SKB

R&D-PROGRAMME 86

Handling and final disposal of nuclear waste.

Programme for research development and other measures.

September 1986

SVENSK KÄRNBRÄNSLEHANTERING AB
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Handling and final disposal of nuclear waste

Programme for research, development and other measures

September 1986

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FOREWORD

The Act on Nuclear Activities (SFS 1984:3) prescribes in its Section 12 that a programme shall be prepared for the comprehensive research and development and other measures that are required to safely handle and finally dispose of the radioactive waste from the nuclear power plants. The responsibility lies primarily with the owners of the nuclear power plants. These owners have commissioned SKB to prepare the prescribed programme. According to Section 25 of the Ordinance on Nuclear Activities (SFS 1984:14), this programme shall be submitted to the National Board for Spent Nuclear Fuel during the month of September every third year beginning in 1986.

The purpose of this programme is to fulfil the above obligations.

Stockholm in September 1986

SVENSK KÄRNBRÄNSLEHANTERING AB

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INTRODUCTION

The Act on Nuclear Activities (SFS 1984:3) obligates the owners of the Swedish nuclear power plants to jointly prepare a comprehensive programme for the research and development work and other measures required for the safe management and disposal of the waste from nuclear power.

Svensk Kärnbränslehantering AB - SKB (Swedish Nuclear Fuel and Waste Management Company) - has been commissioned by its owners, the Swedish nuclear utilities, to develop, plan, construct and operate plants and systems for the management and disposal of spent nuclear fuel and radioactive waste from the Swedish nuclear power plants.

SKB is also responsible for the extensive research activities within the field of nuclear waste for which the State has made the Swedish nuclear power producers responsible.

SKB is owned by Forsmarks Kraftgrupp AB (FKA), OKG Aktiebolag, Sydsvenska Värmekraft AB (SVAB, owned by Sydkraft AB) and Vattenfall (the Swedish State Power Board).

The above utilities have commissioned SKB to prepare the programme for research and development prescribed by the Nuclear Activities Act. The programme, which is described in this report, provides an overview of all measures up to the implemented final disposal. An account is given of a more detailed research programme for the period 1987–1992.

SKB's research through 1983 was presented in the KBS-3 report, which was submitted in support of the applications for fuel-loading permits for Forsmark 3 and Oskarshamn 3.

The programme also presents in brief some research results obtained after the publication of the KBS-3 report in May 1983. A more detailed account of these results is provided in the SKB series of Technical Reports.

The comments made in connection with the review of the KBS-3 report have been taken into account in preparing the programme.

For those parts of the waste system that have already been taken into operation or are under construction - transportation and handling systems, central interim storage facility for spent nuclear fuel (CLAB) and final repository for reactor waste (SFR) - the research and development stage has already largely been passed. The programme presented here therefore pertains primarily to the treatment and final disposal of spent fuel.

The report is divided into three parts.

Part I - General - presents the premises for waste management in Sweden and the waste types that are produced in the Swedish nuclear power programme. A brief description is then provided of the measures required for the handling and final disposal of various waste forms. A summary of planned research and development concludes Part I.

Part II - Choice of final disposal system - contains an account of the investigations that are required to provide a basis for the choice of system and site for final disposal of the waste.

Part III describes a research programme for the years 1987–1992. The Act on Nuclear Activities requires that the programme "present a survey of all measures that may be necessary" and "specify the measures that are intended to be taken within a period of at least six years". Parts I and II are intended to fulfil the first requirement, while part III fulfils the requirement on a detailed six-year plan.

1 PREMISES

1.1 Guidelines for Swedish radioactive waste management

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

The following general guidelines apply to the waste management system:

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

1.2 Applicable legislation etc

The obligations of the owners of nuclear power reactors with regard to handling and final storage of radioactive waste are regulated in the Act on Nuclear Activities, in the Ordinance on Nuclear Activities and in certain licences and guidelines issued by the Government. An overview of the most important provisions is provided in the Appendix.

The provisions and guidelines entail in brief that the owners of nuclear power plants shall ensure that:

- the necessary measures are taken in order to safely handle and finally dispose of generated nuclear waste and to decommission and dismantle nuclear power plants and appurtenant facilities in a safe manner.
- the comprehensive research and development activities that are required to carry out these measures are conducted, including studies of alternative methods for handling and disposal.
- a programme for research and development and other measures is prepared every third year starting in 1986, including an account of the results of completed research.

The R&D programme shall also describe how the comments made in connection with the review of KBS-3 have been taken into account or are intended to be taken into account. The Government has further stipulated that the work carried out during the 1980s must not entail any final commitment to a site or method for final disposal of the spent nuclear fuel.

1.3 Background

Research regarding the handling and final disposal of radioactive waste started on a large scale in Sweden in connection with the establishment of the National Council for Radioactive Waste (PRAV) in 1975. The Council was created on the recommendation of the AKA Committee /1-1/. The research was intensified in connection with the enactment of the "Stipulation Act" in 1976-77, when the KBS (Nuclear Power Safety) project was started by the nuclear utilities. The project work was administratively tied to SKB. The project developed two final disposal methods: KBS-1 for vitrified high-level reprocessing waste (1977) /1-2/ and KBS-2 for the handling and final storage of unreprocessed spent nuclear fuel (1978) /1-3/.

The KBS-1 report was submitted in support of applications for fuel-loading permits for the Ringhals 3 and 4 and Forsmark 1 and 2 reactors. The Government issued fuel-loading permits in 1979 and 1980.

When the Financing Act /1-4/ entered into force, the National Council for Radioactive Waste was abolished, and the National Board for Spent Nuclear Fuel (NAK), later (SKN), was created. The purpose of this Board is to review, assess and supervise the activities of the nuclear utilities (SKB) within the waste management field.

In 1983, SKB presented a new report on the final disposal of spent nuclear fuel. The report was based on the same method as that described in KBS-2, but the new report, KBS-3, was based on a much broader and deeper body of knowledge /1-5/.

The KBS-3 report was presented in support of the applications for fuel-loading permits for the Forsmark 3 and Oskarshamn 3 reactors. The Government granted these licences under the new Act on Nuclear Activities /1-6/ in June 1984. A research programme /1-7/ prepared by SKB in February 1984 was also submitted as a ground for issuance of the licence.

The results from SKB's research work are reported continuously in SKB's technical reports. Annual summaries are included in the SKB Annual Report /1-8; 1-9/.

2 WASTES FROM THE SWEDISH NUCLEAR POWER PROGRAMME

2.1 Classification of radioactive waste

Radioactive waste from the Swedish nuclear power programme varies widely in terms of form and activity content, all the way from virtually inactive trash to spent fuel, which has a very high activity content. Different waste forms therefore impose different demands on handling and final disposal.

From the handling viewpoint it is practical to distinguish between low-level, intermediate-level and high-level waste. Low-level waste can be handled and stored in simple packages, without any special protective measures. Intermediate-level waste must be radiation-shielded for safe handling. High-level waste requires not only radiation shielding but also cooling for a certain period of time in order to permit safe storage.

From the viewpoint of final disposal, the half-life of the constituent radioactive materials is of great importance. A distinction is made between short- and long-lived wastes.

Short-lived waste mainly contains radionuclides with a half-life shorter than 30 years, ie it will have decayed to a harmless level within a few hundred years. This waste will be deposited in the Swedish Final Repository for Reactor Waste - SFR. This repository is currently being built at Forsmark in rock at a depth of 50 metres underground. Some very low-level and short-lived waste can be dumped on a simple landfill (shallow land burial).

Long-lived waste remains radioactive for thousands of years or more and requires a more qualified final disposal.

Figure 2-1 shows examples of classification of wastes from the nuclear power programme from the viewpoint of activity and life.

Life	Radioactivity		
	High-level	Intermediate-level	Low-level
Long (thousands of years)	Spent fuel	Certain core components	
Short (a few hundred years)			Maintenance waste
		Ion exchange resins Discarded components Decommissioning waste	

Figure 2-1. Example of classification of radioactive waste.

2.2 Waste from the nuclear power plants

The waste from the nuclear power plants is usually divided into the following groups in terms of its subsequent handling:

- spent nuclear fuel
- operating waste (reactor waste)
- core components and reactor internals
- decommissioning waste

2.2.1 Spent nuclear fuel

Most of the radioactive substances (approx 99%) that are formed in a nuclear power plant are present in the spent fuel.

Some of the fuel types used in Swedish power reactors are described in KBS-3 /2-1/. A fuel assembly for a boiling water reactor (BWR), see Figure 2-2, contains approximately 180 kg of uranium, while an assembly for a pressurized water reactor (PWR) contains about 460 kg of uranium. The design differs somewhat between different manufacturers and between fuel produced at different times. From the viewpoint of final disposal, the differences between different fuel types are generally of no consequence. This also applies to odd fuel assembly types with oxide

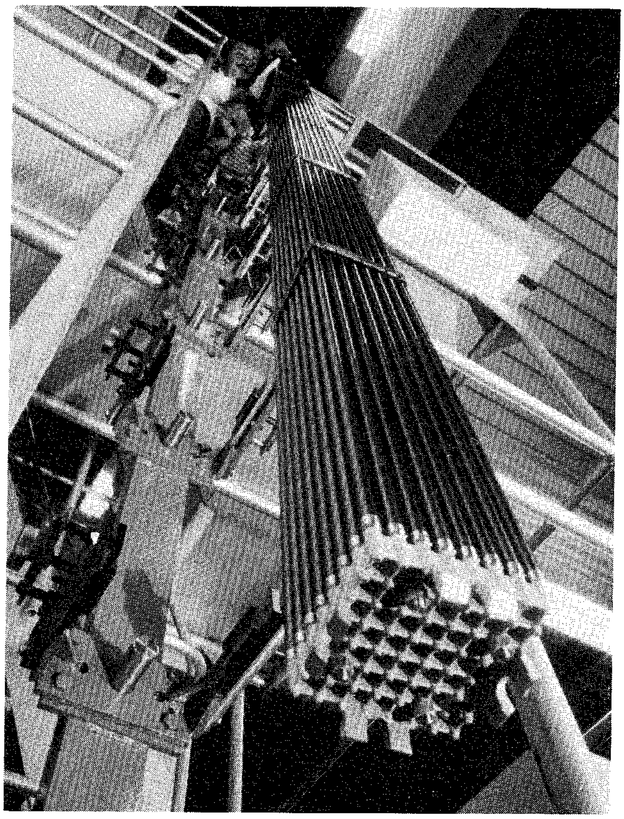


Figure 2-2. Fuel assembly for boiling water reactor.

fuel clad in zircaloy, for example MOX fuel and Ågesta fuel.

The spent fuel consists mainly of unfissioned uranium, while most of the radioactivity is due to the fuel's content of fission products and transuranics. Examples of composition, activity level and other data for spent fuel are given in /2-2/.

The high level of activity in spent fuel means that it continues to emit heat for a long time after it has been discharged from the reactor. This is of great importance in determining how the spent fuel will be handled and disposed of. Between 1 and 40 years after discharge, the residual power decreases by a factor of 10. It then takes another 1000 years or so for the residual power to decrease by yet another factor of 10.

2.2.2 Operating waste

The category "operating waste" includes a number of different types of waste obtained in the operation and maintenance of the reactors. The main constituent is ion exchange resins and filters obtained continuously during operation from cleanup of the reactor water. The operating waste also includes replaced components from the reactor systems as well as protective clothing, plastic, paper, insulating materials etc that have been used in areas where activity is present and can therefore be contaminated.

The operating waste is low- and intermediate-level and mainly contains radionuclides with half-lives shorter than 30 years. The concentration of long-lived radioactive materials is very low. The activity in the operating waste will therefore have decayed to a harmless level within a few hundred years or less.

The operating waste is treated at the nuclear power plants to give it a packaging and a form that is appropriate for its subsequent handling. Different treatment methods are applied at different nuclear power plants, see Figure 2-3. This is described in greater detail in /2-3/.

Similar waste also comes from the operation of the central interim storage facility for spent nuclear fuel, CLAB, and from Studsvik.

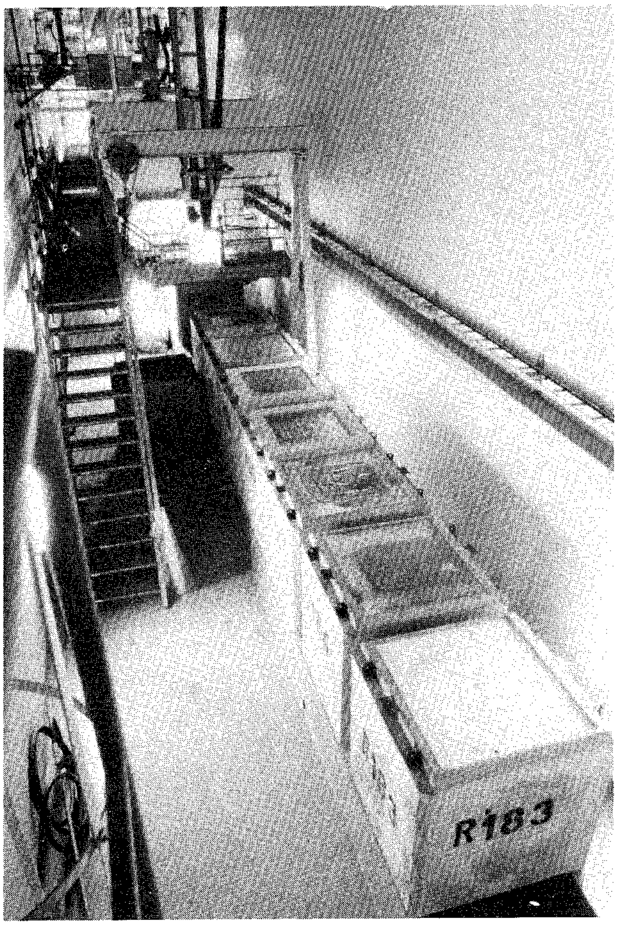


Figure 2-3. Solidification of ion exchange resin in concrete moulds at Ringhals nuclear power station.

2.2.3 Core components and reactor internals

Components located in or near the core inside the reactor vessel are exposed to a strong neutron flux and thereby obtain a high induced activity. Some of these components, for example neutron detectors, are successively replaced at intervals of a few years. Other, for example the moderator tank, are used for the entire lifetime of the reactor and only become waste when the reactors are dismantled.

Fuel channels and other components in the fuel assemblies are included among the core components here.

The core components and some reactor internals have a very high radiation level when they are discharged from the reactor. The radioactivity is dominated by cobalt-60, which has a half-life of about 5 years, which means that the radiation level declines by a factor of 1000 in 50 years. Core components and reactor internals also contain some radionuclides with a long half-life, such as nickel-59 (90 000 years) and niobium-94 (20 000 years). The radiotoxicity of these nuclides is lower than that of the transuranics, and requirements on the final disposal of these components are therefore lower than for spent fuel.

2.2.4 Decommissioning waste

When a nuclear power plant is finally shut down, parts of the facility are radioactive and must therefore be disposed of in a safe manner. These parts include the reactor vessel and reactor internals, as well as the concrete immediately adjacent to the reactor vessel, which has induced activity. They also include different parts of the reactor systems that have been radioactively contaminated. However, most of the plant has not come into contact with radioactivity and the waste can therefore be handled as normal waste from the dismantling of industrial facilities.

The waste obtained from decommissioning consists primarily of components of steel, eg tanks, pipes and valves, from the reactor's process systems. It also includes large quantities of concrete, 90% of which is inactive. The dismantling and demolition work also gives rise to a certain amount of process waste from water and air cleaning systems that are in operation during the decommissioning period.

The radioactive decommissioning waste is all low- and intermediate-level. However, the activity level varies considerably between different parts. A large portion of the scrap can be released for unrestricted reuse. The concrete and some other materials can be deposited on an ordinary industrial landfill, possibly adjacent to the reactor facility. However, most of the active decommissioning waste has an activity level that warrants deposition in SFR. As mentioned above, certain highly radioactive reactor internals are also obtained from decommissioning and require special treatment.

A large portion of the activity consists of surface contamination, which can be removed by means of various decontamination methods. The quantity of material that can be declassified is therefore dependent on how far the decontamination work is carried.

2.3 Other radioactive waste

In addition to from the nuclear power plants, radioactive waste is obtained in Sweden above all from the Central Interim Storage Facility for Spent Nuclear Fuel, CLAB, and the coming treatment plant for spent fuel, BSAB, as well as from the Studsvik Research Facility. Waste from the use of radioactive materials in industry, medical care and research is also collected at Studsvik.

2.3.1 Waste from CLAB and BSAB

The waste from CLAB is of the same kind as the operating waste from the reactors. It is also treated in the same manner. Similar waste will also be obtained from the treatment plant for spent fuel, BSAB.

2.3.2 Waste from Studsvik

Waste from the operation of the R2 research reactor as well as from R&D activities concerned with radioactive products, such as fuel rods, is generated in Studsvik. The fuel that is used in R2 is sent back to the USA and therefore does not have to be disposed of in Sweden. Other waste from R2 is of a similar type to the operating waste from the nuclear power plants and is also treated in a similar manner.

However, the waste from R&D activities is of a different character. Some of this waste contains considerable quantities of long-lived transuranics and therefore requires a similar final disposal as the spent fuel.

Fuel from the Ågesta reactor as well as from the R1 research reactor is also stored at Studsvik. This fuel must also be taken care of in the Swedish waste management system.

2.3.3 Waste from reprocessing

In the reprocessing of spent nuclear fuel, uranium and plutonium are separated from fission products and other transuranics. This process gives rise to both high-level vitrified waste, which contains most of the radioactivity, and low- and intermediate-level waste solidified in cement or bitumen. Most of the waste from reprocessing contains large quantities of transuranics and is therefore long-lived.

The Swedish power industry has reprocessing contracts with BNFL in Great Britain and with COGEMA in France. Only the contracts with COGEMA call for the waste to be returned to Sweden. SKB does not currently plan to use these contracts and is working instead to transfer them to other customers. Reprocessing waste is therefore no longer included in the Swedish plans for the back end of the nuclear fuel cycle.

2.4 Estimated waste quantities

The total quantity of radioactive waste from the Swedish nuclear power programme has been estimated in PLAN-86 /2-4/. The results are shown in Figure 2-4.

Product	Main Source	Unit	Number of units	Volume in final storage m^3
Spent fuel		tonnes U	7 800	
Alpha-contaminated waste	Low- and intemediate level waste from Studsvik	barrels	18 000	6 000
Core components	Reactor internals	concerete cubicals	2 300	19 000
Low- and intermediate level waste	Operations waste, from nuclear power plants and waste treatment facilities	barrels and concrete cubicals	100 000	95 000
Decommissioning waste	From decommissioning of nuclear power plants and waste treatment facilities	10–20 m^3 containers	5 600	113 000

Figure 2-4. Main types of radioactive waste products.

3 MANAGEMENT OF RADIOACTIVE WASTE FROM THE NUCLEAR POWER PLANTS

3.1 General

The safe handling and final disposal of the waste from nuclear power requires planning, construction and operation of a number of facilities and systems. Figure 3-1 shows the different parts of the planned Swedish waste management system. These parts are described in detail in the annual report of the costs for management of the radioactive waste products of nuclear power, PLAN 86, which the power utilities have submitted through SKB /3-1/. Only a brief overview is given here.

The facilities are also planned with regard to the radioactive waste in Sweden that is not attributable to electricity-producing reactors (see Chapter 2).

The design of the system is based on the following fundamental principles:

- Short-lived waste will be disposed of as soon as possible after it has been generated,
- Spent fuel will be stored for about 40 years before it placed in a final repository. Heat generation in the final repository is thereby limited.
- Other long-lived waste will be disposed of in connection with the final disposal of spent fuel.

Essential parts of the waste management system are already in operation or are under construction. The central interim storage facility for spent nuclear fuel, CLAB, and the transportation system are both in operation. The final repository for reactor waste, SFR, is under construction. Remaining parts for which decisions have not yet been taken are a treatment plant for spent fuel, BSAB, and a final repository for long-lived waste, SFL. These facilities will not be built until after 2010, according to present-day plans. Extensive R&D work is being conducted for these parts of the system aimed at finding a suitable design and site (see Chapter 4).

Management of the radioactive waste products of nuclear power also includes decommissioning the nuclear power plants and other facilities when they have been taken out of operation and final disposal of the waste from decommissioning.

