cases a governing equation of the diffusion type for the flow in the fracture cant be valid. The reason is that the fracture aperture depends not only on the local pressure, but also on the multidimensional stress field and the deformation of the rock. Another reason for the increasing flow may be fracture propagation with time-lag between pressure change and fracture opening. /15.3-9/

15.3.5 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 Wire Line drilling technique (WL) was chosen and a rig with drillers experienced in WL coring was contracted. The hole was drilled from 200.8 m to a total depth of 1700.5 m with standard NQ dimension (diam. 75.7 mm). The time needed was roughly 900 hours for core drilling and tests during drilling. This was approximately 200 hours less than scheduled. The average rate was just under 2 m/h, core-trips and time for shut-downs included. The average bit life was roughly 70 m and 22 bits were used. The number of core trips was 302, giving an average core length of 5 m. The core recovery was close to 100% (0.6 m loss). To minimize contamination by drilling fluid entering the rock the hole was air-lift pumped. This was performed by using a 200 m deep predrilled hole, (diam. 215 mm), in which the air-lift equipment and core drilling casing were installed. The predrilling was successfully carried out in two steps using the DTH-method modified for straight hole drilling.

Inclination and drilling parameters were recorded during the core drilling. Furthermore, the amount of flushing water entering and leaving the hole were recorded. At certain levels short pumping tests were performed using a packer and air-lift technique. Finally the hole was completed to allow further investigations.

From a technical drilling point of view the WL system proved to be very successful. However, at certain levels high torque became a potential risk due to unsatisfactory hole cleaning and the fact that no lubricating fluid additive was allowed to be used, because of groundwater contamination aspects. For future similar projects it is recommended that the air-lift system should be modified to avoid sedimentation of cuttings in the predrilled hole /15.3-10/.

During 1993 the investigation phase commenced and the following activities were accomplished during 1994:

- Compilation of technical data and administrative documents.
- Compilation of mineralogical and petrographic core mapping.
- Analysis of borehole radar reflectors.
- Groundwater chemistry sampling and analyses.
- Evaluation of hydraulic tests while drilling.
- Initiation of hydraulic testings.

In 1995 the hydraulic testing programme will continue and successively the rock-mechanical aspects will be emphasized. An integrated analysis and interpretation is foreseen to late 1995 or 1996. /15.3-11, 15.3-12, 15.3-13, 15.3-14, 15.3-15, 15.3-16, 15.3-17, 15.3-18/

15.3.6 Geochemistry

Geochemistry involves the chemical processes and interactions taking place in the bedrock and which are of importance for assessment of the long-term safety of a repository. In this context it is mainly the chemistry of the groundwater which is considered. The chemistry of the minerals is of interest only through its potential effects on the hydrochemistry and on the retardation of radionuclides transported by the groundwater. In favourable and stable hydrochemical conditions the copper canisters are likely to remain intact for millions of years.

The groundwater chemical composition is a result of chemical processes and mixing. A good knowledge of the chemical processes makes it possible to differentiate between mixing and reaction, and to delineate the end-members which are mixed to the samples collected. The end-members can be considered as tracers added to the groundwater at different occasions in the geological past. When and if these occasions can be defined it is to some extent possible to track the evolution of the groundwater system, sometimes very far back into the past. When the conditions of the past are known the knowledge can be used to predict the conditions of the future.

Äspö

Within the Äspö HRL project geochemistry has been developed further as a practical investigation tool. Some important results reported in 1994 are:

- Evaluation of data from tunnel section 2265-2874 m /15.3-19/.
- Trace elements in water from low-conductive rocks in the Äspö Hard Rock Laboratory /15.3-20/.
- SKB/DOE Hard Rock Laboratory Studies. Task 3. Geochemical investigations using stable and radiogenic isotopic methods /15.3-21/.
- A compilation of data for the entire tunnel length has been made regarding groundwater flow measurements and hydrochemistry monitoring in surface boreholes on Äspö /15.3-22/. A similar compilation of data from the tunnel is reported in the 1995 year series.

During 1995 all results from the pre-investigation and the construction phases will be evaluated in view of the verification of pre-investigation methods. Future activities are concentrated to different types of experiments.

An important field of refining the hydrochemistry investigation methods has been the test of prediction methods /15.3-19/. Numerical and analytical mathematical methods have been applied to the same data sets and the predicted values are compared to the observations. The underlying concepts can be evaluated through the comparison of predictions and outcome.

The integration of hydrology and hydrochemistry models is subject to a specially defined project together with the international partners of the Äspö project. A geochemistry workshop was held in June of 1994 at Äspö. The outcome of the workshop is two modelling tasks to be incorporated into a geohydrochemical description of Äspö. Proceedings of the workshop are published in the international cooperation report series /15.3-23/. More details are given in the Annual Report of the Äspö HRL project /15.3-24/.

Redox conditions

The most important chemical issue in the deep repository is a reducing environment. At undisturbed conditions this will always be the case. During operation however, oxidizing conditions could be expected due to an enhanced inflow of oxidizing surface water. The redox experiment in block scale at Äspö has demonstrated that even in such a case the biological activity is fast enough to reduce the infiltrating oxygen rich water if the content of organic matter is greater than the amount of oxygen. The final reports will be published in 1995.

Reactions between the groundwater and the rock forming minerals result in weathering of the minerals. In the absence of organic matter it is the weathering process releasing reducing elements, iron and sulphide, which reduce the oxygen that has been trapped in the repository at closure. A careful examination of the weathering of biotite and chlorite has recently been finalized /15.3-25/. This study has also been the basic background for planning of the REX (redox experiment in detailed scale), see Äspö HRL Annual report /15.3-24/.

Groundwater mixing-reaction modelling

The investigations of the Laxemar deep borehole KLX02, see section 15.3.5, have been used as a test case for future repository site hydrochemical investigations. The modelling has improved the identification of end-members in the Simpevarp region groundwater system, see Figure 15.3-1. A recent report on the investigation and results is a fundamental basis for any further geochemical modelling in the area /15.3-26/. At a depth of 1400 m and downwards, the total salinity is 8%, i.e. more than twice the one of the atlantic ocean. This brine has probably been stagnant for millions of years.

The basic knowledge of conditions at the different study sites, combined with the detailed knowledge of the mixing end members and palaeohydrogeological conditions at Äspö, has given the basis for using a prediction model for forecasting the hydrochemical conditions of any given site. In the development of the predictive tool data from the Swedish Geological Survey well records have been used. The greatest difficulty is to convert the relatively shallow well records data to deep groundwater conditions.

For further improvement of the end member mixing modelling, especially to understand the palaeohydrogeology of Äspö, the past conditions of the Baltic Sea areas have been examined through a literature review /15.3-27/. A systematic description of important parameters, oxygen, deuterium, strontium isotopic ratios, carbon dioxide pressure etc. has been defined for the glaciation cycle, before, during and after an ice age.

A detailed study of a single fracture calcite has been utilized by a laser technique, where a thin section of the sample is vapourized and analyzed in a mass-spectrometer for C-13 and O-18 isotopic ratios. As earlier indicated the results prove that the calcite has been precipitated in different generations. Uranium disequilibrium series analyses date some of these generations to be less than 120.000 years, while most of them are older. The isotopic

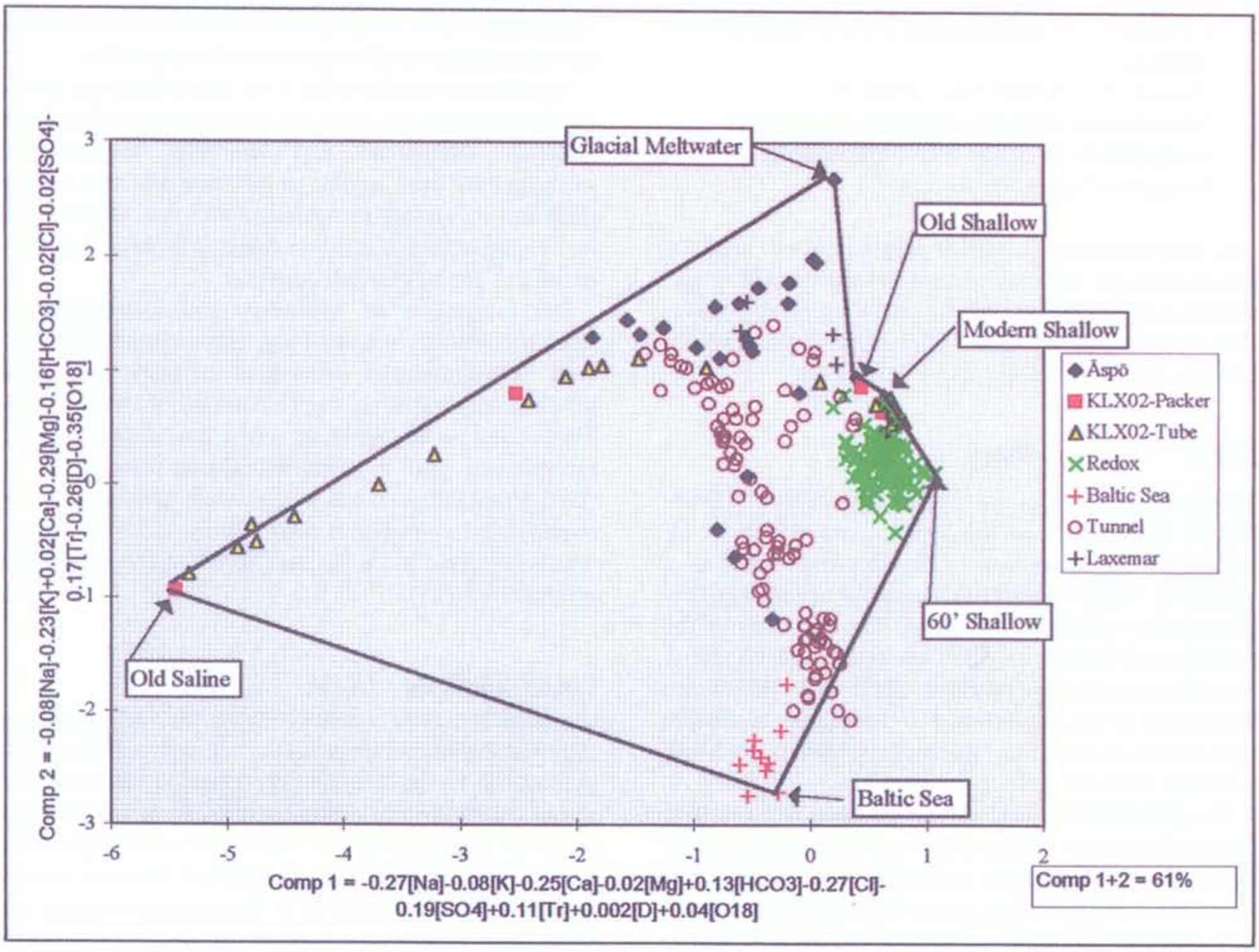


Figure 15.3-1. Multivariate procedure (Principal Component analyses) used to identify end-members for groundwater mixing modelling in the Äspö-Laxemar region.

differences tell that the equilibrium conditions have differed when the calcites were formed.

15.3.7 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 invested quite a lot in developing site investigation techniques and instruments, resulting in a high level of competence in this field. Work in this field during 1994 was organized as follows:

- **in Deep Repository Project;**
  Most of the development, modification and purchase of methods and instruments, is tightly connected to the preparation for the coming site investigations for the Deep repository. This work is further described in chapter 13.
- **in the Äspö Hard Rock Laboratory;**
  Development of Instruments and Methods for ongoing and future experiments during operational phase of the Äspö HRL. Also some supplementary instrument work for the construction phase was made during 1994. This work is described in /15.3-28/.
- **in Supporting Research and Development;**
  No real instrument development work has been made under this heading. However, instrument work aiming at prepare for measurement in the deep borehole KLX02 is described here.

Preparation for deep borehole measurements

To recall from last years annual report, the deep borehole KLX02 was drilled to 1700 m depth. However, due to instability in a fracture zone at approximately 1430 m depth all measurements will stop at that depth. But even that depth is deeper than 1000 m, which has been the "standard" design depth for all instrument developments carried out by SKB. This means that all instruments must be checked and sometimes modified before measuring down in the deeper parts of KLX02.

Hence, during 1993 geophysical logging of various kinds, borehole radar and hydrochemical investigations were carried out in the deep borehole. In 1994 a hydraulic testing programme was started in the autumn. In order to fulfil the requirements of testing at deeper levels the Pipe String System for hydraulic tests was checked and modified. The strength of the pipe string joints was sufficient but the lift rig had to be upgraded. The packers were modified for higher differential pressure. The downhole system was set up in order to support both injection tests and pumping tests to be made without lifting the system or even deflating the packers. For that purpose a second pipe connection beside the pump and additional downhole valves for switching between pumping and injecting mode was installed.

After the first successful test, the system was stuck in the borehole during hoisting, probably due to a piece of rock falling out in between the packers. When over-stressing the pipe string it was broken just above the upper packer, where the pipe strength is reduced, and the signal cable and hydraulic tubing could be taken out from the hole. The upper packer was now situated at about 1700 m, in the reamed-up part of the borehole (the lower packer at 470 m). A fishing operation with a drilling rig was established. By using a special designed, hydraulic operated fishing tool, the upper packer was grabbed and the drill hammer vibrated the packer free, and the hole was open again. The hydraulic testing programme will continue during spring 1995.

The next planned measurements in the deep borehole will be rock stress measurements. The hydraulic fracturing method, normally conducted by a 1000 m umbilical hose system, will be used. But this time the high pressure fracturing system will be hoisted up and down the borehole with the Pipe String System, mentioned above. The preparation of the instrument modification was started in 1994.

Other instrument and method activities are discussed in Chapter 13. Among these activities are the implementation of a new borehole-TV, BIP-1500 System, which was also used in the KLX02, down to 1400 m depth.

15.3.8 Miscellaneous activities

During 1994 SKB organized a short course in Hydrogeological Decision Analysis. The course provided an introduction to the application of decision analysis to engineering design for projects in which the hydrogeological environment plays an important role.

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 points of view could be ventilated. The following seminars have been arranged with participation of the authorities and different experts in the broad field of geoscience:

- Direct fault dating trials at the Äspö Hard Rock Laboratory.
- Reconstructing the last 100 million years tectonic history of Sweden.
- Siting and probabilistic geological maps.
- Hydrogeological decision analysis.
- The impact of regional topography on groundwater flow.
- The Swedish height data base.

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 international meetings as well as to publish papers in scientific journals (see also Appendices 2 and 7 in part III).

15.4 CHEMISTRY

15.4.1 Solubility and speciation of radionuclides

Experiments with plutonium have been given high priority due to the importance of plutonium solubility and mobility for the long-time safety of radioactive waste disposal. However, plutonium is difficult to work with for reasons such as safety and a complicated redox chemistry. Therefore much effort has been spent on preparations during the last year. It remains to be seen what can be achieved in terms of measurements and determination of thermodynamic constants.

Technetium(VII) is soluble and has a high mobility in the form of the negative pertechnetate ion. This would be the stable form of technetium in aerated groundwater, but under reducing conditions as found in deep groundwater we would expect technetium to appear as Tc(IV). Tetravalent technetium has a low solubility and will be retained effectively by sorption on minerals. Although we know that Tc(IV) is thermodynamically the stable form under reducing groundwater conditions it was felt necessary to confirm that the reduction took place. There are two reasons for that. First redox reactions are sometimes inhibited. Secondly literature data on the rate of technetium reduction are inconsistent. Therefore experiments have been performed on technetium reduction in groundwater-mineral systems. The spontaneous reduction of pertechnetate to Tc(VI) in natural systems has been confirmed and the details of the experiments will be published in 1995.

Experimental studies of the solubility of microcrystalline ThO_2 in carbonate and phosphate media respectively have been published as a part of a dissertation by Eric Östhols at the Dept. of Inorganic Chemistry at the Royal Institute of Technology, Stockholm /15.4-1/. Equilibrium constants were obtained and the importance of carbonates versus the unimportance of phosphates under repository conditions were confirmed by the results.

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 and we are also actively taking part in the EU project CHEMVAL.

15.4.2 Organic complexes, colloids and microbes

Dissolved organic matter in groundwater has been sampled and studied since 1982 with the aim to elucidate the potential influence on radionuclide release and transport. The results have been used in the performance assessment studies KBS-3 (1983) and SKB 91 (1992). The actions taken have been to reduce the sorption coefficients (K_d-values) of the more sensitive radionuclides according to the analysed concentrations of humic and fulvic acids, and the results from the laboratory measurements /15.4-2/. An overview has been jointly produced by experts on performance assessment and organic influence from Canada (AECL), Finland (TVO), France (ANDRA), Japan (PNC), Sweden (SKB and University of Linköping) and Switzerland (PSI) /15.4-3/. It was recognised that humic and fulvic acids will form complexes with for example three-valent actinides and that surfaces of inorganic colloids will be influenced. However, due to the low concentrations of these substances in deep granitic groundwater, their effects on solubility and sorption are ranging from small to insignificant in this environment. In comparison the concentration in surface water would be much higher and humic complexes more important there.

Some open questions still remain, such as; what are the nature of the hydrophilic carboxylic acids that are found together with the humic substances, what is the geochemical and geomicrobial influence of dissolved organics, how can they be used in the evaluation of a site etc.

The conclusions made in the overview were based on the results of recent studies of concentrations and characteristics of humic substances, for example the dissertation by Irina Valarié at the Dept. of Water and Environmental Studies, Linköping University /15.4-4/, where functional groups and physico-chemical properties of fulvic acids have been determined. The complexation of radionuclides with humic substances have been studied by Maria Nordén and recently presented in her dissertation at the Dept. of Water and Environmental Studies, Linköping University /15.4-5/. The results support the approach made in KBS-3 and SKB-91 to make minor corrections of some sorption coefficients, see Figure 15.4-1.

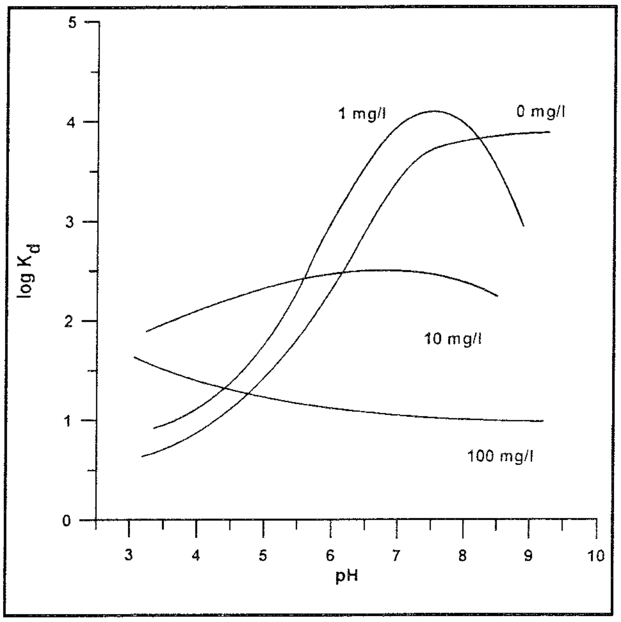


Figure 15.4-1. *The effects of fulvic acid concentration on the adsorption of Eu on alumina (0.10 M $NaClO_4$) /15.4-5 and 15.4-6/.*

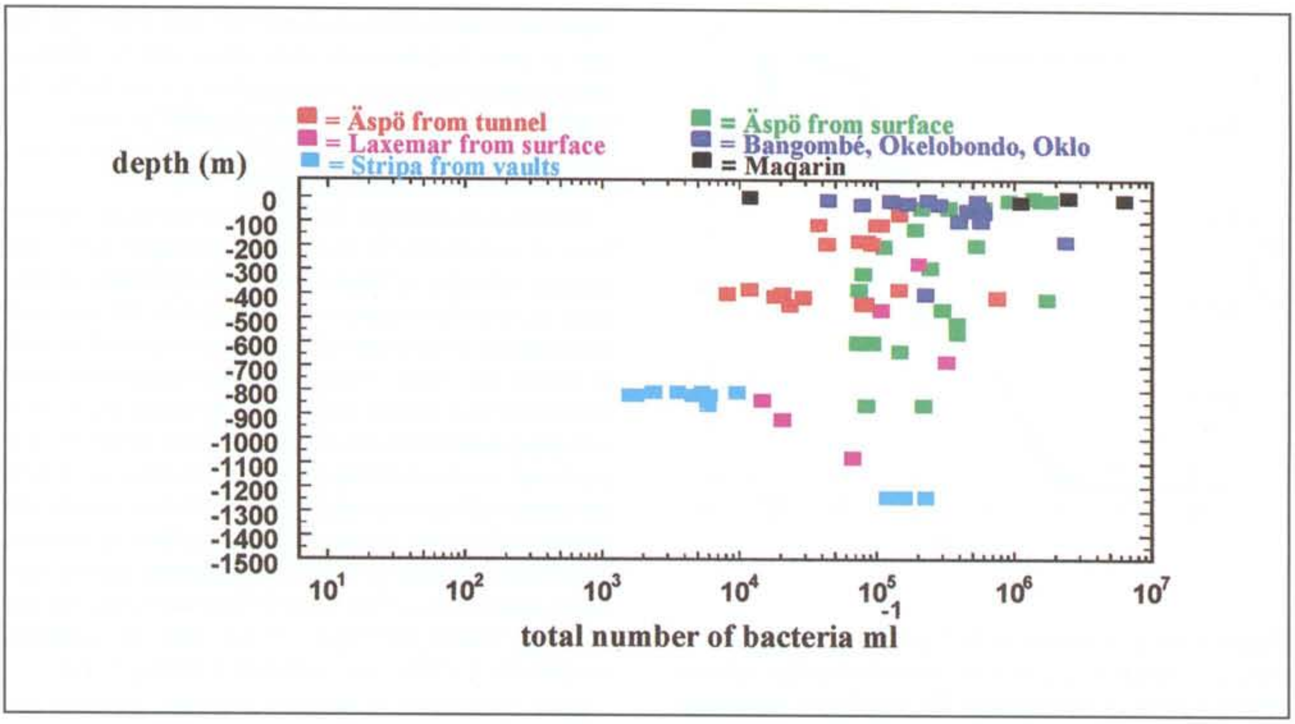


Figure 15.4-2. *The total number of bacteria in groundwater down to 1 240 m, determined with the acridine orange counting technique. Data has been collected over a period of 9 years from 30 boreholes at 49 different sections /15.4-9 and 15.4-10/.*

Recent sampling of dissolved natural organics has been made in groundwater from the deep borehole in Laxemar (near Äspö Hard Rock Laboratory) and from the site of the fossil reactors in Bangombé (near Oklo in Gabon).

Column experiments with inorganic colloids and radionuclides have continued. The results will presumably be summarised in a dissertation by Birgit Sätmark in 1995. Radionuclide transport by naturally occurring inorganic particles is considered relatively unimportant in deep granitic groundwater /15.4-2/. The concentrations of colloids there are to low to be significant. However, according to recent publications colloids can be carried by gas bubbles. This has been demonstrated by experiments /15.4-7 and 15.4-8/. We have decided to investigate this to see, if it is of any importance for the performance of the near-field and the rock as barriers to radionuclide dispersal.

Recent sampling of natural colloidal particles has been made in groundwater from the deep drillhole in Laxemar (near Äspö).

Sampling of bacteria from deep groundwater continues. A variety of underground environments has been investigated so far, see Figure 15.4-2. Much of the sampling has been concentrated to underground conditions typical for a deep repository in Sweden such as Äspö Hard Rock Laboratory, Laxemar (near Äspö) and Stripa mine. Uranium rich environments in Oklo, Okelobondo and Bangombé in Gabon and in Palmottu, Finland have also been sampled as a part of the analogue investigations carried out there. For that reason samples have also been taken from the hyperalkaline groundwaters in Maqarin, Jordan. SKB has together with AECL and ANDRA supported the microbial investigation of the bentonite backfill from the buffer mass heater test in URL (Underground Rock Laboratory) in Canada. The microbe study in URL is managed by AECL.

The 16S-rRNA gene sequencing technique has become increasingly more important as a method to characterise bacteria. This method also provides a way to discriminate between genuine deep bacteria and those due to sample contamination. The sampling and analyses are performed by researchers from the University of Gothenburg.

15.4.3 Sorption and diffusion

Radionuclide sorption on mineral phases has been investigated in detail, to find the sorption mechanisms. Such experiments using thorium and silica as model substances have been reported by Eric Östhols in his dissertation at the Dept. of Inorganic Chemistry, Royal Institute of Technology, Stockholm /15.4-1/. The spectroscopic method EXAFS (Extended X-ray Absorption Fine Structure Spectroscopy) was used to determine how thorium is bound to the silica surface and parameters of the surface complexation model were measured by normal wet-chemistry methods, such as titrations. Determination of parameters for detailed modelling of sorption mechanisms has also been reported by Karl Vannerberg in his licentiate thesis, presented at the Dept. of Nuclear Chemistry at Chalmers

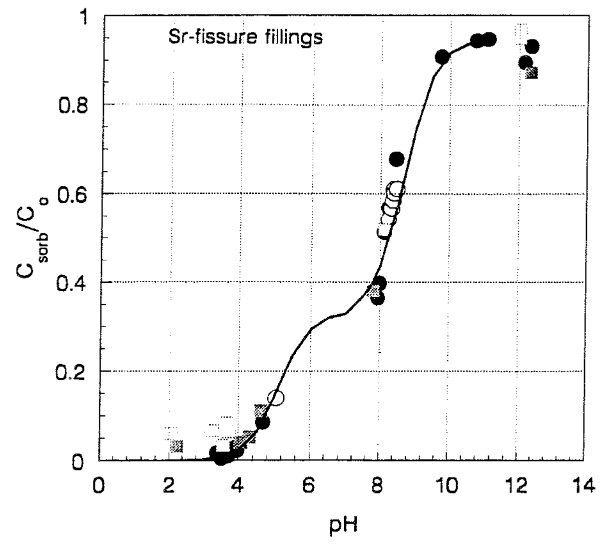


Figure 15.4-3. Sorption of Sr^{2+} on fracture filling minerals as a function of pH. The different symbols refer to different series of experiments. The full line is calculated using surface titration data /15.4-12/.

Technical University /15.4-11/. In this study ions of Na, Co, Pm(III) and Np(V) were used for sorption on goetite, hematite and silica.

In our opinion these investigations serve to explain the details of radionuclide sorption on minerals, but they also support the more simplistic approach of using sorption coefficients (K_d-values) in performance assessment calculations of radionuclide transport in rock fractures. For example, the more elaborate surface complexation model is difficult to use for that purpose. However, an important task in performance assessment is to foresee the variations in K_d-values in different scenarios. It may be possible to use detailed sorption models to find the variations in sorption due to changes in the water chemistry. An example of that is a recent study of strontium sorption on fracture filling minerals /15.4-12/. The substrate was characterised by surface titration and careful measurements of strontium sorption/desorption were performed. Complete reversibility was demonstrated and the dependence of sorption on pH explained, see Figure 15.4-3.

The method of surface titration has also been applied to the clay mineral montmorillonite in order to establish the acid/base buffering properties of bentonite /15.4-13/. The results were interpreted by a two-site model with surface sites and edge sites. This will be used to describe the chemical composition and stability of bentonite pore water.

Diffusion of radionuclides into the connected water filled micropores of the rock, i.e. matrix diffusion, is a considerable retention mechanism and therefore plays a very important role in the performance assessment of the rock as a barrier to radionuclide dispersion. A lot of investigations of matrix diffusion have been performed over the last 15 years by laboratory experiments and by observations in nature (analogue investigations). Considering the importance of the subject it was decided to make a literature search and a summery of the present state-of-the-art. Work started towards the end of 1994.

Diffusion of cesium in bentonite is of particular importance in a scenario of an initially damaged spent fuel canister. It is also of importance for performance assessment of near-field barriers in a repository for low- and intermediate level waste when bentonite backfill is used to isolate the waste. Numerous experiments have been performed with cesium diffusion in bentonite, but there is still some uncertainty about what is the appropriate chemical model. An attempt has therefore been made to explain the cesium diffusion assuming sorption in bentonite by ion exchange /15.4-14/. It was demonstrated that the sorption behaviour of cesium in compacted bentonite (and in bentonite suspensions) could be described with a one-site ion exchange model, see Figure 15.4-4. The ion exchange constant for Cs^+/Na^+ was measured to $\log K_{ex}{}^o = 1.6$.

More experiments on diffusion of cesium, strontium and iodine in bentonite clay have been started. The aim is to measure directly the constants governing the rate of mass transport through a bentonite buffer and the uptake of radionuclides in such a case (D_a, D_e and K_d).

15.4.4 Validation experiments

Tracer migration experiments are being carried out in an overcored natural rock fracture. A large fractured drill core (a single natural fracture) has been arranged in a laboratory setup in such a way that different rock pressures can be applied perpendicular to the fracture plane. These experi-

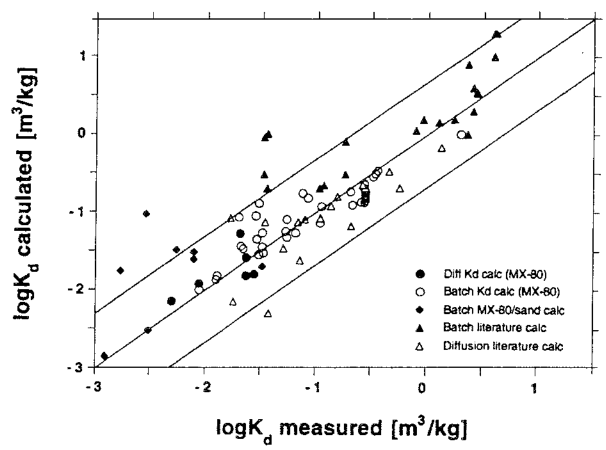


Figure 15.4-4. Comparison of measured and calculated sorption coefficients for cesium in bentonite clay, evaluated from batch and diffusion experiments. The model is based on the assumption of one-site ion exchange /15.4-14/.

ments have taken more time than originally expected due to several technical problems such as: lack of stiffness (volume changes in the fracture due to variations in the internal hydraulic pressure), formation of bubbles in the water, non linearity in the optical detection system etc.

In-situ experiments with radionuclides are planed for the Äspö Hard Rock Laboratory to be carried out in the so called CHEMLAB-probe. 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 has been constructed to test the functions and the response to pressure and pressure differences. A diffusion cell has also been constructed that will be installed in 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 performed where synthetic cement pore fluids are percolated through columns filled with crushed rock minerals. British Geological Survey is performing the experiments, jointly supported by NAGRA, NIREX and SKB. The reactions with granitic minerals are slow, but the CSH (Calcium Silica Hydrate) phases formed tend to diminish the flow porosity in the columns. This is in general agreement with observations made in old concrete samples, see Section 15.5.5. The column experiments have been 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. The calculations are made by research teams at BGS, Harwell and PSI.

15.5 NATURAL ANALOGUE STUDIES

15.5.1 Jordan

The minerals, groundwater and hydraulic conditions at the hyperalcaline springs in the Maqarin area of NW Jordan are being investigated as a natural analogue to concrete in a nuclear waste repository. The analogue study in Jordan is part of an international project which started in 1990 jointly funded by the NAGRA, NIREX and Ontario Hydro. SKB became involved in 1991. The results of the first phase of the project have been compiled and reported /15.5-1/. The project is now in its third phase which is funded by NAGRA, NIREX, HMIP (Her Majesty's Inspectorate of Pollution, UK) and SKB. The third phase is being administrated by SKB.

The rock consists of Cretaceous marls and bituminous limestones overlain by Tertiary chalks and limestones /15.5-2/. The rock-forming minerals are calcite, quartz, dolomite, apatite, pyrite and clays, such as illite and kaolinite. Travertines, stalactites and stalagmites are common around springs and seepages. The organic content of the bituminous rock is between 15 - 20%, mainly of kerogenic nature. The bituminous rock has undergone spontaneous combustion in many places, where temperatures above 1000°C have been reached that caused widespread thermal metamorphic reactions. The hyperalcaline groundwaters are generated by the reactions between normal aquifer waters with the thermally metamorphosed (burnt) marls which contain burnt lime and calcium silicates. The reaction products increase the pH from around neutral to between 12 - 13. The hydration reactions generate minerals such as portlandite, ettringite, thaumasite and numerous other cement minerals.

Groundwater and minerals were sampled from boreholes, an exploration adit, various seepage localities and natural springs in the Maqarin area. Three sampling boreholes were drilled at the beginning of phase III of the project. Groundwater parameters such as pH, Eh and temperature were measured in-situ. Major and trace element ions, and environmental isotopes were analysed subsequently. Regarding trace element studies, the main focus has been on Sn, Se, Ni, Pb, Ra, Th and U. Samples for analyses of microbes, colloids and dissolved organic substances were also taken.

An important objective of the study has been to make "blind" predictive calculations of the trace element solubilities in the hyperalcaline waters, and subsequently to compare the results between the various modelling teams and with observations /15.5-3/. Thermodynamic data can be poor in the high pH-region and calculated values have to be used with caution when the pH is high. The Maqarin results are used to test the applicability of thermodynamic models in the high pH-region.

Recently a study has been published where carbonation reactions in Portland cement grout are compared to the carbonation reactions observed in Maqarin and central Jordan /15.5-4/. The attenuation of carbon-14 in cement is considered an important barrier function for low and intermediate level waste from the Canadian CANDU reactors. The study is not entirely conclusive, but the analogue observations tend to support the laboratory observations.

The specific objectives of the phase III study include the following:

- Establish the origin and chemistry of the western spring groundwaters using hydrogeological and isotopic data.
- Petrographical and mineral chemical studies of textures and mineral phases resulting from high pH water-rock interactions.
- Examine the effects of the hyperalcaline groundwater-rock interactions on the accessibility of the host rock to radionuclide diffusion.
- Test codes that couple mass transport and chemical reactions, and are used to assess the influence of cement in a repository.

- Investigate the zeolites at the eastern and western spring localities, and compare to literature information on zeolite formation under hyperalcaline conditions.
- Investigate the clay minerals at Maqarin and in cenral Jordan to assess their stability under hyperalcaline conditions.
- Study the role of colloids and organics in trace element transport at the eastern and western spring localities.

15.5.2 Oklo

Evidence for ancient nuclear reactions in the uranium ore bodies at Oklo, Gabon, was discovered in 1972 when isotopic analysis of the ore gave a lower than normal $^{235}U/^{238}U$ ratio. Early studies at the Oklo site showed the potential for using the chemistry of the zones where nuclear reactions had occurred – so-called reactor zones – and the nearby country rock as analogs for many of the processes that might occur in association with the disposal of high level nuclear waste /15.5-5/. At the time when the Oklo uranium sustained nuclear reactions (nearly 2000 million years ago) the $^{235}U/^{238}U$ ratio in the ore was 0.0368, which is similar to the ratio used in present nuclear reactor fuels and is five times higher than the present naturally occurring uranium isotopic ratio.

The uranium deposits are located in a sedimentary sequence with the deposits occurring in a sandstone layer about 3 to 6 meters thick. The uranium-rich layer is overlain by mudstones, shales, dolomites, and organic-rich shales. The sedimentary sequence was formed 2065 million years ago and the uranium became trapped in the sandstone later, probably because of precipitation through interaction with the organic matter.

Over the past few years a project called "Oklo, Natural Analogue for a Radioactive Waste Repository" has been conducted by the French CEA with support from the CEC and participation by SKB and others /15.5-6/. A total of 16 reactor zones have been identified at Oklo, and an additional two zones were found in uranium deposits nearby at Okelobondo and at Bangombé, which is about 20 km to the south. The recent investigations at Oklo have focused on reactor zones 10 and 13 at the Oklo mine and the small, near-surface remains of the reactor zone at Bangombé. More limited studies have been conducted at Okelobondo.

The objectives of the Oklo Natural Analogue project were as follows:

- Investigate and describe the most recently discovered reactor zones at Oklo.
- Study the migration of fission products from the reactor zones both due to ancient events and to recent phenomena.
- Carry out mathematical modelling of the present water and solute transfer pathways from the nuclear reactor zones to the surface discharge areas.

Through these studies, it is hoped that insights will be gained into the potential performance of a high level radioactive waste repository. In particular, the present objectives of the Oklo project are to develop a second phase of study that will focus on the application of results from Oklo studies to the validation of process models for the Performance Assessment tasks of waste repository programs.

Work conducted by SKB in conjunction with the Oklo project has centered on hydrogeology and hydrogeochemistry investigations of the Bangombé reactor zone. The Bangombé zone lies close to the present topographic surface and is in a region with relatively simple tectonic setting. This has several advantages over the main Oklo site reactor zones. First, the area has not been disturbed by mining activities, so interpretations of the data are less complicated than for the mined areas at Oklo. Second, the near surface location allows access to the zones of interest using short boreholes, thus reducing the logistic difficulties and costs for sampling operations. Finally, the near-surface location has resulted in the reactor zone becoming subjected to oxidizing conditions, which allows us to follow the changes in the ore material as it is met by a redox front.

The original ore body contains abundant organic matter in the form of nodules of graphitic bitumen. The organic matter imposed a highly reducing environment that protected the uranium deposit from dissolution and dispersion because of the very low solubility of U^{4+}. Rain water that percolates into the Bangombé ore body now carries dissolved oxygen to the uranium and can begin to oxidize the uranium to the U^{6+} state, which has a much higher solubility. The amount of uranium remaining at the Bangombé site in the reactor zone is too small to have sustained criticality and produced the observed depletions in ^{235}U. This suggests strongly that a large amount of uranium has been removed by weathering in the near-surface oxidizing environment. In contrast, the deeper reactor zones at Oklo appear to have retained most of their uranium *in situ* or very nearby, both during and after the period of criticality /15.5-7/. Comparison of the uranium behavior at the Oklo and Bangombé sites should be of assistance in evaluation of the potential effects of oxidizing conditions that might be produced due to radiolysis reactions in water in a high level waste repository.

The Bangombé reactor area was the subject of an extensive drilling campaign in the autumn of 1992 and a follow-up program in summer of 1993. A total of 7 new boreholes were drilled and cored to provide geological and geochemical samples as well as forming the basis for a detailed hydrologic and hydrogeochemical sampling program. In addition, 4 old exploration boreholes were reopened and cleaned. The local geology and the borehole locations are shown in Figure 15.5-1. The hydrology data collected from these boreholes have been analyzed and used to develop a model for the local hydrologic system at Bangombé. Water enters the rock units from rainfall on the plateau to the SW of the reactor zone and percolates

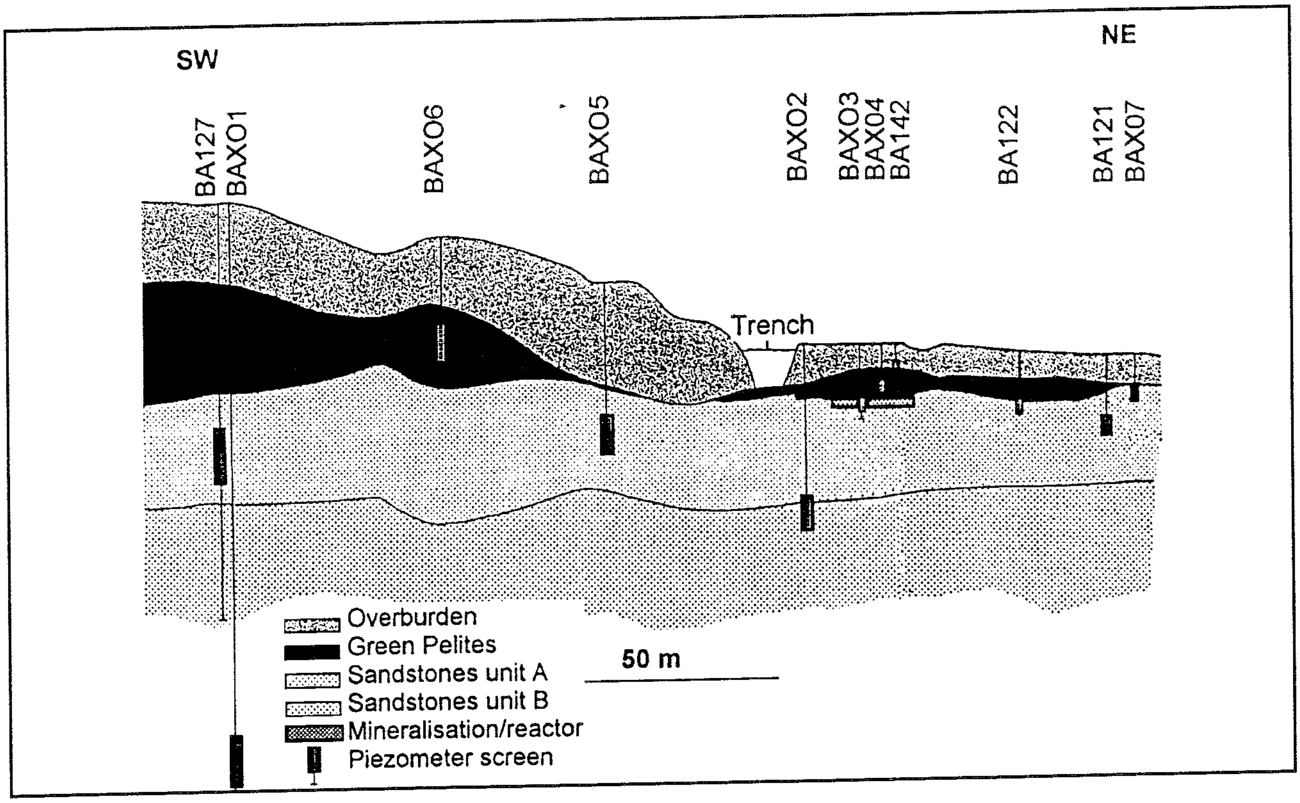


Figure 15.5-1. *The Bangombé site. Geology and location of boreholes and piezometers.*

downward until it finds a lateral flow path. Groundwater flow in the vicinity of the reactor zone is vertically upward with discharge occurring to topographic low points to the NE. Figure 15.5-2 shows measured piezometer levels that were used to develop the local flow model at Bangombé /15.5-8/.

Rainwater that enters the ground contains little or no dissolved chemicals and has a pH of about 4.5 to 5 because of dissolved CO_2 from the atmosphere. As water passes through the soil and underlying rock units, it slowly dissolves small amounts of the solids and changes its chemistry. The general trend of evolution of the water with time when the rocks are relatively rich in silica will be to increase the level of total dissolved solids and to increase in pH as the silica content in solution increases. Water samples have been collected from the Oklo/Okelobondo area and analyzed to determine their chemical composition. The most soluble major cation in natural waters is sodium, so it is the best indicator of the extent of reaction between the water and the country rocks. For an area where the rocks are similar in composition, following the increase in sodium content in the water is equivalent to mapping the residence time of the water in the ground, or its age. Figure 15.5-3 shows the conceptual hydrogeological model for the Oklo region with the sodium concentrations for water samples mapped onto the cross-section /15.5-9/. As can be seen from the map, water enters the unit at topographic high points and has low sodium values. As the water flows through the rocks, it increases in sodium. The highest sodium values are seen in the center of the flow region where the water begins to flow upward toward the discharge areas under the Mitembe river.

Another water chemistry feature that can be used to estimate residence time, and hence flow rate in the ground, is the tritium content of the water. Atmospheric hydrogen has a rather well known content of tritium (^3H) relative to non-radioactive isotopes of hydrogen. When water is isolated from the atmosphere and from other sources of tritium, the tritium content decreases because of radioactive decay. Thus, a decrease in tritium content would correspond to an increase in the age of the water – i. e., the length of time the water has been in the groundwater system. For the Oklo waters, another indicator of age is the increase in pH from the original values of 4.5 to 5 towards a value appropriate for equilibrium with clay minerals. We would then expect a plot of tritium content versus pH to show a negative correlation if the only factor involved was age of the water. Figure 15.5-4 /15.5-9/ shows that for the Oklo waters a rather good correlation is found, indicating that residence time of the water in the rock system is the dominant factor in the chemical evolution of the water.

Another parameter of importance in water chemistry is the oxidation potential of the water. This will have a very strong effect on the corrosion of canister materials and on the solubility of the waste form in the repository. Modelling of redox control in water systems is complicated by

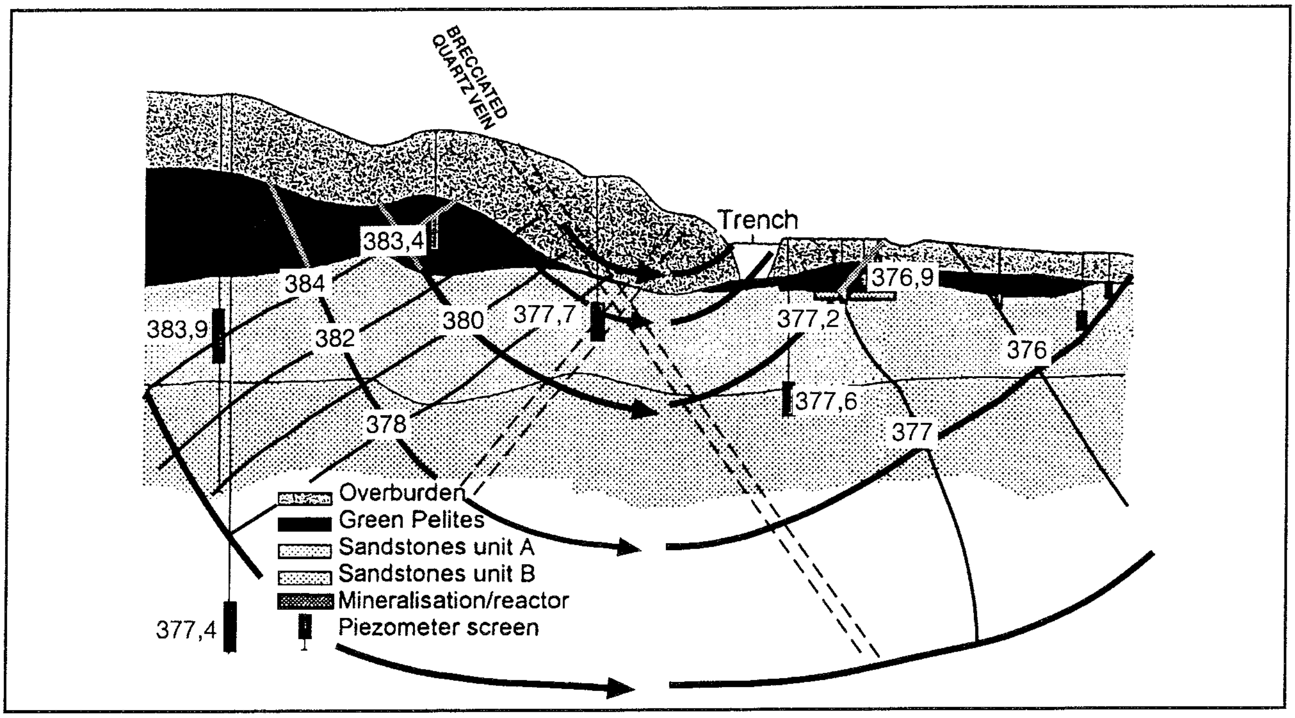


Figure 15.5-2. The Bangombé site. Piezometer measurements, hydraulic gradient (——) and groundwater flow directions (▬▬)

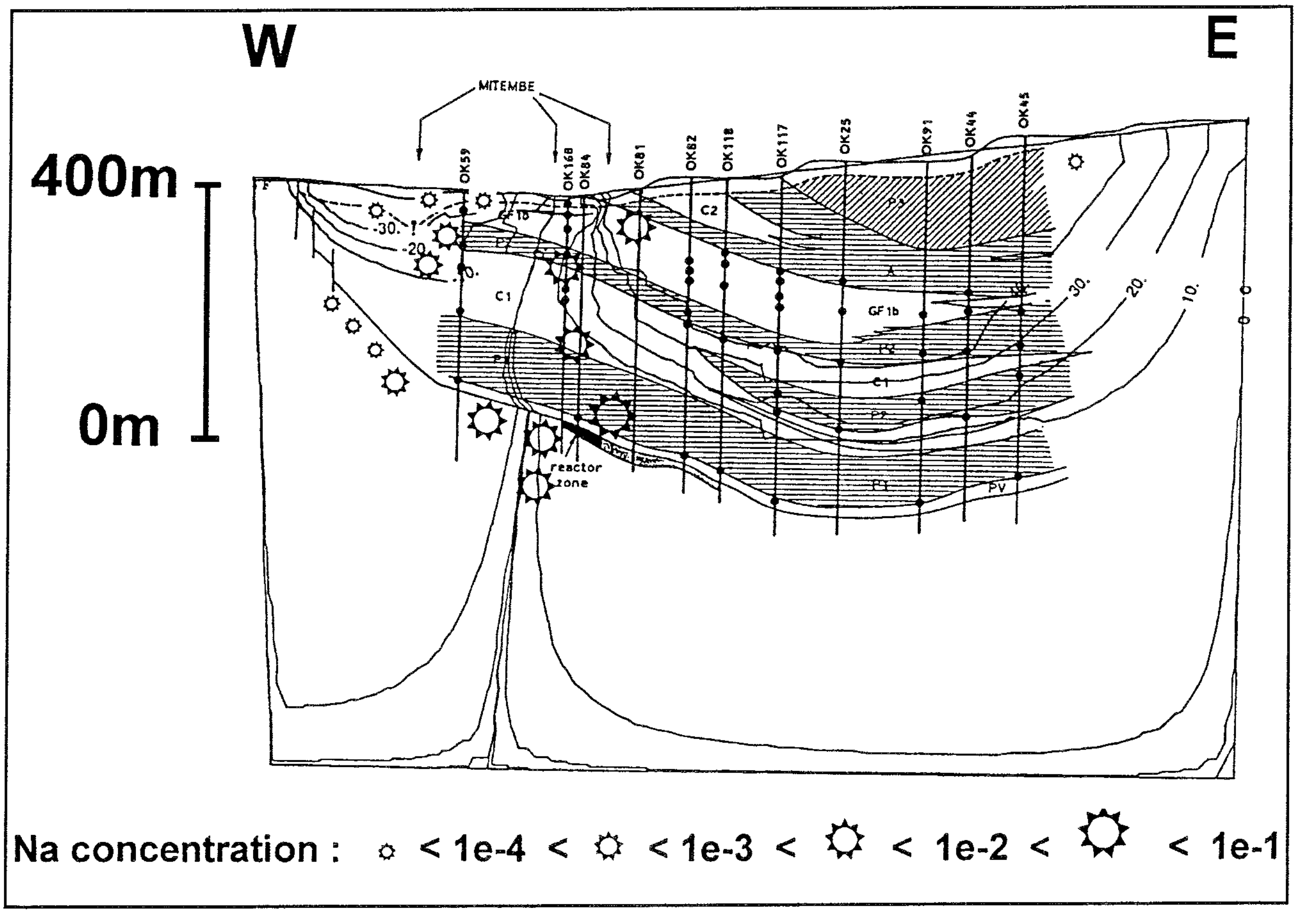


Figure 15.5-3. The Oklo-Okelobondo site. Location of boreholes for hydraulic measurements, sodium concentration levels (mol/l) and the hydraulic gradient.

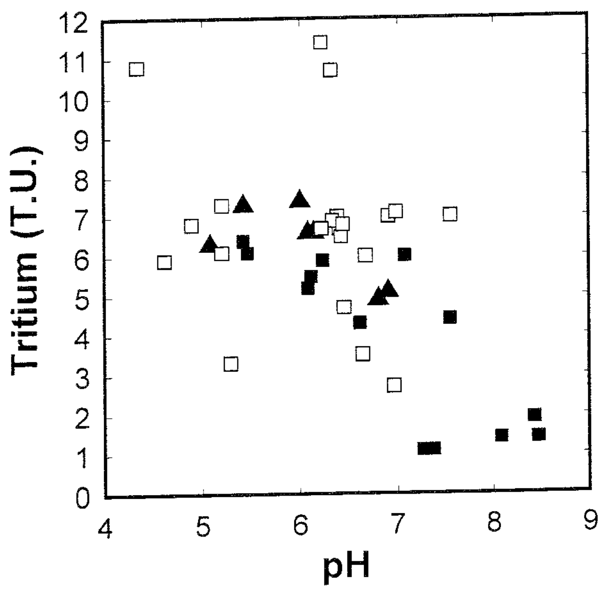


Figure 15.5-4. Tritium content and pH in groundwater at the Oklo-Okelobondo site.

processes that have sluggish kinetics, so the system frequently cannot be modelled simply with thermodynamic equilibrium models. At Oklo, the water chemistry redox has been studied in detail. The rocks contain iron in the +2 oxidation state. When this dissolves, there is Fe(II) in solution, sometimes in equilibrium with Fe(II)carbonate (siderite). The dissolved ferrous iron can then react with dissolved oxygen or other redox active species to give Fe(III). Because of the lower solubility of ferric iron, this precipitates to give $Fe(OH)_3$ (ferrihydrite). For units containing abundant organic matter, the iron II-III redox control gives way to very reducing conditions imposed by the organics /15.5-9 and 15.5-10/.

The reactor zones at Oklo were first identified because their $^{235}U/^{238}U$ was lower than the natural terrestrial value of 0.00725, with the lowest value found so far being 0.0029 /15.5-11/. It was originally thought that most of the uranium had remained *in situ*, despite the severe conditions of the nuclear criticality event and hydrothermal alteration that accompanied the event. Later, however, it was realized that some uranium had been mobilized and could be identified by the unusual isotopic depletion in the 235/238 ratio. Clay minerals in the argillaceaous rocks in the neighbourhood of the reaction zone 10 show uranium with 235/238 ranging from 0.0056 to the normal value of 0.00725, indicating movement either during the period of criticality or later /15.5-12/. One clay sample with low uranium concentration was found to have a uranium component that showed a higher than natural 235/238 ratio. This is interpreted to show migration of ^{239}Pu during or shortly after the period of nuclear reactions /15.5-12/. The Pu was incorporated into the structure of a clay mineral formed in the alteration halo around the reactor zone and then decayed *in situ* to ^{235}U. The amount of Pu involved in the migration was small, so the enriched ^{235}U can only be seen when the total U in the mineral is low.

The evidence of depleted uranium ratios in clay minerals around the reactor zones shows that migration of uranium occurred at some time in the past, but does not tell us when the movement occurred. Uranium isotopic analysis of water samples can reveal, if they show depleted uranium ratios, that uranium migration is occurring today. The solubility of uranium in the Oklo/Okelobondo/Bangombé groundwaters is low, even in the Bangombé region that is influenced by near-surface oxidizing conditions, so only small amounts of uranium are found in the waters. Groundwaters with significant depletions of uranium isotopic composition have been found in both Okelobondo and Bangombé drill hole samples, with the lowest ratio being 0.00683 /15.5-12 and 15.5-13/. Since the reactor zones occur within a much larger ore deposit that did not undergo natural fission reactions, the uranium dissolved in the groundwater is a mixture of uranium with natural isotopic composition and that from reactor zones with depleted compositions. Even though the effect of the lower isotopic composition is diluted, it provides a unique tracer for studies of uranium migration since the source of the uranium in solution can be identified.

The uraninites at Oklo and Bangombé are of particular interest to the waste management community because they are the closest naturally occurring material in chemical composition to spent nuclear reactor fuel. When uranium fissions, the fission products are contained within the original uranium oxide material in a variety of ways. Some elements are retained in solid solution in the crystal lattice; rare earth elements are an example of this type of fission product. Other elements combine to form a separate phase present as small grains that collect within or along the boundaries of uraninite grains. In reactor fuels, a 5-metal phase containing Ru, Mo, Rh, Pd, and Tc is found. Some other fission products, such as Cs, are retained in the fuel lattice, but are relatively easily lost (at least in part) if the fuel is subject to alteration.

Studies of the uraninites at Oklo and Bangombé on the microscopic scale show evidence for dissolution of the original uraninite crystals and the separation of Ru and other metals into small grains in a fashion analogous to that seen in reactor fuels /15.5-13 and 15.5-14/. Isotopic analyses of U and Pb at Oklo have shown that Pb, which is the daughter product from the decay of uranium by alpha emission, has been removed from the uraninite grains and precipitated nearby, sometimes in fractures in the uraninite grains themselves, as PbS approximately 750 my ago. This Pb migration has been attributed to the thermal effects of a dyke intrusion near the ore body at that time /15.5-13/. Unfortunately, it is not possible with presently available data to determine the time of the uranium mobilization event or events. The restructuring of uraninites observed on the microscopic scale could reflect, in large part, events that occurred during the high temperature, hydrothermal period associated with the fission reactions themselves.

Work completed so far has shown that the Oklo/Okelobondo/ Bangombé reactor zones hold great promise as a natural analog for processes associated with nuclear waste disposal. To date, however, direct use of these data in performance assessment of repository processes has not been undertaken. Plans are currently being formulated to develop a program that will provide a more direct linkage between the analog studies and performance assessment. This program will be proposed as a multinational effort to the CEC for the next research program period.

15.5.3 Palmottu

A 1.7 to 1.8 billion year old uranium-thorium deposit at lake Palmottu in southwestern Finland is being investigated as a natural analogue to spent fuel in granitic rock. The discontinuous subvertical ore zone is 1 to 15 m thick and extends from the surface and down to a depth of about 300 m. The total length is about 400 m. The average grade of the ore is 0.1 % U and uranium occurs mainly as uraninite, its alteration products (e.g., coffinite) and zircon. Thorium is present as monazite. The host rock consists of Precambrian gneisses and migmatites. The dominant minerals are K-feldspar, quartz and biotite. Fracture minerals include calcite (dominant), kaolinite, sulphides and iron oxyhydroxide.

The uranium mineralisation was discovered in the late 1970s and investigated by 62 inclined prospecting boreholes.

The Palmottu Analogue Project started in 1988, first funded directly by the Finnish Ministry of Trade and Industry Energy Department and after that through STUK (Finnish Centre for Radiation and Nuclear Safety). Involved in the project are GTK (Geological Survey of Finland), Department of Radiochemistry at the University of Helsinki, Laboratory of Engineering Geology and Geophysics at the Technical University of Helsinki and VTT (Technical Research Centre of Finland).

One reason for setting up this study was that the mineralisation is situated in a host rock with the same hydrogeological, hydrochemical and geological conditions that are anticipated for a Finnish (and Swedish) spent fuel repository in the Fennoscandian Shield. The uraninite has chemical properties in common with spent fuel and the fact that the mineralisation extends from the ground surface and downwards makes it possible to study and compare the geochemical reaction of uranium under both oxidising (near the surface) and reducing (at depth) conditions. For example, it has been indicated by the Palmottu investigations that uranium is capable of controlling the redox environment /15.5-17/.

The main technical objectives of the project include the following:

- Characterisation of the structural and geohydrological conditions of the deposit area.
- Identification and quantification of the phenomena that have controlled the liberation of radionuclides from their primary minerals.
- Identification and quantification of the phenomena that have controlled the retardation of radionuclides in the rock-water system.
- Identification of the factors favouring the migration of radionuclides.
- Determination of the time-dependence of the processes identified.
- Assessment of the net migration of radionuclides.

The results and progress of the project have been presented in the series of yearly progress reports from GTK /15.5-15, 15.5-16, 15.5-17 and 15.5-18/.

SKB has participated in the study as an "active observer", which has implied support of the field investigations by, for example, radar measurements /15.5-19/ and spinner logging /15.5-20/, and participation in the planning discussions.

15.5.4 Cigar Lake

The 1.3 billion year old (1.3 10^9 a) uranium deposit Cigar Lake in northern Saskatchewan, Canada has been studied as a natural analogue to a deep repository for spent fuel. SKB has been engaged in the Cigar Lake project from 1989 to 1992 together with AECL and later Los Alamos National Laboratory. The final report was issued in 1994 /15.5-21/. Important conclusions relevant to the long-time safety of spent fuel disposal were drawn in areas such as:

- UO_2 dissolution and stability.
- The importance of clay sealing.
- Colloid transport.
- Influence of natural organics and microbes.
- Evolution of groundwater chemistry.
- The effect of radiolysis.
- Radionuclide migration in the near-field.

This is treated in detail in the final report /15.5-21/. However, considering the wealth of data from the project and that Cigar Lake is the most "complete" analogue to a deep spent fuel repository so far available, it seemed worthwhile to make a more extensive evaluation. For this purpose a working group was set up in spring 1994 to concentrate on those Cigar Lake results of most relevance to the SKB concept for spent fuel disposal. The following issues have been treated by the working group:

- Formation of the orebody and alteration halo.
- Comparison with present day conditions.
- Determination of large-scale changes that have occurred.
- Radiolysis.
- Stability of UO_2.
- Radionuclide and trace-element solubility and speciation.
- Physical properties of the clay horizon.
- Geochemistry across the ore/clay interface.
- Clay horizon as a barrier to radionuclide migration.

- Role played by colloids, microbes and organic substances.
- Coupling of hydrogeology and hydrochemistry.

The working group has completed its task and the results have been reported. A concluding report will be edited.

15.5.5 Old concrete

Old constructions made of Portland cement have been sampled to investigate the development of the cement paste /15.5-22/. This is much dependent on the environment. For example, samples taken from the foundation of an old school in the Swedish town Gävle were found to be porous and carbonated. The school had been built at the end of the 19th century. Since then the concrete had been subjected to humid but unsaturated (aerated) conditions. A considerable portion of unhydrated clinker still remained. On the other hand, it was found that the cement paste in samples taken from locations under water in a dam (tunnel) in Älvkarleby in Sweden from 1917 was as tight as modern cement paste with a water/cement ratio below 0.35. The strength of the old concrete was about 100 Mpa. The results indicate that Portland concrete will slowly hydrate under water-saturated conditions, develop additional strength and become less conductive.

Continued hydration of remaining clinker particles has also been indicated in samples from a 90 year old water tank from the castle in the Swedish town Uppsala. The porosity of the paste today corresponds to a water/cement ratio of about 0.4. Large crystals of portlandite are found in the cement paste and large crystals of ettringite, calcium aluminate and portlandite are found in the pore spaces. The concrete is still in good conditions and the underlying steel tank has been well protected from corrosion.

Where flowing water has penetrated the concrete construction, as can be observed at certain locations in the tunnel at the Älvkarleby dam, it is interesting to note that portlandite seems to remain in favour of the clinker particles, which have been dissolved. This indicates that the rest of the cement paste remains stable until all the old clinker has been consumed.

The results underline the importance of having a tight concrete to start with and to avoid hydraulic gradients over the construction. Saturated conditions, a tight concrete and stagnant groundwater will improve the quality of the cement by slow hydration reactions.

15.6 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, possibly causing external dose,
- accumulate in foodstuffs like plants, animals and fish,
- be consumed and cause to 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 feed contaminated water into different receptors (well, river, lake) and the contaminants can be transported through different physical compartments like soils, sediments, waters and air. The processes considered include chemical/physical activity such as sedimentation, biological activity such as bioturbation and human activity such as farming.

This part of the modelling is done with compartment models for which volumes and transfer factors between compartments have to be calculated. Solving the (linear) differential equations produces time dependant concentrations for the different compartments.

After this the accumulation in foodstuffs, intake and dose calculations are pure multiplication for each scenario.

15.6.1 Validation of models

The vast number of transport processes involved, can be rationally treated with compartment models where several processes are put together into one transfer rate. 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 /15.6-1/, VAMP /15.6-2/ and PSAC /15.6-3/. The numerical performance of a code is easier to validate, and has been done in PSAC.

BIOMOVS

The 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 /15.6-1/.

In 1991 the second phase, BIOMOVS II, was started, jointly managed by the five organisations AECB, AECL, CIEMAT, ENRESA and SSI. SKB has put emphasis on the theme "Reference Biospheres", as it is of great value to get an international consensus how to deal with the modelling and conceptual uncertainties arising with time. A general methodology and a list of FEPs (features events and processes) have been published. The RES method has proven to be a useful tool in demonstrating process interactions for different scenarios.

The proposed "reference" methodology and FEP list, is also used and tested in a related theme "Complementary studies" with emphasis on the processes involved in modelling. In a validation scenario for ^{14}C within the "Validation and Uncertainties" group, we are stochastically testing the model used for the SFR safety assessment with almost all parameters as 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 the aquatic part of this programme, modelling of ^{137}Cs in lakes and uncertainty analysis is intercompared between several working groups from several countries. The implications are that simpler models with site specific parameters reflecting retention time give the best estimation /15.6-2/.

15.6.2 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 /15.6-4/. The total amount of leached ions is considerable and may significantly have contributed to the salinity of the groundwater in the bedrock. /15.6-5/.

Dose factors in the Äspö area

A set of more realistic dose factors were calculated for seven nuclides; ^{14}C, ^{99}Tc, ^{129}I, ^{135}Cs, ^{237}Np, ^{240}Pu and ^{241}Am. 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 /15.6-6/. The volumes, currents and residence times in the straits around Äspö have also been estimated /15.6-18/.

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. An inventory of good candidate sites were produced 1993 /15.6-7/. A specific scenario was submitted for a validation exercise in BIOMOVS but not enough knowledge seams to be present to predict nuclide transfers in soils and sediments for this limited time span.

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. This project is now in the documentation phase /15.6-8,13,14,15,16/

15.6.3 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 theoretical 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 well 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. /15.6-9/.

15.6.4 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. The need for consideration of protection of nature within the EIA process has been pointed out by both

SSI and SKI. The effects on plants and animals can be summarised as

- Change in species diversity or number of individuals.
- Reduction of number of individuals of rare and threatened species.
- Introduction of new species or prevention of normal regrowth
- Reduction of agriculture or otherwise productive area.
- Degradation of habitat of existing species.

These effects are not likely to occur at acute doses below 0.1 Gy or doserates below 1 mGy/d for animals or 10 mGy/d for plants /15.6-10/.

A literature survey was completed during 1993 /15.6-11/ and is now being followed by an attempt to estimate the natural and seminatural levels of radionuclides in nature /15.6-12/. Estimating the doses that some species normally get 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 BACKGROUND

In addition to the short-lived LLW and ILW that is sent to SFR there is also some long-lived LLW and ILW. The quantities are relatively minor and the main sources are waste from research activities and used components from the power reactors which have been situated inside or near the reactor core (core components and reactor internals). Core components are stored at CLAB and research waste is collected, stored and conditioned at Studsvik in SE Sweden.

The present concept for disposal of this waste is to build a deep underground facility near to the repository for spent fuel and at a similar depth. It will consist of three parts: SFL 3, 4 and 5. The waste is packed in steel drums and containers of steel or concrete. Concrete is also used for conditioning of some of the waste such as spent ion-exchange resin filters etc. SFL 3 is designed as a cavern with concrete caissons where waste from Studsvik and operational waste from CLAB and the encapsulation plant will be emplaced. SFL 4 consists of tunnels for decommissioning waste from CLAB and the encapsulation plant. This waste will arise very late in the program. SFL 5 consists of caverns for the disposal of reactor core components and internal parts, all packed in concrete containers. Concrete, sand and bentonite will be used as backfill in the various parts of the repository.

The total volume of waste is estimated to about 25 000 m^3 (sum of outer volume of the waste packages). Not all of this waste falls into the category of long-lived LLW and ILW. More than half of the total volume consists of operational waste and decommissioning waste that could in principle be disposed of in SFR. However, the intention is that SFL 3-5 should receive all LLW and ILW that arises in the post-closure period of SFR.

Solid and liquid waste are treated at Studsvik. The raw waste consists of activated and contaminated scrap metals, precipitations, ashes, ion exchange resins, glove boxes, disused radiation sources and contaminated laboratory outfit, and radiation protection equipment 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. 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. 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 at present is to put the waste in concrete containers, backfill with concrete and send the concrete moulds for disposal in SFL 5.

16.2 A PRESTUDY

At the end of 1992 it was decided to make an inventory of waste for SFL 3-5, to continue work on the design and to compile data for the safety assessments that will become necessary later on. In order to stimulate and direct these efforts it was decided to perform a preinvestigation that started early 1993 and ended late 1994. The aim of the preinvestigation was to make a first preliminary assessment of the near-field barriers to radionuclide dispersion. For the calculations we used the design which is presented in Plan 93 /16-1/. An actual site has not been selected yet, so we used general assumptions about the hydrogeological conditions in the repository rock based on earlier experiences and evaluations of field investigations.

16.2.1 Waste characterisation

A first and important step in the preinvestigation was to make an inventory and characterisation of the waste. Calculations and best estimates were made of the radionuclide content and other safety relevant components in the waste, such as metals, organic materials, concrete etc, see Tables 16-1 and 16-2. The waste inventory is presented in a report "Low and Intermediate Level Waste for SFL 3-5" /16-2/. The information was used to calculate temperature, gas formation and other parameters that were needed to assess the performance of the near-field barriers.

The waste volume, including the packages, was estimated to about 5000 m^3 in SFL 3, 10 000 m^3 in SFL 4 and 10 000 m^3 in SFL 5, giving a total volume of about 25 000 m^3. This is less than one third of the total volume of waste that is planned to be disposed of in SFR 1. The total activity in SFL 3-5 at repository closure was calculated to roughly 10^{17} Bq.

Table 16-1. Amounts (metric tonnes) of different materials in SFL 3-5 waste (excluding packagings).

Material	SFL 3	SFL 4	SFL 5	Total
Metals				
Steel	217	8800$^{b)}$	1900	10917
Aluminium	51			51
Lead	7.5			7.5
Cadmium	1.2			1.2
Brass and copper	7.5			7.5
Beryllium	0.3		0.3	0.6
Hafnium			4	4
Zircaloy			30	30
Organics				
Ion-exchange resins	270			270
Cellulose	46			46
Plastic/Rubber	67			67
Others	2.8			2.8
Concrete/Cement$^{a)}$	2360	850		3210
Others				
Ferrocyanide precipitates	4.6			4.6
Uranium contaminated ashes	2.9			2.9
Total	3038	9650	1934	14622

a) solidified waste and contaminated concrete,
b) including transport casks and transport containers.

The dominating metal in the waste is steel, mostly stainless steel, which will be present in all repository parts. The total quantity was estimated to 11 000 metric tonnes. Aluminium, which has a strong potential for gas formation, is mainly found in the Studsvik waste. This waste is allocated to SFL 3 and the estimated amount is about 51 metric tonnes.

It has been established that waste containing organic material will be concentrated to SFL 3 and that the cellulose content will be low, about 0.5% of the total weight of the concrete in the waste packages. Cellulose can potentially generate complexing agents and has therefore attracted special attention.