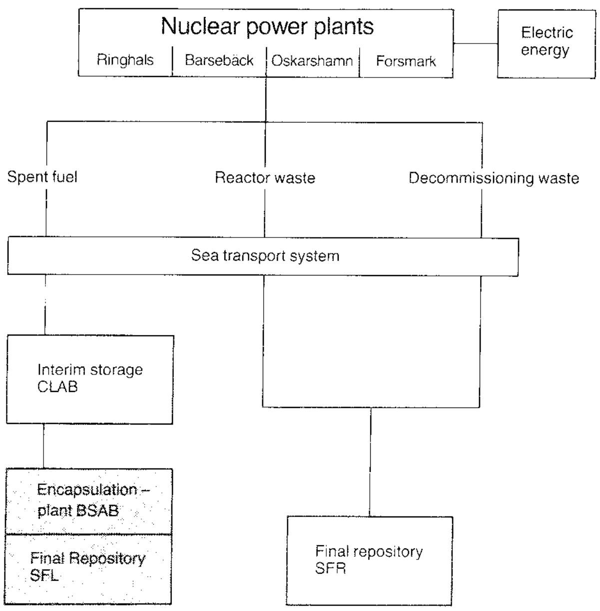


Figure 3-1. The Swedish Waste Management System.

3.2 Possible final disposal principles

A number of possible principles for final disposal are described in SKN PLAN 85 /3-2/ and in SKBF's PLAN 82 Part 1 /3-3/. A condensed summary of the discussion in these references is provided below.

The concept "final disposal" entails that the waste is to be isolated without any requirements on surveillance and in such a manner that it is difficult or impossible to get at. "Monitored final disposal" is sometimes talked about in the public debate. A monitored storage is included as an inescapable link in the handling chain. It can be prolonged over a very long period of time without any major technical or safety-related problems. Sooner or later, however, the waste must be transferred to a repository without supervision and the repository must be sealed. We cannot demand or assume that future generations will bear the burden of resource-consuming surveillance and maintenance of the repository. A repository that is dependent for its safety on continuous surveillance and maintenance measures cannot be regarded as a final repository.

In the final disposal of spent fuel, safeguarding of fissionable material must also be provided for. This means that the final repository must be designed and sealed in such a manner that recovery of the fissionable material involves such extensive and well-planned efforts that a covert retrieval can be ruled out.

The following principles for final disposal of radioactive waste have been proposed in the international discussion:

- Deep disposal in continental geological formations.
- Disposal in shallow soil or rock strata
- Disposal beneath the seabed in deep-sea sediments
- Seadumping
- Disposal in or under inland ice sheets (eg Antartica)
- Launching into space (or to the sun)

Disposal of long-lived waste at great depth (several hundred metres or more) in continental geological formations is the principle that is prioritized by all countries that conduct extensive research and development on disposal of radioactive waste. It is also the only principle that is deemed available and feasible as far as Sweden is concerned within the foreseeable future.

Disposal in shallow soil or rock strata (a few tens up to 100 metres deep) entails restrictions on land use following disposal. This principle can only be applied to short-lived waste or waste with low radiotoxicity. The principle is applied in the SFR.

Disposal beneath the seabed in deep-sea sediments outside the continental shelf is being studied by a number of countries, including a joint international project under the auspices of OECD/NEA. This principle, which has certain attractive features, would require international agreements or conventions and cannot be applied as an independent Swedish solution.

Seadumping or disposal in or under inland ice sheets is not feasible in Sweden.

Launching into space would certainly render the waste inaccessible in a convincing manner, but a prerequisite is that the reliability of the launching procedure can be guaranteed. The recources for such a disposal are hardly available in Sweden.

Another conceivable final treatment principle would involve rendering the long-lived radioactive materials in the waste harmless by means of nuclear "combustion" (transmutation to stable or short-lived nuclides). However, such a system requires advanced reprocessing as well as reactors with a high neutron flux (eg fast breeder reactors). If this method is to be realized at all, it can only be realized within the framework of a far more extensive nuclear energy programme than that which has been adopted in Sweden.

Accordingly, the research programme has been oriented towards the final goal that final disposal of the spent nuclear fuel shall be achieved deep down in the Swedish bedrock. The KBS-3 report has described one method based on this principle. The method has been approved from the standpoint of safety and radiation protection.

The purpose of SKB's research and development is to provide a broad information base for the final choice of method. In principle, the work is not bound to any given method. It is aimed in a generic way at the study of matters of importance to many alternatives in rock. This means that a number of other methods are also being studied and evaluated in present and future research.

3.3 Facilities and systems in operation or under construction

3.3.1 Final repository for reactor waste, SFR

The final repository for reactor waste, SFR, is currently being built at the Forsmark Nuclear Power Station /3-4/. Operating waste from the Swedish nuclear power plants will be emplaced in SFR, along with similar waste from CLAB and Studsvik. The Studsvik waste also includes waste from the use of radioisotopes within research, industry and medicine.

The waste to be disposed of in SFR is low- and intermediate-level and short-lived, which means that it will have decayed to a harmless level within a few hundred years. Figure 3-2 shows the quantities of wastes that are planned to be deposited in SFR.

SFR is situated in rock with a rock cover of about 50 m. It consists of various rock caverns, designed with reference to the different activity contents of the different kinds of waste, see Figure 3-3.

SFR is being built in two phases, the first of which will be taken into service in 1988, while the second is planned to be put into operation at the end of the 1990s.

The application for a siting permit for SFR stated that the facility may later be expanded so that core components and reactor internals can also be deposited there. In the earlier mentioned PLAN-86, it is assumed for practical reasons that this waste is instead disposed of in connection with the final repository for long-lived waste. However, the possibility of depositing it in SFR should be kept open.

Rock vaults for the final disposal of decommissioning waste are also planned within SFR. These vaults will be built when it is time to decommission the nuclear power plants.

3.3.2 Central interim storage facility for spent nuclear fuel, CLAB

The fuel will be stored for about 40 years in the central interim storage facility for spent nuclear fuel, CLAB, which is located adjacent to the Oskarshamn station. During this period, the fuel's activity content and residual heat will decline by about 90%. CLAB was taken into operation in 1985, thereby relieving the pressure on the storage capacity for spent fuel in the nuclear power plants /3-5/.

CLAB consists of an above-ground receiving building and underground storage complex in rock, see Figure 3.4. The fuel is handled and stored under water. The capacity of the facility is now about 3 000 tonnes of spent fuel in four pools. An expansion is

	Storage volume (m^3)
Operating waste	
Intermediate-level	65 000
Low-level	25 000
	90 000
Decommissioning waste	
Intermediate-level	12 000
Low-level	88 000
	100 000

Figure 3-2. Waste to be disposed of in the SFR.

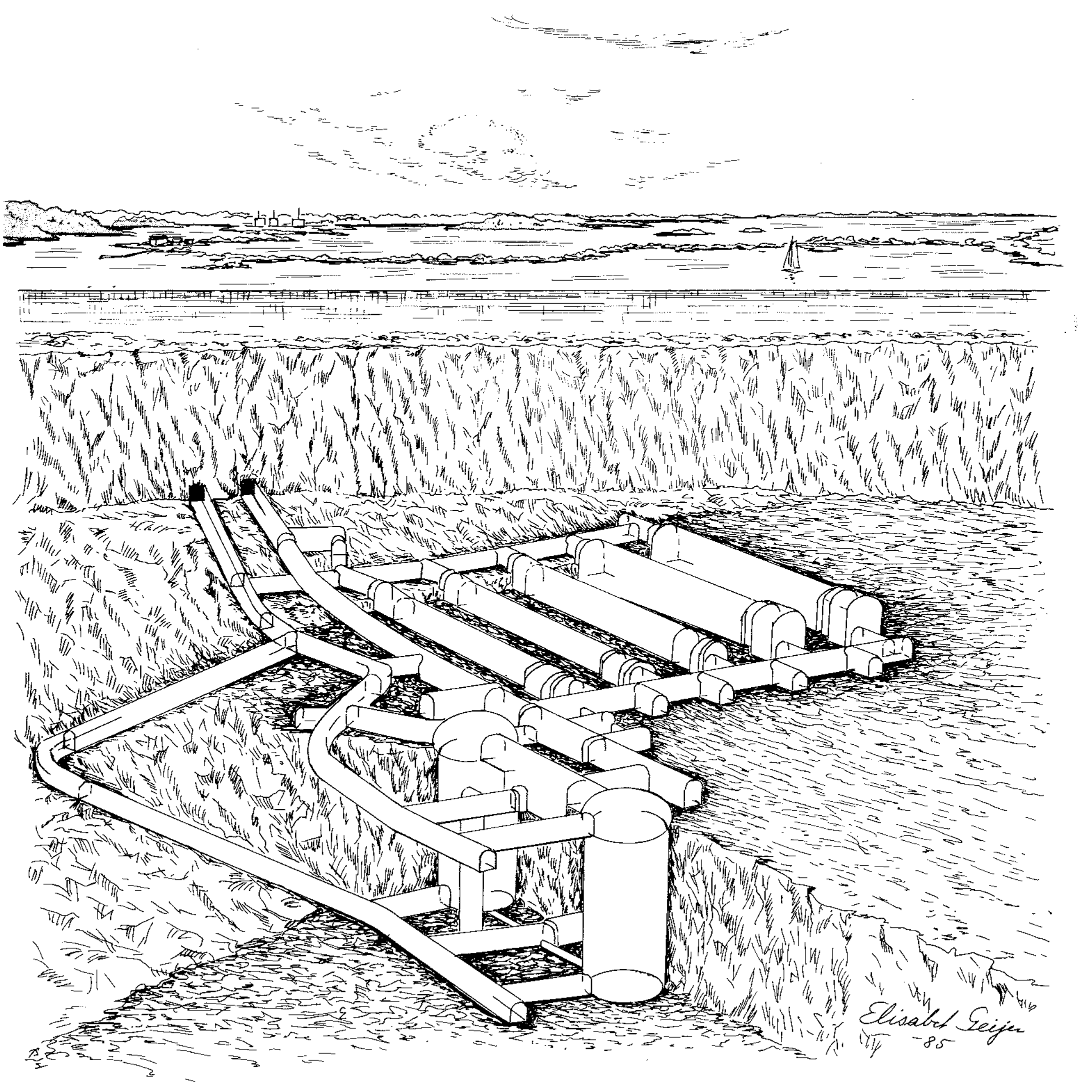


Figure 3-3. Final repository for reactor waste (SFR).

planned for the mid-1990s so that all fuel from the Swedish nuclear power programme, about 8 000 tonnes, can be stored in CLAB. The facility is prepared for this and the expansion can be carried out at the same time as fuel is being brought in and stored in the pools in the existing rock cavern.

Core components and reactor internals can also be stored in CLAB.

3.3.3 The transportation system

A transportation system based on sea transports is used for shipments of spent fuel and radioactive waste /3-6/. It consists of a ship, M/S Sigyn, transport containers and terminal equipment,see Figure 3-5. The transport containers meet the stringent requirements on radiation shielding and ability to withstand external stresses that have been issued by the IAEA. Different types of transport containers are used for spent fuel and for low- and intermediate-level waste.

M/S Sigyn has been in use since 1982. At the present time, fuel is being shipped from the nuclear power plants to CLAB. Starting in 1988, most of the shipments of operating waste to the SFR will also be carried out by Sigyn. If needed, the transportation system can later be augmented with equipment for eg rail shipments for the transports to the final repository for long-lived waste. The need will be dependent on where the final repository is sited.

3.4 Future facilities and systems

3.4. Encapsulation plant for spent fuel, BSAB

Before spent fuel is placed in the repository, it will be encapsulated in a canister that facilitates handling and provides a tight containment of the fuel for a given duration. KBS-3 describes encapsulation of the fuel in a copper canister, which provides a total containment over a very long period of time /3-7/. Other materials may also be considered, as is evident from the R&D programme described in Chapter 4 and Part III.

The design of the encapsulation plant is dependent on which encapsulation method will be used and on the location of the facility. In PLAN 86, the plant has been assumed to be located adjacent to the final repository for long-lived waste, whereby the canisters can be taken down into the final repository immediately after encapsulation. Another alternative is that it will be situated at CLAB, whereby encapsulated fuel must be transported to the final repository.

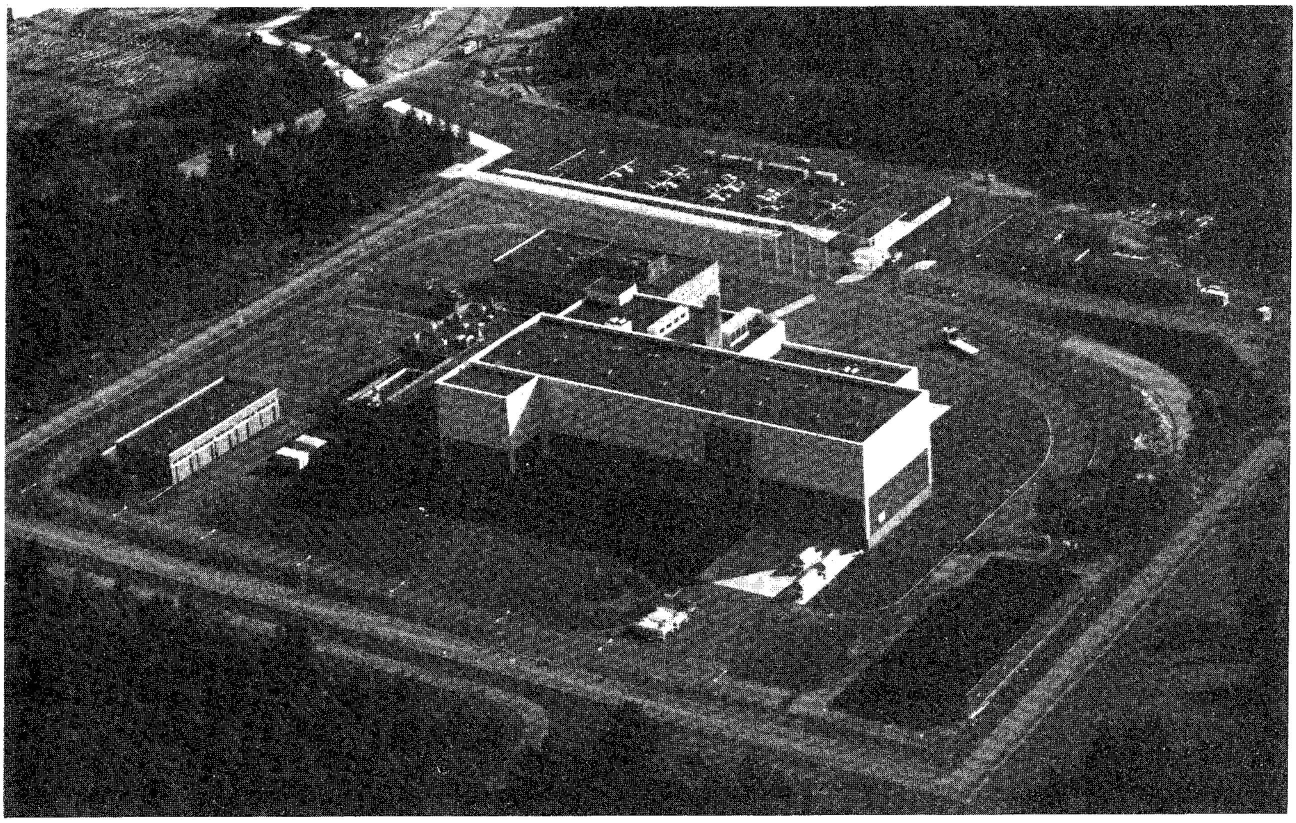


Figure 3-4. Central interim storage facility for spent nuclear fuel (CLAB).

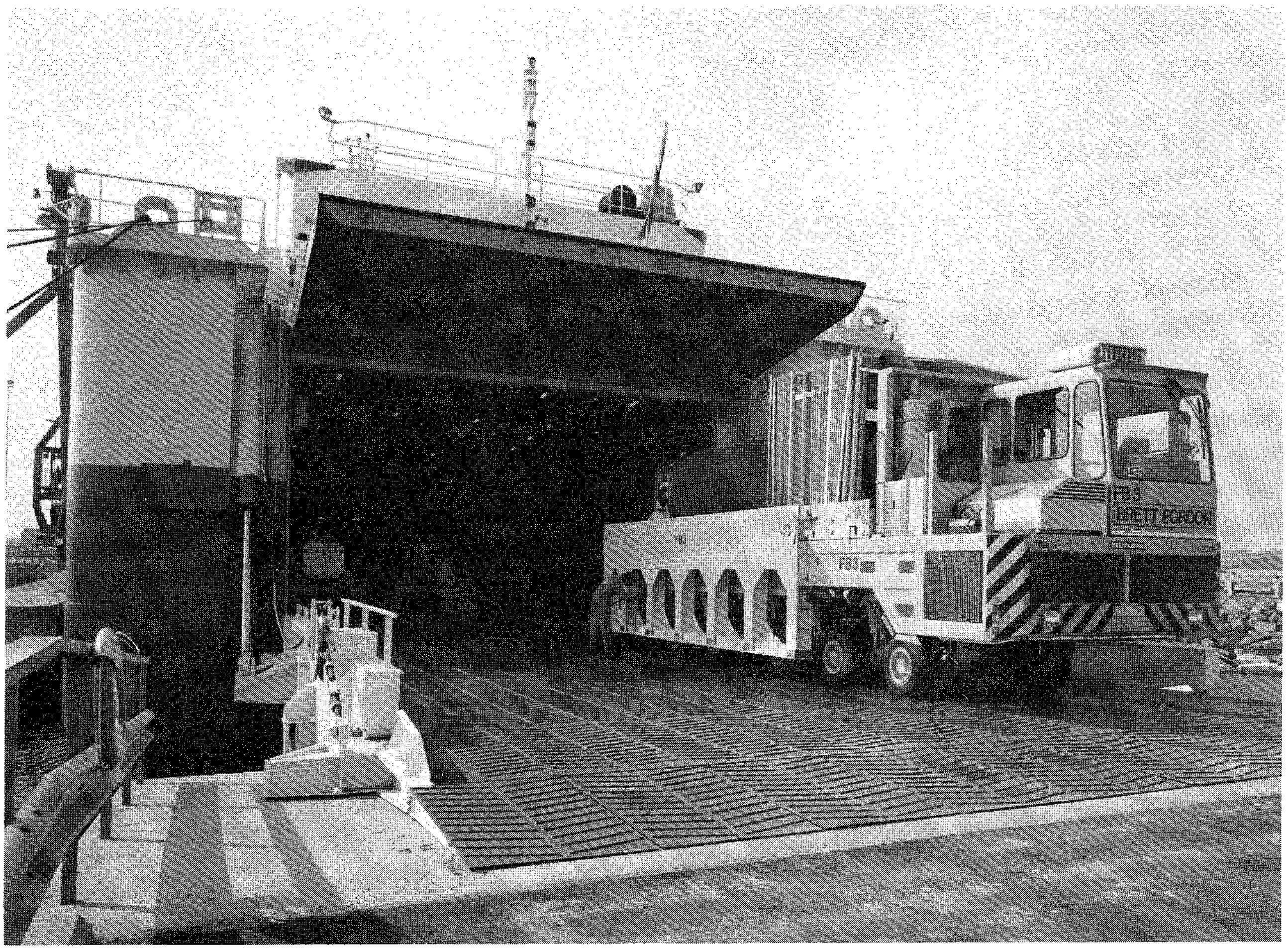


Figure 3-5. Transport vehicle with fuel transport cask on its way out of M/S Sigyn's cargo hold.

A final choice of material and method for encapsulation entails a firm commitment to a specific final disposal method and should therefore not be made earlier than necessary. Encapsulation of the fuel is planned to take place immediately before its deposition in the final repository. It is therefore not necessary to begin construction of the encapsulation plant until around the year 2010, according to present planning.

3.4.2 Final repository for long-lived waste, SFL

The final repository for long-lived waste, SFL, is planned to be taken into service around the year 2020. It is intended to be situated deep in crystalline rock. The site has not yet been chosen. SFL will be used primarily for disposal of the spent fuel, but also other long-lived waste, above all from Studsvik. For practical reasons, some low- and intermediate-level waste from the operation and subsequent decommissioning of CLAB and the encapsulation plant is also assumed to be disposed of in connection with the SFL.

A possible design of the final repository for spent fuel is described in KBS-3, see Figure 3-6. The method involves depositing copper canisters containing spent fuel in holes drilled in the floor of tunnels at a depth of about 500 m. In the boreholes, the canisters are embedded in compacted bentonite. When deposition in a tunnel is concluded, the tunnel is sealed with a sand/bentonite backfill. Until a decision is taken concerning the location and design of the facility, alternative designs of the final repository will be studied, as described in Chapter 4 and in Part III.

The repository for other long-lived waste has not yet been studied in the same degree of detail as the repository for the spent fuel. One possible design, where the waste is emplaced in different kinds of rock vaults at a depth of about 500 m, is described in PLAN 86.