16.2.2 Chemical data

Laboratory experiments and literature studies of important chemical properties were performed within the prestudy to get data for the assessment of near-field barrier performance. The studies included cellulose degradation, concrete leaching, sorption and diffusion of radionuclides in concrete and bentonite. During 1993 the following investigations were initiated at different organisations:

- Batch studies of radionuclide sorption. Crushed concrete from SFR is used as the solid substrate. Both normal construction concrete and porous backfill concrete is represented. Fresh cement porewater and leached concrete porewater are used as the liquid phase. Radionuclides are used and the elements studied are: Eu, Th, Np, Am, Cm, Pm, Co, Ra, Ni and Cs. For some of the elements the dependence on concentration is included in the study (Dept. of Nuclear Chemistry, Chalmers University of Technology).
- Radionuclide diffusion in cement paste. The elements studied are: Ni, Cs and tritium (Dept. of Nuclear Chemistry, Chalmers University of Technology).
- Static leaching of cement paste. Synthetic groundwater is used to simulate deep geochemical conditions varying from saline (NASK water) to normal (Allard water). The ions that are analysed in the leachate are: Na^+, K^+, Ca^{2+}, Mg^{2+}, OH^-, SO_4^{2-}, Cl^-, and Si_{tot} (Dept. of Nuclear Chemistry, Chalmers University of Technology).
- Radionuclide diffusion in a 85/15 mixture of sand/bentonite (Wyoming MX-80) in a cement dominated chemical environment. Radionuclides are used and the elements studied are: Cs, Tc, and Ni (Dept. of Nuclear Chemistry, Chalmers University of Technology).
- Solubility measurements of Ni, Pu and Eu (Eu as model of three-valent actinides) under cementitious chemical conditions (Dept. of Nuclear Chemistry, Chalmers University of Technology).
- Studies of the formation of poly-hydroxy compounds during the degradation of cellulose in an aerobic or anaerobic environment at pH 10 and 12 (Dept. of Water and Environmental Studies, Linköping University).
- Chemical degradation of gluconic acid in an aerobic or anaerobic environment at pH 10 and 12 (Dept. of Water and Environmental Studies, Linköping University).
- A library of model compounds has been compiled in order to identify the degradation products from cellulose and gluconic acid by capillary electrophoresis (Dept. of Water and Environmental Studies, Linköping University).
- The formation of metal complexes with poly-hydroxy compounds is being investigated (Dept. of Water and Environmental Studies, Linköping University).
- The influence of poly-hydroxy compounds on the absorbtion of metal ions on concrete and rock minerals is being studied (Dept. of Water and Environmental Studies, Linköping University).
- The present state of knowledge on concrete stability under deep repository conditions is being summarised (Swedish Cement and Concrete Research Institute, Stockholm).

Laboratory experiments and calculations performed indicated that the leaching of concrete in the repository is slow and that pH will remain above 12.5 during at least the first 10^6 years. Sorption in concrete is an important barrier function that works for most of the radionuclides in the waste. The value of solubility retention is less well established but demonstrated to be effective for radionuclides of Ni (and Zr) in SFL 5. Solubilities of for example

Table 16-2. Radionuclide inventory in SFL 3-5 at year 2040 given in Bq.

Nuclide*)	Half life	SFL 3	SFL 4	SFL 5	Total
H-3	$1.2\cdot10^{1}$	$1.9\cdot10^{15}$	$1.6\cdot10^{9}$	$2.4\cdot10^{15}$	$4.3\cdot10^{15}$
Be-10	$1.6\cdot10^{6}$			$1.4\cdot10^{11}$	$1.4\cdot10^{11}$
C-14	$5.7\cdot10^{3}$	$9.0\cdot10^{12}$		$9.3\cdot10^{13}$	$1.0\cdot10^{14}$
Fe-55	$2.7\cdot10^{0}$	$6.5\cdot10^{11}$	$9.3\cdot10^{13}$	$5.1\cdot10^{14}$	$6.1\cdot10^{14}$
Co-60	$5.3\cdot10^{0}$	$8.3\cdot10^{13}$	$5.4\cdot10^{13}$	$5.2\cdot10^{15}$	$5.3\cdot10^{15}$
Ni-59	$7.5\cdot10^{4}$	$9.4\cdot10^{12}$	$3.8\cdot10^{10}$	$1.2\cdot10^{15}$	$1.2\cdot10^{15}$
Ni-63	$9.6\cdot10^{1}$	$8.0\cdot10^{14}$	$6.0\cdot10^{12}$	$1.1\cdot10^{17}$	$1.1\cdot10^{17}$
Sr-90 a	$2.9\cdot10^{1}$	$9.9\cdot10^{11}$	$1.1\cdot10^{12}$	$3.8\cdot10^{11}$	$2.5\cdot10^{12}$
Zr-93	$1.5\cdot10^{6}$	$4.7\cdot10^{7}$	$5.4\cdot10^{7}$	$2.2\cdot10^{12}$	$2.2\cdot10^{12}$
Nb-93m	$1.4\cdot10^{1}$	*$1.9\cdot10^{7}$*	$2.6\cdot10^{8}$	$1.9\cdot10^{12}$	$1.9\cdot10^{12}$
Nb-94	$2.0\cdot10^{4}$	$9.2\cdot10^{9}$	$5.5\cdot10^{8}$	$3.1\cdot10^{12}$	$3.1\cdot10^{12}$
Mo-93	$3.5\cdot10^{3}$	$1.8\cdot10^{7}$	$5.4\cdot10^{7}$	$3.8\cdot10^{7}$	$1.1\cdot10^{8}$
Tc-99	$2.1\cdot10^{5}$	$3.0\cdot10^{9}$	$5.4\cdot10^{7}$	$3.3\cdot10^{11}$	$3.4\cdot10^{11}$
Ru-106 b	$1.0\cdot10^{0}$	$6.5\cdot10^{5}$	$5.7\cdot10^{10}$	$7.0\cdot10^{1}$	$5.7\cdot10^{10}$
Sb-125 c	$2.8\cdot10^{0}$	$9.2\cdot10^{10}$	$5.4\cdot10^{12}$	$2.1\cdot10^{9}$	$5.5\cdot10^{12}$
I-129	$1.6\cdot10^{7}$	$1.9\cdot10^{7}$	$4.4\cdot10^{5}$	$3.1\cdot10^{5}$	$1.9\cdot10^{7}$
Cs-134	$2.1\cdot10^{0}$	$3.6\cdot10^{9}$	$7.1\cdot10^{11}$	$2.1\cdot10^{7}$	$7.2\cdot10^{11}$
Cs-135	$2.3\cdot10^{6}$	$1.9\cdot10^{8}$	$1.6\cdot10^{7}$	$1.1\cdot10^{7}$	$2.2\cdot10^{8}$
Cs-137 d	$3.0\cdot10^{1}$	$2.1\cdot10^{13}$	$1.1\cdot10^{12}$	$3.9\cdot10^{11}$	$2.3\cdot10^{13}$
Eu-152	$1.3\cdot10^{1}$	$2.9\cdot10^{10}$			$2.9\cdot10^{10}$
Eu-154	$8.8\cdot10^{0}$	$5.6\cdot10^{9}$			$5.6\cdot10^{9}$
Eu-155	$5.0\cdot10^{0}$	$4.0\cdot10^{9}$			$4.0\cdot10^{9}$
Pb-210 h	*$2.2\cdot10^{1}$*	*$7.8\cdot10^{11}$*			*$7.8\cdot10^{11}$*
Ra-226 e	$1.6\cdot10^{3}$	$9.8\cdot10^{11}$			$9.8\cdot10^{11}$
Ac-227 g	*$2.2\cdot10^{1}$*	*$4.4\cdot10^{6}$*			*$4.4\cdot10^{6}$*
Th-230	*$7.7\cdot10^{4}$*	*$2.7\cdot10^{3}$*		*$1.3\cdot10^{0}$*	*$2.7\cdot10^{3}$*
Th-232 f	$1.4\cdot10^{10}$	$3.0\cdot10^{9}$			$3.0\cdot10^{9}$
Pa-231	*$3.3\cdot10^{4}$*	*$8.7\cdot10^{6}$*			*$8.7\cdot10^{6}$*
U-234	*$2.4\cdot10^{5}$*	*$1.5\cdot10^{7}$*		*$9.4\cdot10^{3}$*	*$1.5\cdot10^{7}$*
U-235	$7.0\cdot10^{8}$	$8.2\cdot10^{9}$			$8.2\cdot10^{9}$
U-236	*$2.3\cdot10^{7}$*	*$6.6\cdot10^{5}$*		*$2.4\cdot10^{1}$*	*$6.6\cdot10^{5}$*
U-238	$4.5\cdot10^{9}$	$2.0\cdot10^{10}$			$2.0\cdot10^{10}$
Np-237	*$2.1\cdot10^{6}$*	*$2.5\cdot10^{7}$*		*$1.3\cdot10^{3}$*	*$2.5\cdot10^{7}$*
Pu-238	$8.8\cdot10^{1}$	$1.3\cdot10^{11}$	$1.8\cdot10^{8}$	$9.8\cdot10^{7}$	$1.3\cdot10^{11}$
Pu-239	$2.4\cdot10^{4}$	$2.1\cdot10^{12}$	$3.4\cdot10^{7}$	$2.4\cdot10^{7}$	$2.1\cdot10^{12}$
Pu-240	$6.5\cdot10^{3}$	$4.6\cdot10^{11}$	$3.9\cdot10^{7}$	$2.7\cdot10^{7}$	$4.6\cdot10^{11}$
Pu-241	$1.4\cdot10^{1}$	$2.2\cdot10^{12}$	$1.2\cdot10^{10}$	$1.9\cdot10^{9}$	$2.2\cdot10^{12}$
Am-241	$4.3\cdot10^{2}$	$1.6\cdot10^{12}$	$1.2\cdot10^{7}$	$2.1\cdot10^{8}$	$1.6\cdot10^{12}$
Am-243	$7.4\cdot10^{3}$	$9.0\cdot10^{8}$	$3.9\cdot10^{6}$	$2.7\cdot10^{6}$	$9.1\cdot10^{8}$
Cm-243	$2.9\cdot10^{1}$	$4.2\cdot10^{8}$	$7.4\cdot10^{7}$	$2.6\cdot10^{7}$	$5.2\cdot10^{8}$
Cm-244	$1.8\cdot10^{1}$	$9.6\cdot10^{9}$	$2.2\cdot10^{7}$	$4.8\cdot10^{6}$	$9.6\cdot10^{9}$
Total		$2.8\cdot10^{15}$	$1.6\cdot10^{14}$	$1.2\cdot10^{17}$	$1.2\cdot10^{17}$

*) The estimated inventory of nuclides formed by ingrowth up to the time of repository closure is given in italic.
a Sr-90 is in equilibrium with the daughter nuclide Y-90,
b Ru-106 is in equilibrium with the daughter nuclide Rh-106,
c Sb-125 is in equilibrium with the daughter nuclide Te-125m,
d Cs-137 is in equilibrium with the daughter nuclide Ba-137m,
e Ra-226 is in equilibrium with daughter nuclides until Pb-210,
f Th-232 is in equilibrium with daughter nuclides,
g Ac-227 is in equilibrium with daughter nuclides,
h Pb-210 is in equilibrium with daughter nuclides.

Ni in concrete cannot be calculated from existing thermodynamic databases, because there is a lack of constants relevant for high pH conditions. In this case it is necessary to rely on direct measurements of solubilities.

Important results in this field have been obtained in other countries with long-lived LLW and ILW. Therefore 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 the prestudy, where references have been made to recently published data from NAGRA and NIREX.

16.2.3 Scenario selection

Safety assessments of radioactive waste repositories are based on predictive modelling of the performance of engineered barriers and natural barriers for very long time scales. Assumptions must be made on the future evolution of engineered barriers and natural conditions in order to evaluate the performance of a repository. One way to describe the possible sequences of processes and events that influence the release of contaminants from a repository is to formulate scenarios. There is an advantage to do this in a systematic way so that the scenarios are documented together with all the material used for the identification, formulation and selection of scenarios.

We decided to use a method recently developed and tested by SKI /16-3/. The method is based on the use of Influence Diagrams with the documentation linked to it. Features, Event and Processes, FEPs, considered relevant for the deep disposal of waste are compiled, described, sorted and screened. The majority of the FEPs remaining after screening are assigned to the Process System. FEPs kept outside the Process System, External FEPs, are considered as scenario generating FEPs and hence scenarios are formulated by combining the Process System with one or a combination of external FEPs. An Influence Diagram is constructed from the Process System where FEPs within the system are represented by boxes and interactions between FEPs are illustrated by lines between the boxes. The Influence Diagram shows, in a structured and well documented way, how the Process System responds to External FEPs.

Within the prestudy an inventory was made of FEPs that can influence the performance of the repository barriers to radionuclide release. Premises for a Reference Scenario were defined and the importance of the identified FEPs for this Reference Scenario was evaluated. A Reference Case was selected from that and analysed. This is a relatively new approach and the exercise has contributed to the development in this relatively new field which is frequently referred to as the scenario method for performance assessment. A more detailed description of the performed study is given in one of the reports from the prestudy /16-4/.

We conclude that it was possible to carry out the different steps of a systematic scenario methodology based on Influence Diagrams to obtain a Reference Scenario and to define a Reference Case to be quantitatively analysed as well as prepare a list of remaining issues which should be addressed in future studies. An important result so far is the data base with FEPs descriptions, specification of influences and protocols of the decisions behind the development of the Reference Scenario. The use of Influence Diagrams is a stringent way to develop and document the scenarios to be further analysed and evaluated. One drawback is the graphical description with its complex system of boxes and arrows.

16.2.4 Performance of near-field barriers

Calculations were performed to test the resistance of the near-field barriers to radionuclide release. Two modelling approaches were used. First the stirred tank model was used to get an indication of release levels and important radionuclides. All transport resistances in the waste packages, concrete structures and sand backfill were neglected in this approach, and the calculations were performed for all radionuclides in the inventory for which chemical and physical data were available.

Release calculations for the defined Reference Case of the Reference Scenario were performed with the computer code TRUMP /16-5/ considering advective and diffusive transport of radionuclides in the barriers, see Figure 16-1. A subset of radionuclides were selected for the calculations. The subset consisted of the nuclides judged to be representative with respect to their abundance in the waste, their mobility in the barriers and their expected contribution to dose calculations. The TRUMP-model was also used to calculate the release of lead and beryllium from SFL 3 to exemplify the release of chemotoxic elements from the repository.

To get a measure of the radiotoxicity of the calculated near-field release, a conversion to intermediate doses was made by assuming that the total release from the repository was captured in a well with a capacity of 2000 m^3/year and that an individual consumed 0.6 m^3/year of this well water, see Table 16-3.

The calculations of contaminant transport, conversion to intermediate dos etc are described in detail in one of the reports from the prestudy /16-5/. Also presented in that report is a calculation of the temperature increase due to the decay of radionuclides and estimates of gas generation due to corrosion, microbial action and radiolysis. The calculated temperature increase was less than 2°C and therefore neglected. Gas formation caused by corrosion of steel and aluminium is of importance, but the consequences of this has not been evaluated in detail in the prestudy.

16.2.5 Results and conclusions from the prestudy

The prestudy has involved a first attempt to characterise the waste presently planned for SFL 3-5, the testing of a systematic scenario methodology and a first evaluation of the barrier performance. The conclusions from the study are as follows:

The metallic waste from the reactors disposed of in SFL 5 will dominate the total activity in SFL 3-5. At repository closure, the activity in the different parts will decrease in the order SFL 5 > SFL 3 > SFL 4 with more than one order of magnitude difference between them.

SFL 4 is dominating the calculated release for the first 10 000 years despite the relative low content of radionuclides compared to SFL 3 and 5. The main reason for this is the limited retention in SFL 4. The dominating radionuclides are Cs-137, Ni-53 and Ni-59.

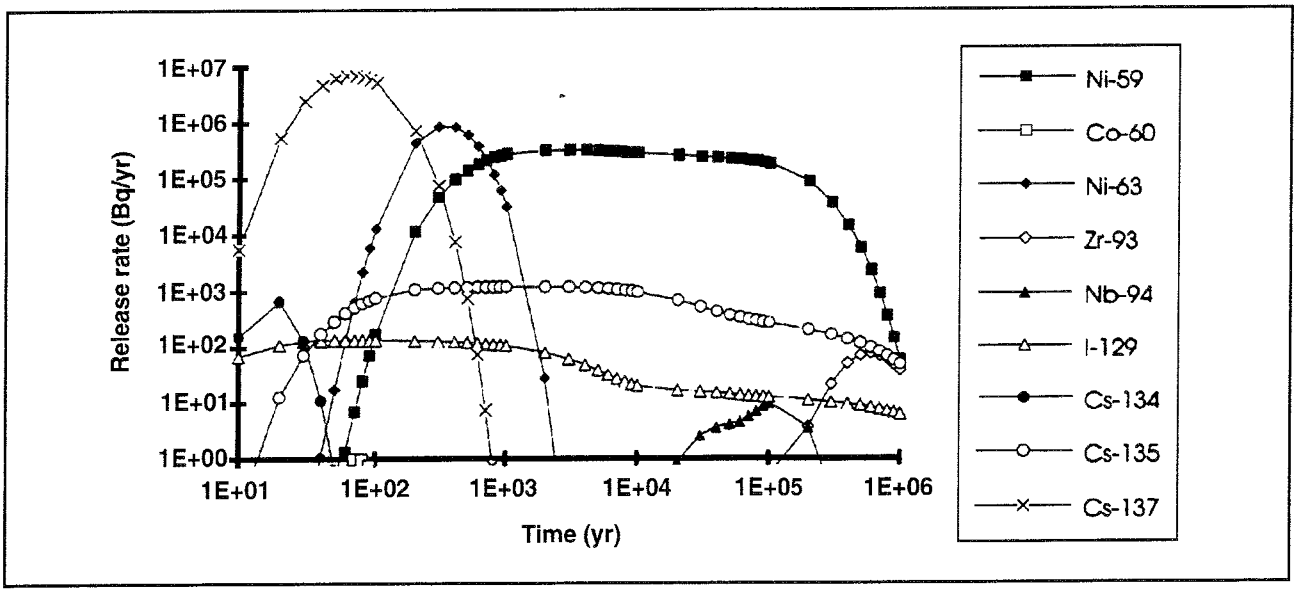


Figure 16-1. Radionuclide release from SFL 3-5, Reference Case.

Table16-3. Maximum intermediate doses from maximum near-field releases above 1 Bq/year, Reference Case.

Radionuclide	Half-life (year)	Maximum intermediate dose (Sv/year) SFL 3	SFL 4	SFL 5
Ni-59	$7.5 \cdot 10^{4}$	$1 \cdot 10^{-9}$	$7 \cdot 10^{-9}$	$1 \cdot 10^{-9}$
Co-60	5.3		$3 \cdot 10^{-11}$	
Ni-63	$9.6 \cdot 10^{1}$		$5 \cdot 10^{-8}$	
Zr-93	$1.5 \cdot 10^{6}$		$6 \cdot 10^{-13}$	$3 \cdot 10^{-11}$
Nb-94	$2.0 \cdot 10^{4}$		$3 \cdot 10^{-12}$	$6 \cdot 10^{-12}$
I-129	$1.6 \cdot 10^{7}$	$4 \cdot 10^{-10}$	$5 \cdot 10^{-9}$	$2 \cdot 10^{-10}$
Cs-134	2.1		$4 \cdot 10^{-9}$	
Cs-135	$2.3 \cdot 10^{6}$	$2 \cdot 10^{-10}$	$6 \cdot 10^{-10}$	$1 \cdot 10^{-10}$
Cs-137	$3.0 \cdot 10^{1}$		$3 \cdot 10^{-5}$	$1 \cdot 10^{-8}$

SFL 3 and 5 are dominating the calculated release after 10 000 years. The dominating radionuclides are Ni-59, Zr-93 and Cs-135.

Assuming that the total calculated near-field release was captured in a well with a capacity of 2000 m^3/year and an annual water consumption of 0.6 m^3 per individual, the estimated intermediate doses were always bellow 0.1 mSv/year for all the radionuclides studied. The highest intermediate dose arises from Cs-137 after about 100 years.

A well capturing the near-field release of the chemotoxic elements lead and beryllium from SFL 3 would obtain concentrations of these elements that are below the guideline values of drinking water. This demonstrates that the barriers which are effective to prevent release of radionuclide will also be efficient in this case.

No attempt was made to change the conceptual design given in Plan 93 /16-1/ and according to the prestudy it provides the barrier functions needed for the long-time safety of the repository.

The summary report of the prestudy will appear in 1995 /16-7/.

16.3 SECOND PHASE

The preliminary nature of the prestudy should be remembered and further work is needed prior to a complete safety assessment. The investigations have therefore been continued in a second phase starting in october 94 with the main aim to prepare for a safety assessment that will begin by mid 96. The second phase of the study of other long-lived waste consists of the following parts:

- Preparation of tables with radionuclide content and waste composition to be used in a safety assessment.
- Preparation of a chemical data base containing information on water chemistry, concrete composition and chemistry, radionuclide sorption, diffusion and solubility, organic complexes and colloids.
- Analysis of alternative scenarios (e. g. ice age), hydraulic influences, the effects of colloids, microbes and gas formation.
- Compilation of barrier properties; waste package, concrete construction, near-field rock, backfill of concrete, bentonite and sand.
- Comparison between different design alternatives.
- Testing and development of transport models.

The last point, "testing and development of transport models", is connected to the safety assessment program of SFL 2, because ideally the same calculation models should be used for all the different parts of the deep repository.

17 THE ÄSPÖ HARD ROCK LABORATORY

The Äspö Annual report /17-1/ provides a detailed description of the achievements for 1994 and the reader is referred to this publication for further information.

17.1 BACKGROUND

The scientific investigations performed within SKB's research program are part of the work for investigating a suitable site for and designing a repository for spent nuclear fuel. This requires extensive field studies regarding rock characterization methods and the interaction between different engineered barriers and the 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. The proposal 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 arrived at a decision in principle to site the facility on southern Äspö, about 2 km north of the Oskarshamn Nuclear Power 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 within 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, descriptions of the natural conditions in the bedrock and prediction of changes that will occur during construction of the laboratory. The investigations have been summarized in six Technical Reports /17-2 – 17-7/. 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 and testing integration, and to increase the database on the bedrock in order to improve models on groundwater flow and radio-

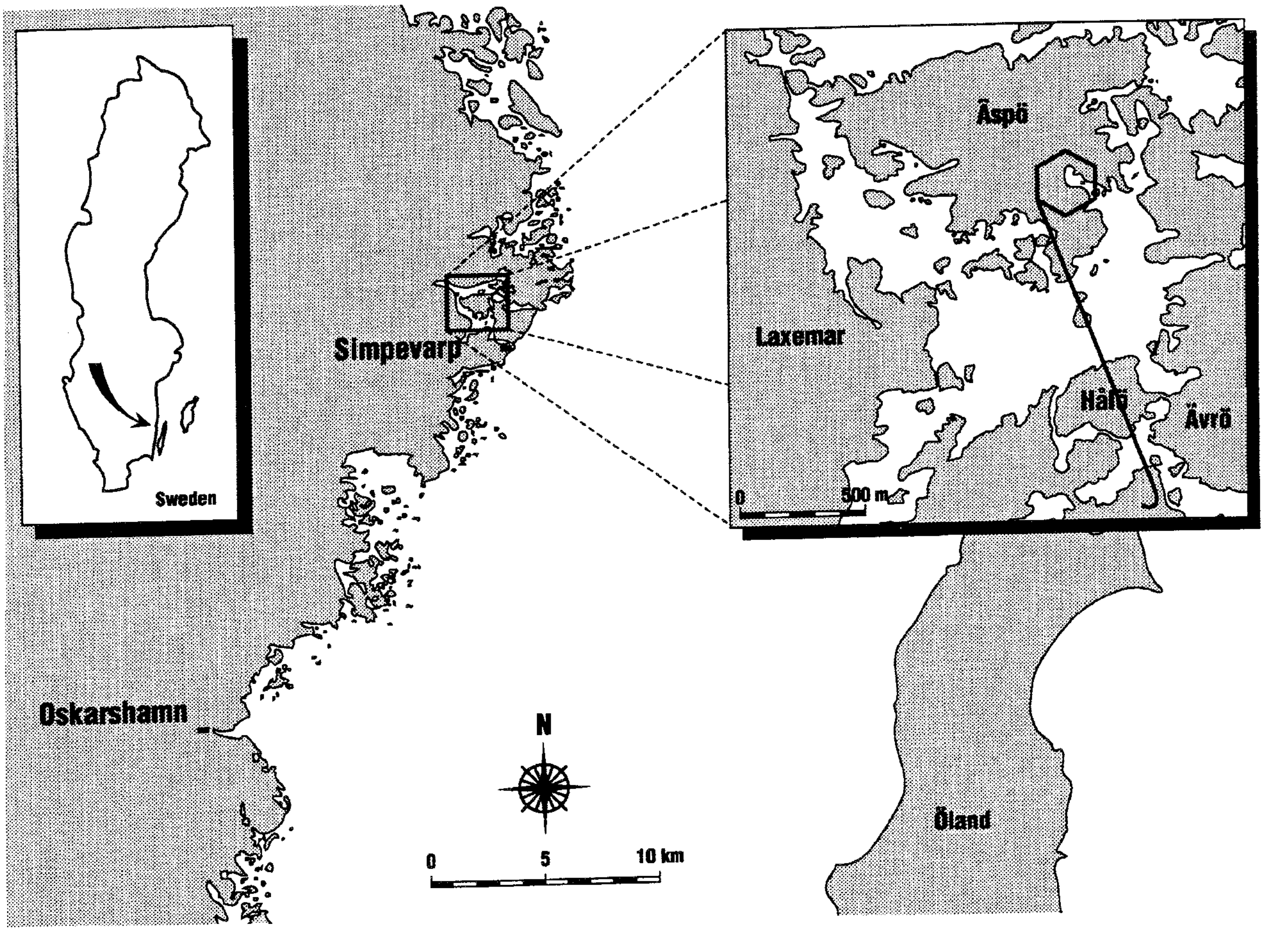


Figure 17-1. Location of the Äspö Hard Rock Laboratory.

nuclide migration. A program for the operating phase was outlined in the RD&D-Programme 92. The operating phase is aimed at research and development on models for groundwater flow and radionuclide transport, tests of methods for construction and handling of waste and pilot-tests of important parts of the repository system. Detailed plans have been now prepared for several of the projects planned for the operating phase.

17.2 INVESTIGATIONS AND EXPERIMENTS - NEW RESULTS 1994

Stage goal 1 – Verification of pre-investigation methods

Excavation of the main access tunnel was completed in September 1994 and the investigations tied to the construction work a few months thereafter. The main experiences gained during the first two phases of the Äspö HRL will be compiled in a report that will be completed in 1995. In general, the site characterization approach used has been found useful. The idea of dividing the investigations into different stages, scales and key issues has simplified the evaluation work considerably and further use of this approach is advocated. Due to the lithological heterogeneity, it seems that block scale predictions were not as useful as site and detailed scale predictions.

Based on data from the pre-investigation phase it was found difficult to determine:

- The exact position and orientation of minor sub-vertical fracture zones (e.g. NNW-structures at Äspö).
- The detailed character and importance of sub-vertical fracture zones.
- The relative importance of the different sub-horizontal fracture zone indications.
- The location and distribution of minor rock units at depth (e.g. greenstone lenses and veins of fine-grained granite).
- The validity of the theoretical model of the scale dependency of hydraulic properties.
- The hydraulic properties of minor rock types.
- The absolute water pressures in boreholes at great depth due to varying salinity with depth.
- The groundwater chemistry in low conductive rock masses.

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. Stress measurements have been conducted in short holes drilled from selected locations along the access ramp. The CSIRO Hollow Inclusion overcoring technique has been used, and 3-5 overcoring tests made in each borehole at a distance from the ramp sufficient to ensure that data are not influenced by excavation-induced stresses.

Some of the data obtained are indicated in Figure 17-2. The most striking characteristic is a consistent, near-horizontal, NW-SE orientation of the maximum stress. This is in accordance with results from the surface boreholes and seems to apply for the entire site. The stress field is highly anisotropic with differences between the maximum and minimum principal stresses of a factor of three or more. The maximum stress increases rapidly with depth, resulting in magnitudes of some 30 MPa at 400 m depth. This is in the high range as compared to general background data from Scandinavia.

The island of Äspö is divided into two main granite blocks by the more than 100 m wide fracture zone EW-1 (Äspö shear-zone) trending NE. The zone EW-1 was indicated very early in the pre-investigation phase by aerogeophysical measurements. Geological and ground geophysical investigations complemented with an inclined core borehole (KAS04) contributed to a more exact localization and characterization of EW-1. Data from a borehole drilled from the tunnel (KA1755A) mainly support the prediction of EW-1 as a complex fracture zone comprising two intense highly fractured branches, partly mylonitized.

The statistical distribution of the hydraulic conductivity for tunnel section 2265-2875 agrees approximately with the predictions. However, the estimated hydraulic conductivity in the tunnel is somewhat less than the hydraulic conductivity estimated from the surface holes.

The predicted composition of the groundwater in major fracture zones and the salinity in the zones is different from the observation. The reason for this is currently not well understood. There are, however, different possible explanations such as mixing ahead of the tunnel front and/or incorrect conceptual models.

The recalculations of the drawdowns caused by the construction of Äspö HRL using the measured flow into the tunnel and with the same numerical model as was used for the predictions has been published in /17-8/. The simulations indicate for example that there should be a conductive structure crossing the elevator shaft above -215 m to get reasonable drawdowns close to the shaft with the given flow rates into the shafts.

Stage goal 2 – Finalize detailed investigation methodology

The detailed characterization of a repository will encompass investigations during construction of shafts/tunnels to repository depth. Finalizing the detailed investigation methodology is Stage goal 2 of the Äspö project.

Detailed characterization work produces large amounts of data. 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

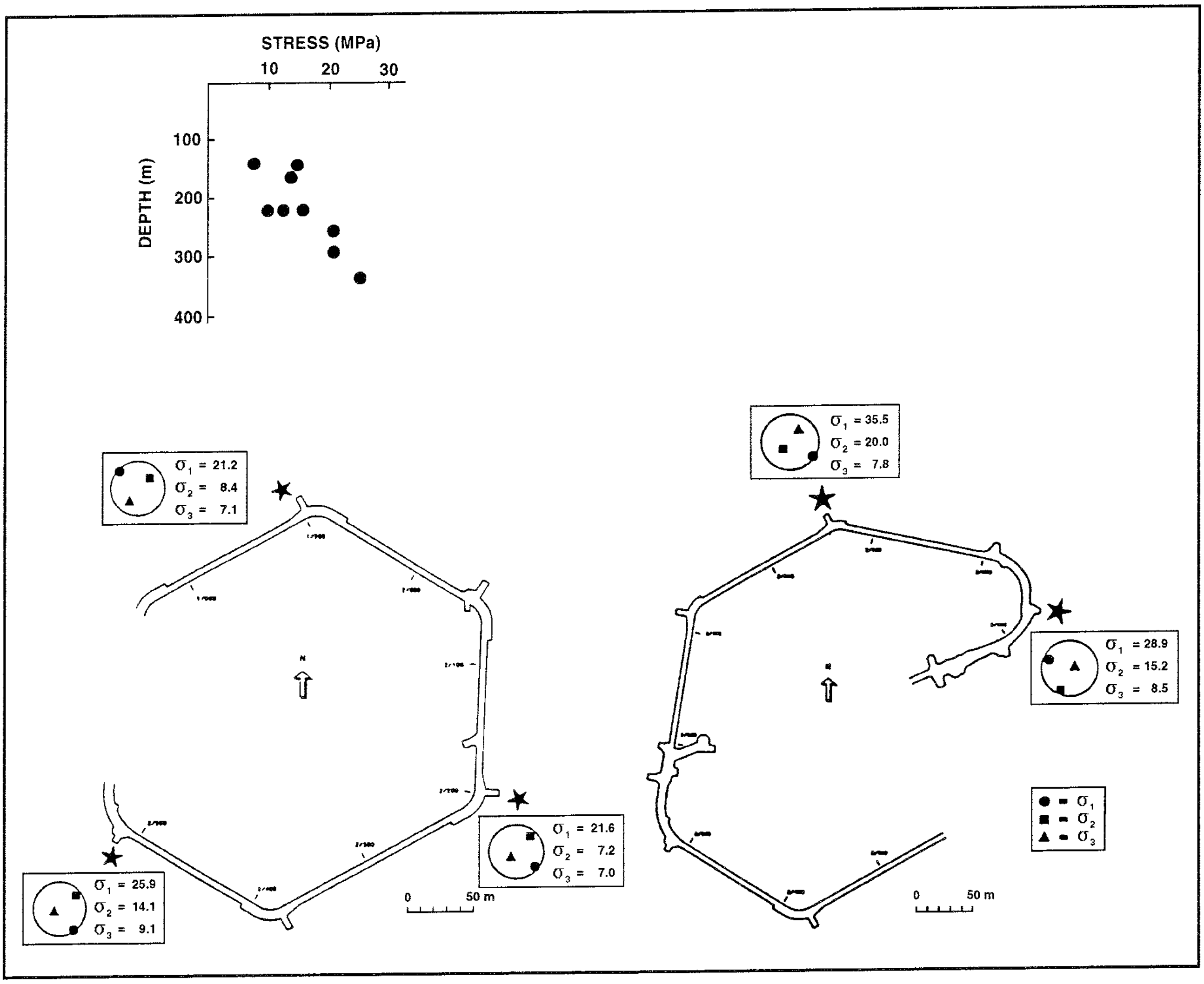


Figure 17-2. Compilation of stress measurement results. Overall trend with depth for maximum principal stress (upper) and data from recently completed tests (lower).

exacting requirements on quality and overview. This methodology is applicable to the planned detailed characterization work for a deep repository. The methodology was first developed for conventional tunnelling. Starting at a depth of about 420 m, the tunnel has been excavated using full-face boring – TBM. This has facilitated a test of different excavation methods and associated modifications of data collection methodology and procedures.

In the pre-investigation phase, the characterization of the rock was to a large extent based on data collected from boreholes. In the construction phase, a lot of data are collected by observations made in drifts. However, observations made in boreholes and in tunnels differ with respect to the quality and density of data collected for a specific parameter and also with respect to what types of data that can be collected. A study has been initiated in order to understand how the differences in data collected in boreholes and tunnels influence our understanding of the rock. The first step of this study was to investigate if geophysical borehole logging methods can be used as a tool to determine lithology, RQD, RMR and type of alteration in a borehole. Another purpose was to compare the information obtained from a borehole and the actual situation in a tunnel parallel to the borehole. The investigation was made in two 200 m cored boreholes parallel to the tunnel (KA1131B and KA2048B).

The results show that geophysical borehole logging together with interpretations based on pattern recognition techniques can be used in order to determine lithology and RQD in a borehole. Prediction models of alteration could not be established, since the core mapping did not provide a good estimate of alteration. In one borehole, RMR was estimated using geophysical measurements and information obtained from the drilling report. The results from this test indicate that a good estimate of RMR in the borehole can be obtained. The study also shows that boreholes give very useful information but must not be used as an infallible information source, especially as structures may change character away from the borehole. Moreover, there is a need to use a borehole radar with directional antenna or an oriented core to obtain information on the orientation of fractures.

Borehole KA3191F was drilled from the TBM assembly hall in the center line of the TBM tunnel down to the lowest position of the excavation at a depth of 450 meters below ground surface in the vicinity of the shafts. The borehole was 210 m long. The objective of the hole was to provide characterization data in advance of TBM-tunnelling and to provide data for comparison with geological and geophysical data collected from the tunnel.

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 experiment is performed in two test drifts near the TBM Assembly hall at an approximate depth of 420 m below the ground surface. Measurements of rock properties have been made before, during, and after excavation. The investigation program includes measurements of fracturing, rock stress, seismic velocities, displacements, and permeability.

The core logging and drift mapping shows that the ZEDEX experiments were carried out in a volume of rock which is predominantly Äspö Diorite. Two main sets of dikes have been observed at the ZEDEX site, which have self consistent orientations (i.e. NorthWest).

Acoustic Emission (AE) monitoring of micro-cracking due to stress release was made when TBM excavation was stopped during the night at 9 m, 15 m, 22 m, and 25 m measured from the start of the TBM tunnel. When the TBM stopped at 9.0 meters the majority of the recorded and subsequently located AE activity (232 events) defined a narrow zone directly in front of the position of the TBM face, see Figure 17-3. Generally, events were located around the tunnel within 1 meter of the tunnel perimeter and ahead of the tunnel face.

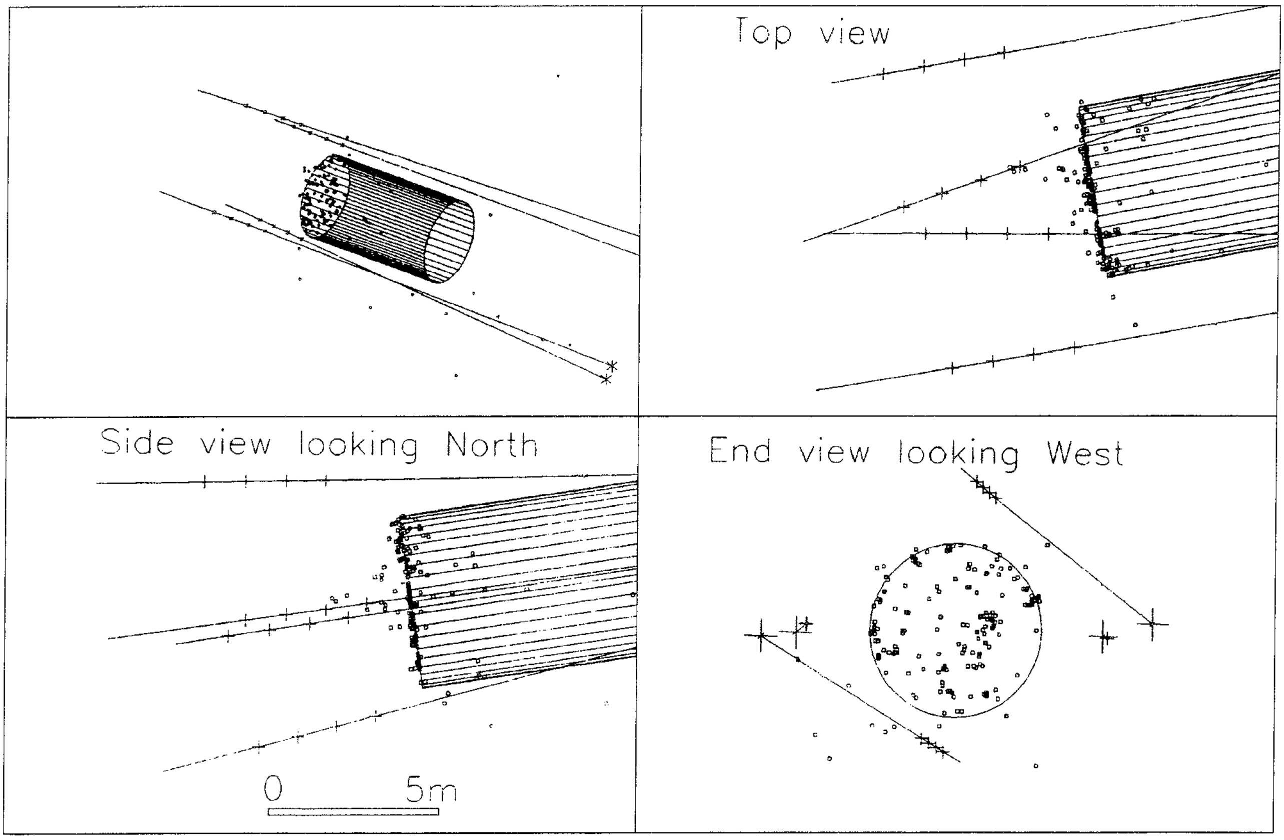


Figure 17-3. Acoustic Emission source locations while the tunnel boring machine was stopped overnight at 9 m from its starting position (232 events).

The preliminary analysis of the results indicates that the measurable changes in properties induced by excavation of the TBM tunnel are small to negligible.

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 to the canister, and
- 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 conceptualization of heterogeneity, the ability to collect realistic data over an entire repository area, and the ability to carry out realistic calculations. It is important to test and demonstrate different approaches in practice in preparation for the licensing process.

The conductivity of a single rock fracture is governed by the geometry of the fracture aperture. The geometry of a fracture was studied in the Pore Volume Characterization project which was completed in 1994 /17-9/. A highly conductive, minor fault at the tunnel section 1/140 was selected for the study. Before excavation of this section of the tunnel, the fracture had been grouted with a red-colored cement grout. Five boreholes with a diameter of 200 mm were drilled parallel to the fracture plane in order to obtain core samples containing segments of the fracture plane. The result from this study shows larger aperture values, larger aperture variation and longer correlation distances as compared to results from similar studies reported in the literature. The explanation for this is suggested to be the difference in type of fracture studied and the difference in scale of measurements. The frequency distribution of the aperture shows that a large part of the data lies below the measurement limit, i.e. that the "contact area" is large (approximately 40%).

Several experiments are planned for the Operating Phase of the Äspö HRL. These experiments require sites which meet specific requirements with respect to rock conditions and groundwater properties. A separate project was carried out which provided base data and recommendations for locating experiments /17-10/. Based on this work a provisional allocation was made of experimental sites for the Radionuclide Retention Experiment (RN), the Redox Experiment on a local scale (REX) and the Tracer Retention Understanding Experiment (TRUE) at the experimental level (340-m level). It was identified that access to the allocated rock volumes, with one exception, is facilitated by drilling 20-30 m long boreholes from existing niches along the tunnel spiral. A separate project, the SELECT project, was set up to realize the above intention.

The plans for tracer experiments outlined in the SKB RD&D-Programme 92 comprised experiments in the Detailed and Block Scales. The experiments in the Detailed Scale consisted of three; Pore Volume Characterization (PVC), Multiple-Well Tracer Experiment (MWTE), and the Matrix Diffusion Experiment (MDE). During 1994 detailed Test Plans were prepared for MWTE and MDE. Following review and evaluation the SKB HRL Project management decided to integrate the Detailed and Block Scale experiments within a common framework. This framework is described in a "Program for Tracer Retention Understanding Experiments" (TRUE) /17-11/. The basic idea is that tracer experiments will be performed in cycles with an approximate duration of 2-3 years. At the end of each tracer test cycle, results and experiences gained will be evaluated and the overall program for TRUE revised accordingly.

The general objectives of the TRUE experiments /17-11/ are to:

- Develop the understanding of radionuclide migration and retention in fractured rock.
- Evaluate to what extent concepts used in models are based on realistic descriptions of rock and if adequate data can be collected in site characterization.
- Evaluate the usefulness and feasibility of different approaches to model radionuclide migration and retention.

A test plan which details the work during the First TRUE Stage has been prepared /17-12/. The defined objectives of the First TRUE Stage are:

- to conceptualize and parametrize an experimental site on a detailed scale (L~5m) using conservative tracer tests in a simple test geometry,
- to improve tracer test methodologies for conservative tracer tests in a detailed scale,
- to develop and test a technology for injection of epoxy resin on a detailed scale and to develop and test techniques for excavation (drilling) of injected volumes and subsequent analysis,
- to test sampling- and analysis technologies to be employed in the analysis of matrix diffusion, and
- to assess the usefulness of applied models.

The project Degassing of groundwater and two phase flow has been initiated to improve our understanding of observations of hydraulic conditions made in drifts, interpretation of experiments performed close to drifts, and performance of buffer mass and backfill, particularly during emplacement and repository closure. To provide a basis for defining the scope of the project a literature review has recently been completed and reported /17-13/. This report also presents results of some initial laboratory tests on two-phase flow properties in artificial fractures.

These tests show flow reductions by approximately a factor of two for two-phase flow conditions compared to single phase (water) flow.

The in-situ test program began with a pilot test with the objective to get data on the magnitude of degassing effects on permeability, time scales required for resaturation, and requirements on equipment for subsequent tests. The test showed no two-phase flow effects. Subsequent measurements indicated that the gas contents of KA2512A (0.5% v/v) were probably too low to cause two-phase flow effects. The results show no evidence of other processes that might reduce transmissivity at low borehole pressures, such as calcite precipitation, increase in effective stress, or turbulence.

The Redox experiment in Block Scale was completed in 1994. The purpose of the block scale redox experiment was 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 lasted until 1994. The results of the first two years have been reported /17-14/. 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. No oxygen breakthrough was observed and the chemical composition remained constant throughout the experimental time. The explanation for this is that the high content of organic matter in the infiltrating surface water has been biologically oxidized 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.

The detailed scale experiment (REX) is planned to focus the question of oxygen and other redox active material that is trapped in the tunnels when the repository is closed. The objectives of the experiment are:

- How does oxygen trapped in the closed repository react with the rock minerals in the tunnel and deposition holes and in the water conducting fractures?
- How long time will it take for the oxygen to be consumed and how far into the rock matrix and water conducting fractures will the oxygen penetrate?
- What is the role of microbes in the transient stage after closure of the repository?

A draft test plan for the experiment has been prepared.

Laboratory studies under natural conditions are extremely difficult to conduct. Even though the experiences from different scientists are uniform it is of great value to be able to demonstrate the results of the laboratory studies in situ. It is possible to have the natural contents of colloids, of organic matter, of bacteria etc in the experiments. Laboratory investigations have difficulties to simulate the natural conditions in the groundwater and are therefore dubious as validation exercises. It is therefore suggested to use the CHEMLAB probe, see Figure 17-4, to conduct validation experiments in situ at undisturbed natural conditions. The CHEMLAB probe is a borehole laboratory built in a probe, in which migration experiments will be carried out under ambient conditions regarding pressure and temperature and with use of the formation groundwater surrounding the probe. The manufacturing of the probe is presently under way.

A "Task Force" with representatives of the project's international participants has been formed. The Task Force is a forum for the organizations supporting the Äspö Hard Rock Laboratory Project to interact in the area of conceptual and numerical modelling of groundwater flow and solute transport in fractured rock. In particular, the Task Force shall propose, review, evaluate and contribute to such work in the project. Much emphasis is put on building of confidence in the approaches and methods in use for modelling of groundwater flow and nuclide migration in order to demonstrate their use for performance and safety assessment.

The evaluation of Task No 1, the LPT2 pumping and tracer tests, is in progress. The different modelling activities have been reported in the Äspö International Cooperation Report (ICR) Series. A wide variety of conceptual as well as numerical models have been used to predict water flow and tracer breakthrough in this rather large scale. The very large data base available have been utilized to different extent and the calibration efforts are varying.

Task No 2 was finalized during 1994. This concerned design calculations for some of the planned experiments at the Äspö site, for the Matrix Diffusion Experiment and for the Multiple Well Test Experiment. Five reports concerning Task No 2 have been printed in the Äspö ICR series.

The hydraulic impact of the tunnel excavation at Äspö HRL was defined as the 3rd Modelling Task. The objective will be to evaluate how the monitoring and the study of the hydraulic impact of the tunnel excavation may help for site characterization. Task No 3 will be an exercise in forward as well as inverse modelling.

A 4th Modelling Task was defined as predictive analyses of the TRUE 1st stage experiment in the detailed scale. Site characterization data will become available next year and these data are the basis for the predictions.

Stage goals 4 and 5 – Development of construction and handling methods, pilot tests

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

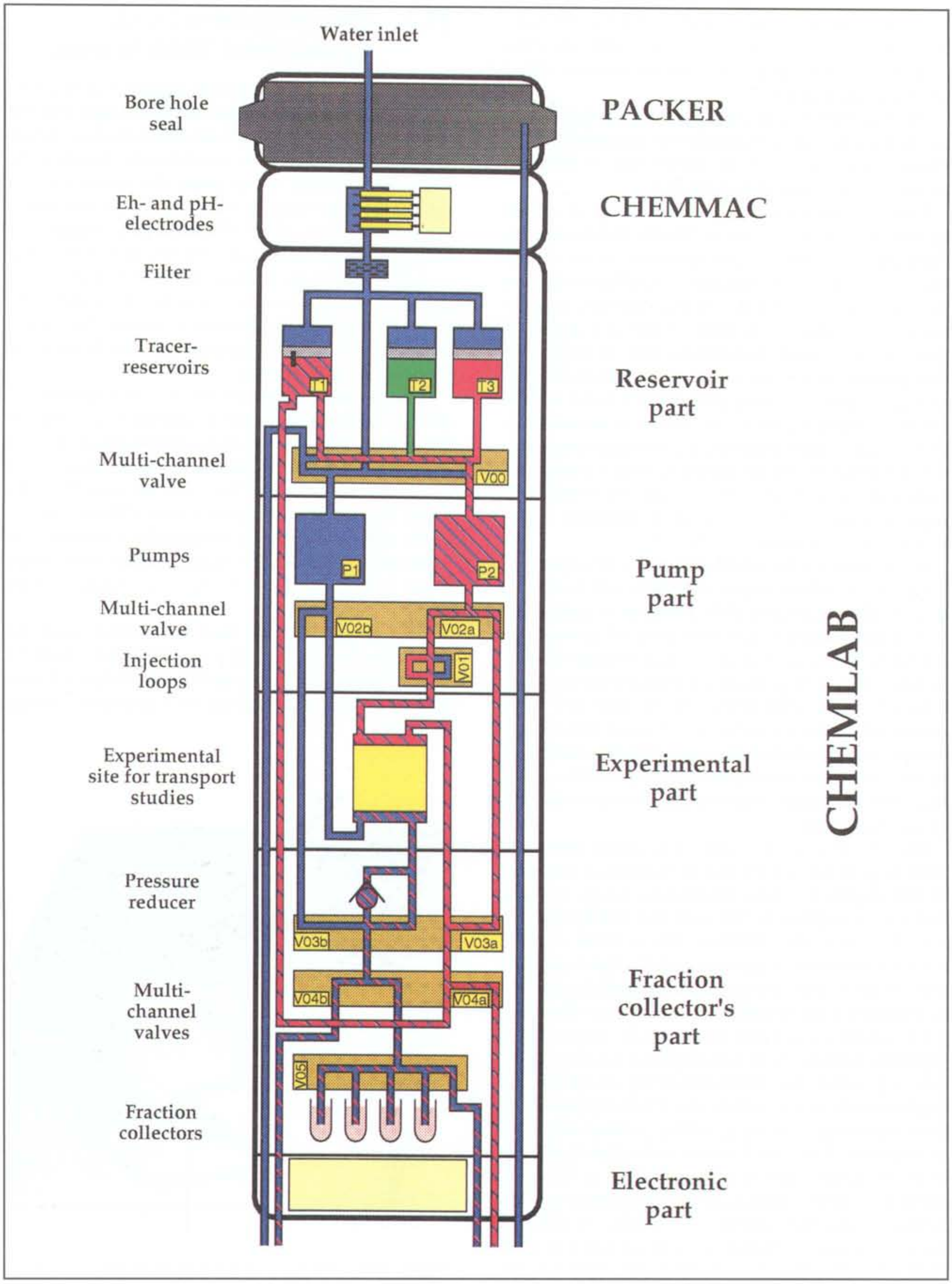


Figure 17-4. *Schematic illustration of the CHEMLAB probe.*

corrodants 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. Current experience from the construction of the Äspö facility will be evaluated and reported.

Plans for construction of an initial stage of a deep repository were presented in RD&D-Programme 92. 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 recognized within SKB. For example: A part of a deposition tunnel will be built and backfilled at Äspö. In conjunction with planning, design and construction, work descriptions and quality plans are being 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. A programme for the prototype repository was prepared during 1994 /17-15/.

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 performance of the prototype will then be monitored at 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. In addition to the prototype repository, studies will be undertaken to test alternative materials and methods for backfill of deposition tunnels.

The concept of rock volume descriptions within the SKB program for suitable nearfield design is being developed to provide a basis for planning, design, and construction of a repository. The term rock volume descriptions has not a strict definition, but is aimed at using existing information on geology, stability, building conditions, hydrogeology, and groundwater chemistry at every investigation stage of repository establishment. The maximum number of canisters on a specific length of the repository tunnel is given with respect to practical conditions, e.g. tunnel-dimensions and drilling equipment. An important issue is how well this maximum capacity can be used, depending on geology, stability, hydrogeology, and geochemistry. A measure, or index, of the capacity relative to the maximum capacity may be defined as the probability at a specific confidence level that a canister position within a given rock volume is acceptable. A Markov-Bayes Geostatistical Model, partly developed within the SKB siting program, was modified and applied in the calculations /17-16/.

17.3 ENGINEERING AND CONSTRUCTION WORK

The construction of the Äspö HRL comprises several parts and stages. A tunnel ramp has been excavated from the Simpevarp peninsula 1.5 km out under the Äspö Island. The descent to the tunnel is situated in the vicinity of the Oskarshamn nuclear power plant. The research tunnel reaches the Äspö island at a depth of 200 m. The area of the tunnel section is 25 m^2. The tunnel then continues in a hexagonal spiral under Äspö. The first turn of the spiral was completed in the summer of 1993. The depth at that point is 340 m below sea level and the total length of the tunnel was 2600 m from the tunnel entrance. The tunnelling of this first construction part was done by means of conventional drill and blast.

In the second part of the spiral (from 340 to 460 m level), full-face boring with a Tunnel Boring Machine, TBM, has been tested. The first part of the second spiral follows a hexagonal shape and was done by drill and blast. A rock cavern was excavated at 420 m level for assembly of the TBM. The tunnel then goes down to the 450 m level close to the shafts and continues horizontally westward to an experimental volume. The diameter of the TBM drilled tunnel is 5 m. Figure 17-5 shows an overview of the facility.

Three shafts have been built for communication and supplies to the experimental levels. Two shafts (diam 1.5 m) are built for ventilation, and one shaft (diam 3.8 m) is built for the hoist. The shafts are excavated by raise-boring technique.

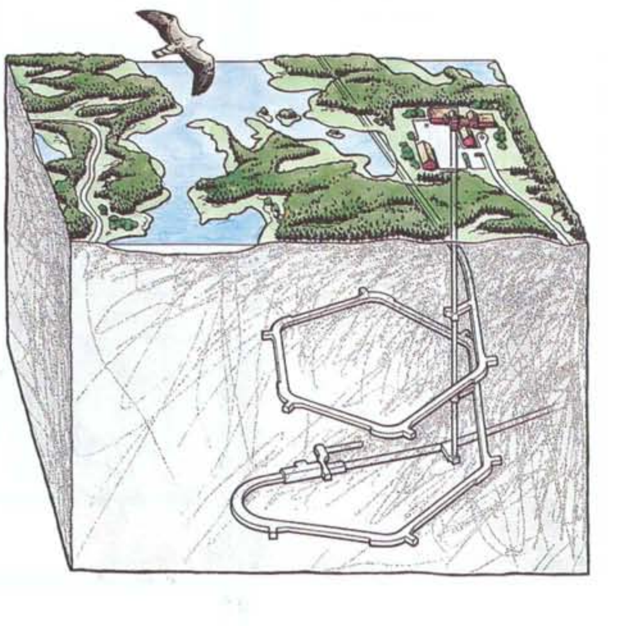


Figure 17-5. *Overview of the Äspö Hard Rock Laboratory facilities.*

Office and storage buildings have been built on the Äspö Island as well as buildings for ventilation equipment and machinery for the hoist. Together, these buildings comprise the "Äspö Research Village", which is designed to look like other small villages in the surrounding archipelago.

The tunnelling from the 340 m level down to the cavern for assembly of the TBM started in November 1993 and was finalized in March 1994. The rock cavern was excavated in April and the assembly of the TBM started in May.

The TBM drilling started on June 14th and was completed on September 16th. 420 m of tunnel was excavated by the TBM. Boreholes for grouting and hydraulic tests have been performed successfully from the TBM, with two drilling rigs. Holes have also been bored through the drilling head.

All excavation work was completed in February 1995.

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 methodology, rock excavation, measurement 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 Äspö HRL. Presently (April 1995) 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 National pour la Gestion des Dechets Radioactifs (ANDRA), France.
- United Kingdom Nirex Limited (NIREX), United Kingdom.
- National Cooperative for the Disposal of Radioactive Waste (NAGRA), Switzerland.
- United States Department of Energy (USDOE), USA.

During autumn 1994 negotiations with Bundesministerium für Forschung und Technologie (BMFT) in Germany has been taken place regarding cooperation in the Äspö Hard Rock Laboratory.

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.

SKB is also carrying out further research work related to the disposal in very deep boreholes. A brief account of the work conducted on the alternative methods during 1994 is given in the following sections.

18.1 KTH WORK ON TRANSMUTATION

18.1.1 Introduction

The research activities in the project "*Safety analysis of accelerator-driven systems for transmutation of nuclear waste and for nuclear power production*" during its second year were concentrated on studies of two different accelerator-driven systems. The first one, proposed by Los Alamos National Laboratory and the second, proposed by a CERN-group, headed by C Rubbia. Having in mind the aim of this project – evaluation of the prospects of accelerator-driven systems from the point of view of their safety and feasibility for Swedish conditions we have also been developing ideas on how to design an accelerator-driven system suitable for the Swedish nuclear power program.

The international contacts and cooperation were very extensive during the reported period. The cooperation with Los Alamos National Laboratory has been continued and broadened, a common project was carried out with the Rubbia's group, contacts were established with some research centers in Russia.

18.1.2 Research

The research activities 1994 were concentrated on the detailed analysis of the neutronics and some safety aspects of two different accelerator-driven systems:

1. Graphite-moderated, thermal neutron system with the molten-salt fuel with capabilities to transmute (burn) minor actinides, rapidly burn weapon plutonium, to transmute some of the fission products and finally to produce net energy based on U-Pu or Th-U fuel cycles – so called Los Alamos system.

2. Water-moderated, thermal (or epithermal) neutron system with the fast Th-U fuel devoted only to energy production – so called Rubbia-system.

A detailed, 3-dimensional geometry model of these systems were designed and a number of computer simulations were performed based on the Monte-Carlo technique. The simulations were focused on investigations of some important parameters of these systems like: reactivity margins, temperature reactivity coefficients, power distribution etc. The calculations of the Rubbia-system were performed with the close cooperation with the senior engineers from ABB and a lot of efforts were put into designing of as realistic spallator system as possible. The results of these investigations were presented on the International Conference on Accelerator-Driven Transmutation Technologies in Las Vegas /18-1/. The analysis of the results for the Rubbia-system lead to the conclusions that it would be virtually impossible to achieve all the safety advantages claimed for this system (inherent subcriticality, economical reliability etc.) Along with our involvement in the simulations of the Rubbia-system we performed a number of studies and calculations on the Los Alamos system. The temperature reactivity coefficients and some of the neutron kinetics parameters were simulated for the graphite Pu-burner and Thorium energy producer. Some of the results were reported on Las Vegas Conference (paper in final revision) and we contributed to the further development of this system.

From July 94 one graduate student from the group, Erik Möller, began his studies and research at the Los Alamos Laboratory. The efforts are put into developing of the numerical procedures for burn-up simulation coupled with the Monte-Carlo technique. It will allow us to perform 3-D simulations on short-time neutron kinetics, reactivity calculation, system dynamics and long time burn-up calculations. Most of the results will be reported on the Global-95 Conference in France and these results will be basis for E. Möller's "licentiat" Autumn 1995. Erik Möller has also taken part in designing of the molten lead spallation source experiment.

18.2 CTH WORK ON PARTITIONING

18.2.1 Introduction

In 1993 a R&D project was initiated at the Department of Nuclear Chemistry, CTH, with the objective to investigate separation processes intended for transmutation purposes (partitioning). It will always be required to separate the radionuclides to be transmuted from different matrixes. The questions dealing with partitioning can roughly be divided in two different areas, first the separation of radionuclides intended for transmutation from different types of waste forms such as spent nuclear fuel or high level liquid waste, HLLW and secondly the separation of the radionuclides not transmuted in an irradiation cycle. It will never be possible to transmute all radionuclides within one irradiation cycle, so transmutation must be interleaved with separation in order to remove the transmutation products. The requirements of the partitioning process will depend on the transmutation strategy chosen. Generally two transmutation concepts are considered,

i critical assemblies where it is enough fissile material in order to sustain a chain-reaction (e.g. thermal or fast reactors) the excess neutrons are used for transmutation of non-fissile radionuclides,

ii sub-critical assemblies that uses an accelerator driven spallation target to produce neutrons that transmutes radionuclides by fission or neutron capture. The neutronics will determine what radionuclides (e.g. mixtures), the amount of radionuclides and tolerable amounts of other elements (e. g. neutron poisons) that can be present in the assembly.

Several types of partitioning processes are considered. Aqueous based, molten salt and molten metal based separation schemes have been proposed. Of these, aqueous based separation has been used for reprocessing of spent nuclear fuel for more than 50 years. With regard to the current knowledge, aqueous processes seems to be the most realistic concept within a time perspective of 10-20 years. The molten salt and molten metal processes have to be proven with regard to technical applicability and recoveries of radionuclides, which will require large efforts of research.

The research project at the Department of Nuclear Chemistry, CTH, was decided to be focused on aqueous based separation processes in order to evaluate if it is possible to meet all requirements that would be put on a partitioning process to be used for transmutation purposes. Some of the requirements on partitioning processes are discussed together with different objectives for transmutation in /18-2/.

18.2.2 Separation research

Aqueous based separation procedures utilizing solvent extraction techniques can be used for separation of radionuclides from high level waste. Aqueous based processes can also be used in connection with transmutation if the irradiated target can be transformed to an aqueous solution.

Dissolution of solid target materials can be achieved in strong acids or bases. Among the mineral acids, nitric acid has shown to be most appropriate for dissolution of spent nuclear fuel in reprocessing. It was therefore decided that the partitioning studies in this project will be focused on aqueous phases consisting of nitric acid.

The basic principle of solvent extraction is transfer of elements between two immiscible solvents, such as water and kerosene. The transfer is usually facilitated by an extraction reagent (extractant), which often is more soluble in an organic solvent than in the water phase. Several different types of extractants can be considered, depending on the chemical bindings that are formed between the extracted element and the extractant. In principle it is possible to speak about three different types of extractants;

i ion-pair forming reagents acting as liquid ion-exchangers forming ion-pairs with the extracted elements,

ii chelate forming reagents forming strong complexes, of covalent character, with the extracted elements and

iii solvating reagents which usually are more losely bound to the extracted elements but making them coordinatively saturated.

Since some of the most radiotoxic elements in high level waste are the actinides, one of the important research topics in solvent extraction chemistry has been to find suitable extractants for the separation of actinides from fission products and other elements. One of the problems is to separate the trivalent actinides from the lanthanides. Usually actinides and lanthanides are extracted together in the first stage of the process and the trivalent actinides and lanthanides are then separated from each other in a second stage. Recent development in solvent extraction chemistry shows, however, that it may be possible to develop extractants that separates all actinides and even separates the trivalent actinides from the lanthanides.

The research project at the Department of Nuclear Chemistry is focused on two different types of extractants, anion-exchange reagents and new nitrogen containing extractants.

Anion-exchange extractants

In 1993 one PhD student was engaged in the project with the objective to investigate the extraction of various elements from nitric acid using Aliquat-336 (tricaprylmethylammonium nitrate). Aliquat-336 is a liquid anion exchanger consisting of a quaternary ammonium salt. The use of Aliquat-336 for separation in connection with transmutation was first proposed by Los Alamos National Laboratory, LANL, in their baseline separation process /18-3/. In addition to Aliquat-336, the extractant HDEHP (bis-2-ethylhexyl phosphoric acid) was suggested to be used for separation of trivalent actinides from the lanthanides in a second stage of the process. This part of the process is based on the CTH-process, that earlier was developed at the Department of Nuclear Chemistry, CTH /18-4/.

During an initial literature survey it was found that there is a considerable lack of extraction data for Aliquat-336, which motivated an experimental programme. The first experimental results were presented in the annual report of 1993 /18-5/. In 1994 the extraction investigation of some trivalent elements with Aliquat-336 has been finished. The results were presented in a paper at the International Conference on Accelerator-Driven Transmutation Technologies and Applications (ADTT) that was held in Las Vegas USA, July 1994 /18-6/. The paper concluded that most of the trivalent elements attained the best extraction at about 2 M nitric acid, where Aliquat-336 is supposed to extract the actinides plutonium and neptunium according to the LANL process. Using 0.2 M Aliquat-336, lanthanum has the highest distribution ratio, about 0.05, among the trivalent elements. A first process calculation shows, however, that the trivalent elements not will interfere in the Aliquat-336 part of the process. During the experiments it was found that nitric acid will influence the distribution ratios to a large extent. It was therefore decided to investigate the extraction of nitric acid. By potentiometric titration of both the aqueous and organic phases using sodium hydroxide it was possible determine the extraction behaviour of nitric acid. In order to avoid a two-phase titration, the organic phases were titrated in ethanol. Mass balances showed to be better than 5% for all titrations. The extraction of nitric acid as function of the initial concentration of nitric acid in the aqueous phase is shown in Figure 18-1 and the extraction of nitric acid as a function of the Aliquat-336 concentration in the organic phase is shown in Figure 18-2. These results will later be used for a model approach of the Aliquat-336 extraction system.

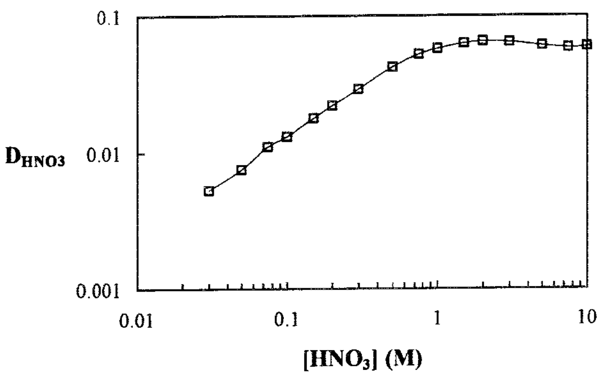


Figure 18-1. *Distribution ratios for nitric acid as a function of the initial nitric acid concentration using 0.20 M Aliquat-336 was dissolved in 1,3-diisopropyl benzene with 5% by volume dodecanol.*

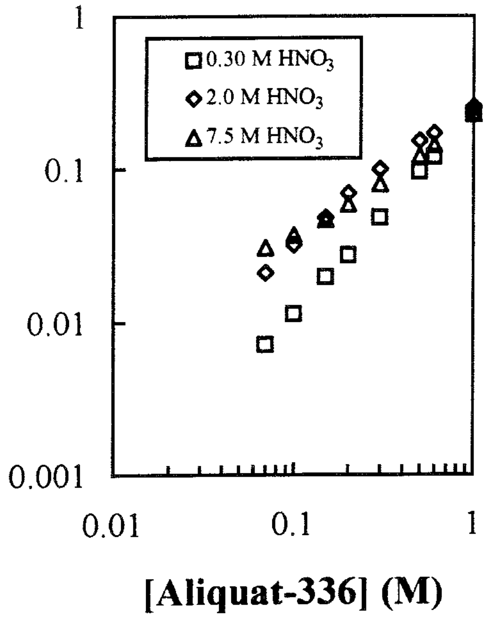


Figure 18-2. *Distribution ratios for nitric acid as a function of the Aliquat-336 concentration in the organic phase. Aliquat-336 was dissolved in 1,3-diisopropyl benzene with 5% by volume dodecanol.*

Amide extractants

In 1994 additional one PhD student was engaged in the project with the objective to look for new interesting extractants that can be used for partitioning. The work during 1994 has been focused on a literature survey for new extractants that can be of interest in connection with partitioning and transmutation. The literature survey is presented in /18-7 – 18-8/.

Extractants containing oxygen-, phosphorous-, nitrogen-, or sulphur-donor groups are considered as good extractants for separation of actinides. Most of the investigated extractants are efficient for both actinides and lanthanides. This is due to the formation of strong complexes between the hard acceptor f-series elements (actinides and lanthanides) and hard donor groups such as N-C=O and P=O.

In order to separate actinides and lanthanides there have been an interest to use lipophilic nitrogen donor extractants. Such extractants will extract the actinides better than lanthanides because of a stronger covalent character of the actinide-nitrogen bound. Nitrogen-oxygen containing extractants are not only interesting because of the possibility to separate actinides and lanthanides. They are also completely incinerable, which means that they do not contribute to any secondary waste. The different types of nitrogen containing extractants considered are monoamides, diamides and picolinamides. Most of the research with amides as extractants for actinides has been done at CEA in France.

The monoamide N,N-di(2-ethylhexyl)-3,3-dimethylbutyramide, see Figure 18-3A, is considered to have an optimal structure for extraction of tetra- and hexa-valent actinides, i. e. plutonium and uranium. It is considered to be possible to replace TBP (tributyl phosphate) in the current PUREX-reprocessing facilities with this monoamide, only requiring minor changes of the facilities. This monoamide have several advantages compared with TBP. It is completely incinerable and the extraction selectivity is higher for uranium compared with plutonium /18-9/.

Diamides or N,N-tetraalkylmalonamides, see Figure 18-3B, are efficient extractants for tri-, tetra- and hexa-valent actinides /18-10 – 18-11/, but they will also extract lanthanides. Other nitrogen containing complexing agents such as TPTZ (tri-pyridyl triazine) may be used in a second step of a separation procedure in order to separate the trivalent actinides from the lanthanides. It is considered to be possible to use diamides for advanced reprocessing, i. e. separation of actinides from HLLW. Pilot tests with diamides using high active waste solutions are planned at e. g. the European Transuranium Institute in Karlsruhe. In order to gain knowledge about diamides, an experimental programme has been initiated at the Department of Nuclear Chemistry, CTH. The molecule structure of the diamide is important for the extraction capability. The possibility to synthesize diamides, with alternative structures to the previously studied diamides, is investigated. Changing the basicity of the functional groups in the molecule, by changing the substitutents (i. e. the R-group in Figure 18-3B, may improve the extraction capability.

Picolinamides, see Figure 18-3C, are newly synthesized extractants with very interesting qualities. Picolinamides seems to extract all tri-, tetra- and hexa-valent actinides without any extraction of lanthanides. Musikas et al. /18-12/ found a separation ratio of about 100 between americium and neodymium. The separation from fission products seems also to be good. The molecular structure of picolinamides is still not optimized. By changing the substitutents (i. e. R, R' and R" in Figure 18-3C) it may be possible to optimize the extraction capability, the synthesis procedure and thereby the price. At the Department of Nuclear Chemistry, CTH, a study of the possibility to synthesize picolinamides with different substituents has been initiated.

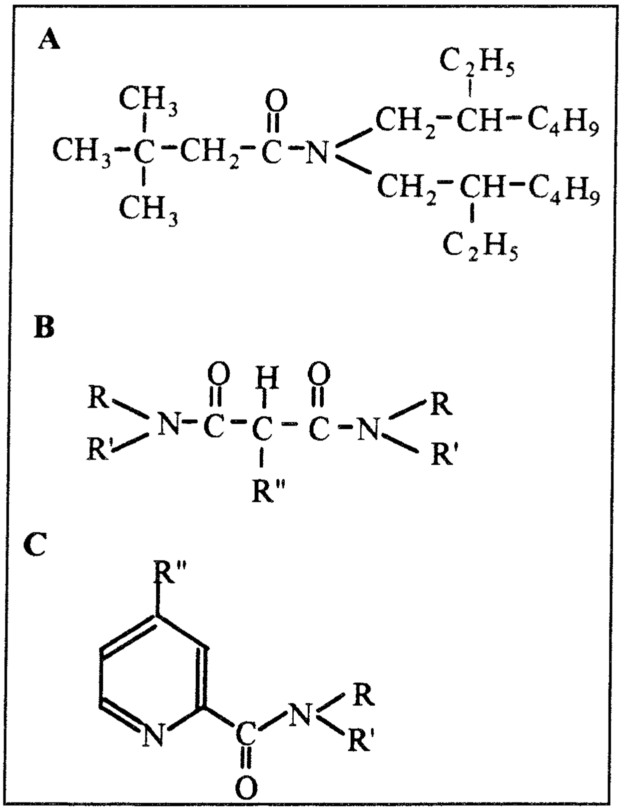


Figure 18-3. *Amide extractants*

A. *Monoamide (N,N-di-(2-ethylhexyl) 3,3, dimethylbutyramide).*
B. *Diamide, where R, R' and R" usually are alkyl-substitutents.*
C. *Picolinamide, where R, R' and R" usually are alkyl-substitutents.*

18.3 COLLABORATIONS ON PARTITIONING AND TRANSMUTATION

Sweden
A group was formed during 1993 with the objective to coordinate the Swedish research in partitioning and transmutation /18-13 – 18-14/. The coordination-group consists of representatives from universities and industry:

- Chalmers University of Technology, Göteborg, Prof J O Liljenzin, Dr M Skålberg,
- Royal Institute of Technology, Stockholm, Prof T Thedéen, Dr W Gudowski, Dr F Jannouch,
- Uppsala University, Prof H Condé,
- Manne Siegbahn Laboratory, Stockholm, Dr M af Ugglas,
- The Industrial Group, Dr C Mileikowsky.