3.5 Timetable

An overall timetable for the measures that have to be adopted for handling and disposal of the radioactive waste from the Swedish nuclear power programme is shown in Figure 3-7. The timetable is based on practical considerations and serves as a basis for the planning of R&D work and other measures. It is also used as a basis for calculating the costs for management of the waste from nuclear power in Sweden /3-1/.

The timetable is not final and changes in one direction or the other may prove to be warranted.The consequences of changes in the main timetable have been analyzed in /3-8/. It shows that relatively large changes can be accepted without any safety-related consequences.

Thus, if desired, interim storage in CLAB can be

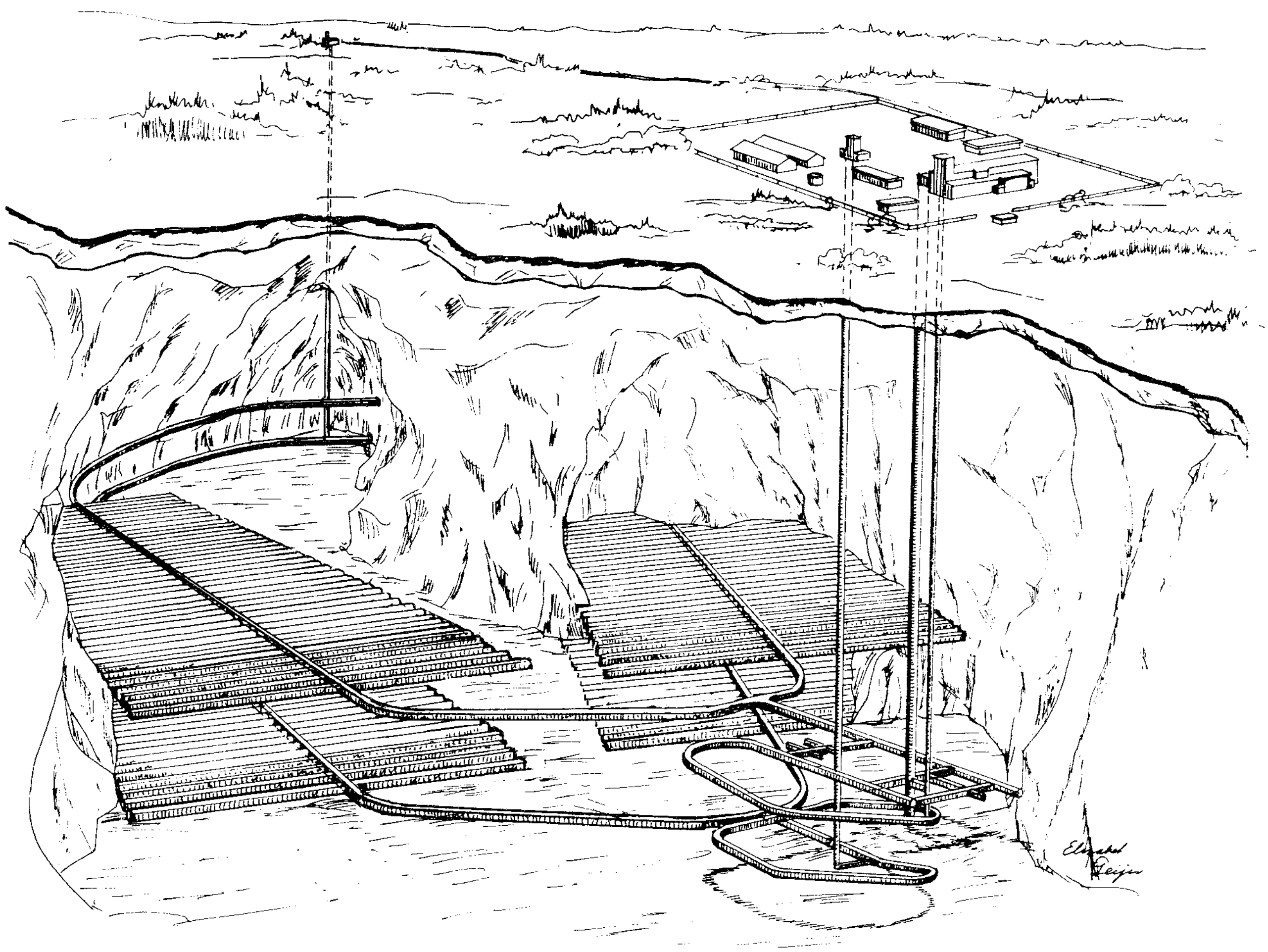


Figure 3-6. Perspective view of final repository for spent fuel - SFL.

continued for a longer period than 40 years. In practice, no commitment is made to the choice of final disposal system until encapsulation of the fuel has begun. It is therefore assumed that construction of BSAB will begin at roughly the same time as construction of SFL. Consequently, the start of construction will be a crucial time of decision.

3.6 Decommissioning of nuclear power plants

Studies on the decommissioning of nuclear power plants /3-9/ show that decommissioning can be carried out using currently available technology. Work is currently underway to further refine the technology in a number of decommissioning projects in other countries. Exchange of experience between these projects is coordinated under the auspices of OECD/NEA. SKB provides the program coordinator for this work and has access to the results. Otherwise, no development work is scheduled for the immediate future. The waste from decommissioning can be treated and disposed of in a manner similar to that used for other comparable types of waste.

In the planning it is assumed that the nuclear power plants will be dismantled immediately after they have been taken out of operation, which means that final disposal of the decommissioning waste can begin a couple of years later, see Figure 3-7. This is technically feasible. However, other factors may make it practical to postpone dismantlement for some decades. Such a change does not effect the R&D planning, however.

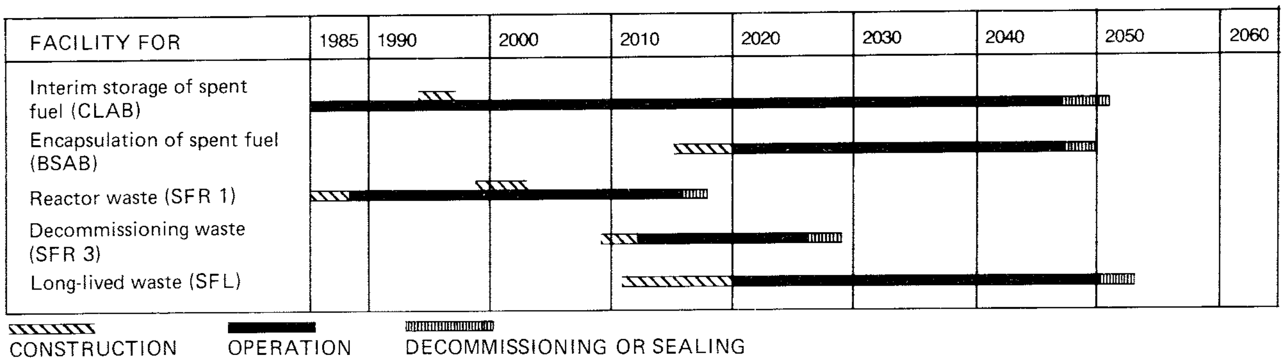


Figure 3-7. Overall timetable for facilities in the Swedish nuclear waste management system.

4 OVERVIEW OF PLANNED RESEARCH AND DEVELOPMENT

4.1 Goal of the research

Goals and guidelines for radioactive waste management in Sweden are given in Section 1.1. The research and development work shall be conducted in such a manner that the measures described in Chapter 3 can be carried out according to the given timetable and the goals of waste management can thereby be achieved.

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

The research and development work shall be conducted with due regard to:

- environment and safety,
- economy,
- comprehensiveness,
- flexibility,
- relevance,
- broad acceptance in society, both among specialists and government authorities and among the general public.

The requirement on comprehensiveness in the research means that various alternatives shall be studied and evaluated. Flexibility should therefore be retained for as long as possible. Effective R&D requires defined goals and delineated frames. It is therefore important to select and focus the research work in such a manner that priority is given to the most interesting and realistic alternatives. The research must be continuously related to those phenomena that are of relevance to the function and safety of the final repository.

Up to 1984, the main goal of SKB's research was to demonstrate that a safe final disposal of spent nuclear fuel can be effected in Sweden. Efforts were concentrated on a specific method. This is described in the KBS-3 Report /4-1/. The safety account in KBS-3 is based on a number of pessimistically chosen premises. Credit is not taken for inadequately understood conditions and factors if they act in a favourable direction. Methods and data have consistently been selected to provide an estimated upper limit for the impact of the final repository on the biosphere. The safety analysis in KBS-3 therefore contains considerable margins of safety that were not possible to quantify at the time.

One important goal of the continued R&D work is to gain better knowledge of the actual margins of safety. Improved knowledge in this respect provides a better basis for an optimization of the final disposal method and allows greater freedom in the choice of a repository site.

4.2 Some points of departure for the R&D work

The different types of waste that are obtained from the Swedish nuclear power programme have been described in Chapter 2. Measures to manage and dispose of these waste types are described in Chapter 3. Most of the waste can be handled and disposed of in the same or a similar manner as the waste that is to be disposed of in the SFR.

Spent fuel and certain other waste types containing large quantities of long-lived radionuclides require a more qualified final disposal, however. Research is primarily aimed at refining methods for this more qualified disposal. The main field of research is thus final disposal of spent nuclear fuel deep down in the Swedish bedrock.

The function of the final repository is based on a system of barriers that prevent or limit the dispersal of radioactive materials from the final repository. Some of the barriers are natural (geological) and some are engineered (canister, buffer, waste matrix). The research concerns the properties and performance of these barriers with the aim of arriving at an optimized choice of barrier system and repository site. Factors that influence these choices and the fields of knowledge and research needs involved are presented in Part II of this report.

Final disposal of the spent fuel can be effected in a number of different ways. The method described in the KBS-3 Report /4-1/ is until now the most thoroughly analyzed in an international context. The Swedish Government and regulatory authorities have approved it as acceptable with regard to safety and radiation protection. This method is therefore a reference alternative for further studies of other interesting alternatives.

Research and development work can be divided into the following three main areas:

- Studies of the various parts of the barrier system. Alternative designs and materials.
- Geoscientific investigations. Fundamental studies of geological conditions and investigation methods.
- Reconnaissance and surveys for choice of site.
- Development of models for performance and safety analyses.

An analysis of the research and development and other measures required up to the time of a siting application is presented in Part II of this report. A more detailed account of planned R&D during the six-year period 1987-1992 is presented in Part III of the report. A brief account is also provided there of the international research that is of relevance for the Swedish waste management programme.

The following sections in this chapter present an overall plan for the R&D work and a resumé of the most important parts of the contents of parts II and III. For a general description of the safety-related function of the repository, see Part II, Chapter 2.

4.3 Overall plan for the R&D work

4.3.1 1984 R&D programme

In connection with the KBS-3 report, the further research and development that was required was described in a research programme /4-2/. The programme contained an overall timetable for the research work. According to this timetable, basic R&D and geological area characterization were to be carried out during the 1980s. During the 1990s, the geological investigations were to be concentrated on more detailed studies of a few sites, including the sinking of shafts at one or more sites. Furthermore, the research concerned with the design of the repository was to be aimed at an optimization of the systems. The plans also called for a technical safety evaluation during the period 1995-2000 with the goal of submitting a siting application in the year 2000. The latter goal also applies in the present programme. However, the experience and results gained thus far call for a more precise definition and some modification of the stages leading to this goal.

4.3.2 Programme for R&D and other measures

An overall timetable for the measures that have to be adopted for handling and disposal of radioactive waste products from the nuclear power programme is described in Section 3.5 and Figure 3-7. According to this timetable, the planned start of construction for the final repository for long-lived waste and the encapsulation plant for spent fuel is the year 2010. Figure 4-1 shows an overall timetable for the R&D, technology development and other measures that are required prior to the start of construction.

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

In parallel with this, the general area characterization that has been going on since the end of the 1970s will be completed. In the early 1990s, a couple of sites will be selected for detailed investigations. These investigations should not be begun later than 1993 for

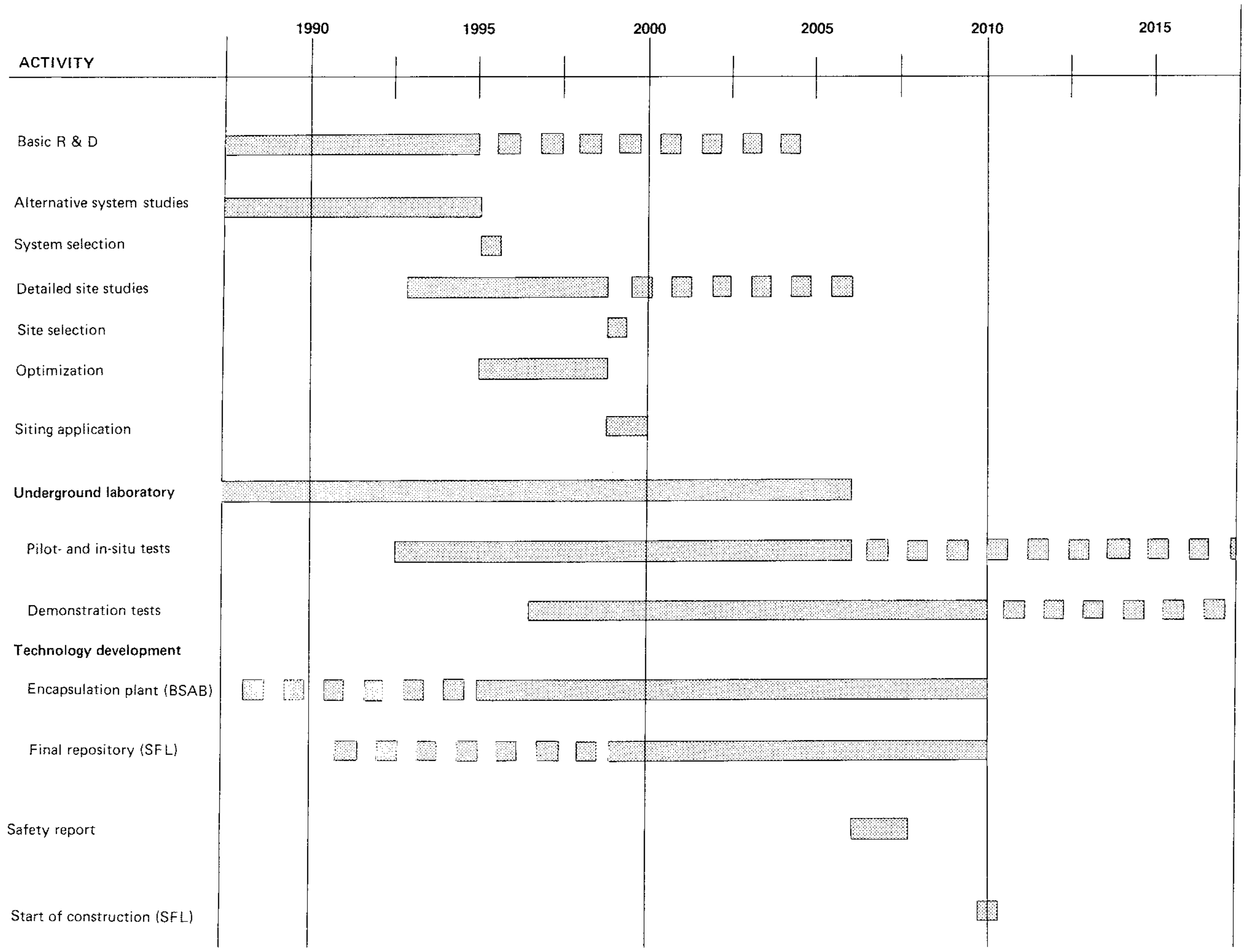


Figure 4-1. Overall timetable for measures up to the start of construction of the final repository and the treatment plant.

all the sites that could be candidates for a siting application in the year 2000.

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

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

For the period 2000-2010, the emphasis is foreseen to lie on technology development and demonstration of the function of the chosen system. Pilot tests and long-term in-situ tests should be begun in good time before the year 2000 in order to provide support for a siting application. These tests should be conducted in the underground research laboratory that is presented in greater detail in section 4.5.4. Larger-scale and integrated demonstration trials will probably be conducted at a later stage either in the underground research laboratory or on the selected repository site. The design of these trials is dependent on the development of the technology. Certain demonstrations and in-situ tests are also foreseen during the construction phase.

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

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

4.4 Studies of the barrier system

4.4.1 Alternative designs

As mentioned earlier, the waste in a final repository is surrounded by a system of barriers which together provide the long-term isolation and protection required for safety reasons. The barriers are natural and engineered. The properties of the natural barriers are determined by conditions on the repository site. One goal of the R&D work is to adapt (optimize) the engineered barriers and the design of the repository to the conditions existing on the repository site.

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

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

A systematic review of possible alternatives is presented in a background report /4-3/.

The conditions of vital importance for the safety of the final repository and for the choice of barrier system are:

- the interaction between the groundwater and the waste form,
- the interaction between the waste and the repository environment,
- the properties of materials in engineered barriers (canister and buffer),
- the technology for manufacture and application of engineered barriers (canister, buffer, sealing of rock etc).

These conditions must be clarified for all alternatives studied.

The continued work leading to a choice of system for the final repository for spent fuel will be focussed in the beginning and in the mid-1990s on a few, selected main alternatives.

4.4.2 Engineered barriers

All alternatives being considered for final disposal in rock include the following components:

- Waste form (waste matrix).
- Canister.
- Buffer and backfill material.

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

Extensive research on vitrified waste has been conducted in Sweden for a number of years. This work is being pursued within the JSS project (JSS = Japan-Switzerland-Sweden). High-level waste glass from France is being studied. An important part of the work is development and verification of a mathematical model. This work is expected to provide good guidance for the work on a corresponding model for spent fuel. The JSS project is scheduled to be completed as of the end of 1987. However, since a very large portion of international waste research is concentrated on this waste form, some continued follow-up in Sweden is important. See further sections 2.3, 7.5 and 7.7 in part III.

Spent fuel for final disposal must be encapsulated in a canister. The canister may have different functions, from a simple handling protection to long-term containment and/or adequate radiation shielding. The canister designs being studied in Sweden have primarily focussed on such a material and wall thickness that a containment with a very long service life is obtained. In this connection, manufacturing technology has been studied for certain ceramic canisters and for canisters of relatively thick-walled copper. In other countries (Switzerland, USA, West Germany and others) canisters with shorter corrosion life have been studied, especially canisters made of steel.

Further work on canister materials is aimed at gathering additional data so that a choice of system can be made in the mid-1990s. A renewed review of possible materials will be carried out over the next two years.

Further research on copper is aimed primarily at improving knowledge of pitting corrosion and developing the technique for welding of thick-walled copper.

The most important question with regard to ceramic canister materials (Al_2O_3, TiO_2 and others) is the risk of so-called "delayed fracturing". A satisfactory answer must be found to this question before a ceramic material can be chosen as a principal alternative for a highly durable canister.

Studies within the SKB programme have recently commenced on steel as a canister material. This work ties in with studies previously conducted by organizations in other countries and by SKN. Local corrosion of steel is being given first priority. Stress corrosion cracking is being investigated by NAGRA in Switzerland. Under a bilateral agreement between NAGRA and SKB, an exchange of results from the various investigations is taking place.

The service life of a steel canister is judged at best to be around a thousand years in the environment that can be expected in a final repository. This is a much shorter life than for eg copper or certain ceramic materials. It is, however, sufficient to isolate the waste during the period of elevated temperature caused by the residual heat in the spent fuel. The choice of canister material is thus to some extent dependent on how long the redundancy in the system provided by an intact canister is needed. This in turn is dependent on how good the data and the knowledge on the other barriers are. See further section 2.4 in part III.

The function of the backfill and buffer material is indicated by the name. The material is intended to serve as:

- a mechanical protection or support for the waste packages,
- a chemical and mechanical buffer,
- a barrier to the flow of groundwater.

Efforts to date have been concentrated on bentonite and mixtures of sand and bentonite as a buffer material. This applies to both the KBS designs and SFR and other Swedish studies. A relatively low temperature (max 80°C) of the bentonite material has been assumed in all of these applications.

Further work is being focussed on studying the possibility of using higher temperatures, other possible clay materials and chemical conditioning of the buffer. The goal here as well is to have collected sufficient data by the mid-1990s to permit a choice of material and system optimization. See further section 2.5 in part III.

4.5 Geoscientific investigations

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

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

Progressive development of measurement methods and instruments is necessary in order to obtain representative and reliable data on the bedrock in the field. The geological investigations are focussed on sites that are representative for possible repository sites and on detailed investigations of those sites that are selected as candidates for the final choice of site for the siting application. Chapter 4 in part II presents an analysis of the importance of geoscientific factors for the choice of final repository system. The following sections summarize the planned work within the areas of groundwater movements, rock stability and study-site investigations. The plans for an underground research laboratory are also presented, along with the planning for the choice of site for the final repository. Radionuclide transport and other geochemical matters are dealt with under section 4.6.