The group has been involved in applications of funding for Swedish research in partitioning and transmutation and is also involved in arranging the second international conference on Accelerator-Driven Transmutation Technologies and Applications (ADTT) that is planned to be held in Sweden 1996.

Japan
Japan Atomic Energy Research Institute (JAERI), Department of Fuel Cycle Safety Research initiated a collaboration with the Department of Nuclear Chemistry, CTH, during 1993. It is agreed to exchange information, results and personnel between JAERI and CTH. In November 1994 professor Jan-Olov Liljenzin visited JAERI as a

guestscientist for one month. This initiated a closer collaboration between JAERI and CTH. One of the first topics studied in this collaboration, is the definition of permissible losses from partitioning.

France

A collaboration with Dr Claude Musikas was initiated in 1994. Dr Musikas, who is a former research director at CEA, was invited to the Department of Nuclear Chemistry, CTH, in July 1994, where he gave two seminars about amide extraction. It was agreed that Dr Musikas will follow the work with amide extractants at the Department of Nuclear Chemistry, CTH, and review the research programme for these extractants.

USA

An agreement between the Los Alamos National Laboratory, LANL, and the Department of Nuclear Chemistry, CTH, about exchange of information and results was formed in 1992. The research objectives for partitioning and transmutation have been changed at LANL since then and there is now only little interest in aqueous based partitioning at LANL. There is, however, one group working with Aliquat-336 at LANL who presented their results at the International Conference on Accelerator-Driven Transmutation Technologies and Applications (ADTT) that was held in Las Vegas USA, July 25-29, 1 994.

The cooperation between the KTH-group and Los Alamos National Laboratory initiated 2 years ago has further developed. Dr Charles Bowman, the head of ADTT-group visited Stockholm in May 94 and gave several seminars. Waclaw Gudowski, KTH, has visited Los Alamos preparing the program for Erik Möller studies there, and participating in Los Alamos research activities. For the time being we run the common projects in developing of the numerical procedures fol burn-up simulation coupled with the Monte-Carlo technique in order to be able to perform the integrated 3-D simulations on short-time neutron kinetics, reactivity calculation, system dynamics and long time burn-up calculations.

Others

In the first part of 1994 the cooperation between Rubbia's group at CERN and the KTH-group was established and the extensive analysis of the Rubbia's-system was performed and has been published.

The contacts were established by the KTH-group with scientists from Russia working in the frame of ISTC project: "Feasibility Study of Principal Technologies in Accelerator Based Conversion of Military Pu and Long-Lived Radioactive Waste". W Gudowski has participated in their workshop in October 94.

Initial discussions about collaboration within the frame of the European Community started during a visit by the CTH-group to Germany in November 1994.

18.4 GEOSCIENTIFIC APPRAISAL OF CONDITIONS AT LARGE DEPTHS

SKB is conducting complementary background research related to assessment of conditions at larger depths in the geosphere.

As part of this work, a project has been established with the overall objective is to improve understanding of parameters and processes at large depths in the geosphere, and of concern to waste disposal. The scope is multidisciplinary, and embraces geology, geohydrology, geophysics, geochemistry and geomechanics. The depth interval considered is roughly 1000-5000 m. At the present stage efforts are concentrated to the study of important characteristics of the geological medium. Implications with respect to possible disposal concepts and drilling development are followed up.

In a first phase, data from the literature on fundamental parameters are compiled and reviewed. Examples of parameters of interest are frequency of fractures and fracture zones, pore pressure, hydraulic conductivity, temperature and stress conditions. The focus is on information from continental shield areas, in order to obtain data that are relevant with respect to Swedish bedrock. As compared to the uppermost 1000 m, data from larger depths parameters are sparse. Important sources of from which information is gathered are, however:

- Deep boreholes.
- Deep mines.
- Seismic data, either from natural or induced ground seismic activity, or from seismic investigations.
- Other geophysical information.

As a introductory activity, an inventory of existing deep boreholes has been made. Research-oriented national deep drilling programmes have been conducted, or are currently underway, in a number of countries. These programmes have generated comprehensive geoscientific information. In particular data from deep holes penetrating crystalline formations in the former Soviet Union and in Germany have been found valuable in the present context.

In a second phase of the project, the intention is to integrate interpretation work, with the aim to develop descriptive models of the geosphere at depth. Important issues that should be addressed include the validity of using existing, localized data from large depths as a basis for more generalized descriptions, and the possibilities to extrapolate surface or near-surface information on various parameters to support predictions of conditions at large depths.

19 INTERNATIONAL COOPERATION

An important part of SKB's 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 SKB's BILATERAL AGREEMENTS WITH FOREIGN ORGANIZATIONS

SKB has signed formal bilateral agreements with the following organizations in other countries:

- USA – US DOE (Department of Energy),
- Canada – AECL (Atomic Energy of Canada Ltd) and ONTARIO HYDRO,
- Switzerland – NAGRA (Nationale Genossenschaft für die Lagerung Radioaktiver Abfälle),
- France – CEA (Commissariat à l'Energie Atomique), ANDRA, DCC and IPSN,
- EC – EUROATOM,
- Finland – TVO and IVO,
- 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 to two years 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 1994 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 AND ONTARIO HYDRO, CANADA

During 1994 SKB has reviewed parts of the AECL Environmental Impact Statement document. AECL has taken part in the Äspö Hard Rock Laboratory international meetings.

The cooperation has mainly been concentrated to the following issues:

- Natural analogues. Concerning the joint AECL/SKB work at Cigar Lake see section 15.5.4.
- Buffer and Backfill. SKB has together with ANDRA in France supported the AECL investigation of the bentonite backfill from the buffer mass heater test in URL, see section 15.4.2.
- Spent fuel. Cooperation work has during 1994 been performed with AECL Research and through the spent fuel workshop held in Canada, see section 15.1.

19.4 COOPERATION WITH NAGRA, SWITZERLAND

SKB has during 1994 had an extensive cooperation with NAGRA. Some of the items involved have been

- safety analysis and performance assessment,
- natural analogue studies, see section 15.5.1,
- underground construction material performance, see section 15.2.4 and 15.4.4,
- other long-lived waste than spent nuclear fuel, see section 16.2.2.

19.5 COOPERATION WITH CEA, ANDRA, DCC AND IPSN, FRANCE

The cooperation with organizations in France have mainly concerned the following issues:

- Natural analogues. SKB is engaged in the CEC sponsored natural analogue project in Oklo which CEA is managing, see section 15.5.2.
- Instruments. IPSN/CEA in Cadarache, France, has performed development work on a borehole probe (CHEMLAB), see section 17.2.
- Buffer and Backfill. As mentioned in section 19.3 above, ANDRA has participated in the work on bentonite buffer from the Canadian URL facility, see section 15.4.2.
- Other long-lived waste than spent nuclear fuel. Informal exchange of experience has been established, see section 16.2.2.

19.6 COOPERATION WITH TVO AND IVO, FINLAND

SKB has a very close cooperation with TVO in many fields of the research on nuclear waste management. Following areas have during 1994 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.
- Boring technology for full-scale deposition holes, see section 13.2.
- Documentation work on relevant information on buffer and backfill materials, standardized and recommended laboratory and field test methods etc, see section 15.2.1.
- SKB is following the investigations at a uranium mineralization in Palmottu as an observer, see section 15.5.3.

SKB and TVO scientists have during 1994 had numerous meetings where information and experience exchange have been carried out.

19.7 COOPERATION WITH JNFL, JAPAN

During 1994 the cooperation has been carried out through study visits at SKB facilities and through informal information exchange meetings.

19.8 COOPERATION WITH NIREX, UK

Though there is no formal agreement on general information exchange with NIREX, a lot of general cooperation work has been performed outside the Äspö HRL work in which NIREX is participating. The areas where this cooperation has been made are mainly:

- Natural analogue studies, see section 15.5.1.
- Other long-lived waste than spent nuclear fuel, see section 16.2.2.

19.9 COOPERATION WITH EURATOM, CEC

19.9.1 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.

19.9.2 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 has run from 1991-1994 and comprised temperature effects, ion strength effects, organic complexes, sorption, coprecipitation and coupled geochemical transport, see section 15.4.1.

19.9.3 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.

19.10 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 1994 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 1994 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 Terrestial, Urban and Aquatic Environment and Acquisition of Data for that Purpose" (VAMP), see section 15.6.

19.12 OTHER INTERNATIONAL COOPERATION

19.12.1 BIOMOVS

As indicated in section 15.6 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 1994 taken active part in the scenario definition work where the RES methodology work, see section 14.2, has been used.

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 15.3.4 .
Member from SKB: Lars-Olof Ericsson

19.13 INTERNATIONAL COOPERATION IN THE ÄSPÖ HARD ROCK LABORATORY

As is mentioned in Chapter 17 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 1994 /17-1/.

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 94,
- 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 SKB HRL Progress Reports,
- in SKB Djupförvar Projektrapporter,
- 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 1994 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 1994, see Appendix 2.

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

20.3 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 1994 about 10 700 references. The software used to manage the database is AskSam which has a powerful free-text search capability.

20.4 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.

20.4.1 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. It is run on a SUN (UNIX) workstation running INGRES. 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.

20.4.2 Structure

Like all relational databases the data tables are free tables that each contain a set of information. In this database there are 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" is 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".

20.4.3 Documentation

The data acquisition techniques are documented in technical reports. 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 and Users Guide are of course important

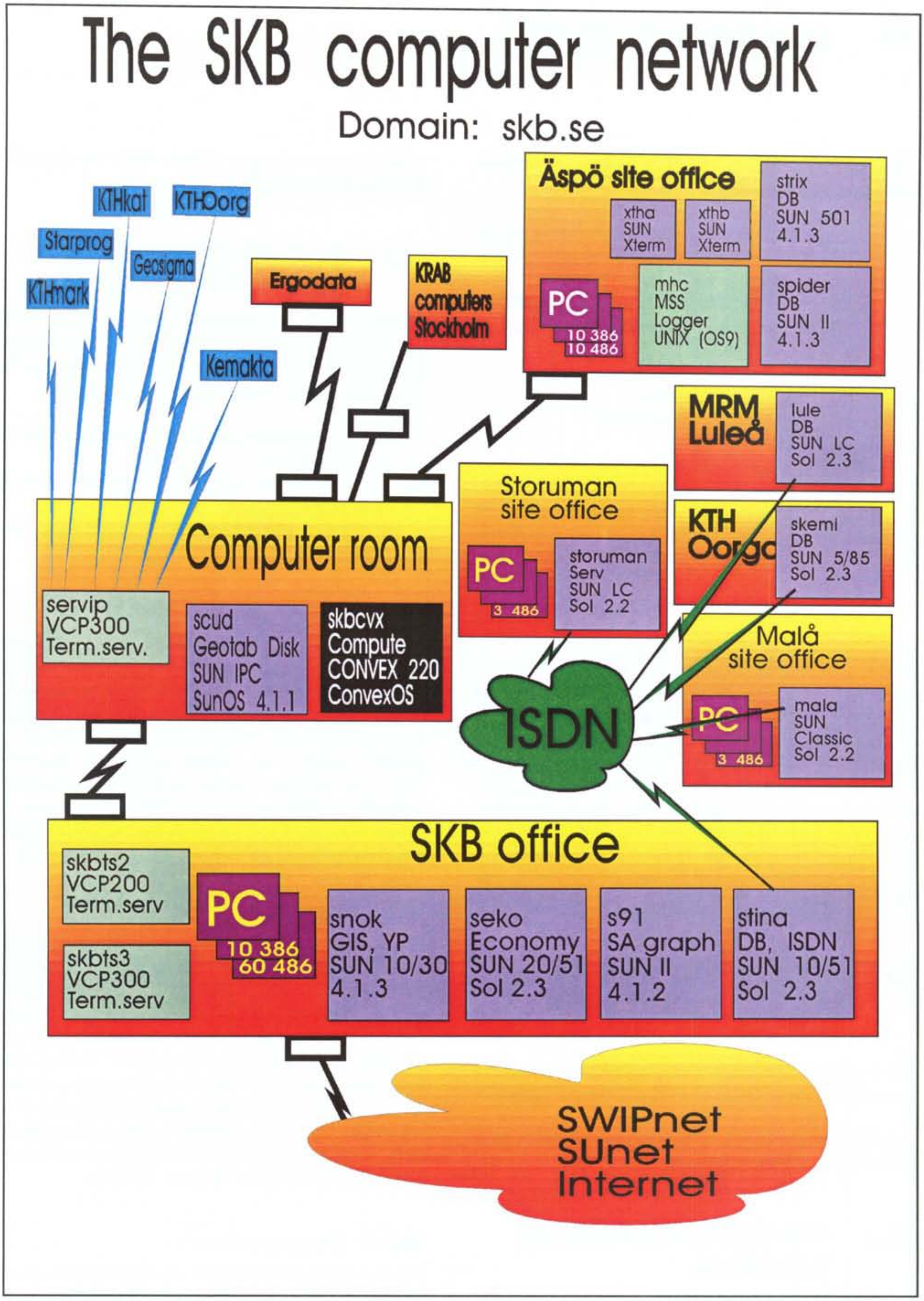


Figure 20-1. The SKB computer network.

documents for the occasional user. All documentation is in English.

20.4.4 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.

20.4.5 Statistics

Hydro 350000 1.6 m geof .47 geolo .05 kemi

Data are as mentioned above structured in "sciences", "subjects" and "methods" and tables. Currently there are about 500 tables containing ca 10 columns each and about 4.7 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. Data type of each column is described in the ca 450 "domains" defined in the system.

Total data volume is about 1.5 Gbyte.

20.4.6 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 are checked again by the investigator and signed off.

20.4.7 Future development

Due to difficulties in the process of gathering data, the Äspö laboratory has developed an activity oriented database application " SADB. This approach has shown to be more efficient when it comes to adding data to the database. Geotab and SADB will therefore be fused into a new database system " SICADA. This fusion is planned to be finalized in mid 1995.

20.5 COMPUTER SYSTEM AT SKB

An overview of the network and the computers at SKB is shown in Figure 20-1.

20.5.1 Computer Network – LAN and WAN

The computers owned by SKB are placed in six 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, the offices in Storuman and Malå 800 km north of Stockholm and at two consultants in KTH Stockholm and Luleå.

The computers at all sites are connected to a local area network (LAN type "thin wire ethernet"). The LANs in Stockholm and Äspö are connected via two pairs of ethernet bridges, operating over leased 64kbps lines. SUN workstations are routing the traffic via ISDN connections to Storuman, Malå, Luleå and KTH, 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. This facilitates implementation of new communication applications.

The SKB network is very open in the sense that an 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 (64 kbps) is mostly 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. All workstations and PCs have direct connection to the internet and the use of common tools as WWW is increasing.

As SKB is contracting several companies for different work in the computer system a wide area network (WAN) with serial communication 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.

20.5.2 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 has 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 1995 mail applications for PCs are planned.

20.5.3 Minisupercomputer

The CONVEX C220 is a 2-processor vector computer. Despite it's age (1989), it can still outperform most current workstations " especially when it comes to memory intensive floating point calculations. 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.

20.5.4 Workstations and measuring system

Currently 12 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 (GIS and CAD). One workstation will run the legal accounting system in 1995.

The different data media coped with are Exabyte tapes (2, 5 and 7 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.

20.5.5 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.

REFERENCES PART II

Chapter 12

12-1 See 5-1

12-2 SKI's evaluation of SKB's RD&D-Programme 92. Summary of reviews
Kjell Andersson, KARINTA-konsult.
SKI Teknisk Rapport 93:15, Mars 1993. (In Swedish)

12-3 SKI's evaluation of SKB's RD&D-Programme 92.
Review Report
SKI Technical Report 93:30, July 1993

12-4 SKI's evaluation of SKB's RD&D-Programme 92. Summary and Conclusions
SKI Technical Report 93:24, May 1993

12-5 Final Disposal of Spent Nuclear Fuel.
KASAMs Review of the Swedish Nuclear Fuel and Waste Management Co's (SKB's) RD&D-Programme 92
KASAM SOU 1993:67

12-6 Government decision 40. 1993-12-16.
Program för forskning m m angående kärnkraftavfallets behandling och slutförvaring. (In Swedish)

12-7 See 5-2

12-8 SKI's Evaluation of SKB's Supplement to RD&D-Programme 92
SKI Rapport 95:20, June 1995

Chapter 13

13-1 See 5-2

13-2 Almén K-E, Olsson P, Rhén I, Stanfors R, Wikberg P
January 1995
Äspö Hard Rock Laboratory – Feasibility and usefulness of site investigation methods. Experiences from the pre-investigation phase.
SKB Technical Report TR 94-24, Stockholm.

13-3 Whitaker S H, Brown A, Davidson CC, Gascoyne M, Lodha G S, Stevenson D R, Thorne G A, Tomson D
May 1994
AECL strategy for surface-based investigations of potential disposal sites and the development of a geosphere model for a site.
SKB Technical Report TR 94-18, Stockholm.

13-4 Öhberg A, Saksa P, Ahokas H, Ruotsalainen P, Snellman M
May 1994
Summary report of the experiences from TVO's site investigations.
SKB Technical Report TR 94-17, Stockholm.

13-5 SKB
Äspö Hard Rock Laboratory. Annual Report 1994.
May 1995
SKB Technical Report TR 95-07, Stockholm

13-6 Kou S, Lindqvist P-A, Tan X
May 1994
Conceptual model of crack structure in rock caused by mechanical excavation.
SKB Djupförvar Projektrapport PR 44-94-022, Stockholm

13-7 Lindqvist P-A, Suarez del Rio LM, Montoto M, Tan XC, Kou SQ
March 1994
Rock indentation database – Testing procedures, results and main conclusions.
SKB Djupförvar Projektrapport PR 44-94-023, Stockholm

Chapter 14

14-1 See 12-6
(In Swedish)

14-2 See 5-2

14-3 Andersson J (ed. and author), Carlsson T, Eng T, Kautsky F, Söderman E, Wingefors S
December 1989
The joint SKI/SKB scenario development project.
SKB Technical Report TR 89-35, Stockholm

14-4 Höglund L O, Winberg A
January 1994
Complemetary memo-text for FEPs defined in SKB TR 89-35 related to geochemistry and hydrogeology and visualization of FEPs in a tree structure.
SKB Arbetsrapport AR 94-11, Stockholm

14-5 Stephansson O, Hudson J A
August 1993
SKI/SKB FEPs identification and characterization via the 'Rock Engineering Systems' approach.
SKB Arbetsrapport AR 93-36, Stockholm

14-6 Eng T, Hudson J, Stephansson O, Skagius K, Wiborgh M
November 1994
Scenario development methodologies.
SKB Technical Report TR 94-28, Stockholm

14-7 Skagius K, Wiborgh M
September 1994
Testing of influence diagrams as a tool for scenario development by application on the SFL 3-5 repository concept.
SKB Arbetsrapport AR 94-47 Vol. 1 and 2, Stockholm

14-8 Final Storage of Spent Nuclear Fuel – KBS-3
1983
SKBF/KBS, Stockholm

14-9 See 5-4

14-10 Werme L
September 1990
Near field programme of the advance cold process canister.
SKB Technical Report TR 90-31, Stockholm

14-11 Hudson J A
Rock Engineering Systems: Theory and Practice.
Ellis Harwood, Chichester, UK, 1992

14-12 Widén H, Sellin P
September 1994
Performance of the SKB Copper/Steel Canister.
SKB Technical Report TR 94-14, Stockholm

14-13 Hoch A R, Sharland S M
October 1993
Assessment study of the stresses induced by corrosion in the Advanced Cold Process Canister.
SKB Technical Report TR 94-13, Stockholm

14-14 Wikramaratna R S, Goodfield M, Rodwell W R, Nash P J, Agg P J
November 1993
A preliminary assessment of gas migration from the Copper/Steel Canister.
SKB Technical Report TR 93-31, Stockholm

14-15 Lovius L, Eriksson L
January 1994
Development of a transient version of HYDRASTAR. HYDRASTAR ver 1.4.
SKB Arbetsrapport AR 94-12, Stockholm

14-16 SKB
User's guide to HYDRASTAR 1.4
February 1994
SKB Arbetsrapport AR 94-14, Stockholm

14-17 Morris S T, Cliffe K A
October 1994
Verification of HYDRASTAR: Analysis of hydraulic conductivity field and dispersion.
SKB Technical Report TR 94-21, Stockholm

14-18 Eriksson L O, Oppelstrup J
December 1994
Calibration with respect to hydraulic head measurements in stochastic simulation of groundwater flow – A numerical experiment using MATLAB.
SKB Technical Report TR 94-30, Stockholm

14-19 LaVenue A M, RamaRao B S, de Marsily G, Marietta M G
March 1995
Pilot point methodology for automated calibration of an ensemble of conditionally simulated transmissivity fields. 2. Application.
Water Resources Research 31(1995):3, pp. 495-516

14-20 Elert M, Grundfelt B, Widén H, Boghammar A
September 1994
Modelling of radionuclide transport in the far-field. Requirements for safety analysis.
SKB Arbetsrapport AR 94-44, Stockholm

14-21 Elert M, Neretnieks I, Kjellbert N, Ström A
April 1992
Description of the transport mechanisms and pathways in the far field of a KBS-3 type repository.
SKB Technical Report TR 92-09, Stockholm

14-22 Elert M
December 1994
Note on the use of PARTRACK-PHOENICS for performance assessment modelling.
SKB Arbetsrapport AR 94-57, Stockholm

14-23 Gylling B, Moreno L, Neretnieks I, Birgersson L
April 1994
Analysis of LPT2 using the Channel Network model.
SKB HRL International Cooperation Report ICR 94-05, Stockholm

14-24 Gylling B, Moreno L, Neretnieks I
February 1994
Data requirements for the channel network model.
SKB Djupförvar Projekt Rapport PR 44-94-014, Stockholm

Chapter 15

15.1-1 SKB Annual Report 1993
May 1994
SKB Technical Report TR 93-34, Stockholm

15.1-2 García Alonso J I, García Serrano J, Babelot J-F, Closset J-C, Nicolaou G, Koch L
1993
Laser ablation ICP-MS on spent nuclear fuel.
in: Application of Plasma Mass Spectrometry II.
Eds. G Holland and A N Eaton, Royal Society of Chemistry, London (1993) pp.193-204

15.1-3 Forsyth R S, Eklund U-B
1995
Spent nuclear fuel corrosion: The application of ICP-MS to direct actinide analysis.
SKB Technical Report TR 95-04
(Also presented at the 4th International Conference on Plasma Source Mass Spectrometry, University of Durham, UK, 11th-16th September 1994)

15.1-4 Skålberg M, Eliasson L, Skarnemark G, Torstenfelt B, Forsyth R, Holmér A, Winqvist B, Allard B
1988
Diffusion of radionuclides from spent oxide fuel into compacted bentonite.
Sci. Tot. Environ. 69 (1988) 347.

15.1-5 Albinsson Y, Forsyth R, Skarnemark G, Skålberg M, Torstenfelt B, Werme L
1990
Leaching/migration of UO_2-fuel in compacted bentonite.
Mat. Res. Soc. Symp. Proc. 176 (1990) 559.

15.1-6 Ramebäck H, Albinsson Y, Skålberg M, Werme L
1994
Release and migration of ^{90}Sr from spent UO_2-fuel in bentonite clay.
Radiochimica Acta 66/67 (1994) 405

15.1-7 Werme L O, Forsyth R S
1989
The SKB Spent Fuel Corrosion programme.
SKB Technical report TR 89-14, Stockholm

15.1-8 Ramebäck H
1994
Analysis of β^--emitting radionuclides: ^{90}Sr and ^{99}Tc. Applied in spent nuclear fuel research.
Licentiate Thesis.
Dept. of Nuclear Chemistry, Chalmers University of Technology, Göteborg, Sweden

15.1-9 Eriksen T E, Eklund U-B, Werme L, Bruno J
1995
Dissolution of irradiated fuel. A radiolytic balance study.
Submitted for publication in Journal of Nuclear Materials.

15.1-10 Casas I, Bruno J, Cera E, Finch R J, Ewing R C
1994
Kinetic and thermodynamic studies uranium minerals. Assessment of the long-term evolution of spent nuclear fuel.
SKB Technical Report TR 94-16, Stockholm

15.2-1 Pusch R, Karnland O, Hökmark H
1990
GMM – A general microstructural model for qualitative and quantitative studies of smectite clays.
SKB Technical Report TR 90-43, Stockholm

15.2-2 Pusch R
1994
Gas transport through smectitic clay and crystalline rock. A state-of- the-art report on gas release from a KBS-3 type repository.
SKB Arbetsrapport AR 94-61, Stockholm

15.2-3 Börgesson L, Johanesson L-E, Sandén T, Hernelind J
1995
Modelling of the physical behaviour of water saturated clay barriers. Laboratory tests, material models and finite element application.
SKB Technical Report (in preparation)

15.2-4 Börgesson L
1995
Swelling and homogenization of bentonite granules in buffer and backfill. Finite element modelling of the microstructural behaviour.
SKB Arbetsrapport (in print)

15.2-5 Hökmark H
1995
Smectite to illite conversion in bentonite buffer. Application of a technique for modelling degradation processes.
SKB Arbetsrapport AR 95-07, Stockholm

15.2-6 Karnland O, Warfinge P, Pusch R
1995
Smectite-to-illite conversion models. Factors of importance for KBS3 conditions.
SKB Arbetsrapport (in press)

15.2-7 Karnland O, Pusch R, Sandén T
1994
Concerning bentonite/cement interaction, 4 months tests.
SKB Arbetsrapport AR 94-22, Stockholm

15.2-8 Börgesson L, Hernelind J
1994
DECOVALEX Test case 3. Calculation of the Big-Ben experiment. Coupled modelling of the thermal, mechanical and hydraulic behaviour of water-unsaturated buffer material in a simulated deposition hole.
SKB Arbetsrapport AR 94-49, Stockholm

15.2-9 Karnland O, Pusch R
1995
Cementation phenomena of importance for the performance of smectite clay buffers in HLW repositories.
Paper to be presented at The Fifth International Conference on Radioactive Waste Management and Environmental Remedation, ICEM95, in Berlin, Germany September 3-8, 1995

15.2-10 Johanesson L-E, Börgesson L, Sandén T
1995
Compaction of bentonite blocks. Development of technique for industrial production of blocks which are manageable by man.
SKB Technical Report (in press)

15.3-1 Hakami E, Larsson E
1994
Geometry and hydraulic characteristics of rock fractures – Laboratory experiments with water flow in natural fractures.
SKB Arbetsrapport AR 94-18

15.3-2 Larson S-Å, Tullborg E-L
1994
Tectonic regimes in the Baltic shield during the last 1200 Ma – A review.
SKB Technical Report TR 94-05

15.3-3 Henkel H, Roslund M
1994
First order steep shearzones in Sweden. (in Swedish)
SKB Arbetsrapport AR 94-56

15.3-4 Wannäs K O, Flodén T
1994
Tectonic framework of the Hanö Bay area, southern Baltic Sea.
SKB Technical Report TR 93-18

15.3-5 Röshoff K
1994
Generisk studie av sprickbildningsmekanismer. Kort om bildning, tillväxt och uppträdande. Delrapport nr 2.
SKB Arbetsrapport AR 94-27

15.3-6 Johansson J, Stille H
1994
PM angående lager för utbränt kärnbränsle – en bergprojektörs synpunkter.
SKB Arbetsrapport AR 94-20

15.3-7 Börgesson L, Hernelind J
1994
DECOVALEX – Test Case 3. Calculation of the Big Ben Experiment.
SKB Arbetsrapport AR 94-49

15.3-8 Börgesson L, Hernelind J
1994
DECOVALEX – Test Case 2. Calculation of the Fanay-Augères THM test.
SKB Arbetsrapport AR 94-55

15.3-9 Claesson J, Follin S, Hellström G
1994
DECOVALEX – Test Case 6. High pressure testing in fractured crystalline rock.
SKB Arbetsrapport AR 94-48

15.3-10 Andersson O
1994
Deep Drilling KLX02. Drilling and documentation of a 1700 m deep borehole at Laxemar, Sweden.
SKB Technical Report TR 94-19

15.3-11 Lindblad K (ed.)
1994
Djupborrning KLX02 – Etapp 1. Lilla Laxemar, Oskarshamns kommun.
Tekniska dokument i samband med borrning.
SKB Arbetsrapport AR 94-16

15.3-12 Follin S
1994
Djupborrning KLX02 – Etapp 1. Lilla Laxemar, Oskarshamns kommun.
Evaluation of the hydraulic testing of KLX02.
SKB Arbetsrapport AR 94-21

15.3-13 Munier R
1994
Drilling KLX02 – Phase 2. Lilla Laxemar, Oskarshamns kommun. Description of geological structures in and near boreholes KLX01 and KLX02, Laxemar.
SKB Arbetsrapport AR 94-23

15.3-14 Carlsten S
1994
Drilling KLX02 – Phase 2. Lilla Laxemar, Oskarshamns kommun. Correlations of radar reflectors between borehole KLX01 and KLX02.
SKB Arbetsrapport AR 94-28

15.3-15 Andersson O
1994
Djupborrning KLX02 – Etapp 1. Lilla Laxemar, Oskarshamns kommun. Projektbeskrivning och administration.
SKB Arbetsrapport AR 94-34

15.3-16 Andersson O
1994
Djupborrning KLX02 – Etapp 1. Lilla Laxemar, Oskarshamns kommun. Utvalda tekniska rådata.
SKB Arbetsrapport AR 94-36

15.3-17 Kornfält K, Wikman H
1994
Drilling KLX02 – Phase 2. Lilla Laxemar, Oskarshamns kommun. Petrological classification of core samples and drill cuttings.
SKB Arbetsrapport AR 94-50

15.3-18 Andersson O
1994
Djupborrning KLX02 – Etapp 1. Lilla Laxemar, Oskarshamns kommun. Projektprogram och metodbeskrivningar.
SKB Arbetsrapport AR 94-35

15.3-19 Wikberg P, Skårman C, Laaksoharju M
1994
Groundwater chemistry and transport of solutes.
Evaluation of the data from tunnel section 2265-2874 m.
SKB HRL Progress Report 25-94-21

15.3.20 Wikström L, Björklund A
1994
Trace elements in waters of low-conductivity rocks in the Äspö Hard Rock Laboratory.
SKB HRL Progress Report 25-94-28

15.3-21 Wallin B, Peterman Z
1994
SKB/DOE Hard Rock Laboratory Studies.
Task 3. Geochemical investigations using stable and radiogenic isotopic methods.
SKB HRL International Cooperation Report ICR 94-06

15.3-22 Ittner T, Gustafsson E
1994
Groundwater chemistry and transport of solutes. Presentation of surface borehole data during pre-investigation and tunnel construction.
SKB HRL Progress Report 25-94-38

15.3-23 Wikberg P (chairman), Banwart S (proc. ed.)
1994
Proceedings of the Äspö International Geochemistry Workshop,
June 2-3, 1994, Äspö Hard Rock Laboratory.
SKB HRL International Cooperation Report ICR 94-13

15.3-24 See 13-5

15.3-25 Malmström M, Banwart S, Duro L, Wersin P, Bruno J
1995
Biotite and chlorite weathering at 25°C. The dependence of pH and (bi)carbonate on weathering kinetics, dissolution stoichiometry, and solubility; and the relations to redox conditions in granitic aquifers.
SKB Technical Report TR 95-01

15.3-26 Laaksoharju M, Smellie J, Nilsson A-C, Skårman C
1995
Groundwater sampling and chemical characterisation of the Laxemar deep borehole KLX02.
SKB Technical Report TR 95-05

15.3-27 Wallin B
1995
Palaeohydrological implications in the Baltic area and its relation to the groundwater at Äspö, south-eastern Sweden – A literature study.
SKB Technical Report TR 95-06

15.3-28 See 13-5

15.4-1 Östhol E
1994
Some processes affecting the mobility of thorium in natural groundwaters.
Doctoral thesis, Dept. of Inorganic Chemistry, Royal Institute of Technology, TRITA-OOK-1038, Stockholm

15.4-2 Allard B, Karlsson F, Neretnieks I
1991
Concentrations of particulate matter and humic substances in deep groundwaters and estimated effects on the adsorption and transport of radionuclides.
SKB Technical Report TR 91-50

15.4-3 Karlsson F, Allard B, Hummel W, Sargent F P, Vieno T, Voinis S, Merceron T, Yoshikawa H
1994
Natural organic substances in granitic groundwater and their implications for nuclear waste disposal.
In "Workshop of Binding Models Concerning Natural Organic Substances in Performance Assessment", held jointly by OECD/NEA and PSI in Bad Zurzach, Switzerland, 14-16 September 1994

15.4-4 Valarié I
1994
Physico-chemical properties of some aquatic fulvic acids – functional groups and stability. Doctoral thesis, Dept. of Water and Environmental Studies, Linköping University

15.4-5 Nordén M
1994
The complexation of some radionuclides with natural organics – implications for the radioactive waste disposal. Doctoral thesis, Dept. of Water and Environmental Studies, Linköping University

15.4-6 Nordén M, Ephraim J H, Allard B
1994
The influence of fulvic acid on the adsorption of europium and strontium by alumina and quartz: Effects of pH and ionic strength.
Radiochemica Acta, Vol 65, pp 265-270

15.4-7 Wan J, Wilson J L
1994
Visualization of the role of the gas-water interface on the fate and transport of colloids in porous media.
Water Resources Research, Vol 30, No 1, pp 11-23

15.4-8 Wan J, Wilson J L
1994
Colloid transport in unsaturated porous media.
Water Resources Research, Vol 30, No 4, pp 857-864

15.4-9 Pedersen K, Ekendahl S
1990
Distribution and activity of bacteria in deep granitic groundwaters of southeastern Sweden.
Microb Ecol, Vol 20, pp 37-52

15.4-10 Pedersen K, Ekendahl S
1992
Incorporation of CO_2 and introduced organic compounds by bacterial populations in groundwater from deep crystalline bedrock of the Stripa mine.
Journal of General Microbiology, Vol 138, pp 369-376

15.4-11 Vannerberg K
1994
Modelling of sorption mechanism.
Licentiate thesis, Dept. of Nuclear Chemistry, Chalmers University of Technology, Göteborg

15.4-12 Eriksen T E, Daquing Cui
1994
Experimental study of strontium sorption on fissure filling material.
SKB Technical Report TR 94-27

15.4-13 Wieland E, Wanner H, Albinsson Y, Wersin P, Karnland O
1994
A surface chemical model of the bentonite-water interface and its implication for modelling the near-field chemistry in a repository for spent fuel.
SKB Technical Report TR 94-26

15.4-14 Wanner H, Albinsson Y, Wieland E
1994
Project Cesium – An ion exchange model for the prediction of distribution coefficients of cesium in bentonite.
SKB Technical Report TR 94-10

15.5-1 Alexander W R (Editor)
1992
A natural analogue study of the Maqarin hyperalcaline groundwaters. Source term description and thermodynamic database testing.
NAGRA Technical Report NTB 91-10

15.5-2 Khoury H N, Salameh E, Clark I D, Fritz P, Bajjali W, Milodowski A E
1992
A natural analogue of high pH cement pore waters from the Maqarin area of northern Jordan I: Introduction to the site.
Journal of Geochemical Exploration, Vol 46, pp 117-132

15.5-3 Alexander W R, Dayal R, Eagleson K, Eikenberg J, Hamilton E, Linklater C M, McKinley I G, Tweed C J
1992
A natural analogue of high pH cement pore waters from the Maqarin area of northern Jordan II: Results of predictive geochemical calculations.
Journal of Geochemical Exploration, Vol 46, pp 133-146

15.5-4 Clark I D, Dayal R, Khoury H N
1994
The Maqarin (Jordan) natural analogue for ^{14}C attenuation in cementitious barriers.
Waste Management, Vol 14, No 5, pp 467-477

15.5-5 Cowan G A
1978
Migration paths for Oklo reactor products and application to the problem of geological storage of nuclear wastes.
IAEA-TC-119, International Atomic Energy Agency, Vienna, pp 693-699

15.5-6 Blanc P-L
1994
Oklo, natural analog for transfer processes in a geological repository.
Mirage Project – 3rd Phase, Final meeting report, Brussels, 15-16-17 November, 1994 (to be published in the EUR report series)

15.5-7 von Maravic H
1993
Oklo Working Group meeting – Proceedings of the second joint CEC-CEA progress meeting held in Brussels on 6 and 7 April 1992.
CEC report EUR14877EN

15.5-8 Winberg A, Smellie J A T
1993
Bangombé area descriptive geological and hydrogeological model.
Working document prepared for CEC/CEA/SKB Oklo Natural Analogue Study. SKB/Conterra AB

15.5-9 Toulhoat P, Gallien J P, Louvat D, Moulin V, l'Henoret P, Guerin R, Ledoux E, Gurban I, Smellie J, Winberg A
1993
Present-time migration around the Oklo Natural Reactor. Evidence of uranium isotopic anomalies in groundwaters close to the reactor zones.
Manuscript prepared for the Migration 1993 conference

15.5-10 Toulhoat P, Gallien J P, l'Henoret P
1992
Far field hydrogeochemistry in the Oklo reactor area (Gabon).
In Oklo Working Group meeting – Proceedings of the second joint CEC-CEA progress meeting held in Brussels on 6 and 7 April 1992.
CEC report EUR14877EN

15.5-11 Naudet R, Renson C
1975
Résultats des analyses systematiques de teneurs isotopiques de l'urnium.
IAEA-SM-204, International Atomic Energy Agency, Vienna, pp 265-291

15.5-12 Bros R, Turpin L, Gauthier-Lafaye F, Holliger Ph, Stille P
1993
Occurrence of naturally enriched ^{235}U: Implications for plutonium behaviour in natural environments.
Geochim. Cosmochim. Acta, Vol. 57, pp 1351-1356

15.5-13 Blanc P-L
1995
Oklo, Natural Analogue for a Radioactive Waste Repository: A Summary of the Main Results.
Report prepared for an Oklo discussion meeting held in Paris, January 9-10, 1995

15.5-14 Eberly P, Janeczek J, Ewing R C
1994
Petrographic Analysis of Samples from the Uranium Deposit at Oklo, Republic of Gabon.
Radiochimica Acta (in press)

15.5-15 Blomqvist R, Jaakkola T, Niini H, Ahonen L
1991
The Palmottu analogue project. Progress report 1990.
GTK Report YST-73, Espoo

15.5-16 Suksi J, Ahonen L, Niini H
1992
The Palmottu analogue project. Progress report 1991.
GTK Report YST-78, Espoo

15.5-17 Ahonen L, Blomqvist, Suksi J
1993
The Palmottu analogue project. Progress report 1992.
GTK Report YST-82, Espoo

15.5-18 Ruskeeniemi T, Suksi J, Niini H, Blomqvist R
1994
The Palmottu analogue project. Progress report 1993.
GTK Report YST-85, Espoo

15.5-19 Carlsten S
1993
Borehole radar measurements at the Palmottu natural analogue study site, Finland 1993.
SKB Arbetsrapport AR 93-39, Stockholm

15.5-20 Andersson J-E, Jönsson S, Nyberg G
1994
Flow meter logging in the Palmottu test site.
Geosigma Report 94048, Uppsala

15.5-21 Cramer J, Smellie J (Editors)
1994
Final report of the AECL/SKB Cigar Lake analogue study.
SKB Technical Report TR 94-04 (Also available as AECL-10851)

15.5-22 Lagerblad B
1995
Gammal betong blir bara bättre. Presentation (in Swedish) at "CBIs informationsdag 1995" in Stockholm, March 16, 1995. Swedish Cement and Concrete Research Institute, ISSN 0284-6896, pp 63-68

15.6-1 FINAL REPORT. BIOMOVS.
March 1993
Technical report 15, SSI, Stockholm

15.6-2 Bergström U, Sundblad B, Nordlinder S
Models for predicting radiocaesium levels in lake water and fish.
In Nordic radioecology. The transfer of radionuclides through Nordic ecosystems to man. Elsevier Science Publ to be published

15.6-3 NEA PSAG: PSACOIN
1993
Level 1B Intercomparison. Ed by R A Klos, J E Sinclair, C Torres, U Bergström, D A Galsson.
NEA/OECD, Paris

15.6-4 Smellie J, Laaksoharju M
November 1992
Final evaluation of the hydrochemical pre-investigations in relation to geological and hydraulic conditions.
SKB Technical Report TR 92-31, Stockholm

15.6-5 Landström O, Aggeryd I
1994
Chemical composition of sediments from the Äspö area and interaction between biosphere and geosphere.
SKB Arbetsrapport AR 94-13, Stockholm

15.6-6 Nordlinder S, Sundblad B, Stiglund Y
1994
The importance of different types of recipients for the individual doses from inflow of radionuclides via the groundwater.
SKB Arbetsrapport AR 94-25, Stockholm

15.6-7 Aggeryd I, Sundblad B, Landström O, Mathiasson L, Stiglund Y
1993
Inventering av platsers lämplighet för studier av naturliga analogier.
SKB Arbetsrapport AR 94-41, Stockholm, Studsvik ES93/57

15.6-8 Mathiasson L
1994
Fältmätningar 1993 inom Gideåområdet.
SKB Arbetsrapport AR 94-24, Stockholm

15.6-9 Puigdomenech I, Bergström U
Calculated Distribution of Radionuclides in Soils and Sediments.
To be published in Nuclear Safety

15.6-10 IAEA
Effects of ionizing radiation on plants and animals at levels implied by current radiation protection standards.
STI/DOC/10/332, 1992

15.6-11 Jones C
November 1994
Methods for assessments of the effect of high-level waste disposal on populations of species other than man – an overview.
Kemakta Arbetsrapport AR 93-15

15.6-12 Jones C
Radionuclide contents in the biosphere in Sweden – a review of information.
Kemakta Arbetsrapport AR 94-01.
To be published as SKB Technical Report

15.6-13 Carbol P, Skålberg M, Skarnemark G
Results of measurements of shallow and deep groundwaters sampled within the Gideå site during the period October 1986 – June 1991.
To be published as SKB Arbetsrapport

15.6-14 Sundblad B, Nordqvist R, Jönsson S
1994
The turnover of 137Cs within a forest ecosystem described by two modelling approaches – Gideå study site.
The Science of the total environment 157 (1994): pp. 139-146

15.6-15 Carbol P, Skålberg M, Skarnemark G
Source term of radionuclides deposited within the Gideå site after the Chernobyl accident.
To be published as SKB Arbetsrapport

15.6-16 Carbol P, Skålberg M, Skarnemark G
1994
Activity analyses of soil profiles sampled within the Gideå site during the period October 1986 – June 1991.
SKB Arbetsrapport AR 94-37, Stockholm

15.6-17 Landström O, Aggeryd I, Mathiasson L, Sundblad B
1994
Chemical composition of sediments from the Äspö area and interaction between biosphere and geosphere.
SKB Arbetsrapport AR 94-13, Stockholm

15.6-18 Sundblad B, Mathiasson L
1994
Recipient studies at the Äspö Hard Rock Laboratory.
SKB Arbetsrapport AR 94-52, Stockholm

Chapter 16

16-1 PLAN 93
1993
Costs for management of the radioactive waste from the nuclear power production.
SKB Technical Report TR 93-28, Stockholm

16-2 Lindgren M, Brodén K, Carlsson J, Johansson M, Pers K
1994
Low and intermediate level waste for SFL 3-5.
SKB Arbetsrapport AR 94-32, Stockholm

16-3 SKI
1995
The SKI repository performance assessment project Site-94.
SKI Report (in preparation), Stockholm

16-4 See 14-7

16-5 Edwards A L
1969
TRUMP-A computer program for transient and steady state temperature distribution in multidimensional systems.
National Technical Information Service, National Bureau of Standards, Springfield, Va, USA

16-6 Lindgren M, Pers K
1994
Radionuclide release from the near-field of SFL 3-5. A preliminary study.
SKB Arbetsrapport AR 94-54, Stockholm

16-7 Wiborgh M (ed.)
1995
Prestudy of final disposal of long-lived low and intermediate level waste.
SKB Technical Report TR 95-03, Stockholm

Chapter 17

17-1 See 13-5

17-2 Stanfors R, Erlström M, Markström I
1991
Äspö Hard Rock Laboratory. Overview of the investigations 1986-1990.
SKB Technical Report TR 91-20, Stockholm

17-3 Almén K-E, Zellman O
1991
Äspö Hard Rock Laboratory. Field investigation methodology and instruments used in the pre-investigation phase, 1986-1990.
SKB Technical Report TR 91-21, Stockholm

17-4 Wikberg P, Gustafson G, Rhén I, Stanfors R
1991
Äspö Hard Rock Laboratory. Evaluation and conceptual modelling based on the pre-investigations 1986-1990.
SKB Technical Report TR 91-22, Stockholm

17-5 Gustafson G, Liedholm M, Rhén I, Stanfors R, Wikberg P
1991
Äspö Hard Rock Laboratory. Predictions prior to excavation and the process of their validation.
SKB Technical Report TR 91-23, Stockholm

17-6 Smellie J, Laaksoharju M
1992
Äspö Hard Rock Laboratory. Final evaluation of the hydrogeochemical pre-investigations in relation to existing geologic and hydraulic conditions.
SKB Technical Report TR 92-31, Stockholm

17-7 Rhén I, Svensson U (eds), Andersson J-E, Andersson P, Eriksson C-O, Gustafsson E, Ittner and Nordqvist R
1992
Äspö Hard Rock Laboratory. Evaluation of the combined long-term pumping and tracer test (LPT2) in borehole KAS06, SKB.
SKB Technical Report TR 92-32, Stockholm

17-8 Svensson U
1994
Calculations of pressure, flow and salinity fields using measured inflow to the tunnel.
SKB HRL Progress Report PR 25-94-27

17-9 Hakami E
1994
Pore Volume Characterization. Aperture distribution of a highly conductive single fracture.
SKB HRL Progress Report PR 25-94-30

17-10 Olsson O, Stanfors R, Ramqvist G, Rhén I
1994
Localization of experimental sites and layout of turn 2. Results of investigations.
SKB HRL Progress Report PR 25-94-14

17-11 Bäckblom G, Olsson O
1994
Program for tracer retention understanding experiments.
SKB HRL Progress Report PR 25-94-24

17-12 Winberg A
1994
Tracer Retention Understanding Experiments (TRUE). Test plan for the first TRUE Stage.
SKB HRL Progress Report PR 25-94-35

17-13 Gale J E
1994
Assessment of the coupled effects of degassing and excavation fracture deformation on drift inflows – feasibility study and preliminary experiments – single fractures.
SKB HRL Progress Report PR 25-94-29

17-14 Banwart S, Gustafsson E, Laaksoharju M, Nilsson A-C, Tullborg E-L and Wallin B
1994
Large scale intrusion of shallow water into a vertical fracture zone in crystalline bedrock: Initial hydrochemical perturbation during construction at the Äspö Hard Rock Laboratory, southeastern Sweden.
Water Resource Research, 30, (6), 1747-1763

17-15 Bäckblom, G, Börgesson, L
1994
Programme for backfill tests and Äspö Prototype Repository.
SKB HRL Progress Report PR 25-94-36

17-16 Rosén L, Gustafson G
1994
Suitable near-field design. Stage 1, Application of a Markov-Bayes geostatistical model.
SKB HRL Progress Report PR 25-94-33

Chapter 18

18-1 Möller E, Gudowski W
July 1994
The neutronics of an accelerator-driven energy amplifier.
International Conference on Accelerator Driven Transmutation Technologies, Las Vegas, 25-29 July 1994

18-2 Liljenzin J O
November 1994
Actinide chemistry for transmutation purposes.
Paper presented at the Specialist's Meeting of Chemistry and Technology of Actinide Elements, Kyoto University Research Reactor Institute at Kumatori, November 17, 1994

18-3 Jarvinen G D, Marsh S F, Schroeder N, Smith B F, Villarreal R, Walker R B, Yarbo S L, Yates M A
1992
Baseline actinide blanket processing for the Accelerator Transmutation of Waste (ATW) program.
Los Alamos National Laboratory Report LA-UR-92-63

18-4 Liljenzin J O, Skålberg M
1991
The CTH-process for actinide and fission product separation from HLLW.
Proceeding Specialists Meeting on Accelerator-Driven Transmutation Technology for Radwaste and Other Applications, 24-28 June 1991, Saltsjöbaden, Stockholm, Statens Kärnbränslenämnd, Sweden, Los Alamos National Laboratory, USA, 1991. LA-12205C Conference, SKN Report No. 54

18-5 SKB Annual Report 1993
May 1994
Chapter 18.
SKB Technical Report TR 93-34, Stockholm

18-6 Landgren A, Liljenzin J O, Skålberg M
July 1994
The extraction of some trivalent elements with Aliquat-336.
Proceeding International Conference on Accelerator-Driven Transmutation Technologies and Applications (ADTT), Las Vegas, USA, July 25-29, 1994

18-7 Spjuth L
December 1994
Abstract from the literature report "Interesting Extractants for the Separation of Actinides, Version 1.0".
Internal Report, Department of Nuclear Chemistry, Chalmers University of Technology, Göteborg

18-8 Spjuth L
December 1994
Litteratursammanställning av några extraktionsreagens för separation av aktinider, Version 1.0.
Internal Report, Department of Nuclear Chemistry, Chalmers Tekniska Högskola, Göteborg (In Swedish)

18-9 Gasparini G M, Grossi G
1986
Long chain disubstituted aliphatic amides as extractant agents in industrial applications of solvent extraction.
Solvent Extr. Ion Exch. 4(6) (1986), p. 1233

18-10 Musikas C
1987
Solvent extraction for the chemical separations of the 5f elements.
Inorg. Chim. Acta, 140 (1987), p. 197

18-11 Musikas C, Bourges J, Madic C, Cuillerdier C, Adnet J M
1991
Recent progress in the chemical separations for the ACTINEX-project.
Proceeding OECD/NEA Workshop on Partitioning of Actinides and Fission products, Mito, Japan

18-12 Musikas C, Cuillerdier C, Coutin C
April 1992
Picolinamides, A possible family of extractants for the one step actinide (VI), (IV) and (III) separation from the spent nuclear fuel dissolution liquors.
Proceeding 22'emes Journées des actinides, Mérible, France

18-13 Condé H, Bäcklin A, Carius S, Traneus E, Gudowski W, Möller E, Thedéen T, Liljenzin J O, Skålberg M, af Ugglas M, Mileikowsky C, Tenerz E, Hannerz K, Sundqvist C, Pind Ch
July 1994

Accelerator-driven nuclear synergetic system – An overview of the research activities in Sweden.

Proceeding International Conference on Accelerator-Driven Transmutation Technologies and Applications (ADTT), Las Vegas, USA, July 25-29, 1994

18-14 Liljenzin J O, Skålberg M, Gudowski W, Thedéen T, Condé H, Carius S, af Ugglas M, Mileikowsky C, Tenerz E, Hannerz K, Sundqvist C, Pind Ch
1994

Planerad svensk forskningsverksamhet inom acceleratorbaserad transmutation av kärnavfall och energiproduktion.

Svenska Fysikersamfundets tidskrift, f, Fysik Aktuellt, Nr 2, p. 26-40, maj 1994 (In Swedish)

SKB ANNUAL REPORT 1994

Part III

Appendices

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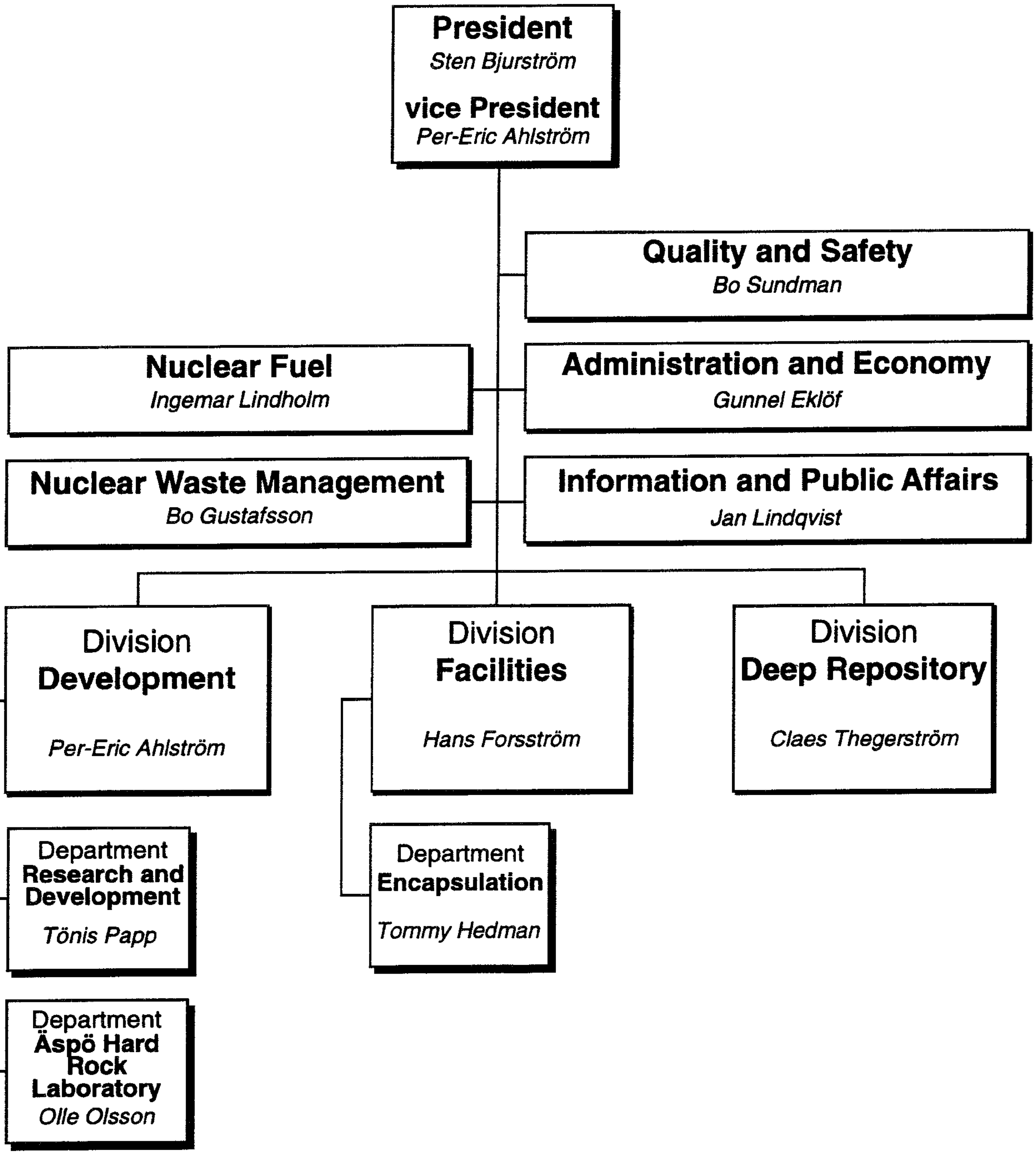
ORGANIZATION CHART FOR SKB
APRIL 1995



SKB TECHNICAL STAFF

Note: Several persons of the staff work in more than one function; sometimes these functions belong to different divisions or departments.

DEVELOPMENT

Per-Eric Ahlström	Vice President, Director Development
Göran Bäckblom	Äspö Evaluation, Project Manager Overview Studies
Monica Hammarström	International Cooperation
Fred Karlsson	Chemistry, Natural Analogues, Other Waste Types
Peter Wikberg	Geochemistry, Groundwater Chemistry

Research and Development:

Tönis Papp	Research Director
Lars O Ericsson	Geoscience
Allan Hedin	Uncertainties – Safety Analysis
Lena Morén	Scenario – Safety Analysis
Sverker Nilsson	Biosphere – Safety Analysis, Computers, Databases
Virginia Oversby	Natural Analogues
Patrik Sellin	Near-field – Safety Analysis
Kastriot Spahiu	Nuclear Fuel
Anders Ström	Far-field – Safety Analysis

Äspö Hard Rock Laboratory:

Olle Olsson	Director of Äspö Hard Rock Laboratory
Olle Zellman	Plant Manager Äspö
Leif Jirhem	Project Administrator, Manager Experimental Services
Katinka Klingberg	Project Coordinator, Chemistry
Mats Ohlsson	Manager Computer Systems
Gunnar Ramqvist	Project Coordinator
Leif Stenberg	Project Coordinator, Geology

DEEP REPOSITORY

Claes Thegerström	Director Deep Repository
Kaj Ahlbom	Project Manager Storuman
Karl-Erik Almén	Site Investigations
Gunnar Bäckström	Public Affairs
Torsten Eng	Project Manager Nuclear Communities Studies, EIA Studies
Torbjörn Hugo-Persson	Site Manager Malå
Håkan Jonsson	Site Manager Storuman
Bengt Leijon	Project Manager Malå
Christer Svemar	Design Studies, Buffer and Backfill Material
Jerker Tengman	Project Administrator
Erik Thurner	Field Measurements, Instruments

FACILITIES

Hans Forsström	Technical Director Facilities
Bo Gustafsson	Deputy Director
Swen Berger	Transportation
Jan Carlsson	Quality Assurance, SFR – Safety and Waste, Other Waste Types
Peter Dybeck	SFR – Operation, Transportation
Marie Johansson	SFR – Safety and Waste
Stig Pettersson	Engineering & Costs, Design Studies, Layout
Per Riggare	SFR – Safety and Waste
Bo Sundman	SVAFO
Maria Wikström	Engineering & Costs
Jan Vogt	CLAB, Encapsulation Process System

Encapsulation:

Tommy Hedman	Project Manager
Olle Broman	Project Administrator
Göran Fröman	Process Systems
Kristina Gillin	Process Systems
Kjell Mårtensson	Fuel Storage
Olle Sanner	Layout
Lars Werme	Canister, Nuclear Fuel

QUALITY AND SAFETY

Bo Sundman	Director

NUCLEAR FUEL

Ingemar Lindholm	Director Nuclear Fuel Supply
Eva Backlöf	Transport Manager
Göran Schultz	Contracts

NUCLEAR WASTE MANAGEMENT

Bo Gustafsson	Director Nuclear Waste Management
Lars B. Nilsson	Senior Consultant

LECTURES AND PUBLICATIONS 1994

Channeling experiments in crystalline fractured rocks
Abelin, H; Birgersson, L; Widén, H; Ågren, T; Moreno, L; Neretnieks, I
J. of Contaminant Hydrology 15(1994): 129-158

Hantering av radioaktivt avfall – Erfarenheter och utveckling i Sverige
Ahlström, P-E
Föredrag vid Svenska Tekniska Vetenskapsakademin i Finland, 24 mars 1994

Implementation strategies
Ahlström, P-E
Radioactive Waste Management Committee (RWMC) Workshop on Environmental and Ethical Aspects of Long-Lived Radioactive Waste Disposal, OECD/NEA Paris, September 1-2, 1994

La gestión de residuos radioactivos en los países de la AEN/OCDE – Suecia
Ahlström, P-E
Estratos. Empresa Nacional de Residuos Radioactivos No 30 – Invierno 1994, pp. 40-46

Sweden takes steps to solve waste problem
Ahlström, P-E
Forum for Applied Research and Public Policy 9(1994):3, pp. 119-121

The Swedish route to final disposal
Ahlström, P-E; Thegerström, C
Nuclear Europe Worldscan, No. 1/2 January/February 1994, pp. 46-47

Experiences from site investigation in crystalline rocks. Overview of fracture-oriented studies in the Swedish research programme for radioactive waste disposal
Almén, K-E
Geological Society, Hydrogeological Group meeting on "Fracture Characterization and Evaluation", British Geological Survey, Nottingham, March 29, 1994

Exploratory drilling and borehole testing for the nuclear waste disposal programme in Sweden
Almén, K-E
Applied Hydrogeology 2(1994):3, pp. 48-55

I tunneln säkras framtiden
Anderson, M
Byggindustrin 64(1994):29, 15-19

Lyckad wire-lineborrning vid Äspö
Andersson, O
Borrsvängen 4/94, pp. 26-29

Conclusions from WG-2: The analyses of the Finnsjön experiments
Andersson, P; Winberg, A
GEOVAL '94, Paris, France, 11-14 October 1994

Boring of full-scale deposition holes in the TVO-research tunnel
Autio, J; Salo, J-P
Äspö Hard Rock Laboratory Int. Workshop on the Use of Tunnel Boring Machines for Deep Repositories, Äspö, June 13-14, 1994

Intrusion of shallow water into a vertical fracture zone in crystalline bedrock – A large scale redox experiment
Banwart, S; Gustafsson, E; Laaksoharju, M; Nilsson, A-C; Pedersen, K; Tullborg, E-L; Wallin, B; Wikberg, P
Nordiska Geol. Vintermöte, Luleå, januari 1994

Large-scale intrusion of shallow water into a vertical fracture zone in crystalline bedrock: Initial hydrochemical perturbation during tunnel construction at the Äspö Hard Rock Laboratory, southeastern Sweden
Barnwart, S; Gustafsson, E; Laaksoharju, M; Nilsson, A-C; Tullborg, E-L; Wallin, B
Water Resources Research 30(1994):6, pp. 1747-1763

Redox processes in disturbed groundwater systems: Conclusions from an Äspö-HRL study
Banwart, S; Wikberg P
Geoval '94, Paris, France, 11-15 October 1994

Models for predicting radiocaesium levels in lake water and fish
Bergström, U; Sundblad, B; Nordlinder, S
In: Nordic Radioecology. The transfer of radionuclides through Nordic ecosystems to man, ed. by H. Dahlgaard, Elsevier Science B V, 1994

Direct disposal of spent fuel – a European view
Bjurström, S
ENC '94, Lyon, France, October 2-6, 1994

Eskers, subglacial groundwater flow and deduction of subglacial melting rates and water discharges from former ice sheets
Boulton, G S; Punkari, M; Caban, P E; Wallroth, T
Submitted to J. Glaciology, February 1994

Mid-latitude ice sheets through the last glacial cycle: Glaciological and geological reconstructions
Boulton, G S; Payne, A
NATO ASI Series, Vol. I22, Long-Term Climatic Variations. Eds. J-C Duplessy and M-T Spyridakis, Springer-Verlag, Berlin Heidelberg, 1994

Environmental chemistry of organic pollutants. Comparison in safety assessment from nuclear waste to hazardous waste
Bruno, J
Lecture at European Environmental Research Organization, 1994

Experimental study of the U(VI)Fe(OH)3 surface precipitation/co-precipitation equilibria
Bruno, J; de Pablo, J; Duro, L; Figuerola, E
Geochimica Cosmochimica Acta (1994)

Experimental study of the U(VI)-Fe(OH)3 co-precipitation equilibria. The application of the solubility conditional constant concept
Bruno, J; de Pablo, J; Duro, L; Figuerola, E
4th Int. conf. on the Chemistry and Migration Behaviour of the Actinides and Fission Products in the Geosphere, 1994

Recent advances in long-term assessment of spent fuel disposal
Bruno, J
Spent Fuel Workshop '94

Risk assessment of hazardous waste. Comparison in safety assessment from nuclear waste to hazardous waste
Bruno, J
Lecture at Umeå University, 1994

The assessment of the long-term evolution of spent nuclear fuel matrix by kinetic and thermodynamic studies of natural uranium minerals
Bruno, J; Casas, I; Cera, E; Ewing, R C; Finch, R J; Werme, L O
Abstract at XVIII Int. Symposium on the Scientific Basis for Nuclear Waste Management, Kyoto, Japan, October 23-27, 1994, pp. 361-362

Uranium (IV) Dioxide and simfuel as chemical analogues of nuclear spent fuel matrix dissolution. A comparison of dissolution results in a standard $NaCl/NaHCO_3$ solution
Bruno, J; Casas, I; Cera, E; de Pablo, J; Giménez, J; Torrero, M E
Presented at MRS, Kyoto 1994. Scientific Basis for Nuclear Waste Management XVIII Symposium

Constructability analysis for a deep repository – some thoughts on possibilities and limitations
Bäckblom, G; Leijon, B; Stille, H
2nd Int. Workshop on Design & Construction of Final Repositories, Winnipeg, February 15-16, 1994. AECL (in press)

Erfarenheter från Äspölaboratoriet. Prognoser och utfall av betydelse för anläggningsarbetet
Bäckblom, G
KASAM/SKI Seminarium Göteborg, 13-14 september 1994

Results and experiences from the Äspö Hard Rock Laboratory Characterization Approach
Bäckblom, G; Gustafson, G; Rhén, I; Stanfors, R; Wikberg, P
GEOVAL '94, Paris, France, 11-15 October 1994

TBM use at the Äspö Hard Rock Laboratory
Bäckblom, G; Hedman, T
Int. Workshop on the use of tunnelboring machines for deep repositories Äspö, 13-14 June 1994

Kinetic studies of natural uranium minerals for the long-term evolution of spent nuclear fuel under oxidizing conditions
Casas, I; Cera, E; Bruno, J
Materials Research Symposium Proc. 294, 1994

Accelerator-driven nuclear synergetic system – An overview of the research activities in Sweden
Condé, H; Bäcklin, A; Carius, S; Traneus, E; Gudowski, W; Möller, E; Thedéen, T; Liljenzin, J; Skålberg, M; af Ugglas, M; Mileikowsky, C; Tenerz, E; Hannerz, K; Sundqvist, C; Pind, Ch
Proceeding International Conference on Accelerator-Driven Transmutation Technologies and Applications (ADTT), Las Vegas, USA, July 25-29, 1994

An overview of the ADTT research activities in Sweden
Condé, H; Thedéen, T; Gudowski, W et al.
Paper presented at the International Conference on Accelerator Driven Transmutation Technologies, Las Vegas, 25-29 July 1994

Petrographic analysis of samples from the uranium deposit at Oklo, Republic of Gabon
Eberly, P; Janeczek, J; Ewing, R C
Radiochimica Acta 66/67(1994); pp. 455-461

Precipitation of uraninite in chlorite-bearing veins of the hydrothermal alteration zone (argile de pile) of the natural nuclear reactor at Bangombé, Republic of Oklo
Eberly, P O; Janeczek, J; Ewing, R C
Abstract at XVIII Int. Symposium on the Scientific Basis for Nuclear Waste Management, Kyoto, Japan, October 23-27, 1994, pp. 267-268

Carbon transformations by attached bacterial populations in granitic groundwater from deep crystalline bed-rock of the Stripa research mine
Ekendahl, S; Pedersen, K
Microbiology (1994), 140, 1565-1573

Characterization of attached bacterial populations in deep granitic groundwater from the Stripa research mine by 16S rRNA gene sequencing and scanning electron microscopy
Ekendahl, S; Arlinger, J; Ståhl, F; Pedersen, K
Microbiology (1994), 140, 1575-1583

Mineralogy, geochemistry and petrophysics of hydrothermally metamorphosed granite along fractures
Eliasson, T
Abstracts, Nordic Symposium on Petrophysics in Computer Modelling of Reservoir and Basin Processes, Geol. inst. CTH/GU Publ. B 399, Gothenburg, pp. 35-37

Analysis of long-term geological and hydrogeological changes in the Swedish programme for final disposal of nuclear waste
Ericsson, L O; Boulton, G S; Wallroth, T
In: Characterisation of Long-Term Geological Changes Being Considered for Disposal Sites. Proc. of an OECD/NEA workshop, Paris, 19-21 September 1994

Geovetenskapligt underlag för platsvalet – kommentarer i ett regionalt perspektiv
Ericsson, L O
KASAM/SKI-seminarium om "Acceptanskriterier för berggrunden vid djup geologisk slutförvaring av använt kärnbränsle", Göteborg 13-14 september 1994

Lagring av kärnbränsleavfall
Ericsson, L O
Vårt Livsviktiga Grundvatten, Seminarium arrangerat av Nordiska Ekofonden i samarbete med Kungl. Tekniska Högskolans avd. för Mark- och Vattenresurser, 28 September 1994, Stockholm

The importance of the geological barrier in deep disposal of nuclear waste – present work efforts in perspective
Ericsson, L O
NKS/YJT seminar on "Nuclear Waste in Northern Europe, the situation 1994", Helsinki, April 13-14, 1994

Radioactive waste forms: A review and comparison
Ewing, R C
Abstract at Seminar on Radioactive Waste Management Practices and Issues in Developing Countries, Int. Atomic Energy Agency, Beijing, China, October 10-14, 1994, p. 36

Formation, oxidation and alteration of ianthinite
Finch, R J; Ewing, R C
In: Scientific Basis for Nuclear Waste Management XVII, A. Barkatt and R.A. Van Konynenburg, eds. Proc. of the Materials Res. Soc., vol. 333, Pittsburgh, Pennsylvania, pp. 625-630, 1994

The long-term stability of becquerelite
Finch, R J; Suksi, JM; Ewing, R C
Abstract at XVIII Int. Symposium on the Scientific Basis for Nuclear Waste Management, Kyoto, Japan, October 23-27, 1994, pp. 85-86

The prediction of unknown uranyl oxide hydrate structure types: A comparison of calculated and measured XRD powder patterns
Finch, R J; Hawthorne, F C; Ewing, R C
Abstract at XVIII Int. Symposium on the Scientific Basis for Nuclear Waste Management, Kyoto, Japan, October 23-27, 1994, pp. 87-88

On the use of continuum approximations for regional modeling of groundwater flow through crystalline rocks
Follin, S; Thunvik, R
Advances in Water Resources 17(1994): pp. 133-145

Results from a large scale interference test conducted in fractured crystalline rocks
Follin, S
In: European Geophysical Society Annales Geophysicae Part II: Oceans, Atmoshere, Hydrology & Nonlinear Geophysics, Suppl. II to Vol. 12, 1994, p. C477

Radioactive waste management in Sweden. Experiences and plans
Forsström, H
1994 Summer School "Radioactive Waste Management & Decommissioning", Cambridge, England, June 1994

Spent nuclear fuel corrosion: The application of ICP-MS to direct actinide analysis
Forsyth, R S; Eklund, U-B
4th International Conference on Plasma Source Mass Spectrometry, University of Durham, UK, September 1994

Archives for Millenia
Fryksén, A; Eng, T
Nordisk Arkivnytt 39(1994):2, pp. 46-48

Progress in accelerator-based technologies
Gudowski, W
Paper presented at the Symposium Accelerator Driven Reactors and Nuclear Waste Management, Liblice-Prague, 27-29 June 1994

ADTT-prospects from the Swedish perspective
Gudowski, W
Paper presented at the Symposium Accelerator Driven Reactors and Nuclear Waste Management, Liblice-Prague, 27-29 June 1994

Some nuclear safety aspects of the Los Alamos accelerator based conversion concept
Gudowski, W; Möller, E; Venneri, F
Paper presented at the International Conference on Accelerator-Driven Transmutation Technologies, Las Vegas, 25-29 July 1994

Swedish perspective on accelerator-driven nuclear systems
Gudowski, W; Condé, H
Paper presented at the 3rd International Information Exchange Meeting on Actinide and Fission Product Partitioning and Transmutation, NEA OECD, Cadarache, 12-14 December 1994

A channel network model for radionuclide transport in fractured rock – Testing against field data
Gylling, B; Moreno, L; Neretnieks, I
Presented at Scientific Basis for Nuclear Waste Management XVIII, Kyoto, Oct. 25-27, 1994

Characterization and tracer tests in the full-scale deposition holes in the TVO Research Tunnel
Hautojärvi, A et al.
Geoval '94, Paris, 11-14 October 1994