4.5.1 Groundwater movements

Knowledge of groundwater movements in the bedrock is essential for the analysis of the safety of the final repository. The models that have been used in previous analyses are simplified and based on limited data. For this reason, very conservative assumptions have been made in the safety analyses. The purpose of the continued R&D work is to further refine theories and models that describe the groundwater movements, to determine the necessary data and to validate the models against tests and measurement data.

Field studies of importance for an understanding of groundwater flow are being conducted above all within the following projects.

The international Stripa project includes extensive geohydrological work aimed at method development. The project, which started in 1980, has been carried out in several phases. Phase 3, which began in the summer of 1986 and will end in 1991, includes a major integrated geohydrological experiment where an undisturbed volume (125 x 125 x 50 m) of the Stripa rock will be studied. The methods and experience obtained from previous work will be applied in this experiment. Model development and predictive calculations are being carried out in parallel within the project. See further section 7.3 in part III.

The Canadian AECL, in cooperation with the US-DOE, is conducting extensive geohydrological and other studies at URL (Underground Research Laboratory) in Manitoba. The work includes the sinking of a shaft to a depth of 455 m in a bedrock that resembles the Swedish. SKB has reached a preliminary agreement with the AECL on participation in URL. The studies at URL complement current or planned Swedish studies. They will also provide an important basis for planning of the continued work in Sweden. SKB's participation in URL is planned to extend over the period 1986-1991.

The geohydrological properties of fracture zones are being studied in the "Fracture zone project" initiated by SKB in 1984. In the safety analysis for KBS-3, it was conservatively assumed that the groundwater flow in the fracture zones is very rapid and that radionuclides are not retarded in fracture zones that may surround the repository. Available data show that this is a very pessimistic assumption in many cases. A zone at Finnsjön and a zone on Ävrö are being studied in the fracture zone project. Furthermore, data are being collected from a number of ongoing tunnelling projects that intersect various types of fracture zones. The fracture zone project in its currently planned scope is expected to be completed by 1989. See further chapter 3.1 in part III.

A relatively large quantity of geohydrological data has been collected at SFR. The observations there are planned to continue.

In connection with the field studies mentioned above, mathematical models for the calculation of groundwater flow are being refined. The models are being tested against data from the field measurements. However, these measurements only relate to certain limited and in some respects specific rock formations. Data from a site that is unaffected by other activities that can disturb the groundwater flow are required to test the models on a larger scale.

4.5.2 Stability of the bedrock

In the long time perspective, the safety of the repository is dependent on the stability of the surrounding bedrock. The interpretation of mechanisms and the comparison between seismically active and areas of low seismicity will be facilitated if a deeper understanding can be gained of large-scale mechanisms.

Essential questions are whether earthquakes, ice ages etc. can lead to new fracturing and whether the geological processes can substantially alter the groundwater situation around a repository.

Studies of questions related to bedrock stability are being conducted within the framework of a project entitled "Stability of the bedrock" which was started in 1985 and is scheduled to be completed essentially by 1989. The project includes field studies of seismology, rock mechanics etc. on a site at a zone where relatively large movements have occurred since the most recent ice age, so-called neotectonic movements. The zone is situated near Lansjärv in northern Sweden. See also section 3.2 in part III.

4.5.3 Study-site investigations

Geological investigations on different scales have so far been carried out on a total of 14 sites - see Figure 4-2. Relatively extensive investigations have been carried out on eight study-sites. Limited surface investigations, and in some cases also limited drillings, have been carried out on an additional six sites. On the basis of these investigations and other preliminary studies and reconnaissances, it can be concluded that there are good possibilities of finding sites in Sweden that possess the geological characteristics required for the construction of a safe final repository.

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

Started in year	Site for extensive investigations	Site for limited investigations
1977	Finnsjön	Forsmark
	Kråkemåla	Ävrö
	Sternö	
1980		Kynnefjäll
1981	Svartboberget	Taavinunnanen (Gabbro)
1982	Fjällveden	Gallejaure (Gabbro)
	Gideå	
	Kamlunge	
1983	Klipperås	Bjulebo

Figure 4-2. Site investigations - brief history.

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

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

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

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

See also section 3.3 in part III.

4.5.4 Underground research laboratory

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

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

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

The underground research laboratory should be available when Stripa phase 3 is concluded, ie at the beginning of the 1990s. This means that the preparatory work should start immediately. As is evident from Figure 4-1, activities at the station will probably extend over a period of at least 15 years. Experience from Stripa, URL and SFR should be taken into account in planning, preliminary investigations and design work.

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

Investigations for and establishment of a research laboratory are planned to take place in phases. The first phase, which is planned to begin in early 1987, includes preliminary studies and investigations from the surface. The purpose is to get an idea of the possibilities offered by the geology for the establishment of an underground research laboratory. The information needed to locate a shaft or an entrance tunnel will also be gathered. After evaluation, detailed investigations will be conducted from the surface and in boreholes, followed by shaft sinking (or tunnelling). The final phase includes establishment of the research laboratory and investigations from drifts (tunnels) as they are extended. The final phase is scheduled to start early during the 1990s. Additional investigations and planning are required before the exact time can be determined.

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

See also section 3.4 in part III.

4.5.5 Site selection for the final repository

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

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

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

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

A detailed account of the site selection process is provided in part II.

4.6 Chemistry

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

The chemistry programme includes a large number of investigations with the common goal of describing leakage and dispersal of radioactive materials from the repository to the rock and the biosphere. The chemistry studies have been broken down into the following areas:

- Geochemistry; especially groundwater chemistry.
- Radionuclide chemistry; especially for nuclides important from the standpoint of safety.
- Chemical transport (of radionuclides, corrosive substances, radiolysis products, gases etc).
- Validation of chemical transport models.

Geochemistry and radionuclide chemistry mainly involve collection of relevant data and information on inactive and active substances that are dissolved in or can be dissolved in the groundwater. Chemical transport involves the development of models that quantitatively describe the transport. These models are validated by tests in–situ or in the laboratory and by comparisons with natural analogues.

Chapter 2 in part II and chapter 5 in part III give a detailed account of those phenomena that are important to describe and quantify and of planned R&D for the coming six-year period. Only a few of the larger projects are mentioned in the following.

In order to study how radioactive substances are transported with the groundwater, various tests are being conducted with tracer substances. The tests provide fundamental information on water flows in fractures and on chemical interaction between dissolved substances and fracture or rock minerals. Such tests have been conducted and are being conducted within the Stripa project. Further tests are planned both in phase 3 of the Stripa project and within the framework of the fracture zone investigations. In a later phase, tracer tests will be performed at the underground research laboratory described in section 4.5.4.

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

4.7 Mathematical models and the database

The knowledge and data generated by the R&D work have to be systematized and coupled to theories and models. These models provide a mathematical description of various mechanisms and processes and are necessary tools for analysis and optimization of the final repository system and for description of its long-time function. Work on the development of such models is carried on continuously in conjunction with the experimental work in laboratories and in the field. Examples particularly worth mentioning here are models for groundwater flow in fractured rock, for nuclide transport in the near field, in the rock and in the biosphere and integrated systems of models for function and safety analyses.

Several models have been briefly touched upon in previous sections. A more exhaustive presentation of the development of models for analysis of the total system for final disposal is provided in chapter 6 in part III.

The research work generates a large quantity of data from various fields. In order to systematize these data and render them more readily accessible to all users, SKB is developing a special database system. Data from the geological investigations of the study-sites are being documented to begin with, but the system will eventually be expanded and augmented with data from other areas. It is estimated that the geodatabase will be in operation by the end of 1986 and that more data will successively be added in the coming years. Programs for statistical or other processing and analysis of data will gradually be developed as needed.

4.8 Other R&D areas

The R&D programme also includes work in areas that have not been mentioned in the preceding sections.

The geoscientific field investigations generate considerable experience and new ideas for improved measurement methods. This provides a basis for further instrument development with regard to both new instruments and improvement of old instruments. This development is vital in order to obtain the quality of data on the rock that is required to improve the quantitative understanding of phenomena of importance for safety. The work is being conducted both within the Stripa project, where new methods are being tested, and as SKB projects, where field instruments and data collection systems are being developed. Future development primarily relates to the instruments that are needed for detailed investigations. See further section 3.5 in part III.

Continued development and refinement is planned of the models and data needed for calculation of radionuclide transport in the biosphere. Development of scenario analysis and of acceptance criteria are also foreseen. The latter subject in particular is primarily the concern of the appropriate authorities. Extensive development is foreseen in the coming years, and this requires some participation on the part of SKB as well. See further chapters 4 and 6 in part III.

4.9 International cooperation

A common international view on the scientific bases for safety in handling and final disposal of nuclear waste is of great value. Development work within the nuclear waste management field is therefore pursued to a large extent in international cooperation, interaction and exchange. SKB is involved in this work in many ways. Some of them have been elaborated on in this chapter. SKB's early start on studies of final disposal have given its work a place of international prominence. This put SKB in a good position to achieve a close cooperation with parallel organizations in other countries. A summary of important programmes in other countries and of SKB's international R&D involvements is provided in chapter 7 in part III.

4.10 Execution of the programme

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

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

Safety, function, feasibility and development potential will be continuously analyzed for different alternative system designs in cofunction analysis groups consisting of persons from both SKB and engaged consultants.

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

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

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

SKB will inform the public, regulatory authorities and other concerned parties on plans, work in progress and the results of the activities occasioned by the research programme.

REFERENCES PART I

1-1 Spent fuel and radioactive waste.
Report of the AKA committee
SOU 1976:30 Part 1.
SOU 1976:31 Part 2.
SOU 1976:41 Appendix.

1-2 Handling of spent nuclear fuel and final storage of vitrified high-level reprocessing waste.
Parts I-V.
Kärnbränslesäkerhet, KBS, November 1977

1-3 Handling and final storage of unreprocessed spent nuclear fuel.
Parts I-II.
Kärnbränslesäkerhet, KBS, September 1978.

1-4 Act on the financing of future expenses for spent nuclear fuel etc., SFS 1981:669.

1-5 Final storage of spent nuclear fuel - KBS-3.
Parts I-IV.
SKBF/KBS May 1983.

1-6 Act on nuclear activities, SFS 1984:3.

1-7 Final storage of spent nuclear fuel - KBS-3. Programme for research and development.
SKBF February 1984.

1-8 Annual research and development report 1984.
SKB Technical Report 85-01, June 1985.

1-9 SKB Annual Report 1985.
SKB Technical Report 85-20, May 1986.

2-1 Same as /1-5/.

2-2 LÖNNERBERG B et al.:
"Encapsulation and handling of spent nuclear fuel for final disposal".
SKBF/KBS Technical Report 83-20, May 1983.

2-3 PETTERSSON S and HEDMAN T:
"Managing power station wastes".
Nuclear Engineering International, December 1985.

2-4 PLAN 86 - Costs for management of the radioactive waste from nuclear power production.
SKB Technical Report 86-12, June 1986.

3-1 Same as /2-4/.

3-2 SKN PLAN 85 och förslag till avgift 1986.
(SKN plan 85 and suggestions for fee for 1986).
Nuclear Board for Spent Fuel, October 1985.
(In Swedish)

3-3 Radioactive waste management plan, PLAN 82.
Parts 1 and 2.
SKBF. TR 82-09 June 1982.

3-4 Slutförvar för reaktoravfall.
Preliminär säkerhetsrapport.
("Final repository for reactor waste, preliminary safety report")
(In Swedish)
SKBF March 1982.

3-5 Centralt Lager för Använt Bränsle.
Slutlig säkerhetsrapport.
("Central interim storage facility for spent nuclear fuel, final safety report")
(In Swedish)
SKB 1985.

3-6 Transportsystem för använt bränsle.
Slutlig säkerhetsrapport.
("Transportation system for spent nuclear fuel, final safety report")
(In Swedish)
SKBF March 1982.

3-7 Same as /1-5/.

3-8 Kärnkraftens slutsteg.
Alternativa tidplaner för hantering av använt kärnbränsle. Konsekvenser för planering, säkerhet och kostnader.
("Alternative timetables for management of spent nuclear fuel. Consequences for planning, safety and costs")
(In Swedish)
SKB December 1985.

3-9 Technology and costs for decommissioning a Swedish nuclear power plant.
SKB May 1986.

4-1 Same as /1-5/.

4-2 Same as /1-7/.

4-3 Handling and final disposal of nuclear waste.
Alternative disposal methods.
Background report to R&D programme 86.
SKB September 1986.

SHORT OVERVIEW OF SOME LEGAL REQUIREMENTS ON THE NUCLEAR POWER UTILITIES WITH RESPECT TO NUCLEAR WASTE MANAGEMENT.

The Government and the Swedish Parliament have, in various contexts, formulated society's demands on the assignment of responsibility by the nuclear power plant owners for management of the nuclear waste. A brief summary of the most important provisions of laws, ordinances etc of importance for the R&D programme is provided in the following.

The Act on Nuclear Activities (SFS 1984:3) regulates the obligations of the nuclear power plant owners with respect to handling and final storage of radioactive waste. These obligations are set forth in Sections 10-12 of the Act:

"**General obligations of licence-holders**

Section 10. The holder of a licence for nuclear activity shall ensure that the necessary measures are taken in order to

1. maintain safety, with due consideration to the nature of the activity and the conditions under which it is carried out;
2. safely handle and finally dispose of nuclear waste, or non-recycled nuclear material arising in the activity; and
3. decommission and dismantle in a safe manner plants in which the activity is no longer to be carried out.

Section 11. The holder of a licence to possess or operate a nuclear power reactor shall, in addition to the requirements laid down in Section 10, ensure that such comprehensive research and development work is conducted as is needed in order to meet the requirements set forth in Section 10, subsections 2 and 3.

Section 12. The holder of a licence to possess or operate a nuclear power reactor shall, in consultation with other reactor possessors, prepare or have prepared a programme for the comprehensive research and development work and the other measures stipulated in Section 10, subsections 2 and 3, and in Section 11. The programme shall present a survey of all measures that may be necessary and also specify the measures that are intended to be taken within a period of at least six years. The programme shall, beginning in 1986, be submitted to the Government or the authority designated by the Government every third year for examination and evaluation."

Sections 11-12 state that the research and development work shall be comprehensive, ie shall pertain to all links in the chain, and shall also include reporting and follow-up of alternative methods. In the *special argumentation* on the Act (Gov bill 1983/84:60), it is stated that the purpose of the provision concerning comprehensiveness

"Is that no commitment shall be made to a given handling and disposal method until sufficient knowledge has been obtained to fully grasp and assess the existing safety and radiation protection problems. If a new and better method emerges during the continued work, this should instead be chosen".

In the *Ordinance on nuclear activities* (SFS 1984:14), the following is set forth in Sections 25-26:

Section 25."The programme referred to in Section 12 of the Act (1984:3) on Nuclear Activities shall be submitted to the National Board for Spent Nuclear Fuel for scrutiny and evaluation no later than September every third year beginning in 1986.

Section 26. The National Board for Spent Nuclear Fuel, shall, no later than six months after the deadline stipulated in Section 25, submit to the Government the documents in the matter, together with its own statement of comment on the programme referred to there.

The statement of comment shall include a scrutiny and evaluation of the programme as regards

1. planned research and development activities,
2. reported research results,
3. alternative handling and disposal methods, and
4. the measures intended to be taken".

The research plan reported shall thus also include an account of results achieved.

Permits for Forsmark 3 and Oskarshamn 3 that were issued in June 1984 contain certain directives of importance for the R&D programme for spent nuclear fuel. The permits thus state:

"In connection with the circulation of the application for comment and the expert review of the KBS-3 study, the method has been found acceptable essentially in its entirety with respect to safety and radiation protection. Certain comments have, however, been made with respect to particulars.

Furthermore, in the circulation of the programme for research and development activities for comment, this programme has been found to comply with the requirements set forth in Section 6, second paragraph, point 2 of the Act on Nuclear Activities."

And further:

"The Government calls attention to the obligation set forth in Section 11 of the Act on Nuclear Activities for the holder of a licence to possess or operate a nuclear power reactor to ensure that such comprehensive research and development work is conducted as is needed in order to, among other things, safely handle and finally dispose of nuclear waste etc arising in the activity. The Government prescribes that the programme that is to be submitted in 1986 in accordance with Section 12 of the Act on Nuclear Activities shall also include an account of the research and development activities that have been conducted with respect to the KBS-3 method and how the viewpoints and comments presented in connection with the commenting procedure and expert review have been taken into account and are intended to be taken into account.

The Government calls attention to the fact that a final decision with respect to the handling method for spent nuclear fuel will not be taken until experience has been gained and conclusions have been drawn from the knowledge and improved technology provided by Swedish and international development work."

The state's view on the R&D programme has been further expanded on in the *"guidelines for the 1986 review of the programme of measures with respect to spent nuclear fuel etc..."* issued by the Government on 12 December 1985. These guidelines state, among other things: "During the six-year period (1987-1992), the current phase of bedrock investigations - which are of a fundamental technical-scientific nature and are not aimed at site selection - shall be completed and preparations made for subsequent phases of field investigations. The current phase, which belongs to the 1980s, must not involve any commitments to specific methods or sites for future final repositories. It should be evident from the statement of comment which additional bedrock investigations are intended to be carried out during the 1980s and which sites are concerned.

In the next phase, ie mainly during the 1990s, it is to be expected that further site investigations will also serve as a basis for the gradual narrowing-down of suitable candidate sites for future final repositories. The statement of comment on the research and development programme in this part should include a proposal for a total programme for further test drillings and broadened site investigations based on the results obtained from the current test drillings. The review statement should shed light on an appropriate procedure for how the government authorities will make a decision in site selection questions on the basis of experience gained, results of the bedrock investigations and other parts of the research and development programme etc. Furthermore, a proposal should be presented on how information to concerned localities is to be arranged and who should be responsible for it.

As is evident from the text, the recently mentioned guidelines are aimed primarily at the National Board for Spent Nuclear Fuel, which is responsible for the review of the R&D programme. In the preparation of this programme, however, the Government's guidelines have been taken into account.

Handling and final disposal of nuclear waste

Programme for research, development and other measures

II Choice of final disposal system

CONTENTS PART II

1 INTRODUCTION

As was stated in part I, planning of the research is aimed at being able to submit a siting application for a final repository for long-lived radioactive waste at the turn of the century.

The present situation is that the feasibility of safe final disposal, based on currently available technology, has been demonstrated by the reactor owners and accepted by the authorities. A number of possible sites have been studied with regard to their geological capacity to host a safe final repository. In the same manner a number of possible engineered barriers have been studied that can be incorporated in the final repository system for the purpose of enhancing the repository's capacity to protect man and his environment from radionuclides that are deposited.

In order to make it possible to select from all the designs of safe final repositories the one which is the most favourable, the further research must also include an evaluation of alternatives to the previously described method for handling and final disposal. This is in accordance with legislation and regulatory directives. The intention is to avoid commitment to a given method until sufficient knowledge has been gained concerning the design and reliability of various possible alternatives, and to retain flexibility in the waste management system for as long as possible in order to permit technological advances to be exploited.

However, both the repository site and the engineered barriers incorporated in the repository must have been selected when the time comes to submit a siting application so that the application can be based on a site-specific optimized design of the facility.

2 FACTORS THAT INFLUENCE THE CHOICE OF SITE AND SYSTEM

2.1 General

A final repository for spent nuclear fuel in Sweden must fulfil the safety requirements set down by society. All radioactive waste from the nuclear power programme must be managed and disposed of with good cost- and resource-effectiveness.

The safety requirements are intended to protect man and his environment against harmful impacts of the final repository. The final disposal system shall ensure that releases of harmful substances do not exceed hygienic or radiological limits in the human environment. Reasonable measures shall be taken above and beyond this to reduce the total burden on the public. The goal is that the long-term effects of the repository shall not alter to any essential degree the radiological or other conditions that exist naturally in the area.

During the construction and operating phases, activities must be conducted in such a way that they meet environmental standards and offer a good working environment.

The long-term safety and effectiveness of a final repository are influenced both by the natural characteristics of the geosphere and the biosphere on the site and by the engineered safety barriers that are incorporated in the repository, the so-called near field. Figure 2-1 is a schematic illustration of the repository system and its constituent parts. The arrows show how the different parts of the system are interconnected and the sequence in which the safety analysis must be carried out.

The KBS reports present examples of designs of repositories for high-level and long-lived radioactive waste and analyze their safety. The safety analysis sections describe in detail how the safety assessment has been carried out and how different factors influence safety.