Creep of copper
Henderson, P J
Presented at Int. Seminar on Design and Manufacture of Copper Canisters for Nuclear Waste, Sollentuna, Sweden, April 1994

Joint ANDRA/Nirex/SKB zone of excavation. Disturbance experiment (ZEDEX) at the Äspö Hard Rock Laboratory
Hooper, A J; Olsson, O
Geoval '94, Paris, 11-14 October 1994

Formation of secondary uranium minerals in the Koongarra Deposit, Australia
Isobe, H; Ewing, R C; Murakami, T
In: Scientific Basis for Nuclear Waste Management XVII, A. Barkatt and R.A. Van Konynenburg, eds. Proc. of the Materials Res. Soc., vol. 333, Pittsburgh, Pennsylvania, pp. 653-660, 1994

Mechanisms of lead release from uraninite in the natural fission reactors in Gabon
Janeczek, J; Ewing, R C
Geochimica et Cosmochimica Acta (in press)

Rock mechanical properties of intact rock in TVO's test boring site in Boliden, Sweden
Johansson, E
TVO Work Report TEKA-94-15

International co-operation on decommissioning
Jones, J; Menon, S
1994 Int. Symposium on Decontamination and Decommissioning, Knoxville, Tennessee, April 25-28, 1994

Äspölaboratoriet – erfarenheter från samordning av tunnelbygge med bergundersökningar
Jönsson, L
Diskussionsmöte BK-94. Bergsprängningskommittén

Chemotoxic aspects of radioactive waste in Sweden
Karlsson, F; Wiborgh, M
In: Spectrum '94. Proc. of the Int. Topical Meeting on Nuclear and Hazardous Waste Management, Atlanta, GA, August 14-18, 1994, pp. 1371-1376

Natural organic substances in granitic groundwater and their implications for nuclear waste disposal
Karlsson, F; Allard, B; Hummel, W; Sargent, F P; Vieno, T; Voinis, S; Merceron, T; Yoshikawa, H
In: Workshop on Binding Models Concerning Natural Organic Substances in Performance Assessment, organized jointly by OECD/NEA and Paul Scherrer Institute in Bad Zurbach, Switzerland, 14-16 September 1994

The extraction of some trivalent elements with Aliquat-336
Landgren, A; Liljenzin, J O; Skålberg, M
Proceeding International Conference on Accelerator-Driven Transmutation Technologies and Appplications (ADTT), Las Vegas, USA, July 25-29, 1994

Actinide chemistry for transmutation purposes
Liljenzin, J O
Paper presented at the Specialist's Meeting of Chemistry and Technology of Actinide Elements, Kyoto University Research Reactor Institute at Kumatori, November 17, 1994

Planerad svensk forskningsverksamhet inom acceleratorbaserad transmutation av kärnavfall och energiproduktion
Liljenzin, J O; Skålberg, M; Gudowski, W; Thedéen, T; Condé, H; Carius, S; af Ugglas, M; Mileikowsky, C; Tenerz, E; Hannerz, K; Sundqvist, C; Pind, Ch
Svenska Fysikersamfundets tidskrift, f, Fysik Aktuellt, Nr 2, p. 26-40, maj 1994. (In Swedish)

Radioactive waste – the funnel approach
Lindqvist, J
Opinion '94 Seminar, London, November 25, 1994

A model for radiation energy deposition in natural uranium-bearing systems and its consequences to water radiolysis
Liu, J; Neretniks, I
J. of Nuclear Materials, 1994 (in press)

Data from a uranium ore body on release of dissolved species: Comparison with a near field release model
Liu, J; Neretnieks, I
Geoval '94, Paris, France, Oct. 10-14, 1994

Some evidence of radiolysis in a uranium ore body – Quantification and interpretation
Liu, J; Neretnieks, I
Presented at Scientific Basis for Nuclear Waste Management XVIII, Kyoto, Oct. 25-27, 1994

Transport modelling and model validation in the natural analogue study of the Cigar Lake uranium deposit
Liu, J; Yu, J-W; Neretnieks, I
J. of Contaminant Hydrology 1994 (in press)

Direct fault dating trials at the Äspö Hard Rock Laboratory
Maddock, R H; Hailwood, E A; Rhodes, E J; Muir Wood, R
21st Nordic Winter Geological Meeting, Luleå, Jan. 1994, Abstracts pp. 131

The dissolution of biotite and chlorite at 25°C in the near neutral pH region
Malmström, M; Banwart, S; Duro, L; Bruno, J
J. of Contaminant Hydrology, 1994

Application of exemption concepts, overview of practices in some countries
Menon, S; Teunckens, L
WM 94 Symposium on Waste Management, Tucson, Arizona, February 27 – March 2, 1994

The NEA International Co-operative Programme on Decommissioning
Menon, S
TLG 1994 Decommissioning Conf., Captiva Island, Florida, October 16-19, 1994

Natural analogue studies in the geological disposal of radioactive wastes
Miller, B; Alexander, R; Chapman, N; McKinley, I; Smellie, J
Environmental Science 57, Elsevier, p. 395

Natural analogues revisited
Miller, B; Alexander, R; Chapman, N; McKinley, I; Smellie, J
Fourth Int. Conf. on the Chemistry and Migration Behaviour of Actinides and Fission Products in the Geosphere, Charleston, SC, USA, Dec. 12-17, 1994

A topologic classification of uranium oxide hydrates
Miller, M L; Finch, R J; Ewing, R C
Abstract at Annual Meeting of the Geological Society of America, Seattle, WA, October 24-27, 1994, p. A480

Flow channeling in strongly heterogeneous porous media: A numerical study
Moreno, L; Tsang, C F
Water Resources Res. 30(1994):5, 1421-1430

The neutronics of an accelerator-driven energy amplifier
Möller, E; Gudowski, W
Paper presented at the International Conference on Accelerator Driven Transmutation Technologies, Las Vegas, 25-29 July 1994

Solid bitumen and clay minerals in the Oklo natural fission reactors: Considerations of fission product containment
Nagy, B; Szabó, G; Guczi, J; Janeczek, J; Ewing, R C
Abstract at XVIII Int. Symposium on the Scientific Basis for Nuclear Waste Management, Kyoto, Japan, October 23-27, 1994, pp. 265-266

Long term effects of acidification in environmental contamination
Nebot, P; Bruno, J
Elsevier Publishers, 1994

A review of the effects of channeling and matrix diffusion on spreading of contaminants in fractured formations
Neretnieks, I
Paper presented at the Int. Conference on Deep Well Injection, Berkeley, California, May 9-12, 1994. Proc. LBL in press

Matrix diffusion – How confident are we?
Neretnieks, I
Paper presented at the 6th CEC Natural Analogue Working Group Meeting at Santa Fe, New Mexico, September 12-16, 1994

Nuclear waste repositories in crystalline rock – An overview of flow and nuclide transport mechanisms in the geologic barrier
Neretnieks, I
Paper presented at the MRS Meeting on Scientific Basis for Nuclear Waste Management, XVIII, Kyoto, Japan, Oct. 25-27, 1994

Canister filling materials – Design requirements and evaluation of candidate materials
Oversby, V M; Werme, L O
Scientific Basis for Nuclear Waste Management XVIII, Kyoto, Japan, October 1994

Coordinated site characterization and performance assessment – an iterative approach for the site evaluation
Papp, T; Ericsson, L O; Thegerström, C; Almén, K-E
GEOVAL '94, Paris, France, 11-14 October 1994

Findings about microbial effects from redox experiment at Äspö Hard Rock Laboratory
Pedersen, K
Presented at Tono Geoscience Centre, PNC, Toki, Japan, 28 October 1994

Subterranean bacteria and their influence on radioactive waste disposal
Pedersen, K
Presented at Ishikawajima-Harima Heavy Industries Co., Ltd, Yokohama, Japan, 31 October 1994

The deep subterranean biosphere
Pedersen, K
Presented at Saitama University, Saitama, Japan, 29 October 1994

The deep subterranean biosphere at the Swedish hard rock laboratory (Äspö) – Implications for nuclear waste disposal
Pedersen, K
Presented at Atomic Energy Canada Limited, Whiteshell Lab., Pinawa, Canada, 17 January, 1994

The deep subterranean biosphere at the Swedish hard rock laboratory (Äspö) – Implications for nuclear waste disposal
Pedersen, K
Presented at Teollisuuden Voima Oy, Helsingfors, Finland, 8 March 1994

The deep subterranean biosphere – Distribution, diversity and activity of bacteria in deep groundwater at Äspö hard rock laboratory
Pedersen, K
Presented at University of Western Ontario, Ontario, Canada, 14 April 1994

Decommissioning of Swedish nuclear power plants
Pettersson, S; Lönnerberg, B
1994 Int. Symposium on Decontamination and Decommissioning, Knoxville, Tennessee, USA, April 1994

Release and diffusion of ^{90}Sr from spent UO_2 fuel in bentonite clay
Ramebäck, H; Albinsson, Y; Skålberg, M; Werme, L
Radiochimica Acta 66/67 (1994) 405

Movement of a redox front around a repository for high-level nuclear waste
Romero, L; Moreno, L; Neretnieks, I
Nuclear Technology, 1994 (in press)

Radionuclide release from the KBS-3 repository – Sensitivity to the variability of materials and other properties
Romero, L; Andersson, Å; Moreno, L; Neretnieks, I
Presented at Scientific Basis for Nuclear Waste Management XVIII, Kyoto, Oct. 25-27, 1994

Electron and laser beam welding: The solution for the fabrication and sealing of high level nuclear waste disposal containers
Russell, J D; Sanderson, A
ASM Int. and the Minerals, Metals & Materials Soc. (TMS) Convention, Rosemont, Illinois, USA, 2-6 October 1994 (presentation by C.S. Punshon)

The development of electron beam welding technology for the fabrication and sealing of copper canisters for nuclear waste burial
Sanderson, A
KASAM Int. Seminar, Sollentuna, Sweden 27-28 April 1994

Performance assessment of the copper/steel canister
Sellin, P
ENC '94, Lyon, France, October 2-6, 1994

Disposal of radioactive wastes – can long-term safety be evaluated?
Smellie, J A T
Advisory Group Meeting on Isotope Techniques in the Hydrological Appraisal of Radioactive Waste Disposal Sites, IAEA, Vienna, June 27-30, 1994

Review of natural analogue studies
Smellie, J A T
Plenary Session on Natural Analogues, The 5th Annual Int. High-level Radioactive Waste Management Conference and Exposition, Las Vegas, USA, May 22-26, 1994

Swedish natural analogue programme
Smellie, J A T; Karlsson, F
Sixth CEC Natural Analogue Working Group Meeting, Santa Fe, USA, Sept. 12-16, 1994

The potential use of natural analogue studies in radioactive waste disposal: A review
Smellie, J A T; Karlsson, F; Grundfelt, B
Geoval '94, OECD/NEA, Paris, France, Oct. 11-14, 1994

Abstract from the literature report – Interesting extractants for the separation of actinides, Version 1.0
Spjuth, L
Internal Report, Department of Nuclear Chemistry, Chalmers University of Technology, Göteborg, December 1994

Litteratursammanställning av några extraktionsreagens för separation av aktinider, Version 1.0
Spjuth, L
Internal Report, Department of Nuclear Chemistry, Chalmers University of Technology, Göteborg, December 1994 (in Swedish)

Erfarenheter från tunnelborrning vid Äspö
Stattin, J; Bäckblom, G
TBM-symposium, Stockholm, 13 december 1994, Atlas Copco

Confidence-building in modelling of radionuclide migration in fractured rocks – an international effort within the Äspö Hard Rock Laboratory in Sweden
Ström, A
ENC '94, Lyon, France, October 2-6, 1994

The turnover of cesium-137 within a forest ecosystem described by a compartment modelling approach – Gideå study site, Sweden
Sundblad, B; Mathiasson, L
The Science of the Total Environment 157(1994): pp. 139-146

Aspekter på byggprocessens roll vid val av kriterier
Svemar, C
KASAM/SKI-seminarium om Acceptanskriterier för Berggrunden vid Djup Geologisk slutförvaring av Använt Kärnbränsle, Göteborgs universitet, 13-14 September 1994

Design process for a repository – KBS-3 case
Svemar, C
2nd Int. Workshop on Design & Construction of Final Repositories, Winnipeg, February 15-17, 1994

Safety aspects of ADTT
Thedéen, T
Paper presented at the IAEA Symposium "Radiation and Society", Paris, October 1994

Lokalisering av slutförvar – Svenska programmet
Thegerström, C
Seminarium om "Kärnavfall i Norden, Läget år 1994", Helsingfors, 13-14 april 1994

SKB:s planering av MKB-processen i samband med slutförvaring av kärnavfall
Thegerström, C; Forsström, H
KASAM:s seminarium "Miljökonsekvensbeskrivningen (MKB) och dess roll i beslutsprocessen", Luleå, 24-26 oktober 1994

A fore deep basin to the Caledonides – Evidences of molasse sedimentation
Tullborg, E-L; Larsson, S Å; Björklund, L; Samuelsson, L; Stigh, J
In: 21:a Nordiska Geologiska Vintermötet, Luleå 1994, Abstracts, p. 215

Swedish spent fuel storage programme
Vogt, J
IAEA Int. Symposium on Spent Fuel Storage – Safety, Engineering and Environmental Aspects, Vienna, Austria, October 1994

Experiences from the operation of the Swedish central storage facility for spent fuel, CLAB
Vogt, J; Grahn, P
IAEA Int. Symposium on Spent Fuel Storage – Safety, Engineering and Environmental Aspects, Vienna, Austria, October 1994

Isotope systematics in ground water and hydrogenic deposits at Äspö, Sweden
Wallin, B; Peterman, Z E
In: Proc. of the Fifth Annual Int. Conf. on High Level Radioactive Waste Management, Las Vegas, Nevada, May 22-26, 1994, American Nuclear Society, 4: 2692-2701

Stable and radiogenic isotope systematics in ground water and fracture fillings at Äspö, Sweden
Wallin, B; Peterman, Z E
VM Goldschmidt Conference, Edinburgh, August 28 – September 2, 1994, Mineralogical Magazine 58A: 953-954

Mechanistic sorption modeling of cesium on bentonite
Wanner, H
Int. Workshop on Research and Development of Geological Disposal, 15-18 Nov. 1993, Tokai, Power Reactor and Nuclear Fuel Development Co. (PNC), Proc. of Techn. Session. pp. I-53 through I-62 (pub. 1994)

The acid/base chemistry of montmorillonite
Wanner, H; Albinsson, Y; Karnland, O; Wieland, E; Wersin, P; Charlet, C
Radiochim. Acta 66/67(1994): pp. 157-162

A proposed programme of experimental and theoretical modelling studies of gas migration through bentonite
Wikramaratna, R S; Goodfield, M
Report AEA-ESD-003, AEA Technology, October 1994

Costs for the Swedish radioactive waste management
Wikström, M
ENC '94, Lyon, France, October 2-6, 1994

Estimation of statistical parameters for censored log-normal hydraulic conductivity measurements
Xian-Huan Wen
Mathematical Geology 26(1994):6, pp. 717-731

On the influence of carbonate on mineral dissolution: III. The solubility of microcrystalline ThO_2 in $CO_2 - II_2O$ media
Östhols, E; Bruno, J; Grenthe, I
Geochimica et Cosmochimica Acta Vol. 58(1994):2, 613-623

LIST OF SKB ANNUAL REPORTS 1977 – 1993

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

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

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

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

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

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

1984
TR 85-01
Annual Research and Development Report 1984
Including Summaries of Technical Reports Issued during 1984. (Technical Reports 84-01–84-19)
Stockholm June 1985.

1985
TR 85-20
Annual Research and Development Report 1985
Including Summaries of Technical Reports Issued during 1985. (Technical Reports 85-01–85-19)
Stockholm, May 1986.

1986
TR 86-31
SKB Annual Report 1986
Including Summaries of Technical Reports Issued during 1986
Stockholm, May 1987

1987
TR 87-33
SKB Annual Report 1987
Including Summaries of Technical Reports Issued during 1987
Stockholm, May 1988

1988
TR 88-32
SKB Annual Report 1988
Including Summaries of Technical Reports Issued during 1988
Stockholm, December 1989

1989
TR 89-40
SKB Annual Report 1989
Including Summaries of Technical Reports Issued during 1989
Stockholm, May 1990

1990
TR 90-46
SKB Annual Report 1990
Including Summaries of Technical Reports Issued during 1990
Stockholm, May 1991

1991
TR 91-64
SKB Annual Report 1991
Including Summaries of Technical Reports Issued during 1991
Stockholm, May 1992

1992
TR 92-46
SKB Annual Report 1992
Including Summaries of Technical Report Issued during 1992
Stockholm, May 1993

1993
TR 93-34
SKB Annual Report 1993
Including Summaries of Technical Reports Issued during
1993
Stockholm, May 1994

LIST OF SKB TECHNICAL REPORTS 1994

TR 94-01
Anaerobic oxidation of carbon steel in granitic groundwaters: A review of the relevant literature
Platts, N; Blackwood, D J; Naish, C C
AEA Technology, UK
February 1994

TR 94-02
Time evolution of dissolved oxygen and redox conditions in a HLW repository
Wersin, Paul; Spahiu, Kastriot; Bruno, Jordi
MBT Tecnología Ambiental, Cerdanyola, Spain
February 1994

TR 94-03
Reassessment of seismic reflection data from the Finnsjön study site and prospectives for future surveys
Cosma, Calin 1); Juhlin, Christopher 2); Olsson, Olle 3)
Vibrometric Oy, Helsinki, Finland 1); Section for Solid Earth Physics, Department of Geophysics, Uppsala University, Sweden 2); Conterra AB, Uppsala, Sweden 3)
February 1994

TR 94-04
Final report of the AECL/SKB Cigar Lake Analog Study
Cramer, Jan (ed.) 1); Smellie, John (ed.) 2)
AECL, Canada 1); Conterra, Uppsala, Sweden 2)
May 1994

TR 94-05
Tectonic regimes in the Baltic Shield during the last 1200 Ma – A review
Larsson, Sven Åke 1), 2); Tullborg, Eva-Lena 2)
Department of Geology, Chalmers University of Technology/Göteborg University 1); Terralogica AB 2)
November 1993

TR 94-06
First workshop on design and construction of deep repositories – Theme: Excavation through water-conducting major fracture zones, Såstaholm Sweden, March 30-31 1993
Bäckblom, Göran (ed.); Svemar, Christer (ed.)
Swedish Nuclear Fuel & Waste Management Co, SKB
January 1994

TR 94-07
INTRAVAL Working Group 2 summary report on Phase 2 analysis of the Finnsjön test case
Andersson, Peter (ed.) 1), Winberg, Anders (ed.) 2)
GEOSIGMA, Uppsala, Sweden 1); Conterra, Göteborg, Sweden 2)
January 1994

TR 94-08
The structure of conceptual models with application to the Äspö HRL Project
Olsson, Olle 1), Bäckblom, Göran 2); Gustafson, Gunnar 3); Rhén, Ingvar 4); Stanfors, Roy 5); Wikberg, Peter 2)
Conterra AB 1); SKB 2); CTH 3); VBB/VIAK 4); RS Consulting 5)
May 1994

TR 94-09
Tectonic framework of the Hanö Bay area, southern Baltic Sea
Wannäs, Kjell O; Flodén, Tom
Institutionen för geologi och geokemi, Stockholms universitet
June 1994

TR 94-10
Project Caesium – An ion exchange model for the prediction of distribution coefficients of caesium in bentonite
Wanner, Hans 1); Albinsson, Yngve 2); Wieland, Erich 1)
MBT Umwelttechnik AG, Zürich, Switzerland 1); Chalmers University of Technology, Gothenburg, Sweden 2)
June 1994

TR 94-11
Äspö Hard Rock Laboratory Annual Report 1993
SKB
June 1994

TR 94-12
Research on corrosion aspects of the Advanced Cold Process Canister
Blackwood, D J; Hoch, A R; Naish, C C; Rance, A; Sharland, S M
AEA Technology, Harwell Laboratory, UK
January 1994

TR 94-13
Assessment study of the stresses induced by corrosion in the Advanced Cold Process Canister
Hoch, A R; Sharland, S M
Chemical Studies Department, Radwaste Disposal Division, AEA Decommissioning and Radwaste, Harwell Laboratory, UK
October 1993

TR 94-14
Performance of the SKB Copper/Steel Canister
Widén, Hans 1); Sellin, Patrik 2)
Kemakta Konsult AB, Stockholm, Sweden 1); Svensk Kärnbränslehantering AB, Stockholm, Sweden 2)
September 1994

TR 94-15
Modelling of nitric acid production in the Advanced Cold Process Canister due to irradiation of moist air
Henshaw, J
AEA Technology, Decommissioning & Waste Management/Reactor Services, Harwell, UK
January 1994

TR 94-16
Kinetic and thermodynamic studies of uranium minerals. Assessment of the long-term evolution of spent nuclear fuel
Casas, Ignasi 1); Bruno, Jordi 1); Cera, Esther 1); Finch, Robert J 2); Ewing, Rodney C 2)
MBT Tecnología Ambiental, Cerdanyola, Spain 1); Department of Earth and Planetary Sciences, University of New Mexico, Albuquerque, NM, USA 2)
October 1994

TR 94-17
Summary report of the experiences from TVO's site investigations
Öhberg, Antti 1); Saksa, Pauli 2); Ahokas, Henry 2); Ruotsalainen, Paula 2); Snellman, Margit 3)
Saanio & Riekkola Consulting Engineers, Helsinki, Finland 1); Fintact Ky, Helsinki, Finland 2); Imatran Voima Oy, Helsinki, Finland 3)
May 1994

TR 94-18
AECL strategy for surface-based investigations of potential disposal sites and the development of a geosphere model for a site
Whitaker, S H; Brown, A; Davison, C C; Gascoyne, M; Lodha, G S; Stevenson, D R; Thorne, G A; Tomsons, D
AECL Research, Whiteshell Laboratories, Pinawa, Manitoba, Canada
May 1994

TR 94-19
Deep drilling KLX 02. Drilling and documentation of a 1700 m deep borehole at Laxemar, Sweden
Andersson, O
VBB VIAK AB, Malmö
August 1994

TR 94-20
Technology and costs for decommissioning the Swedish nuclear power plants
Swedish Nuclear Fuel and Waste Management Co, Stockholm, Sweden
June 1994

TR 94-21
Verification of HYDRASTAR: Analysis of hydraulic conductivity fields and dispersion
Morris, S T; Cliffe, K A
AEA Technology, Harwell, UK
October 1994

TR 94-22
Evaluation of stationary and non-stationary geostatistical models for inferring hydraulic conductivity values at Äspö
La Pointe, Paul R
Golder Associates Inc., Seattle, WA, USA
November 1994

TR 94-23
PLAN 94
Costs for management of the radioactive waste from nuclear power production
Swedish Nuclear Fuel and Waste Management Co.
June 1994

TR 94-24
Äspö Hard Rock Laboratory
Feasibility and usefulness of site investigation methods. Experiences from the pre-investigation phase
Almén, Karl-Erik (ed.) 1); Olsson, Pär 2); Rhén, Ingvar 3); Stanfors, Roy 4); Wikberg, Peter 5)
KEA GEO-Konsult 1); SKANSKA 2); VBB/VIAK 3); RS Consulting 4); SKB 5)
August 1994

TR 94-25
Kinetic modelling of bentonite-canister interaction. Long-term predictions of copper canister corrosion under oxic and anoxic conditions
Wersin, Paul; Spahiu, Kastriot; Bruno, Jordi
MBT Tecnología Ambiental, Cerdanyola, Spain
September 1994

TR 94-26
A surface chemical model of the bentonite-water interface and its implications for modelling the near field chemistry in a repository for spent fuel
Wieland, Erich 1); Wanner, Hans 1); Albinsson, Yngve 2); Wersin, Paul 3); Karnland, Ola 4)
MBT Umwelttechnik AG, Zürich, Switzerland 1); Chalmers University of Technology, Gothenburg, Sweden 2); MBT Tecnología Ambiental, Cerdanyola, Spain 3); Clay Technology AB, Lund, Sweden 4)
July 1994

TR 94-27
Experimental study of strontium sorption on fissure filling material
Eriksen, Trygve E; Cui, Daqing
Department of Chemistry, Nuclear Chemistry, Royal Institute of Technology, Stockholm, Sweden
December 1994

TR 94-28
Scenario development methodologies
Eng, Torsten 1); Hudson, John 2); Stephansson, Ove 3); Skagius, Kristina 4); Wiborgh, Marie 4)
Swedish Nuclear Fuel & Waste Management Co, Stockholm, Sweden 1); Rock Engineering Consultants, Welwyn Garden City, Herts, UK 2); Div. of Engineering Geology, Royal Institute of Technology, Stockholm, Sweden 3); Kemakta, Stockholm, Sweden 4)
November 1994

TR 94-29
Heat conductivity of buffer materials
Börgesson, Lennart; Fredrikson, Anders; Johannesson, Lars-Erik
Clay Technology AB, Lund, Sweden
November 1994

TR 94-30
Calibration with respect to hydraulic head measurements in stochastic simulation of groundwater flow – A numerical experiment using MATLAB
Eriksson, L O; Oppelstrup, J
Starprog AB
December 1994

TR 94-31
The implications of soil acidification on a future HLW repository. Part II: Influence on deep granitic groundwater. The Klipperås study site as test case
Wersin, Paul 1); Bruno, Jordi 1); Laaksoharju, Marcus 2)
MBT Tecnología Ambiental, Cerdanyola, Spain 1); Geopoint AB, Spånga, Sweden 2)
May 1994

TR 94-32
Calculated distribution of radionuclides in soils and sediments
Puigdomènech, Ignasi; Bergström, Ulla
Studsvik Eco & Safety AB, Nyköping, Sweden
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EQE International Limited, Birchwood, UK

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Geological Survey of Sweden, Göteborg

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GeoPoint AB, Spånga

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Gesellschaft für Strahlen- und Umweltforschung, Munich, Germany

Golder Associates, Seattle, Washington, USA

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Harwell Laboratory/AEA, Oxfordshire, UK

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Linköping University, Dep. of Chemistry

Luleå University of Technology, Division of Rock Mechanics, Luleå

Lund Institute of Technology, Dep. of Chemical Engineering, Lund

Lunds Tekniska Högskola, Avd för byggnadsteknik, Lund
Lunds Universitet, Avd. Teknisk Geologi, Lund

Malå Geoscience, Malå

MBT Umwelttechnik AG, Hans Wanner, Zürich, Switzerland

MBT Tecnologia Ambiental, Cerdanyola, Spain

Measurements Systems Scandinavia AB (MSS), Åkersberga

Menon Consulting, Nyköping

Mirab, Uppsala

Mitthögskolan i Östersund, Östersund

MRM Konsult, Luleå

MRQ Materialröntgen AB, Göteborg

MRQ Materialröntgen AB, Oskarshamn

National Land Survey of Sweden - GIS-centrum, Stockholm

NCC, Malmö

NIS GmbH, Hanau, Germany

OKG AB, Oskarshamn

Projektstyrning AB, Stockholm

R Allan Freeze Engineering, Inc., White Rock, Canada

Robert Maddock, Woking, UK

Rock Store Design-ROX AB, Nacka

ROX AB, Stockholm

Roy Stanfors Consulting AB, Lund

Royal Institute of Technology, Dep. of Chemical Engineering, Stockholm

Royal Institute of Technology, Dep. of Engineering Geology, Stockholm

Royal Institute of Technology, Dep. of Inorganic Chemistry, Stockholm

Royal Institute of Technology, Dep. of Land and Water Resources, Stockholm

Royal Institute of Technology, Dep. of Materials Science and Engineering, Stockholm

Royal Institute of Technology, Dep. of Nuclear Chemistry, Stockholm

Royal Institute of Technology, Dep. of Water Resources Engineering, Stockholm

Rågård Konsult AB, Spånga

Saanio & Riekkola Oy, Helsinki, Finland

SAFETECH Engineering, Västerås

Saltech AB, Solna

Scandiaconsult Bygg- och Industriteknik AB, Stockholm

Scottish Universities Rescarch & Reactor Centre, Glasgow, UK

Siab AB

SKANSKA Stockholm AB, Danderyd

SKANSKA Sydöst AB, Oskarshamn

Starprog AB, Stockholm

Steph Rock Consulting, Stockholm

Storumans Utvecklings AB, Storuman

Studsvik EcoSafe, Nyköping

Studsvik Material AB, Nyköping

Studsvik Nuclear, Nyköping

SveBeFo, Stockholm

Sven Andersson, Brunnsborrning AB, Uppsala

Svensk Anläggningsprovning AB, Stockholm

Svensk Geofysik AB, Falun

Sveriges Provnings- och Forskningsinstitut, Borås

Sydkraft Konsult AB, Malmö

Technical Research Centre of Finland, Helsinki, Finland

Terra Tema, Linköping

Terralogica AB, Gråbo

Transnucleaire S.A., Paris, France

Triumf Geophysics, Luleå

Turismutveckling AB, Östersund

TWI, Cambridge, UK

Uddcomb Engineering AB, Karlskrona

Umeå University, Umeå

Université Louis Pasteur de Strasbourg, France

University of Edinburgh, Dep. of Geology and Geophysics, Edinburg, UK

University of Gothenburg, Dep. of Gen. & Marine Microbiology, Gothenburg

University of New Mexico, Dep. of Geology, Albuquerque, USA

University of Stockholm, Dep. of Geology, Stockholm

UPEC AB, Stockholm

Uppsala University, Institute of Geology, Uppsala

Vattenfall Energisystem AB, Stockholm

Vattenfall Engineering AB, Stockholm

Vattenfall HydroPower AB, Ludvika

Vattenfall HydroPower AB, Luleå

Vattenfall HydroPower AB, Stockholm

VBB VIAK AB, Gothenburg

VBB VIAK AB, Luleå

VBB VIAK AB, Malmö

VBB VIAK AB, Stockholm

Ventilationstest, Stockholm

Vibrometic Oy, Helsingfors, Finland

Åbo University, Alf Björklund, Finland

ÅF-Energikonsult Stockholm AB, Stockholm

Örnsköldsviks Mekaniska Verkstad AB, Örnsköldsvik

POST-GRADUATE THESES SUPPORTED BY SKB

Metal accumulation by microorganisms – Characteristics and implications for soil systems
Ledin, M
Doctoral thesis, Dept. of Environmental Studies, Linköping University, Linköping, Sweden, 1994

The complexation of some radionuclides with natural organics – implications for radioactive waste disposal
Nordén, M
Doctoral thesis, Dept. of Environmental Studies, Linköping University, Linköping, Sweden, 1994

Analysis of β^--emitting radionuclides: ^{90}Sr and ^{99}Tc, applied in spent nuclear fuel research
Rameböck, H
Licentiate thesis, Dept. of Nuclear Chemistry, Chalmers University of Technology, Göteborg, Sweden, 1994

Physico-chemical properties of some aquatic fulvic acids – functional groups and stability
Valarié, I
Doctoral thesis, Dept. of Environmental Studies, Linköping University, Linköping, Sweden, 1994

Modelling of sorption mechanism
Vannerberg, K
Licentiate treatise, Dept. of Nuclear Chemistry, Chalmers University of Technology, Göteborg, Sweden, 1994

Some processes affecting the mobility of thorium in natural groundwaters
Östhols, E
Doctoral thesis, Dept. of Inorganic Chemistry, Royal Institute of Technology, Stockholm, Sweden, 1994

SKB ANNUAL REPORT 1994

Part IV

Summaries of Technical Reports Issued during 1994

SKB Technical Report 94-01

Anaerobic oxidation of carbon steel in granitic groundwaters: A review of the relevant literature

Platts, N; Blackwood, D J; Naish, C C

AEA Technology, UK

February 1994

ABSTRACT

This report reviews the published literature on the anaerobic oxidation of iron in aqueous solutions which are of particular relevance to Swedish granitic groundwaters. The thermodynamics of iron corrosion in water are briefly considered. Following this the experimental data found in the literature are presented and discussed. Results were found for corrosion of iron in both pure water and solutions containing mineral salts. The literature work on the nature of the films formed on iron surfaces under anaerobic conditions is reviewed and the possible mechanisms of film formation are discussed. Conclusions are drawn on the factors most likely to influence and control film growth.

SKB Technical Report 94-02

Time evolution of dissolved oxygen and redox conditions in a HLW repository

Wersin, Paul; Spahiu, Kastriot; Bruno, Jordi

MBT Tecnologia Ambiental, Cerdanyola, Spain

February 1994

ABSTRACT

The evolution of oxygen in a HLW repository has been studied using presently available geochemical background information. The important processes affecting oxygen migration in the near-field 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.

Both approaches yield consistent rates of oxygen decrease and indicate that 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 the major geochemical and physical parametres is performed. These results indicate that the uncertainties associated with reactive pyrite surface area impose the overall uncertainties of prediction of time scales. Thus, the obtained time of decrease to 1% of initial O_2 concentrations range between 7 and 290 years. The elapsed time at which the transition to anoxic conditions occurs is estimated to be within the same time range. Additional experimental information on redox sensitive impurities in the envisioned buffer and backfill material would further constrain the evaluated time scales.

SKB Technical Report 94-03

Reassessment of seismic reflection data from the Finnsjön study site and prospectives for future surveys

Cosma, Calin 1); Juhlin, Christopher 2); Olsson, Olle 3)

Vibrometric Oy, Helsinki, Finland 1); Section for Solid Earth Physics, Department of Geophysics, Uppsala University, Sweden 2); Conterra AB, Uppsala, Sweden 3)

February 1994

ABSTRACT

Reprocessing of data from the seismic reflection survey performed at Finnsjön in 1987 show that reflection seismics is a viable technique for mapping fracture zones in crystalline rock. Application of state of the art processing algorithms clearly image a gently dipping fracture zone located in the depth interval 200-400 m. In addition, several other reflectors were imaged in the reprocessed section, both gently and steeply dipping ones. Correlations with borehole data indicate that the origin of these reflections are also fracture zones. The data acquisition procedures used at the Finnsjön survey were basically sound and could, with minor modifications, be applied at other sites. The results indicate that both sources and receivers in future surveys should be placed in boreholes a few meters below the ground surface.

SKB Technical Report 94-04

Final report of the AECL/SKB Cigar Lake Analog Study

Cramer, Jan (ed.) 1); Smellie, John (ed.) 2

AECL, Canada 1); Conterra AB, Uppsala, Sweden 2)

May 1994

ABSTRACT

The Cigar Lake uranium deposit is located in northern Saskatchewan, Canada. The 1.3-billion-year-old deposit is located at a depth of about 450 m below surface in a water-saturated sandstone at the unconformity contact with the high-grade metamorphic rocks of the Canadian Shield. The uranium mineralization, consisting primarily of uraninite (UO_2), is surrounded by a clay-rich halo in both sandstone and basement rocks, and remains extremely well preserved and intact. The average grade of the mineralization is ~8 wt. % U; locally grades are as high as ~55 wt. % U.

The Cigar Lake deposit has many features that parallel those being considered within the Canadian concept for disposal of nuclear fuel waste. The study of these natural structures and processes provides valuable insight toward the eventual design and site selection of a nuclear fuel waste repository. The main feature of this analog is the absence of any indication on the surface of the rich uranium ore 450 m below. This indicates that the combination of natural barriers has been effective in isolating the uranium ore from the surface environment. More specifically, the deposit provides analog information relevant to the stability of UO_2 fuel waste, the performance of clay-based barriers, radionuclide migration, colloid formation, radiolysis, fission-product geochemistry, and general aspects of water-rock interaction. The main geochemical studies on this deposit focus on the evolution of groundwater compositions in the deposit and on their redox chemistry with respect to the uranium, iron and sulphide systems.

Since 1984, through cooperation from the owners of the Cigar Lake deposit, analog studies have been conducted. AECL, with support from Ontario Hydro under the auspices of the CANDU Owners Group, initiated international participation in 1989 through collaboration with the Swedish Nuclear Fuel and Waste Management Company (SKB) and, more recently, with the Los Alamos National Laboratory (LANL). This report gives the results of the various studies carried out during the 3-year collaboration between AECL and SKB, as well as a summary of the LANL study. It provides detailed information on the generated databases and models, and integrates this information into conclusions for use in safety as a summary of the LANL study. It provides detailed information on the generated databases and models, and integrates this information into conclusions for use in safety assessment of the Canadian, Swedish and United States disposal concepts.

SKB Technical Report 94-05

Tectonic regimes in the Baltic Shield during the last 1200 Ma – A review

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Department of Geology, Chalmers University of Technology/Göteborg University 1); Terralogica AB 2)

November 1993

ABSTRACT

This report is a review about tectonic regimes in the Baltic (Fennoscandian) Shield from the Sveconorwegian (1.2 Ga ago) to the present. It also covers what is known about palaeostress during this period, which was chosen to include both orogenic and anorogenic events. A summary is given in table form, and a litho-stratigraphic map of Baltica including adjacent sea areas is enclosed.

Plate movements are the ultimate reason for stress build-up in the crust. It is concluded that continental drift and rotation velocity have changed during the earth's history. Periods of convergence and collision between continents are succeeded by periods of continental break-up. The different stress regimes, which prevailed during fracturing, produced specific fracture patterns on different scales. These fractures were reactivated during later favourable stress regimes. Within the next 100 000 years the stress situation of the Baltica crust will not change, except for the effects imposed by the growth and melting of all ice cover.

SKB Technical Report 94-06

First workshop on design and construction of deep repositories – Theme: Excavation through water-conducting major fracture zones, Såstaholm Sweden, March 30-31 1993

Bäckblom, Göran (ed.); Svemar, Christer (ed.)

Swedish Nuclear Fuel & Waste Management Co, SKB

January 1994

ABSTRACT

Final disposal of high-level nuclear waste has not yet been carried out in any country today. The concepts under development are all based on geological repositories, i.e., disposal at a sufficient depth below the surface to provide stable mechanical, hydrological and chemical conditions during the period the waste needs to be isolated from man. In the cases where crystalline bedrock is considered the proposed repository depths vary between 300 – 1000 m.

The construction, operation and sealing of a deep geological repository must meet various criteria that in many respects are more detailed and more demanding than usual in underground construction projects today. The work shall be done so that occupational safety is ensured. The work also shall conform to whatever restrictions are necessary for ensuring pre-closure operational safety and post-closure long-term safety.

March 1993 SKB arranged a two-day international workshop to discuss design and construction of repositories. Close to 40 participants from eight countries shared experiences regarding passage of major water-conducting fracture zones and other matters. This report summarizes the contributions to the workshop.

SKB Technical Report 94-07

INTRAVAL Working Group 2 summary report on Phase 2 analysis of the Finnsjön test case

Andersson, Peter (ed.) 1); Winberg, Anders (ed.) 2)

GEOSIGMA, Uppsala, Sweden 1); Conterra, Göteborg, Sweden 2)

January 1994

ABSTRACT

A comprehensive series of tracer tests on a relatively large scale have been performed by SKB at Finnsjön, Sweden, to increase understanding of transport phenomena which govern migration of radionuclides in major fracture zones. The experimental sequence of tracer tests consisted of; a preliminary tracer test during hydraulic interference tests, a radially converging test and a dipole test. Both sorbing and slightly sorbing tracers were used. The conducted experiments were subsequently selected as a test case in the international INTRAVAL Project, in part because the tests at Finnsjön invite to direct address of validation of geosphere models. This report summarizes the study of the Finnsjön test case within INTRAVAL Phase 2, which has involved nine project teams from seven countries. Porous media approaches in two dimensions dominated, although some project teams utilized one-dimensional transport models, and even three-dimensional approaches on a larger scale. The dimensionality employed did not appear to be decisive for the ability to reproduce the observed field responses. It was also demonstrated that stochastic approaches can be used in a validation process. Only four out of nine project teams studied more than one process. The general conclusion drawn is that flow and transport in the studied zone is governed by advection and that hydrodynamic dispersion is needed to explain the break-through curves. Matrix diffusion is assumed to have small or negligible effect. The performed analysis is dominated by numerical approaches applied on scales on the order of a 1000 m. Taking scale alone into account, the results of most teams are possible to compare. A variety of validation aspects have been considered. Five teams utilized a model calibrated on one test, to predict another, whereas the two teams utilizing stochastic continuum approaches addressed; 1) validity of extrapolation of a model calibrated on one transport scale to a larger scale, 2) performance assessment implications of choice of underlying distribution model for hydraulic conductivity, respectively.

SKB Technical Report 94-08

The structure of conceptual models with application to the Äspö HRL Project

Olsson, Olle 1); Bäckblom, Göran 2); Gustafson, Gunnar 3); Rhén, Ingvar 4); Stanfors, Roy 5); Wikberg, Peter 2)

Conterra AB 1); SKB 2); CTH 3); VBB/VIAK 4); RS Consulting 5)

May 1994

ABSTRACT

In performance assessment a sequence of models is used to describe the function of the geological barrier. This report proposes a general structure and terminology for description of these models. A model description consists of the following components:

- a conceptual model which defines the geometric framework in which the problem is solved, the dimensions of the modelled volume, descriptions of the processes included in the model, and the boundary conditions,
- data which are introduced into the conceptual model, and
- a mathematical or numerical tool used to produce output data.

Contradictory to common practice in geohydrologic modelling it is proposed that the term conceptual model is restricted to define in what way the model is constructed, and that this is separated from any specific application of the conceptual model. Hence, the conceptual model should not include any specific data.

SKB Technical Report 94-09

Tectonic framework of the Hanö Bay area, southern Baltic Sea

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June 1994

ABSTRACT

The tectonic framework and the general geologic development of the Hanö Bay, from the Scanian coast in the west to south of Öland in the east, has been investigated by means of reflection seismic methods. The Hanö Bay is in this paper subdivided into four areas of different geologic settings. These are: 1) The Hanö Bay slope, which forms a southward dipping continuation of the rigid Blekinge coastal plain. 2) The eastward dipping Kalmarsund Slope, which southwards from Öland forms the western part of the Paleozoic Baltic Syneclise. 3) The Mesozoic Hanö Bay Halfgraben, which forms the central and southern parts of the Hanö Bay. The ongoing subsidence of the Halfgraben is estimated to be in the order of 20-60 m during the Quaternary. 4) The Yoldia Structural Element, which forms a deformed, tilted and possibly rotated block of Paleozoic bedrock located east of the Hanö Bay Halfgraben. Two tectonic phases dominate the post-Paleozoic development of the Hanö Bay, these are: 1) The Early Kimmerian phase, which initiated subsidence and reactivated older faults. 2) The Late Cretaceous phase, which is the main subsidence phase of the Hanö Bay Halfgraben. The tectonic fault pattern of the Hanö Bay is dominated by three directions, i.e. NW-SE, NE-SW and WNW-ESE. The two main tectonic elements of the area are the Kullen--Christiansö Ridge System (NW-SE) and the Bornholm Gat Tectonic Zone (NE-SW). Sinistral strike-slip movements in order of 2-3 km are interpreted to have occurred along the Bornholm Gat Tectonic Zone during the Late Cretaceous.

SKB Technical Report 94-10

Project Caesium – An ion exhange model for the prediction of distribution coefficients of caesium in bentonite

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MBT Umwelttechnik AG, Zürich, Switzerland 1); Chalmers University of Technology, Gothenburg, Sweden 2)

June 1994

ABSTRACT

A surface chemical model is established to thermodynamically describe caesium sorption on bentonite. Caesium sorption is studied on Wyoming bentonite MX-80 in solutions of NaCl, KCl, $MgCl_2$, $CaCl_2$, $NaNO_3$ and $Ca(NO_3)_2$ of concentrations varying between 0.025M and 1M, as well as in the weakly saline Allard groundwater and the strongly saline Äspö groundwater. Based on these experiments it is shown that the sorption behaviour of caesium on bentonite can be described, within the experimental and model uncertainties, in terms of a one-site ion exchange model. The ion exchange constant for the replacement of Na^+ on montmorillonite by Cs^+ is $\log K_{ex}{}^{o} = 1.6$. The model predictions compare well with sorption data published in the open literature on both Wyoming bentonite MX-80 and other types of bentonite.

For the analysis of diffusion experiments in compacted bentonite, the apparent diffusivity of tritiated water, HTO, is used as an analogue to estimate the pore diffusivity of Cs+. Since insufficient information is available at present to estimate the porosity actually available for diffusion in compacted bentonite, it is assumed that the diffusion porosity can be approximated by using the value of the bulk porosity. Under these circumstances, the cation exchange capacity (CEC) found to be available for the diffusing species in compacted bentonite corresponds to about 12% of the total CEC of bentonite. It is recognised that the errors made in the estimation of the pore diffusivity and of the diffusion porosity are contained in the reduction factor of the CEC. A discussion of the factors affecting the diffusivities of radionuclides and the problem of establishing consistent sets of diffusivity data is given in the Appendix.

SKB Technical Report 94-11

Äspö Hard Rock Laboratory Annual Report 1993

June 1994

ABSTRACT

The Äspö Hard Rock Laboratory is being constructed in preparation for the deep geological repository of spent fuel in Sweden. This Annual Report 1993 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. As of December 1993, 2760 m of the tunnel had been excavated to a depth of 370 m below the surface.

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

Eight organizations from seven countries are now participating in the work at the Äspö Hard Rock Laboratory and are contributing in different ways to the results being achieved.

SKB Technical Report 94-12

Research on corrosion aspects of the Advanced Cold Process Canister

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AEA Technology, Harwell Laboratory, Didcot, Oxfordshire, UK

January 1994

ABSTRACT

The Advanced Cold Process Canister (ACPC) is a waste canister being developed jointly by SKB and TVO for the disposal of spent nuclear fuel. It comprises an outer copper canister, with a carbon steel canister inside. A concern regarding the use of the ACPC is that, in the unlikely event that the outer copper canister is penetrated, the anaerobic corrosion of the carbon steel container may result in the formation of hydrogen gas bubbles. These bubbles could disrupt the backfill, and thus increase water flow through the near field and the flux of radionuclides to the host geology.

A number of factors that influence the rate at which hydrogen evolves as a result of the anaerobic corrosion of carbon steel in artificial granitic groundwaters have been investigated. A previously observed, time-dependent decline in the hydrogen evolution rate has been confirmed as being due to the production of a magnetite film. Once the magnetite film is about 0.7-1.0 μm thick, the rate of hydrogen evolution reaches a steady state value. The pH and the ionic strength of the groundwater were both found to influence the long-term hydrogen evolution rate. The results of the experimental programme were used to update a model of the corrosion behaviour and hydrogen production from the Advanced Cold Process Canister.

SKB Technical Report 94-13

Assessment study of the stresses induced by corrosion in the Advanced Cold Process Canister

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October 1993

ABSTRACT

The Advanced Cold Process Canister (ACPC) is a concept for the encapsulation of spent nuclear fuel for geological disposal. The basic design of the ACPC consists of an outer oxygen free copper overpack covering a carbon steel inner container.

In this report the stresses exerted on the copper overpack as a result of an early failure of the canister and the subsequent corrosion of the steel are calculated.

SKB Technical Report 94-14

Performance of the SKB Copper/Steel Canister

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Kemakta Konsult AB, Stockholm, Sweden 1); Svensk Kärnbränslehantering AB – SKB, Stockholm, Sweden 2)

September 1994

ABSTRACT

The performance of the SKB copper/steel canister has been analyzed. The present knowledge of long-term function of the canister is summarized. Radionuclide release calculations for a reference failure scenario and the effect of some variations on release rates are shown. The Features, Events and Processes (FEPs) that are affecting the studied scenarios have been classified according to the "Rock Engineering Systems" methodology as defined by SKB for the copper/steel canister.

Radionuclide release rate is calculated for a reference failure scenario where a small hole in the weld of the outer copper overpack is assumed to exist at the time of deposition. The hole in the copper overpack is assumed to be of constant size until the inner steel canister loses its mechanical integrity. The steel is assumed to maintain mechanical stability during 5 000 years and after this time period the hole through the copper is assumed to be 0.1 m^2, which translate to insignificant transport resistance from the canister wall.

The release rates for C-14, Sr-90, 1-129, Cs-137, Pu-239 and Am-241 are calculated for the reference failure scenario and for a number of variations. The variations include glaciation, only few of the Zircalloy tubes damaged, different canister filling materials, variations in sorption properties of the bentonite clay and different life-time of the inner steel canister. The performance of the canister and near-field, concerning the release rates of the studied radionuclides, is as expected, comparable to the release rates obtained in SKB 91.

SKB Technical Report 94-15

Modelling of nitric acid production in the Advanced Cold Process Canister due to irradiation of moist air

Henshaw, J

AEA Technology, Decommissioning & Waste Management/Reactor Services, Harwell, UK

January 1994

ABSTRACT

This report summarises the work performed for SKB of Sweden on the modelling of nitric acid production in the gaseous environment of the Advanced Cold Process Canister (ACPC). The model solves the simultaneous chemical rate equations describing the radiation chemistry of a $He/Ar/N_2/O_2/H_2O$ gas mixture, involving over 200 chemical reactions. The amount of nitric acid produced as a function of time for typical ACPC conditions has been calculated using the model and the results reported.

SKB Technical Report 94-16

Kinetic and thermodynamic studies of uranium minerals. Assessment of the long-term evolution of spent nuclear fuel

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October 1994

ABSTRACT

We have studied the dissolution behavior of uraninite, becquerelite, schoepite and uranophane. The information obtained under a variety of experimental conditions has been combined with extensive solid phase characterizations, performed on both leached and unleached samples. The overall objective is to construct a thermodynamic and kinetic model for the long-term oxidation alteration of $UO_2(s)$, as an analogy of the spent nuclear fuel matrix.

We have determined the solubility product for becquerelite ($\log K_{s0}=32.7 \pm 1.3$) and uranophane ($\log K_{s0}=7.8 \pm 0.8$). In some experiments, the reaction progress has shown initial dissolution of uranophane followed by precipitation of a secondary solid phase, characterized as soddyite. The solubility product for this phase has been determined ($\log K_{s0} = 3.0 \pm 2.9$).

We have studied the kinetics of dissolution of uraninite, uranophane and schoepite under oxidizing conditions in synthetic granitic groundwater. BET measurements have been performed for uraninite and uranophane. For schoepite, the measurement has not been performed due to the lack of sufficient amount of sample. The normalized rates of dissolution of uraninite and uranophane have been calculated, referred to the uranium release, as $1.97 \cdot 10^{-8}$ moles h^{-1} m^{-2} and $4.0 \cdot 10^{-9}$ moles h^{-1} m^{-2}, respectively. For schoepite, the dissolution process has shown two different rates, with a relatively fast initial dissolution rate of $1.97 \cdot 10^{-8}$ moles h^{-1} followed, after approximately 1000 hours, by a slower one of $1.4 \cdot 10^{-9}$ moles h^{-1}. No formation of secondary phases has been observed in those experiments, although final uranium concentrations have in all cases exceeded the solubility of uranophane, the thermodynamically more stable phase under the experimental conditions.

SKB Technical Report 94-17

Summary report of the experiences from TVO's site investigations

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Saanio & Riekkola Consulting Engineers, Helsinki, Finland 1); Fintact Ky, Helsinki, Finland 2); Imatran Voima Oy, Helsinki, Finland 3)

May 1994

ABSTRACT

Teollisuuden Voima Oy (TVO) has completed preliminary site investigations at five sites in Finland. At the end of 1992 TVO presented the final report to the authorities. The preliminary site investigation phase 1986 – 1992 was conducted according to the investigation programme compiled by TVO.

The aim of this report was to compile a report on experiences from TVO's site investigations. The main interest was focused on investigation strategies and the most important investigation methods for the conceptual modelling.

The objective of the preliminary site investigations was to obtain data on the bedrock properties in order to evaluate the areas. The programme was divided into four stages, each stage having its own subobjective. The site-specific investigation programme for each site included a large common part and a small site-specific part.

The strategies (objectives) and experiences from different disciplines, geology, hydrogeochemistry, geophysics and geohydrology, are presented in the report.

The conceptual modelling work procedure including both bedrock and groundwater modelling is described briefly using the Olkiluoto site as an example. Each of the other areas has undergone similar phases of work. The uncertainties associated with conceptual modelling are also discussed.

The usefulness of the investigation strategy and the investigation methods for conceptual modelling is discussed in the report.

Some new equipment, methods or enhancements that have not yet been used in TVO's site investigations have become new tools in site characterisation and are briefly presented in the report.

SKB Technical Report 94-18

AECL strategy for surface-based investigations of potential disposal sites and the development of a geosphere model for a site

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AECL Research, Whiteshell Laboratories, Pinawa, Manitoba, Canada

May 1994

ABSTRACT

The objective of this report is to summarize AECL's strategy for surface-based geotechnical site investigations used in screening and evaluating candidate areas and candidate sites for a nuclear fuel waste repository and for the development of geosphere models of sites. The report is one of several prepared by national nuclear fuel waste management programs for the Swedish Nuclear Fuel and Waste Management Co. (SKB) to provide international background on site investigations for SKB's RD&D programme on siting.

The scope of the report is limited to surface-based investigations of the geosphere, those done at surface or in boreholes drilled from surface.

The report discusses AECL's investigation strategy and the methods proposed for use in surface-based reconnaissance and detailed site investigations at potential repository sites. Site investigations done for AECL's Underground Research Laboratory are used to illustrate the approach. The report also discusses AECL's strategy for developing conceptual and mathematical models of geological conditions at sites and the use of these models in developing a model (Geosphere Model) for use in assessing the performance of the disposal system after a repository is closed. Models based on the site data obtained at the URL are used to illustrate the approach. Finally, the report summarizes the lessons learned from AECL's R&D program on site investigations and mentions some recent developments in the R&D program.

SKB Technical Report 94-19

Deep drilling KLX 02. Drilling and documentation of a 1700 m deep borehole at Laxemar, Sweden

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August 1994

ABSTRACT

In this report the preparation and execution of the deep core drilling KLX 02 is described.

The hole was drilled with the wireline method, NQ dimension (Ø 76 mm, to a final depth of 1700.5 m.

Prior to core drilling a Ø 215 mm pilothole was predrilled to 200 m with controlled hammerdrilling (DTH). In this hole casing and air-lift equipment was installed with the aim to support the circulation of drilling fluid.

During core drilling there was a measurement of major drilling parameters and drilling fluid in and out of hole. As a fluid tracer uranine was used.

Each 300 m of core drilling air-lift pumptests were performed. After completion a flow-meter log was run to finalize the project phase.

It can be concluded that both the predrilling and core drilling methods used proved to be successful. No severe technical problems occurred. However, potential risks have been pointed at in the report.

The air-lift system functioned only partly and has to be modified for further use. Also the technique for monitoring of drilling parameters needs improvement as does the method for air-lift pumptests with packer.

The organisation model for planning and realization functioned satisfactory and can be recommended for similar future projects.

SKB Technical Report 94-20

Technology and costs for decommissioning of Swedish nuclear power plants

Prepared by a working group within the Swedish Power Industry

June 1994

ABSTRACT

This decommissioning study for the Swedish nuclear power plants has been carried out during 1992 to 1994 and the work has been led by a steering group consisting of people from the nuclear utilities and SKB.

The study has been focused on two reference plants, Oskarshamn 3 and Ringhals 2. Oskarshamn 3 is a boiling water reactor (BWR) and Ringhals 2 is a pressurized water reactor (PWR). Subsequently, the result from these plants have been translated to the other Swedish plants.

The study gives an account of the procedures, costs, waste quantities and occupational doses associated with decommissioning of the Swedish nuclear power plants. Dismantling is assumed to start immediately after removal of the spent fuel. No attempts at optimization, in terms of technology or costs, have been made. The nuclear power plant site is restored after decommissioning so that it can be released for use without restriction for other industrial activities.

The study shows that a reactor can be dismantled in about five years, with an average labour force of about 150 persons. The maximum labour force required for Oskarshamn 3 has been estimated to about 300 persons. This peak load occurred the first years but is reduced to about 50 persons during the demolishing of the buildings.

The cost of decommissioning Oskarshamn 3 has been estimated to be about MSEK 940 in January 1994 prices. The decommissioning of Ringhals 2 has been estimated to be MSEK 640. The costs for the other Swedish nuclear power plants lie in the range MSEK 590-960.

SKB Technical Report 94-21

Verification of HYDRASTAR: Analysis of hydraulic conductivity fields and dispersion

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October 1994

ABSTRACT

HYDRASTAR is a code for the stochastic simulation of groundwater flow. It can be used to simulate both time-dependent and steady-state groundwater flow at constant density. Realizations of the hydraulic conductivity field are generated using the Turning Bands algorithm. The realizations can be conditioned on measured values of the hydraulic conductivity using Kriging. This report describes a series of verification studies that have been carried out on the code. The first study concerns the accuracy of the implementation of the Turning Bands algorithm in HYDRASTAR. The implementation has been examined by evaluating the ensemble mean and covariance of the generated fields analytically and comparing them with their prescribed values. Three other studies were carried out in which HYDRASTAR was used to solve problems of uniform mean flow and to calculate the transport and dispersion of fluid particles. In all three cases the hydraulic conductivity fields were unconditioned. The first two were two-dimensional: one at small values of the variance of the logarithm of the hydraulic conductivity for which there exists analytical results that the code can be compared with, and one at moderate variance where the results can only be compared with those obtained by another code. The third problem was three dimensional with a small variance and again analytical results are available for comparison.

SKB Technical Report 94-22

Evaluation of stationary and non-stationary geostatistical models for inferring hydraulic conductivity values at Äspö

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November 1994

ABSTRACT

This report describes the comparison of stationary and non-stationary geostatistical models for the purpose of inferring block-scale hydraulic conductivity values from packer tests at Äspö. The comparison between models is made through the evaluation of cross-validation statistics for three experimental designs. The first experiment consisted of a "Delete-1" test previously used at Finnsjön. The second test consisted of "Delete-10%" and the third test was a "Delete-50%" test. The analysis was carried out using the commercial code Isatis 1.3 (Geovariances, 1994).

Preliminary data analysis showed that the 3 m and 30 m packer test data can be treated as a sample from a single population for the purposes of geostatistical analyses, with the possible exception of the data from well KAS02. Analysis of the 3 m data does not indicate that there are any systematic statistical changes with depth, rock type, fracture zone vs non-fracture zone or other mappable factor. Directional variograms are ambiguous to interpret due to the clustered nature of the data, but do not show any obvious anistropy that should be accounted for in geostatistical analysis. A Kriging neighborhood divided into 8 angular sectors with a radius of 200 m provided good results while making computations efficient compared to the other neighborhoods tested. This neighborhood definition was used for the remainder of the analyses.

Stationary analysis suggested that there exists a sizeable spatially uncorrelated component ("Nugget Effect") in the 3 m data, on the order of 60% of the observed variance for the various models fitted. Four different nested models were automatically fit to the data:

1) Nugget Effect + Spherical
2) Nugget Effect + Exponential
3) Nugget Effect + Spherical(short range) + Exponential(long range)
4) Nugget Effect + Spherical(short range) + Spherical(long range)

Results for all models in terms of cross-validation statistics were very similar for the first set of validation tests, but the model consisting of the Nugget Effect, Spherical and Exponential elementary models performed slightly better overall and was chosen for the additional cross-validation tests.

Non-stationary analysis established that both the order of drift and the order of the intrinsic random functions is low. For the neighborhood selected, drift is either zeroth or first order; the elementary covariance models are zero and third order.

In terms of cross-validation statistics, the non-stationary models were slightly better than the stationary models in terms of Mean Error (ME), but much worse in terms of Mean Reduced Error (MRE) and Mean Square Reduced Error (MSRE). Mean Squared Error (MSE) was slightly better for the stationary case. These results strongly suggest that stationary models will produce smaller cross-validation errors at Äspö. Unlike the situation at Finnsjön, the packer test data at Äspö seem to be very stationary with no trend and only low order drift, so that advantages of using intrinsic random functions are lost and stationary models may more accurately model the covariance.

Regularization of packer test data to larger intervals using Norman's (1992a) formula overpredicts the regularized interval hydraulic conductivity. A simple arithmetic average produces less biased results, but any regularization of this type introduces additional uncorrelated noise into the data, and will tend to obscure the true spatial properties of the hydraulic conductivity field. A moving average regularization process as currently implemented in Inferens 1.1 may also introduce other undesirable effects, and it is recommended that geostatistical analysis and estimation be performed on unregularized data, with regularization to block-scale hydraulic conductivity values performed after geostatistical estimation or simulation.

This study also suggests that conventional cross-validation studies and automatic variogram fitting are not necessarily evaluating how well a model will infer block scale hydraulic conductivity values. It is suggested that a series of stochastic modeling experiments be conducted to examine how sensitive the hydrological modeling results are to uncertainties in the geostatistical inference model and the upscaling process.

SKB Technical Report 94-23

PLAN 94

Costs for management of the radioactive waste from nuclear power production

Swedish Nuclear Fuel and Waste Management Co

June 1994

ABSTRACT

SKB prepares every year, on behalf of the nuclear power utilities, a calculation of the costs for all the measures that are required to manage the spent nuclear fuel from the reactors and the radioactive waste deriving from it and to decommission and dismantle the reactor plants. The cost calculation is submitted to the Nuclear Power Inspectorate (SKI). SKI uses this as a basis for calculating a proposal for the fee for management of the radioactive waste products of nuclear power that is levied on nuclear-generated electricity.

The calculation, which is based on specific scenarios for energy production, waste quantities and required measures, are presented in annually issued reports, the last one PLAN 94, dated June 1994.

PLAN 93 was a comprehensive report giving an overview of the Swedish radioactive waste management system. The 1994 status regarding general premises, facilities, systems, RD&D, etc., differs only slightly from 1993, and the present English edition of PLAN 94 has therefore been reduced to include only an updated set of those tables and other significant data that were included in PLAN 93. The reader is kindly advised to consider the present report as an addendum to PLAN 93.

SKB Technical Report 94-24

Äspö Hard Rock Laboratory – Feasibility and usefulness of site investigation methods. Experiences from the pre-investigation phase

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August 1994

ABSTRACT

One of the main goals set up by SKB for the Äspö HRL project is to "test the quality and appropiateness of different methods for characterizing the bedrock with respect to conditions of importance for a final repository". An extensive investigation programme was carried out during the project's pre-investigation phase that in part was based on experience from SKB's previous site investigations and in part entailed the testing of new or other unestablished methods.

Previous technical reports have described the methods that have been used and the results, models and predictions that have been produced. All the methods used are discussed in the present report in terms of how they have contributed in different analysis stages to the total geoscientific characterization of the rock at Äspö. The usefulness of each method for modelling and prediction on different scales is evaluated, and aspects of the practical execution of the methods under different conditions are discussed.

The report sheds light on the importance of dividing large investigation programmes such as this one into suitable stages to get an opportunity to evaluate the results obtained and plan in detail the investigations in the next stage. Furthermore, the way in which the characterization/modelling work on different geometric scales has been done for the different investigation stages is discussed, along with whether this has been found to be a suitable approach. The importance of pursuing an interdisciplinary strategy throughout the pre-investigation process cannot be overemphasized. For the planning, execution, analysis and reporting of the results of the pre-investigations, this has been guaranteed by an organization in which an interdisciplinary group has been in charge of the investigations, together with the project manager.

SKB Technical Report 94-25

Kinetic modelling of bentonite-canister interaction. Long-term predictions of copper canister corrosion under oxic and anoxic conditions

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September 1994

ABSTRACT

A new modelling approach for canister corrosion which emphasises chemical processes and diffusion at the bentonite-canister interface is presented. From the geochemical boundary conditions corrosion rates for both an anoxic case and an oxic case are derived and uncertainties thereof are estimated via sensitivity analyses.

Time scales of corrosion are assessed by including calculations of the evolution of redox potential in the near field and pitting corrosion. This indicates realistic corrosion depths in the range of 10^{-7} and $4 \cdot 10^{-5}$ mm/yr, respectively for anoxic and oxic corrosion. Taking conservative estimates, depths are increased by a factor of about 200 for both cases. From these predictions it is suggested that copper canister corrosion does not constitute a problem for repository safety, although certain factors such as temperature and radiolysis have not been explicitely included. The possible effect of bacterial processes on

corrosion should be further investigated as it might enhance locally the described redox process.

SKB Technical Report 94-26

A surface chemical model of the bentonite-water interface and its implications for modelling the near field chemistry in a repository for spent fuel

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July 1994

ABSTRACT

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. A pretreated and well-characterised Wyoming MX-80 bentonite has been used for investigating the acid/base characteristics of Na-montmorillonite. The CEC of Namontmorillonite was determined to 108 meq/100 g for pretreated bentonite and to 85 meq/100 g for the bulk material. The BET surface area was (31.53±0.16) 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 (X layer sites) and variable-charge surface sites (edge OH groups) as the reactive surface functionalities. The total population of the surface sites are estimated to TOT-OH = $2.84 \cdot 10^{-5}$ mol/g, TOT-X = $2.2 \cdot 10^{-5}$ 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 $\log K_X^0 = (4.6 \pm 0.2)$.

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, denoted as Y layer sites. The characteristic parameters for the second type of layer sites (Y layer sites) are: TOT-Y = $1.06 \cdot 10^{-3}$ mol/g for pretreated Wyoming MX-80 bentonite and $8.3 \cdot 10^{-4}$ mol/g for raw Wyoming MX-80 bentonite, respectively, and $\log K_X^0 = 3.0$.

Ca-Na-exchange isotherms were measured on pretreated Wyoming MX-80 bentonite. The thermodynamic exchange constant was estimated to $\log K_X^0 = (0.43 \pm 0.17)$.

The near field chemistry under repository conditions is predicted based on the proposed three-site bentonite model. Model computations indicate that the edge OH groups of montmorillonite excert a strong control on the buffer capacity in highly compacted bentonite. Model calculations predict a pH value of 7.3 and an alkalinity of $1.92 \cdot 10^{-2}$ 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.

SKB Technical Report 94-27

Experimental study of strontium sorption on fissure filling material

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December 1994

ABSTRACT

We have carried out a comparative study of sorption and desorption of strontium in groundwater on separated magnetic and size fractions of fissure filling material taken from natural fissures in granitic rock.

Complete reversibility of the sorption process was demonstrated by identical Freundlich isotherms, isotopic exchangeability and pH dependence of the distribution coefficients Rd.

The sorption was found to be strongly pH dependent in the range 3-11. The pH effect can be accommodated in the sorption model by considering the surface areas and surface charges of the minerals in the fissure filling material.

SKB Technical Report 94-28

Scenario development methodologies

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November 1994

ABSTRACT

In the period 1981-1994, SKB has studied several methodologies to systemize and visualize all the features, events and processes (FEPs) that can influence a repository for radioactive waste in the future. All the work performed is based on the terminology and basic findings in the joint SKI/SKB work on scenario development presented in the SKB Technical Report 89-35.

The methodologies studied are a) Event tree analysis, b) Influence diagrams and c) Rock Engineering Systems (RES) matrices. Each one of the methodologies is explained in this report as well as examples of applications.

One chapter is devoted to a comparison between the two most promising methodologies, namely: Influence diagrams and the RES methodology.

In conclusion a combination of parts of the Influence diagram and the RES methodology is likely to be a promising approach.

SKB Technical Report 94-29

Heat conductivity of buffer materials

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November 1994

ABSTRACT

The report deals with the thermal conductivity of bentonite based buffer materials. An improved technique for measuring the thermal conductivity of buffer materials is described. Measurements and FLAC calculations applying this technique have led to a proposal of how standardized tests should be conducted and evaluated. The thermal conductivity of bentonite with different void ratio and degree of water saturation has been determined in the following different ways:

- Theoretically according to three different investigations by other researchers.
- Laboratory measurements with the proposed method.
- Results from back-calculated field tests

Comparison and evaluation showed that these results agreed very well, when the buffer material was almost water saturated. However, the influence of the degree of saturation was not very well predicted with the theoretical methods. Furthermore, the field tests showed that the average thermal conductivity in situ of buffer material (compacted to blocks) with low degree of water saturation was lower than expected from laboratory tests.

SKB Technical Report 94-30

Calibration with respect to hydraulic head measurements in stochastic simulation of groundwater flow – A numerical experiment using MATLAB

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December 1994

ABSTRACT

A simulator for 2D stochastic continuum simulation and inverse modelling of groundwater flow has been developed. The simulator is well suited for method evaluation and what-if simulation and written in MATLAB. Conductivity fields are generated by unconditional simulation, conditional simulation on measured conductivities and calibration on both steady-state head measurements and transient head histories. The fields can also include fracture zones and zones with different mean conductivities. Statistics of conductivity fields and particle travel times are recorded in Monte-Carlo simulations.

The calibration uses the pilot point technique, an inverse technique proposed by RamaRao and LaVenue. Several Kriging procedures are implemented, among others Kriging neighbourhoods. In cases where the expectation of the log-conductivity in the truth field is known the non-bias condition can be omitted, which will make the variance in the conditionally simulated conductivity fields smaller.

A simulation experiment, resembling the initial stages of a site investigation and devised in collaboration with SKB, is performed and interpreted.

The results obtained in the present study show less uncertainty than in our preceding study. This is mainly due to the modification of the Kriging procedure but also to the use of more data. Still the large uncertainty in cases of sparse data is apparent. The variogram represents essential characteristics of the conductivity field. Thus, even unconditional simulations take account of important information. Significant improvements in variance by further conditioning will be obtained only as the number of data becomes much larger.

SKB Technical Report 94-31

The implications of soil acidification on a future HLW repository. Part II: Influence on deep granitic groundwater. The Klipperås study site as test case

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May 1994

ABSTRACT

The effect of acidification on deep groundwater is assessed with a geochemical box model based on the STEADYQL code. The application of the model to the Klipperås study site shows a remarkable agreement between observed and predicted groundwater composition and offers an adequate description of the geochemical evolution of the aquifer. Proton fluxes are shown to be controlled mainly by calcite weathering and organic carbon degradation processes.

The impact of increased acidification is evaluated on the basis of various test cases and by including the soil compartment in the model framework. The results indicate that calcite weathering will be increased by a factor of two to three as a result of increased acidification. Furthermore, the calculations suggest that, once the powerful carbonate buffer is depleted, the buffer capacity is provided mainly by anaerobic respiration and ion exchange processes. Further ongoing acidic loading would lead to neutralization of alkalinity fluxes leaving the system with a very low buffering capacity towards fluctuations in proton fluxes.

Estimation of time scales of aquifer acidification was assessed under the focus of calcite depletion with aid of two acidification scenarios. These predict a time range of 12'400 to 370'000 years for calcite depletion to take place down to 500 meters depth. It is suggested from inherent model assumptions that these estimated time scales are conservative.

SKB Technical Report 94-32

Calculated distribution of radionuclides in soils and sediments

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December 1994

ABSTRACT

The description of the accumulation of radionuclides in some biospheric compartments is in general based on a sorption distribution coefficient K_d. This value is very decisive for the concentration of long-lived radionuclides in reservoirs that are important from the dose point of view.

Sorption is due to several processes such as ion-exchange and a variety of physical and chemical interactions which are difficult to interpret with the current K_d-methodology. In addition, many of the K_d values are obtained from laboratory or geospheric conditions not comparable to conditions prevailing in the biosphere. The main objective with this work is to deepen the knowledge about the theoretical background of K_d-values. To achieve this purpose, available theoretical models for ion-exchange and surface complexation have been adapted for simulation under biospheric conditions. The elements treated are cesium, radium, neptunium, uranium and plutonium. The

results show that a triple layer surface complexation model may be used in estimating K_d-values for actinides as a function of important chemical parameters such as pH and E_h.

It is concluded that by estimating some equilibrium constants and making some careful approximations, surface complexation models can be used for performance assessment of radioactive waste repositories.