Analyses of the safety of different repository systems both abroad and in Sweden carried out to date show that a combination of good site characteristics and suitably chosen engineered barriers in a repository can offer a long-term isolation that meets even stringent release standards.

Since safety can be achieved with different engineered or natural barriers, there is some room for optimization of the system.

A brief review of the safety-related function of the repository and the basis for the safety analysis is presented below. This is followed by a discussion of the importance of certain site- and barrier-specific factors as well as certain socio-economic considerations.

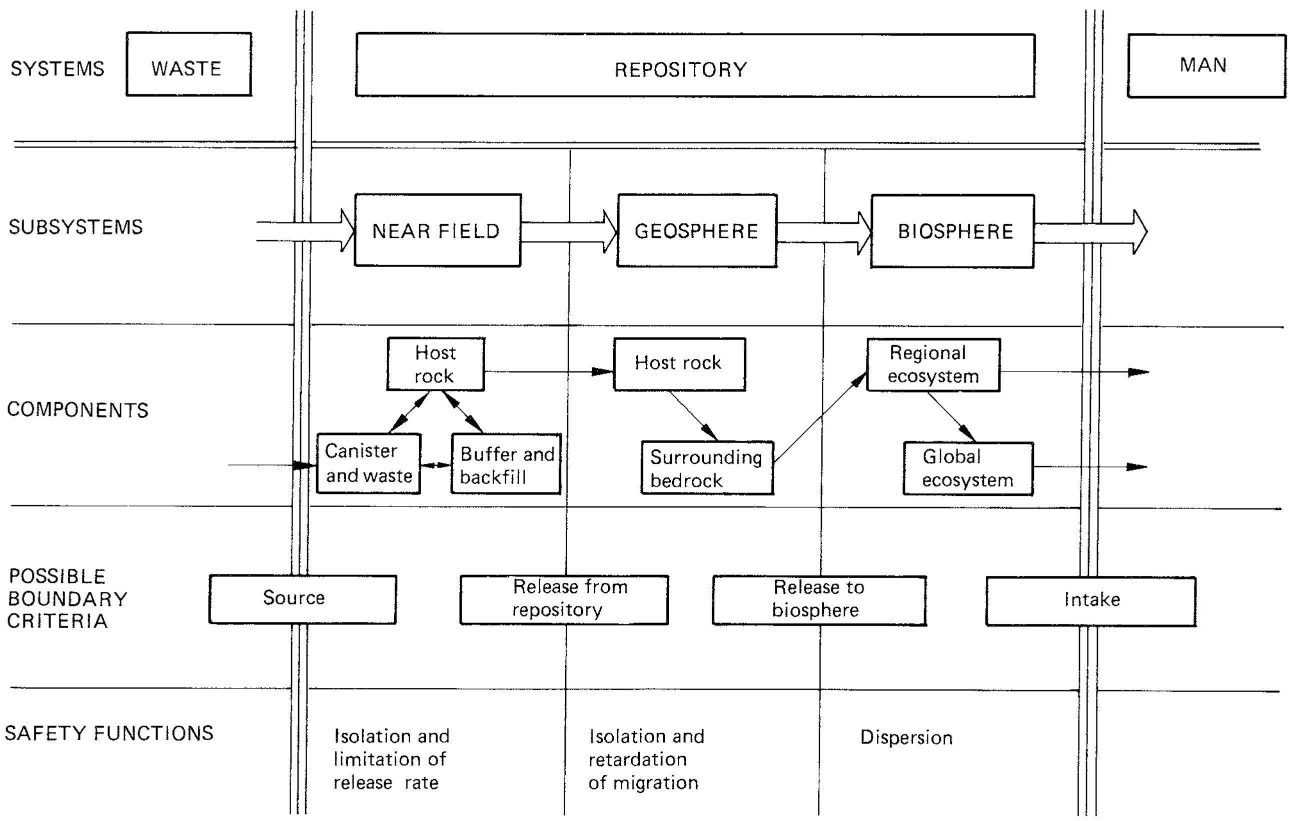


Figure 2-1. System scheme of final disposal in crystalline rock.

2.2 The safety-related function of the repository

Under the conditions that prevail in a repository for radioactive waste below the groundwater table in the Swedish bedrock, radioactive materials can only have an impact on man if they are transported up to the biosphere with the groundwater or if man intrudes into a sealed repository by drilling or other measures. Information on the location, design and content of the repository should be preserved and the repository should be located and designed in such a manner that the risk of inadvertent intrusion is minimized.

Safety against escaping radioactive materials can be achieved by delaying the time when a radionuclide comes into contact with man. In this way, the toxicity of the waste is reduced by decay. Safety can also be achieved by ensuring that the nuclide release takes place slowly or that the nuclides are retarded in transit through the geosphere. In this way, the escaped nuclides will be diluted in groundwater and surface waters, which reduces the maximum concentrations that can occur.

As long as the groundwater is prevented from coming into contact with the waste, no dissolution of the radionuclides in the fuel will take place and the waste will be totally isolated. In the case of disposal below the groundwater table, the most suitable way to achieve such total isolation is by means of a watertight canister around the waste. In the case of dry disposal, any groundwater must be drained away and the isolation period is determined by the period during which the drainage retains its function.

The canister fulfils its safety function as long as it is intact. Its life is influenced by chemical and mechanical conditions in the near field and the inflow of corrosive substances via the groundwater. The inflow of such substances can be limited by a suitable design of the repository or by the addition of sorbing or precipitating substances, so-called chemical conditioning of the near field.

If the waste comes into contact with groundwater, a leaching and transport process begins that can convey the radionuclides from the repository to the groundwater. The leach rate is determined by the properties of the waste, the water flow rate and chemical conditions in the repository as well as by the ambient temperature and any radiolysis phenomena caused by the waste. Transport in the repository is controlled by hydraulic conductivity and diffusivity in the materials in the near field and the surrounding rock and by the thermal gradients and concentration gradients that are formed.

When radioactive materials have left the chemical and hydraulic conditions in the near field altered by the repository, any further transport will take place under conditions existing naturally in the bedrock. Sorption and precipitation on fracture surfaces, as well as dispersion and diffusion of radionuclides into the rock matrix, are influenced by measurable conditions in the rock such as water chemistry and the characteristics of the fracture system, including fracture-filling minerals, porosity, hydraulic conductivity etc. Most substances are retarded along the way so that the travel time for radionuclides is much longer than for the water.

If and when radioactive materials from the repository reach the biosphere, they may be incorporated in different food chains, where they may be either concentrated or diluted. How much finally reaches man depends on the natural conditions in the surface waters and how man makes use of nature.

All factors that influence the repository's impact on man, in the ways outlined above, can be controlled to some extent. Natural conditions can be controlled by the choice of site and near-field conditions, by the choice of material and the design of engineered safety barriers. However, certain repository concepts can only be realized in a special geology or topography.

2.3 Analysis of repository safety

An analysis of how the repository functions over long periods of time requires characterization of the various components of the repository system (data) and description of the interaction that can occur between the components of the repository system and the disposal site (models). Both data and models must, moreover, be relevant for all the reasonably possible conditions under which the repository must be able to function (scenarios). Finally, the prediction of repository performance must be expressed in terms that are the same as or directly comparable with the standards set up by society (criteria).

Data of importance for the analysis are discussed in greater detail in sections 2.4 and 2.5, broken down into geo-related, site-specific data and system-related, barrier-specific data. Data shall provide quantitative information as well as information on the uncertainty of measurements or on the natural variation that characterizes the phenomenon in question.

The models for analysis of repository performance must take into account both the variation in data and possible feedback phenomena. In practical terms, this means that the resulting computer models may be very large and require extreme computer capacity. A simplification of the model systems may then be necessary, especially if the computer simulation is supposed to reproduce the manner in which uncertainties in input data influence the consequences. It must be possible to demonstrate that both the scientific models that simulate actual processes and any simplified analysis models can reproduce the actually existent and dominant phenomena. This is done by verification of the models, comparison with other models and validation against experiments or natural analogues.

The scenarios on which the choice of relevant models is based shall reflect the prevailing conditions and their natural evolution with time as well as the major changes in conditions that can be expected to occur with a certain likelihood. Such changes may, for example, consist of long-term changes in climate, topography, runoff etc. Other changes may stem from human activities such as changes in diet and agriculture or war and attempts to retrieve the waste. Inadvertent disturbances of the repository, such as mining or deep drilling activities, also constitute scenarios whose probability and effects must be assessed. A third type of scenario that is often used in safety analyses is the system-specific scenario, where some barrier is assumed to malfunction. Such scenarios are intended to shed light on the effects of mistakes in manufacture or an incomplete understanding of the existing relationships.

The criteria for what society regards as an adequate level of safety for a final repository are ultimately crucial for the choice of both repository site and system design. Acceptance criteria can be expressed as maximum permissible dose to individuals or groups, maximum permissible risk increase, demands on absolute containment during a given period of time etc. It is up to society to choose acceptance criteria in keeping with its ambitions and resources to protect man and the environment from harmful impact.

2.4 Site-specific factors

The natural conditions existing on a site are of importance for how suitable the site is for harbouring a final repository. The site-specific properties must be evaluated together in the particular combination in which they happen to occur on the site. However, different properties may be more or less decisive for the suitability of the site and with reference to possible designs of the repository.

A fundamental prerequisite is that the repository will be located in an area that is so stable that no decisive changes in the geohydrological or chemical conditions in the bedrock surrounding the repository can be expected within a time perspective of around one million years. If regional fracture zones and known zones of weakness are avoided, most regions of crystalline rock in Sweden are probably capable of meeting this requirement assuming the repository is located at a depth of more than 200-300 m.

The groundwater movements in the geosphere are affected by hydraulic gradients caused by topography, density differences or thermal conditions and by the characteristics of the rock and fracture systems such as hydraulic conductivity, porosity and geometric extent. Accordingly, the groundwater flow around a repository can be influenced by locating the repository in consideration of the above parameters.

The use of long-term-stable flow barriers in the canister's environment or the introduction of a so-called "hydraulic cage", where the flow of water is led around the repository, offer means for circumventing to some extent the very stringent demands on a low rate of water turnover in the bedrock.

The rate of turnover and chemical composition of the groundwater and the geochemical properties of the rock and fracture minerals determine when the canister material will be penetrated by corrosion, and at what rate the radioactive materials will become accessible for transport in the groundwater. The existence of a reducing environment in the repository is crucial for both the long-term stability of the copper canister and a slow fuel dissolution. Another factor that greatly influences the solubility of many safety-related radionuclides is pH. In addition, there are a number of specific substances that can affect the solubility of a given radionuclide by e.g. the formation of solid phases with low solubility or by the formation of soluble complexes.

The near-field chemistry in the analyses performed has mainly influenced environmental safety via leach rate and via precipitation of radionuclides at a possible redox front.

The transport of radionuclides in the geosphere is controlled by groundwater movements in the rock and by the chemical composition of the rock matrix, fracture minerals and groundwater. Diffusion of the nuclides into the rock matrix and the chemical-physical interaction between the nuclides and the minerals retard the transport of the nuclides. All of these phenomena are controlled by site-specific geohydrological properties.

In the study-site investigations conducted to date, the sites have been chosen to find as favourable geological properties as possible. A flat topography with a uniform rock type, which in addition is judged not to have any potential as a valuable raw material has been sought. The sites have also been chosen in such a manner that large marked fracture zones surround an inner block of rock with low hydraulic conductivity.

It is further desirable that the site will be so easily interpreted as regards fracture zones, rock types and geometry that realistic models can be set up. The site must also be of a size that permits disposal of the waste quantities in question and allows the repository to be situated at a depth that rules out the influence of reasonably probable surface effects.

Beyond such factors as are defined by the site, a number of free parameters remain. One example is the layout of the repository, which offers a means of influencing e.g. temperature and space requirements. Another example is the depth of the repository, which offers a means of influencing, within certain limits, groundwater turnover and the minimum distance that must be travelled by released nuclides in the rock in order to reach the biosphere. On some sites, it seems to be possible to situate the repository in virtually stagnant groundwater.

Studies conducted to date demonstrate that acceptable safety is possible to achieve on a number of sites in Sweden and that it is also possible to make use of sites where not all site-specific safety-related factors are optimal.

2.5 System-specific factors

Since the chemical conditions for final disposal are determined to a high degree by the rock available in Sweden, the engineered barrier system must be adapted to these conditions. Choice of material in canisters, chemical buffers, water impervious layers etc. must be made so that the interaction between the site-specific and system-specific factors is favourable and can be understood and quantified. It is particularly important that the repository not be built in such a manner that the special conditions that have been created in the near field can significantly alter those natural conditions in the bedrock on which the long-term safety of the repository is based.

Some of the parameters that affect the long-term safety of a repository can be controlled by appropriate design of the repository. Important effects are obtained by the fact that the geometric configuration of the repository and the location of a deposition hole define the length of the flow pathways to the nearest fracture zone.

The distribution of waste in the rock further influences the temperature in the repository. The excavation of rock creates zones of stress relief around tunnels and shafts, which, together with sealing by grouting and plugging, affects the groundwater's local flow pathways in the repository.

All of these effects are highly system- and site-specific and can in some respects only be treated as statistical distributions. The methods that are employed to determine whether a position for a deposition hole should really be used, also affect the minimum quality that can be ascribed to the rock around the deposition holes in a safety analysis.

The backfill material in the space between the canister and the rock wall is of primary importance for the mass transport between the waste canister and the mobile groundwater. Water turnover and diffusivity can be affected by the use of flow barriers of different materials and thicknesses.

Quantities of radionuclides accessible for leakage can be limited by the choice of wall thickness and material for the canisters surrounding the waste.

It should be pointed out once again that experience gained to date shows that suitable combinations of natural and engineered barriers can offer a considerable margin of safety. In an optimization process, this means that an acceptable final repository on an extremely favourable site could be designed with only limited engineered barriers or, conversely, a less satisfactory repository site could be compensated for by more extensive engineered barriers.

2.6 Socioeconomic factors

It is obvious that public confidence in the safety assessments for a final repository and popular support of official standards concerning what is an acceptable level of safety for a repository are factors of importance for the feasibility of achieving a final repository in national consensus.

The need for social acceptance may dictate that the final disposal system will be designed with greater margins of safety than would otherwise be necessary based on pure safety considerations or on established practice in the society for the avoidance of other types of hazards. In the choice between two types of equivalent engineered barriers, the one which appears safer in the eyes of the public may be preferable. Systems that have achieved international acceptance because they have bee applied in other countries may be preferable to solutions highly adapted to site-specific circumstances.

However, the most important factor for public acceptance of the safety assessments is probably the review procedure and quality control process that is applied to the analysis of repository performance and to the design and construction of the facility. It is essential that these procedures be open to public insight. This should apply to all stages in the process from research, conceptual development, site selection and system selection to siting permits, design, construction and operation.

Since the final disposal scheme is a project costing on the order of SEK 10 billion, it goes without saying that great importance must be attached to economic considerations. The economic considerations primarily relate to construction and operating costs for the facilities, resource consumption (for example material and land needs), effects on the labour and capital markets and needs of services and the like during the construction and operating phases.

As regards construction and operating costs, considerable economic savings should be able to be made by simplified handling procedures or designs occasioned by system changes, better methods of performance analysis or better data.

Finally, location is of great economic importance. Location affects transportation needs as well as infrastructure needs such as power supply, technical services, housing, schools etc.

3 DESCRIPTION OF PRESENT-DAY KNOWLEDGE

A considerable amount of research has been conducted over the past ten years in different countries to establish the feasibility of a safe final disposal of high-level waste in geological media and to develop suitable repository designs.

The geological background material currently available in Sweden comes from some ten study-site surveys including surface studies and drillings down to depths of between 500 and 1 000 m. Internationally, this material constitutes roughly half of the world's site-specific information on deep crystalline bedrock suitable for ultimate disposal of radioactive waste. Other data comes mainly from Canada, Finland, France, Great Britain, Switzerland and the USA.

As far as overall repository design is concerned, the Swedish efforts have been concentrated on studying in detail a few repository concepts, which have constituted the basis for feasibility assessments. Other countries have studied other designs adapted to their own premises as regards waste forms, geology, quantities etc.

In parallel with studies of possible designs and repository sites, knowledge, instruments and analysis methods have been developed further. In many areas, such development work is being pursued independently of the efforts on nuclear waste.

Most of the background material that currently exists in Sweden is published in a series of technical reports by SKB. Through international cooperation, primarily within the IAEA and OECD/NEA, and through formal or informal exchanges of information, SKB also has access to research results obtained in other countries.

This chapter reviews the background material for the future choice of a repository site and a repository system. The background material is presented in greater detail in part III as a point of departure for site-specific R&D work during the period 1987–1992.

3.1 Basis for site selection

3.1.1 General

The Swedish study-site investigations have primarily focussed on bedrock of granite and gneiss.

The research has now advanced so far that the following can be concluded:

- The problems that are of dominant importance for the long-term safety of the repository have largely been identified.
- Instruments have been developed that permit accurate measurement of most essential parameters.
- Models and calculation methods have been developed so that the complex processes that affect safety can be quantified or so that their maximum effects can be shown to be limited.

At the same time, it is possible to point out specific questions where further knowledge has to be gained in order to meet future needs. Examples are radar measurements, modelling of groundwater movements and statistical methods for data sampling, processing and evaluation.

On the basis of the study-site investigations, it can be concluded that it is possible to find many places in Sweden where the necessary geological conditions exist for the siting of a final repository.

3.1.2 Study-site investigations

The study-site investigations have primarily focussed on studies of

- large-scale fractures in the bedrock,
- hydraulic properties of the bedrock,
- chemical composition of the groundwater,
- chemical properties of the rock types and fracture minerals.

Data have been collected and have formed the basis for calculations of the three-dimensional groundwater flow and for the related calculations of nuclide migration in the rock. Interpretation of the geometry of existing fracture zones also provides a basis for a schematic placement of a repository within the studied sites.

The investigations have followed a standard programme adapted to local conditions. This makes it possible to describe the investigated sites in a uniform manner and even to compare them with each other. In choosing the study-sites, consideration is given to such factors as topography, the presence of major fracture zones, rock type distribution and structure of the rock mass, presence of ores and groundwater capacity in nearby wells drilled in rock.

A site selected for closer investigation covers an area of 4-5 km^2. There, surface investigations are conducted including mapping of rock types, fractures and fracture zones. At the same time, geophysical investigations are performed using different methods to obtain an indication of any fracture zones under soil-covered areas and the slope of these zones.

The subsurface investigations include both percussion drilled holes and cored holes. The percussion drilled holes, which are relatively shallow (down to 200 m), are primarily aimed at determining the character and orientation of fracture zones. Up to 16 cored holes have been drilled to a depth of between 500 and 1 000 m within each site. They have been oriented in order to yield maximum information on the geological and hydrological properties of the deep rock mass and on the character and hydraulic conductivity of fracture zones.

The hydraulic conductivity of the rock has been determined by means of water injection tests where the water is injected into sealed-off sections in the boreholes. In connection with this, the natural water head is also measured at different levels in the boreholes.

In order to shed light on the chemical properties of the groundwater and their variations, water samples have been analyzed from different depths in certain boreholes. In this way, a large body of groundwater chemistry data has been collected from the study-sites. More reliable data have been obtained since a mobile system for chemical analysis in the field was taken into use, with eg borehole probes for measurement of Eh and pH.

On the basis of topography, geometry of the fracture systems and measured conductivities and hydraulic gradients, a descriptive model has been set up for each study-site. The groundwater heads within a site have then been obtained by means of numerical calculations. Groundwater flows, flow directions and transport have then been calculated.

In addition to these investigations on selected study-sites, an extensive body of material of interest for waste disposal has been obtained from the areas around the Forsmark and Oskarshamn plants in connection with the construction work for the SFR and CLAB. It must be emphasized that the investigations performed are of a general nature. The final design of a repository requires a higher degree of detail.

The investigations on the different granite-gneiss sites show a relatively consistent pattern as regards certain fundamental parameters such as groundwater chemistry and hydraulic conductivity in sound rock. In other respects, the geology of the sites differs considerably, for example number and extent of water-bearing fracture zones. Accordingly, the comparison material that is available regarding these types of rock is judged at this point to be adequate in terms of the number of sites. However, certain supplementary further studies should be carried out on one or more of the sites.

The coming, more detailed geoscientific investigations are aimed at improving quantification so that the material can better be utilized in the final optimization of the repository system.

The investigations that have been conducted in gabbro do not provide a sufficient basis to determine whether this type of rock could be chosen for a final repository in Sweden. One borehole was drilled on one site, Tavinunnanen, and the rock here was riddled with granite veins. Experience gained to date of gabbro indicates that homogeneous bodies of sufficient size for a final repository are difficult to find. Drillings on one gabbro site, Kolsjön, were commenced in the autumn of 1985 but had to be interrupted due to protests.

Despite comprehensive and ambitious research, it is possible that certain phenomena will remain non-quantifiable. These problems must, as before, be dealt with by introducing limits or pessimistic assumptions in the safety analysis or by designing the repository so that the influence of non-quantifiable factors is minimized or eliminated.

3.1.3 Investigation methods

A continued application of the present-day standard investigation programme on an increasing number of granite-gneiss sites would only lead to a marginal increase in the existing body of knowledge. Since research will increasingly be focussed on providing the knowledge base required for designing an actual repository, detailed studies underground are needed. Methods for such detailed investigations can be developed at an underground research laboratory situated in a type of rock characteristic for the final repository.

3.1.4 Models

In order to permit calculations of the transport of dissolved waste substances, mathematical models must be constructed for the groundwater movements. In analyses performed to date, the sites have been modelled on a km scale as if the rock and major fracture zones consist of a large number of porous elements with differing hydraulic conductivity. The water flows in the repository area that have been obtained in this manner have been assumed to go directly to a fracture zone in the rock (distance 100 m). The fracture zones are then assumed to be able to conduct the groundwater with leached nuclides rapidly up to the biosphere.

However, experience from underground construction and the study-site investigations shows that large portions of the rock mass are completely impervious and that the water flow often takes place in discrete local fracture zones. Since areas with high water turnover can be avoided in connection with canister emplacement, a model development here should enable the rock mass to be utilized more optimally.

3.2 Basis for repository design

3.2.1 General

The design and execution of the repository and the engineered barriers that exist there have been adapted to the environments found on the granite-gneiss sites studied. The purpose of the performance analyses has been to indicate the protective effects that can be irrefutably shown to be possible to achieve. This means that certain combinations of materials and designs have been investigated in detail, while other closely-related alternative designs have not been dealt with at all.

Following is a discussion of the existing knowledge base concerning:

- conceptual designs,
- the waste matrix,
- canisters,
- control of the groundwater flow,
- chemical conditioning,
- nuclide transport in the geosphere.

Where applicable, the subjects are discussed with respect to:

- studied concepts,
- knowledge base and understanding of processes and interactions,
- models and data,
- execution and quality control.

3.2.2 Conceptual design and execution

The Swedish studies of final disposal systems focus on disposal below the groundwater table in crystalline rock and at such a depth that the repository can be regarded as being protected from even extreme surface forces in the event of war or glaciation. The KBS reports describe repository designs based on such a distribution of waste in the bedrock that thermal effects or chemical influence from the repository do not essentially alter the ability of the surrounding bedrock to protect the biosphere from undesirable effects of the final repository.

Geometrically more concentrated repository designs, for example WP-Cave, have been investigated by others, among them SKN. In these designs, a larger, altered rock region is isolated from the environment by engineered barriers. The components incorporated in the aforementioned cases are similar. The waste is surrounded by a canister in order to isolate it from the groundwater for a given length of time. The groundwater's interaction with the canister or waste is limited by flow-hindering and diffusion-limiting materials and by the placement of the canister in relation to water-bearing fractures. The durability of the canister can be increased and the solubility of the radionuclides can be limited by chemical conditioning of the near field.

The repository design is controlled to some extent by the conceptual system solutions. Repositories based on tunnels deep in the bedrock have been analyzed in Sweden as well as in the USA, Canada and Switzerland. The waste can be emplaced in specially drilled deposition holes or in the tunnel itself.

Variations of repository designs where waste canisters are emplaced in groups in special chambers or in closely-spaced sequence in a few long boreholes have not been analyzed in detail.

The detailed distribution of waste in a repository, as well as the shape and depth of the repository, are parameters that can be varied relatively freely in designs with tunnel deposition. Detailed studies of the interaction that takes place in the groundwater environment between the minerals in the bedrock and the components in the repository's near field have only been carried out for granite and gneiss.

Barrier manufacturing technology has been analyzed and tested for copper and aluminium oxide canisters as well as bentonite and bentonite-sand fills.

3.2.3 Waste forms

Most of the studies of high-level waste pertain to vitrified waste from reprocessing. Studies of this waste form have been conducted for a couple of decades in many countries. See further Section 7.5 in part III. Studies of spent nuclear fuel as a waste form began much later and have so far only been made in Canada, the USA and Sweden. The Swedish results relate mainly to BWR fuel, the American to PWR fuel and the Canadian to CANDU fuel. All three are uranium dioxide fuels clad in zircaloy; burnup varies considerably. Studies of the solubility of the waste matrix are reported in Section 2.3 in part III.

As regards the stability of the UO_2 matrix and its ability to retain radionuclides, a number of tests have been performed in various types of leach water and with a duration of up to several years.

Models that describe leaching results are under development but have not yet reached a level sufficient for use in safety assessments. In the absence of such models, the safety assessments have been based on the solubility of the nuclides of interest in the near field and in the geosphere.

3.2.4 Canister

A canister surrounding the waste fills a number of functions. It holds the fuel together in handling units of suitable size; it can constitute a radiation shield for personnel during the handling phase and at the same time protect the fuel against environmental influences. It constitutes a barrier that prevents the groundwater from coming into contact with the waste for a certain period of time.

The main canister material that has been studied in Sweden is copper, but titanium, lead and aluminium oxide have also been studied, as well as to a limited extent iron/steel and titanium oxide. The copper studies show that in the environment existing at repository depth in crystalline bedrock, wall thicknesses of as little as 5 cm can provide fully adequate isolation for a period of on the order of a million years.

Critical factors for the isolation period for copper canisters are the presence of corrosive substances in the groundwater, e g sulphide ions, the possibilities of these substances reaching the canister surface and the degree of inhomogeneity of the corrosion attack. The canister studies are reported in Section 2.4 in part III.

The possibilities of determining the ability of other canister materails to isolate the waste have been limited in previous studies by certain difficulties. For titanium and aluminium oxide, it has been difficult to produce clear evidence that delayed fracturing of the material caused by the slow growth of small, undetected defects does not occur. For iron, it has been difficult to quantify the rate at which hydrogen-generating corrosion can proceed. In recent years, data has been presented by NAGRA, among others, on the performance of iron canisters in granitic rock and in the presence of bentonite.

3.2.5 Control of the groundwater flow

In Sweden, as in many other countries, the search for a material to provide a barrier against water flow in the gap between the canister and the rock has centred primarily on bentonite. This has mainly been because of the plasticity and low hydraulic conductivity of bentonite as well as its ability to swell upon absorbing water. The pH-buffering properties and ion exchange capability of bentonite, along with its great stability over even geological time spans, have been other reasons for the great interest. Buffer materials are dealt with further in Section 2.5 in part III.

After long series of laboratory experiments concluding with large-scale in-situ tests in a natural environment, the applicability of bentonite should be clearly demonstrated. This means that a flow-free environment can be created around a canister. This in turn means that any transport of radioactive materials from the waste to the mobile groundwater must take place through diffusion.

Models for the function and stability of the material have been set up and validated with experimental data to an acceptable level. The main thrust of the continued studies is to determine, among other things, the temperature limits for the material. The technique for handling and applying the material has been tested at Stripa.

Other possible materials for similar purposes have not been studied to as great an extent.

The possibility of creating artificial flow pathways in the rock for the purpose of leading the water past the repository can reduce the rate of water turnover in the repository. The long-term stability of such flow pathways has not yet been analyzed.

3.2.6 Chemical conditions and chemical conditioning

The picture of the chemical composition of groundwater in granite-gneiss is relatively consistent and clear, while some uncertainty remains for groundwater in other rock types. Analysis of the chemical interactions in the investigated repositories shows that the chemical parameter that dominates the safety function is the redox potential of the groundwater. Another parameter that greatly influences the solubility of many radionuclides of importance for safety is pH. In addition, there are a number of specific substances that can affect the solubility of a given substance by e g the formation of solid phases with low solubility or by the formation of soluble complexes.

The rate of canister corrosion and fuel dissolution can be affected by controlling the chemical environment in the near field.

The chemical conditioning that has been studied the most has been the effect of bentonite and concrete in the repository. Both have an influence on pH. Certain studies have also been made of the possibility of controlling Eh via additions of minerals containing bivalent iron (e g vivianite).

Disturbances caused by radioactivity in the repository, by various materials in the repository or by infiltration of surface waters are neutralized by the rock after a given period of time. The rock's ability to neutralize such disturbances and the speed with which disturbances are equalized has mainly been studied with regard to redox potential.

Data and models describing the chemical speciation that takes place under these circumstances have been developed in many parts of the world. Models such as PHREEQE and EQ3/6 have been available in Sweden for a year or so. A compilation of thermodynamic data is being carried out under the auspices of OECD/NEA. Studies of natural systems that serve as analogues of the conditions existing at a final repository for spent fuel are being conducted for the purpose of verifying the mathematical models and will constitute an important part of the future programme. See Section 5.4 in part III.

3.2.7 Transport in the far field

If radionuclides are released to the near field, they can also reach the mobile groundwater, with some delay.

As was mentioned in the preceding section, there is a possibility that the chemical conditions in the near field could have some impact downstream of the repository. The extent of this plume of impact is dependent on, among other things, the chemistry of the near field and the available buffering capacity of the surrounding rock. Another important parameter in this respect is the degree of channelling of the water flow in the rock's fracture systems. Modellings of the nuclide transport have been based on empirical data, mainly from the Finnsjö area, showing that groundwater flow takes place on the average in every fifth fracture.

The ability of the radionuclides to diffuse into the rock's fracture faces is a phenomenon that would strongly delay the transport of escaped substances through the geosphere. A prerequisite for radionuclides to diffuse into the rock matrix around the fractures is that both the rock and the fracture filling minerals have an interconnected micropore system. Evidence of this has been obtained from laboratory experiments and tests in Stripa.

As regards the tendency of the waste substances to sorb on different mineral surfaces, a knowledge base consisting of a large body of material has been gathered, mainly from laboratory tests. The data available within this area would seem to be sufficient in view of the relatively simple models that are used. Further attempts at refinement must concentrate on the various fundamental phenomena of sorption such as precipitation/mineralization, ion isotope exchange, exchange reactions etc.

Mathematical models of nuclide transports have been developed during the KBS studies. Further validations are underway and will continue through lab tests, in-situ tests and evaluation of natural analogues.

4 INVESTIGATIONS LEADING UP TO SYSTEM AND SITE SELECTION

4.1 General plan

A general timetable for the measures that have to be carried out prior to the construction of a final repository for spent nuclear fuel in Sweden is presented in part I, section 4.3. This timetable shows that a siting application is intended to be submitted by the year 2000.

The measures that are required to select a system and a site for the final repository, to design the barriers and to analyze and describe the safety of the system must be carried out in a structured manner during the period up to the year 2000. The work sequence that constitutes the frame within which the individual measures are to fit is presented below, see Figure 4-1.

As is evident from part I, a final repository deep in crystalline bedrock is deemed to be the only realistical alternative for a final repository in Sweden. The repository must be designed so that the engineered safety barriers are adapted to the conditions offered by the bedrock.

Since the site-related conditions for a final repository are largely given through the properties of the Swedish bedrock, the gradual focussing procedure must begin with the selection of a few potential repository sites in the early 1990s for detailed studies. For sites that are candidates for a siting application in the year 2000, these studies should not be commenced later than 1993. During this site culling phase, some culling of alternative barrier designs can probably also be done.

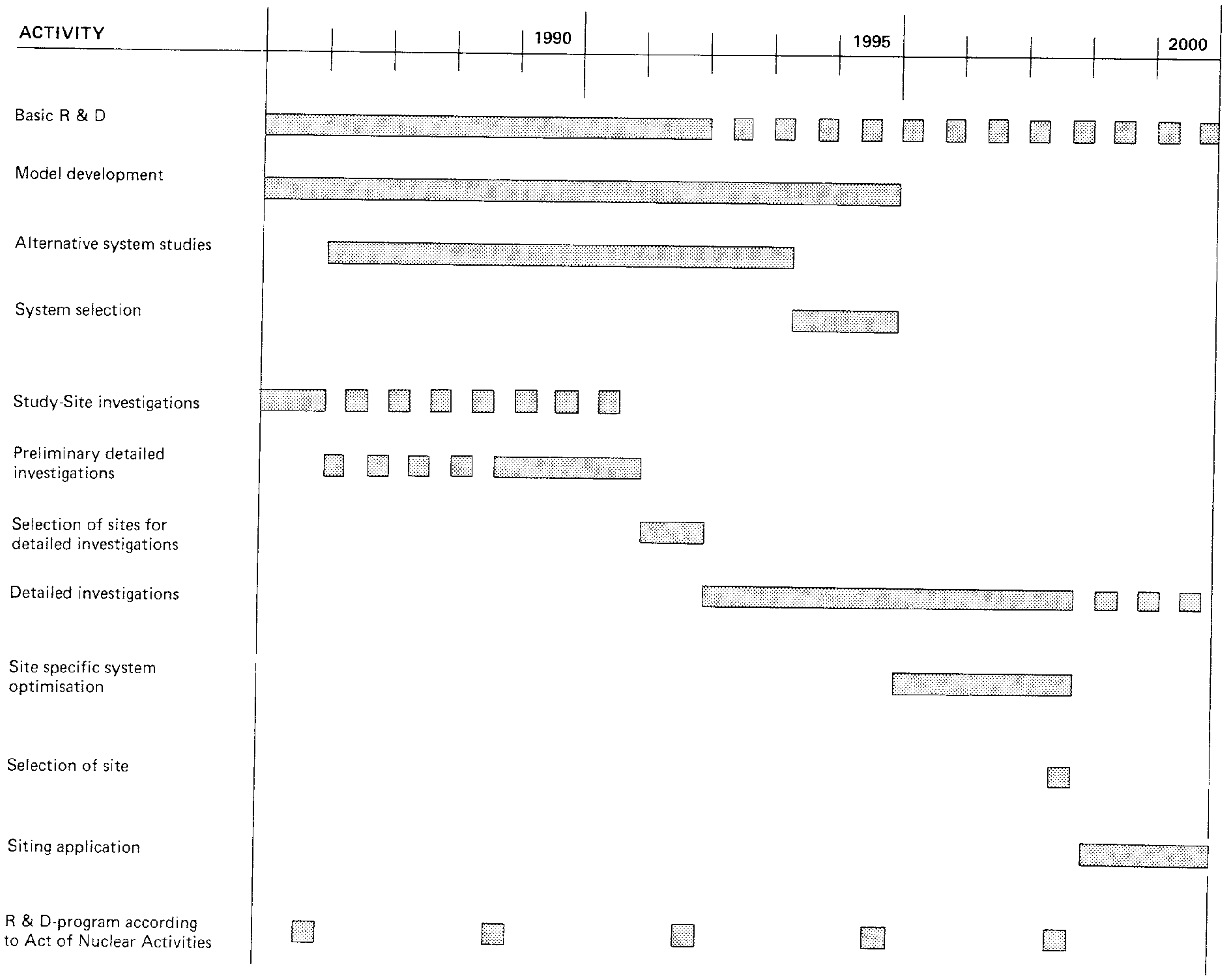


Figure 4-1. Overall timetable for R&D up to siting application for final repository.

In the main, however, the breadth of alternatives in the barrier studies will be retained up until the mid-1990s. During the final years of the period, the study of the barrier alternatives should be concentrated on the analyses of a number of integrated repository systems, i e on the interaction between the different barrier components and between the barrier system as a whole and the surrounding geosphere. It is judged that at the end of the period enough fundamental information on sites and barrier alternatives will be available to allow one or a few designs to be chosen.

The period 1996-1998 is set aside for a site-specific optimization of a final repository on the one or two most suitable sites, whereupon a preliminary safety report will be produced during 1998-1999 as a basis for a siting application.

After the phase where site data and barrier data have become increasingly detailed and the interaction between the different components becomes a principal topic in the investigations, the need for verifying and validating in-situ tests in representative bedrock will increase. For this purpose, an underground research laboratory must be planned in good time. Tunnelling/shaft sinking will be combined with method development for the detailed studies and certain validation experiments for the predictive models.

The activities for evaluation of alternatives, build-up of knowledge, modelling etc that are discussed in the following sections can have very different degrees of urgency. Those that are deemed to be of sufficient prioııty to be included in the plan for 1987–1992 are described in part III. The understanding gained in the research activities may call for reassessments of priorities and changes in the R&D programme.

A gradual focussing of the R&D activities will take place as more information is obtained. In order to give the authorities insight into the activities, a continuous review is required that goes beyond just a follow-up of the results of research and the decisions to cull or give priority to certain alternatives. A dialogue must be maintained with the authorities concerning the continuous adjustments of the R&D programme that are required to get relevant data on the parameters essential for safety.

In practice, three periods are seen to be more important for the focussing process than others. The first is the selection of a few detailed investigation sites in 1990–1992, the second is the development of one or a few integrated engineered barrier systems during the period 1994–1996. The third is the choice of site and system for the safety analysis in around 1998.

It is assumed that a practice will be established for contacts with the authorities during these phases. A detailed plan for frequencies and forms of the exchange of technical information during the site culling phase should be developed in cooperation with the parties concerned during the period 1987–1989.

The methods for the site-specific optimization that is to commence in about 1996 and the contents of the safety report that will constitute a basis for the siting application will be discussed in future research programmes.

4.2 Geoscientific research

In coming research work, SKB intends to refine the geological and geohydrological material that will serve as a basis for the safety analysis.

The goals of the continued geoscientific research are to:

- refine methods for collecting geoscientific data of importance for the choice of site and design of a final repository,
- identify and solve problems judged to be vital for the safety analysis,
- quantify the mechanisms that are relevant for the safety analysis.

4.2.1 Groundwater movements

In the safety analyses performed thus far, large safety margins have been introduced in the calculation of groundwater flow. This has been done in order to take into account substantial uncertainties in models and data. Among other things, the phenomenon of channelling in fracture systems is poorly understood, and sufficient data are lacking to permit modelling of nuclide transport in fracture zones.

A further refinement of geohydrological models – on a 10 m scale nearest the repository and on a scale of 100–1 000 m up to fracture zones – will be carried out so that local fracture patterns can be taken into account to a greater degree. The development of geohydrological models will take place to a large extent within the framework of the Stripa project, see further Section 7.3 in part III. Besides validation experiments, much work will be done to achieve a better understanding of channelling.

In connection with shaft sinking at the Underground Research Laboratory (URL) in Canada, a large experiment to validated groundwater models is being conducted. Independent groups are carrying out model calculations to determine how the sinking of a shaft affects the groundwater conditions. Measured changes will then enable different models to be validated. SKB is participating in this work, which will provide experience for similar experiments at the planned new research laboratory.

Besides participating in international projects, SKB will conduct its own geohydrological projects, partly in connection with the investigations at SFR. Data obtained will be used to further refine and validate the geohydrological models. The groundwater's composition as a function of time will also be analyzed in order to obtain a picture of water turnover. This experience is deemed valuable for planning of detailed investigations at a final repository.

In the absence of models and data for quantifying groundwater movements in fracture zones, it was assumed in the safety analysis in KBS-3 that a radionuclide that reaches a fracture zone immediately reaches the ground surface as well. An increase of knowledge within this area should improve the realism in the description of the groundwater movements.

The fracture zone investigations are aimed at

- developing and testing models for locating and characterizing fracture zones,
- increasing the amount of data available on fracture zones and their properties,
- modelling groundwater flow and nuclide transport in the fracture zone.

4.2.2 Stability of the rock

In a long-range perspective, the safety of the repository is dependent on the stability of the host bedrock. Interpretation of mechanisms and comparisons between seismically active areas and areas of low seismicity will be facilitated if understanding of the large-scale mechanisms can be improved.

Seismic activity in Sweden is very low and earthquakes are of low magnitude. Nevertheless, major movements since the most recent ice age have been discovered in a number of zones. It is essential to determine whether these movements have occurred in old zones of movement or whether new fracturing can be followed through a rock block.

The consequences that movement in the bedrock can have for the mechanical and conductive properties of different rock blocks will be studied.

4.2.3 Underground research laboratory

In order to proceed from the study site investigations onto further research, more detailed knowledge is needed of the geological conditions at some site. An underground research laboratory at a site with suitable geological characteristics and geologically undisturbed conditions is expected to be able to provide essential contributions to the existing body of knowledge within the geosciences. The investigation methods that are later to be used on sites being considered for a final repository can be tested in such a laboratory.

At the same time, a research laboratory provides an excellent opportunity to develop methods and validate models that are used in the safety analysis. The research laboratory can also be used for large-scale tests, as a reference site for studies of various alternatives for repository design, in-situ tests etc.

4.3 Study-site investigations

The investigations performed according to the standard programme and those planned to supplement this programme provide only a general picture of the investigated sites. In order to improve the tectonic and geohydrological picture of the various sites, further studies should be conducted in several of the previously investigated sites. Relevant investigation methods are radar measurements in individual boreholes or between boreholes, reflection seismics, stress measurements, interference tests and tracer tests.

Since a coastal situation is regarded as favourable from the standpoint of safety and transportation, further investigations of such sites may be undertaken in such areas during the period 1990–1992.

The study-site investigations are scheduled to reach a new phase around 1990. One or two sites will be selected by 1993 for detailed geological characterization. The goal is to obtain a detailed body of data for performance evaluations to serve as a basis for the choice of site and system.

The detailed investigations will include sinking of a shaft or tunnelling down to repository depth. The planning will be based on experience from URL and from the follow-up programme at SFR. The underground research laboratory offers an opportunity to develop methods for the detailed investigations.

4.4 Evaluation in preparation for site selection

The site of a final repository shall, together with the engineered barriers, give the repository two intended safety functions:

- Delay the time when the radionuclides may begin to leak from the repository or the time when they may reach the biosphere so that the toxicity of the waste is reduced by the decay of nuclides with short half-lives.
- Limit the rate at which long-lived nuclides are released from the repository or reach the biosphere in order to reduce the maximum concentrations that can arise in the human environment.

As is evident from chapters 2 and 3, the analyses that have been carried out in recent years show that sites exist in Sweden that satisfy with good margin the demands that can be made on a good repository site. This means that other factors of importance to society can be weighed in when selecting a repository site.

In order for a site to be suitable for the location of a final repository for long-lived radioactive waste, a number of characteristics are of interest:

- Geological stability is a fundamental requirement in order to permit predictions of water flows and water chemistry on the time scale for which the safety functions play a role (i e hundreds of thousands of years).
- Low and slow water turnover increases the life of canister materials whose degradation is controlled by dissolution or incoming corrodants and reduces the rate of dissolution of the fuel matrix and any precipitates.
- Water chemistry affects canister life and solubility due to its effects on the chemistry of the near field. In the far field, it controls the speciation of the dissolved substances.
- The mineral composition of the rock and the fractures affects the sorption of radionuclides and buffers the chemistry of the groundwater.
- The porosity and diffusion properties of the rock type and the fracture minerals affect the degree of diffusion into the rock and the rock's buffering properties.
- The fracturing of the rock mass and the proportion of fractures that are water-bearing influence the

size of the rock surface that is accessible for sorption of radionuclides.
- The extent and geometry of the fracture zones affect the flow situation and the transport pathways for groundwater and radionuclides and determine how large a repository can be harboured within a given area.
- The groundwater recipient in the biosphere greatly influences the maximum individual doses that can arise in the vicinity of the repository.

An analysis of the suitability of a repository location must weigh in all of these factors, taking into account their mutual importance and the engineered barriers that may be needed. Within certain limits, material choice and dimensions/design of the engineered barriers can be adapted to prevailing site-specific conditions. However, certain barrier designs may impose demands on the properties of the repository site.

In practice, this means that the site evaluation must be carried out in consideration of possible engineered barriers. The analysis then has the character of a safety analysis, if somewhat simplified.

The analysis has two purposes: To establish whether the site in question is at all qualified to offer adequate safety in consideration of the engineered barriers that are available, and to weigh safety-related factors to permit comparisons.

Sites with good natural barriers to nuclide dispersal should in general require less elaborate systems of engineered barriers in order to achieve society's acceptance than sites with less favourable natural conditions. An optimization of site and system is hereby made possible by the fact that site-related, social and economic factors can be weighed against the cost of necessary engineered barriers.

A final repository must fulfil its purpose both under the probable expected conditions in its environment and under a number of less probable situations that may nevertheless occur. In comparison with previous safety assessments, where the purpose was to establish an upper limit for possible effects under the most unfavourable conditions, greater weight must be attached in the site selection phase to probable scenarios. This must be done in order to prevent the comparison from being dominated by highly unlikely events, which, owing to the fact that they are difficult to model, must be handled conservatively. Comparison criteria based on risk (consequence x probability) have been discussed internationally.

The site comparisons will be carried out successively. In the beginning of the 1990s, an overall evaluation of the available data will be performed in order to select sites for detailed investigations.

Priority must in addition be given to the following measures in order to permit site evaluations:

- The analysis methodology used for the comparisons shall be developed so that, in addition to deterministic analyses, probabilistic assessments of repository performance can also be carried out.
- The quality and validity of the mathematical models shall be further refined. Attempts shall be made to quantify the reliability or uncertainty of the models.
- The site-specific data shall be processed in order to define both probable values and the upper and lower limits of variation of the parameters.
- Alternatives for engineered barriers will be compiled.
- Environmental premises essential to the analysis and possible changes in them will be compiled.
- Comparison criteria and acceptance criteria must be discussed with concerned authorities.

The data planned to be obtained during the first years of the 1990s will comprise the basis for the choice of one or more sites for the geological detailed investigations and will constitute a reference database for the prioritization of the alternative studies for the engineered barriers that are carried out simultaneously, see further section 4.5.

4.5 Investigations concerning engineered barriers

4.5.1 General principles

The need for a wide selection of alternative final disposal methods for a final choice of disposal system applies to both sites and systems for engineered barriers and repository design. Because the detailed site investigations require that shafts or tunnels be excavated to repository depth, these studies will be time-consuming. This means that the number of sites must be narrowed down in 1990–1992 in order to obtain a complete body of data for site selection in time for the siting application in the year 2000. Similar requirements on an early focussing of the work do not exist for the choice of engineered barriers. However, the alternatives should be narrowed down after the sites for the detailed site investigations have been selected. For the most part, flexibility can be retained up to the point when integrated performance analysis of the various components and surrounding environment show that certain alternatives are clearly less favourable than others.

The term "alternative" can be understood in many different ways. Alternatives may consist of certain integrated repository designs (for example KBS-3 and NAGRA's concept) or they may consist of certain given components (such as copper canister alternatives or iron canister alternatives). Moreover, the barriers can be varied in a multitude of ways through the use of design and size variants. Similarly, adaptation to the site can proceed from many different basic alternatives. If consideration is also given to the fact that repository depth, rock types etc. can vary, then a very large number of possible alternatives for final disposal in the Swedish crystalline bedrock are obtained. Studies of these alternatives must be carried out in a reasonably rational manner in order to obtain information for an optimal design of the final repository.

A broader set of alternatives is obtained if research is focussed on the different alternative components that can be incorporated in a system. Since components incorporated in certain designs can often also be combined with other components to obtain new repository designs, the results of apparently narrow goaloriented research become applicable to a large number of design alternatives.

However, certain system designs may entail special boundary conditions for the constituent components. Accordingly, the alternative studies must, in practice, be pursued with an iterative strategy. The study of certain conceptual designs leads to priority for certain component studies, which can in turn lead to reevaluations of the system designs that are possible etc.

The work sequence followed in the study of alternative designs is largely to first elevate the state of knowledge concerning the function of constituent components to such a level that their safety-related role can be defined. Then their total performance in interaction with other components and the bedrock is evaluated and a comparison is made between different alternatives so that a safe and effective total system can be chosen for a given site.

Finally, technology for manufacture, application and quality control must be adapted and any demonstration trials carried out.

In the review of alternatives, certain grounds for priority must be applied for the purpose of scheduling the work and ranking the alternatives.

For scheduling of the work, priority will be assigned on the following grounds:

- Potential safety-enhancing effect.
- General applicability in different barrier combinations.
- Simple technology for manufacture/application.
- Potential for economic effectiveness.
- Availability of background knowledge and expertise.

An evaluation of the work that is needed in order to be able to model the function of the component and quantify its effect will also be of importance in the scheduling. The question of how well the work fits in with the ongoing or future research structure is also important.

In evaluating potential for safety function and economic effectiveness, already studied components will be normative in determining what constitutes sufficient potential.

4.5.2 Overview of alternative studies

A review of different possible alternatives for systems and sites has been made in a special background report: "Handling and final disposal of nuclear waste. Alternative final disposal methods". An overview of different barrier types and alternatives for their design is presented below.

Canister materials (KBS studies: Cu, Pb/Ti, Al_2O_3)

- Passive materials - titanium.
- Corroding materials - carbon steel.
- Non-metallic materials - (Al_2O_3, TiO_2).

Flow barriers (KBS studies: sand/bentonite, compacted bentonite)

- Hydraulic cages.
- Grouting of rock.
- Impervious clay layers (bentonite and the like).
- Encasement in concrete.
- Water displacement with gas .

Chemical conditioning of the near field (KBS studies: vivianite)

- Control of redox potential and redox buffering capacity.
- Control of pH and carbonate content.
- Addition of sorbing materials.
- Addition of diluting materials.

Besides alternative components in the engineered barriers, alternative technical designs of the barriers or the repository and certain specific conceptual designs constitute clear alternatives that must be evaluated, for example

- Dry repository.
- Deep-hole disposal.
- WP-cave.
- Different repository layouts.
- Canister fabrication method.
- Codeposition of different radioactive waste forms.

All alternative ideas should be evaluated with respect to their advantages and disadvantages. The studies that are needed to obtain sufficient understanding and data for their evaluation must be initiated if the alternative is deemed interesting.

The following list takes up a number of such research subjects that must be studied in order to shed light on different alternatives that may prove feasible in the light of the premises that currently exist in Sweden. The studies are discussed from the viewpoint of scheduling and at a detailed level of execution in part III under the various subject headings.

Investigation of natural conditions

- A review of estimates of residual land uplift in order to establish the feasibility of a repository location that guarantees during a certain period of time that any releases will end up in a salt or brackish water sea.
- An investigation of the existence of a transitional zone for the fracturing of the rock at about 1 200-1 500 m depth.

Investigations of the near-field environment at the waste

- The effect of temperatures above 100°C on buffer material and rock in the near field shall be studied in order to establish the limits of permissible temperature in the repository.
- The chemical importance of codeposition or different waste types shall be examined.
- A systematic review shall be carried out of the effect of using concrete in the repository on certain near-field or geosphere processes.
- The question of radiolysis shall be further explored as a basis for the choice of canister thickness.

Release-preventive measures

- A systematic review shall be initiated of different kinds of "getters" or chemical buffers, including their effect on the rest of the system and on the geosphere.
- The design and effect of groundwater control shall be studied. The studies should be coupled to the fracture zone project and should focus on long-term effects.
- The studies concerning injection grouting shall be focussed on long-term function and possible interactions of different materials with other components in the repository system.
- Studies shall be made of alternative canister materials, their degradation and their interaction in the repository.

Design and execution

- Different methods for the manufacture of alternative barrier components shall be studied as they are found to be functionally or economically attractive.
- The different possible designs and executions of the repository shall be reviewed and their economic or functional consequences shall be assessed.

The results of the different studies will be used to initiate new studies or to determine the priority of future studies.

Obviously unfavourable alternatives will be culled in the review of alternatives so that the degree of detail in the studies can progressively be increased for favourable alternatives.

4.5.3 Model development and refinement of data

In parallel with the alternative studies, activities must be continued within the various research fields in order to deepen understanding and knowledge as a basis for identifying, modelling and quantifying relevant processes in the repository.

In order to prove the feasibility of a scheme, it may be enough to establish the fact that its consequences are limited. In a comparison of the safety function of different alternative components or their design, however, higher demands are made on quantification of the probable behaviour of the component so that safety margins and simplified assumptions do not have to be applied to such an extent that essential differences in performance disappear.

In the KBS-3 study, examples of simplified but unfavourable assumptions and safety margins that are difficult to quantify have been presented in a separate list. Following are examples of these and other areas where further development should be able to reduce the need for simplifications or safety margins.

- The presence of solid uranium phases of low solubility in the near field.
- The feasibility of limiting the propagation of a redox front to the buffer materials nearest the canister, possibly by means of chemical conditioning.
- Coprecipitation phenomena and irreversible mineralization.
- The kinetics of certain geochemical and other chemical processes.

These and similar research subjects, as well as the need for quantifying uncertainties in both data and analyses, are discussed under the research subject headings in part III.

Since the nuclear fuel, the groundwater and the crystalline bedrock are features of all alternative repository designs, an improvement of the knowledge base in these areas constitutes a platform for understanding the processes that affect other parts. The assignment of priorities within areas for further research is based primarily on how sensitive the overall safety of the repository is to variations in parameters or models for the different processes and on a best estimate of the development potential within the different areas.

4.5.4 Technology development

In addition to the fundamental technical feasibility assessments included in the study of alternative repository designs, a development and adaptation of technology will have to be carried out for certain alternatives. The technology development studies will not be able to be defined in detail until after the initial alternative reviews, ie during the period 1992–1998.

Most of these studies are expected to be conducted at the encapsulation plant for spent fuel, but some may have to be conducted in a repository-like environment. They will therefore be coordinated with other experimental activities at the underground research laboratory.

4.6 Evaluation preceding the choice of repository system

The process of focussing the research efforts from a broad review of alternatives to a single site-specific optimized repository facility has been outlined in part I and in part II, section 4.1.

The culling of alternative system designs for the final repository must be based, in the same way as the selection of sites for detailed investigations, on the modelling of various repository designs and the role of the studied components in these total systems. This means that analysis models and methods for execution of the analyses must be developed and adapted to the need for comparison and ranking of the alternatives, see Chapter 6 in part III.

The goal of the various research efforts aimed at collecting data on the alternatives is to have collected a sufficient body of data by 1995 to permit integrated performance analysis including site characteristics and the different engineered barrier components.

The scheduling of the investigations of the alternatives must be coordinated with the main timetable. Thus, the couplings that exist to the site-specific conditions must be clarified at an early stage up to about 1990 so that the site culling can be done in awareness of any requirements or restrictions imposed by various alternative barrier designs.

The execution of the comparative analyses must be planned and the necessary detailing of development efforts must be done during the coming three-year period.

Handling and final disposal of nuclear waste

Programme for research, development and other measures

III Research programme 1987–1992

CONTENTS PART III

1 GENERAL

This part III of SKB's 1986 R&D programme deals with research activities over the next six years. Activities concerning the engineered barriers against activity release are described first, followed by studies related to the geosphere and the biosphere, including their natural dispersal pathways and dispersal barriers.

The chemical conditions in the repository and its environs are decisive for both the function of the barriers and the transport of radioactivity through the geosphere and the biosphere to man. Studies within the field of chemistry are therefore presented in a separate chapter. The borderline between barrier studies and chemistry and between the geosciences and chemistry can sometimes be diffuse and is related to some extent to the assignment of responsibilities within SKB's research division.

Like chemistry, development of methods for performance and safety assessment is all-embracing and is dealt with in a separate chapter.

Activities in some other countries that are of particular interest for the Swedish programme are presented at the end of Part III. In addition, SKB's international cooperation is described.

Part I describes overall plans for all the measures required for the management of the waste from the Swedish nuclear power plants and for planned research and development. The investigations that must be carried out prior to a final choice of design and site are discussed in Part II.

The framework within which the R&D activities for different subject areas have been scheduled is given below; see also Figure 1-1:

- Up to the mid-1990s, goal-related research will be conducted concerning alternative designs of the barrier system and the fundamental phenomena of importance for safety, optimization and system and site selection. At the same time, the necessary development of assessment models will be carried out.
- The general study-site investigations that have been going on since the end of the 1970s will be wound up. In the beginning of the 1990s, a couple of sites will be selected for detailed investigations. These investigations should be initiated no later than 1993 for those sites that may be considered for a siting application in the year 2000.

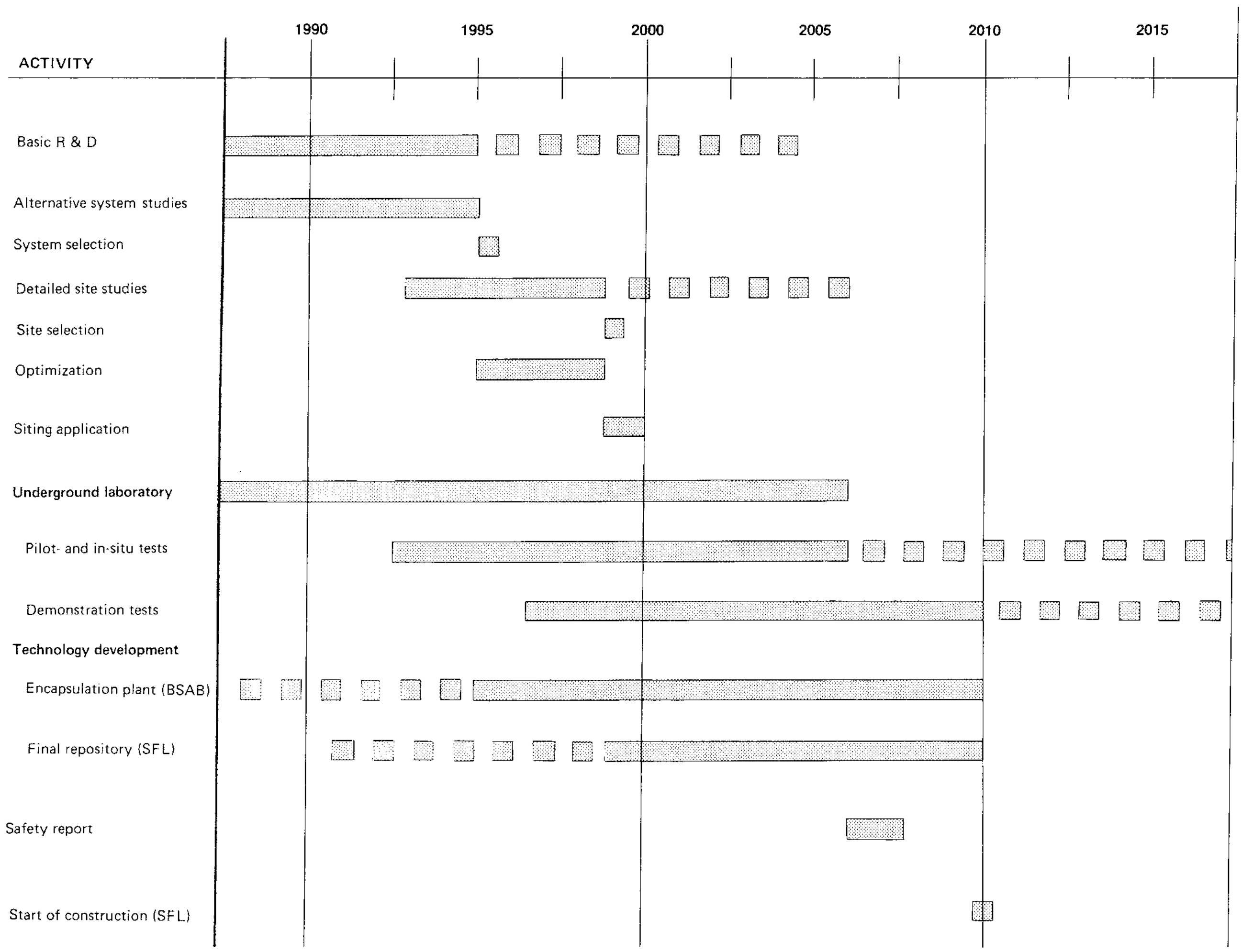


Figure 1-1. Overall timeschedule for measures up to the start of construction for the final repository and the treatment plant.

- In the mid-1990s, the studies of the barrier systems will be summarized and one or two main alternatives will be selected. These alternatives will then serve as a basis for a site-related system optimization of the final repository system.
- Optimization will be carried out until 1998, when one site will be selected for a siting application, which will then be prepared and submitted before the year 2000.

In addition to the research plan, the background, goals of research and present-day state of knowledge within each main area are presented under each subject area. Most of the present-day state of knowledge is presented in greater detail in the KBS-3 report and the SKB annual reports from 1984 and 1985.

No detailed evaluation has been made of how the results of the safety assessments in KBS 1 and 3 are affected by new data. This will follow naturally in connection with the comparison of alternative designs and sites.

The importance of different parameters and conditions for the integrated performance of the parts of a repository system is discussed in Part II, chapters 2 and 3 against the background of their safety functions. The priorities assigned to the research activities must be continuously reevaluated on the basis of both new knowledge gained and the work plans and timeschedules for the execution of the necessary measures.

2 ENGINEERED BARRIERS

2.1 General

R&D activities concerning the design of the repository and engineered barriers included in it are described in this chapter.

The R&D work concerning the design of the engineered barrier system and the overall design of the repository will, during the period up to the mid-1990s, include a review and evaluation of different alternatives. The goal is to select one or possibly two main alternatives in 1995 as a base for a site-related optimization of the final repository system. In 1994-95, the work will be focussed on integrated performance analyses of the different components in the final repository.

The implications of the concepts "alternative design" and "alternative barriers" have been discussed and systematized in a background report /2-1/. Some alternatives that may be considered are also presented there. Others will be defined as the work progresses.

Planned research concerning the design of the repository and the technology for its construction is described first (Section 2.2), followed by a description of research concerning waste forms (Section 2.3), the canister including its manufacture and durability (Section 2.4) and buffer materials including methods for the limitation of water movements in the near field (Section 2.5).

Chemical conditions in the near field and studies of chemical interaction are discussed in Chapter 5.

2.2 Design of repository

2.2.1 Background

The design of a final repository shall, with due regard for the characteristics of the geological media, permit the incorporation and functioning of engineered barriers and limit the temperatures stemming from the residual heat in the spent fuel. The repository shall also be designed, with reference to available excavation methods, for the deposition of canisters in suitable rock and in a suitable geometry.

Adaptation to the site can be based on different basic alternatives. If account is also taken of the fact that repository depth, rock type etc can vary, a very large number of possible variants of rock repositories is obtained. The studied alternatives must be continuously narrowed down in order to obtain a manageable basis for an optimum design of the repository.

2.2.2 Goal of the R&D activities

The goal is to be able to select a conceptual repository design by the mid-1990s. This system will then be optimized with respect to such factors as temperature, canister and sealing measures on the chosen repository site.

Different basic alternatives will be studied and evaluated during the next 6-year period with respect to performance, safety, feasibility, technology and economy. The necessary supplementary R&D activities are defined for prioritized alternatives.

2.2.3 Present-day state of knowledge

A number of different basic alternatives for the design of a final repository for spent nuclear fuel have been proposed. Some of these have been studied in detail, while others have merely been roughly sketched. The most thoroughly studied alternative in crystalline rock, even in an international comparison, is the one described in the KBS-3 report /2-2/.

In KBS-3, the final repository consists of a system of tunnels. The waste canisters are placed in deposition holes drilled from the floor of the tunnels. Each deposition hole contains one canister. Disposal and transport tunnels, together with vertical shafts, serve as channels of communication in the transport and handling of the canisters.

The deposition holes also provide room for buffer material, Figure 2-1, and tunnels and shafts are backfilled with impervious material.

The given quantity of spent fuel is distributed among a number of canisters and deposition holes, spaced according to practical and geological factors and at a distance that is sufficient to limit the temperature in the deposition holes and surrounding rock. The design allows great freedom in arranging the disposal tunnels in a system with variable length, spacing and depth below the rock surface.

The temperature conditions in simulated deposition holes were studied in the Stripa tests /2-3/. In six half-scale deposition holes in realistic rock conditions and with different water flows, the water absorption process was studied both for a canister with a thermal power equivalent to that given in KBS-3 and at more than twice that thermal power. The results showed that the temperature conditions can be predicted with knowledge of the rock's thermal conductivity and an understanding of the relationships between the buffer material's moisture properties and thermal conductivity /2-4/.

The extent to which different clays with different additives differ in these respects is the subject of research. The ways in which properties important to the function of the clays are affected by the magnitude and duration of the temperature change are also being studied, see Section 2.5.

The design of the final repository affects the magnitude and duration of the temperature increase mainly during the first 1000-10 000 years. The maximum temperatures at the canister and in the rock occur at different times.

It is conceivable that the temperature in the buffer material may be permitted to be higher than the limit indicated as a guideline in KBS-3, ie well below 100°C.

A future optimization also requires a deeper understanding of the temperature effects that could lead to significant changes in the properties of the rock surrounding the final repository, see Section 3.1.4.

The development of construction methods for eg full-face boring of tunnels and shafts is progressing independently of SKB's research programme, towards the use of larger machines for, among other things, better ergonomic conditions in underground work. Full-face boring causes less damage to the surrounding rock than blasting. This method can be utilized for canister deposition directly in horizontal tunnels, as described by NAGRA in Switzerland /2-5/ - see Figure 2-2. The method could also conceivably permit larger deposition holes or horizontal deposition holes.

Other alternatives are to utilize designs for the incorporation of impervious barriers that are separated from the deposition chambers for canisters. It is also possible to combine such an impervious barrier with an artificial hydraulic cage that surrounds the entire repository and enables groundwater to flow around the repository instead of through it. The so-called WP-Cave design utilizes these principles - see below.

Methods for backfilling boreholes, shafts and tunnels with impervious material are dealt with in Section 2.5.

If needed, extra sealing measures can be incorporated in the backfill in the form of plugs in boreholes, shafts and tunnels or can be implemented at an early stage, for example in connection with excavation of the rock, in the form of injection grouting or arrangements in the rock surface /2-6/.

Seals and hydraulic cage arrangements should be positioned in relation to the natural flow of the groundwater, especially in the more interconnected and persistent water-bearing zones. These zones are identified before or during excavation of the final repository by means of methods that have been tested at the SFR facility. The development of such methods is described in Sections 3.1 and 3.5.

In parallel with the KBS-3 studies, certain development work has been done via SKN on WP-Cave /2-7/, see Figure 2-3. The idea is to isolate, by means of engineered arrangements, a rock body so well from the surrounding rock that considerable changes in the near field can be permitted without the rock in the far field losing its natural long-term protective properties.

A study within SKB of the WP-Cave design was begun in 1986 aimed at a) identifying critical parameters and processes in the system and providing a basis for a safety assessment, and b) calculating the costs of WP-Cave applied to the Swedish waste management system. The way in which this study is carried out is an example of how the performance of integrated repository systems will be studied at SKB in the future.

2.2.4 1987-1992 research programme

During 1987-1988, an inventory will be carried out of conceptual repository designs. Relationships between technology of construction and method of measuring rock properties that are of importance for the performance of the final repository will hereby be identified.

Requirements on the rock stemming from design or function will be identified. In particular, differences between the final repository design alternatives will be identified in terms of their capacity, in combination with canisters, to isolate the spent fuel from the groundwater or to minimize the turnover of groundwater in contact with the spent fuel.

Assessments of feasibility, safety, performance and cost will be used for the purpose of culling. Reasons why a given design is being given priority for further study, or is considered to be of limited interest or unsuitable, will be documented.

Prioritized alternatives will be studied in greater detail during 1989-1990 in an anticipated rock model. Particular attention will be given to the possibility of adapting the design to the quality of the rock, based on information on the properties of the rock obtained as the construction of the repository's tunnel system proceeds. Data from the study-site investigations will be used to obtain realistic rock descriptions.

Methods of investigating rock in relevant repository designs will be described.

An appraisal of a possible strategy for construction of the final repository, investigation methodology and adaptation to rock characteristics will constitute a basis for the detailed goals and programme for R&D in the underground research laboratory (see Section 3.4). Possible technology development will be defined with timeschedules and plans for any major demonstrations tests.

An evaluation of alternative deposition methods will be carried out during 1991-1992 prior to the selection of sites for detailed geological investigations. Any differences in adaptability will be identified in the light of the more detailed description of rock conditions available at that time.

2.3 Waste forms

2.3.1 Background

Direct disposal of spent fuel is the main alternative for management of the high-level waste obtained from the Swedish nuclear power programme, and the emphasis in the research work lies, both in the shorter and the longer perspective, on studies of this waste form. In order to be able to follow up research activities on waste forms and waste properties in other countries, some domestic competence in the field of vitrified high-level waste must also be maintained and developed. This requires certain R&D activities, which over the next year will be pursued within the framework of the JSS Project. The model development for dissolution/leaching of glass currently in progress is providing an understanding of fundamental phenomena that are probably of importance for spent fuel as a waste form as well. After completion of the JSS Project, no new research on HLW glass is planned. Only a low-level follow-up of previous work

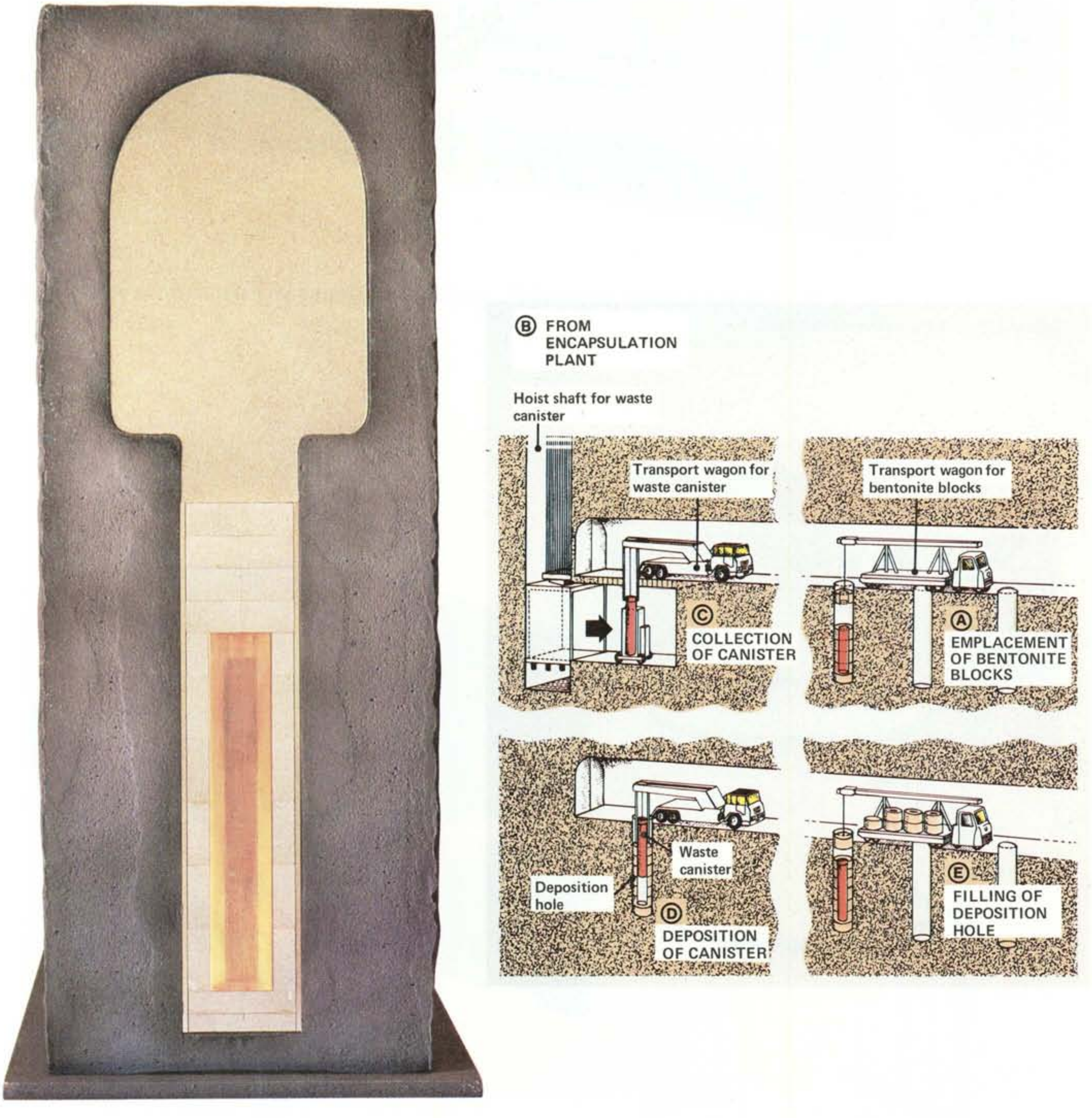


Figure 2-1. According to KBS-3, canisters and blocks of highly compacted bentonite are deposited in holes drilled in the rock underneath the tunnel. The tunnel is then filled with bentonite/sand mixture.

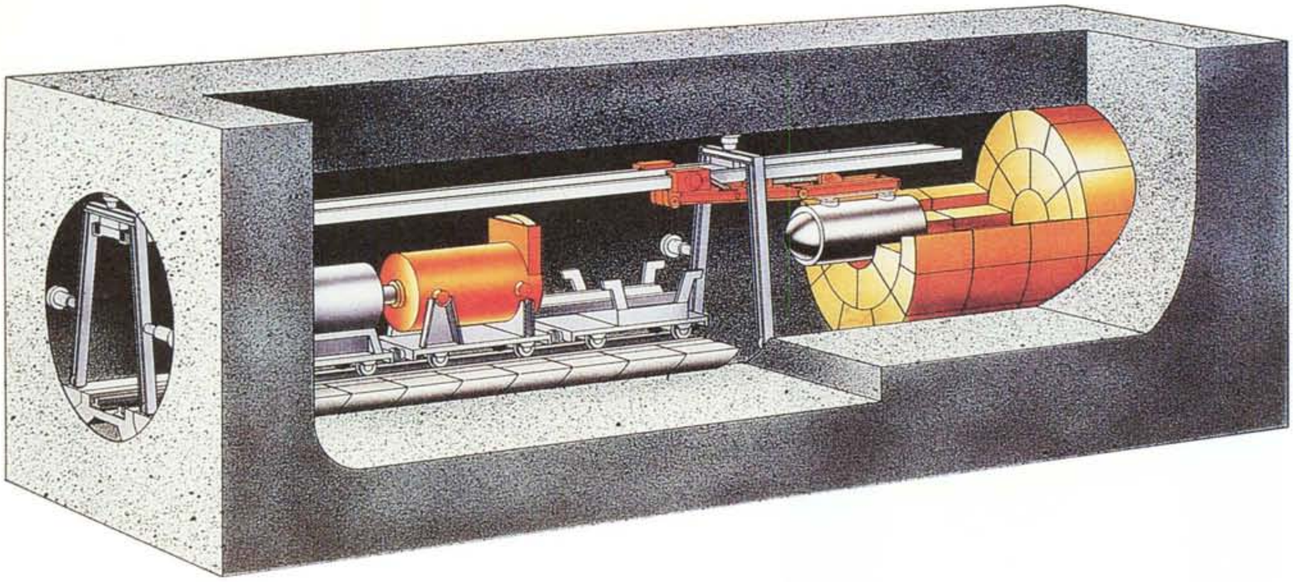


Figure 2-2. According to the NAGRA Gewähr project 1985, canisters and highly compacted bentonite blocks are placed in full-face driven tunnels.

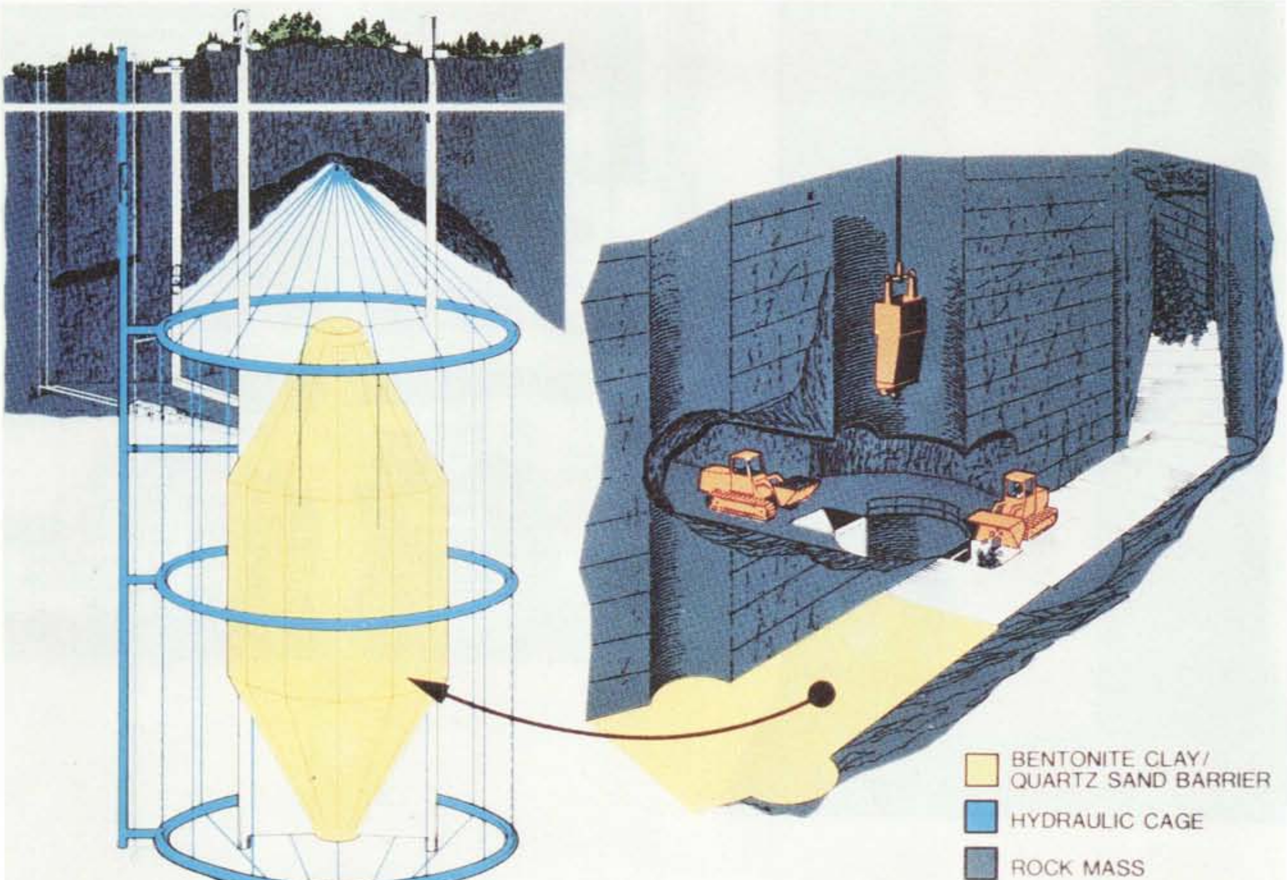


Figure 2-3. In WP-Cave, the final repository is surrounded by an impervious barrier. The figure shows how the barrier is built up.

and international developments will be carried out. The details around the programme for studies of glass are dealt with in Section 7.5. Only the activities concerned with spent fuel are discussed in the following.

2.3.2 Goal of the R&D activities

The goal of the studies of the durability of spent fuel in groundwater systems is to have gained sufficient knowledge of the mechanisms and kinetics of the dissolution of UO_2 by 1995 in order to be able to validate a predictive model that can be used as a source term in safety assessment. Better knowledge of fuel dissolution makes it possible to optimize canister design, canister material and the design of the near field of the canister.

2.3.3 Present-day state of knowledge

Spent fuel is being studied, besides in Sweden, in the USA, Canada, France and West Germany. Of these countries, Canada and the USA have by far the largest programmes. Compared with HLW glass, spent fuel is a relatively new waste form internationally. The first studies of the dissolution/corrosion of spent fuel were published scarcely ten years ago /2-8, 2-9/. Furthermore, few laboratories in the world have the necessary resources and competence to conduct relevant studies. Nevertheless, a good database is beginning to emerge, even though present-day knowledge has not yet provided an adequate theoretical understanding of the fundamental mechanisms involved in fuel leaching.

Spent fuel is the main alternative for commercial waste in the USA and the studies of spent fuel are being conducted within the frameworks of the different disposal projects. The studies are repository-specific inasmuch as they are being carried out in groundwater and together with other components that are specific for each repository geology. Research is being conducted, in parallel to some extent, within the tuff programme (NNWSI) /2-10, 2-11/, the basalt programme (BWIP) /2-12/ and the salt programme (SRP) /2-13/. Spent fuel is the main alternative in Canada as well, and a relatively large programme is being conducted by AECL at the Whiteshell Nuclear Research Establishment (WNRE) in Manitoba /2-14 - 2-19/.

These programmes diverge more or less from the Swedish programme inasmuch as the repository conditions differ from what is expected in Swedish granitic rock. The salt-related programme /2-13, 2-21/ has the least to do with Swedish conditions, while the other programmes exhibit many points in common. In the tuff programme, for example, the composition of the groundwater is very similar to that of the Swedish reference water, while the redox conditions in the repository are oxidizing instead of reducing. Both the basalt programme and the Canadian programme presuppose reducing conditions in the bedrock. The basalt programme, however, focusses on hydrothermal conditions. AECL's programme has a reference water with a considerably higher salt content than the Swedish, although tests have also been performed with water that is typical of Swedish granitic rock as well.

Moreover, the Canadian CANDU fuel differs from LWR fuel in terms of burnup and thermal load. However, these differences are of secondary importance in many cases. Over the past five years, leach experiments mainly with BWR fuel have been carried out in Studsvik under the auspices of SKB /2-22 - 2-24/. Together with foreign studies, these studies have provided information on solubility limits and reaction kinetics and a good database for deeper studies. Together with foreign studies, they have also provided the necessary background material for starting the work on a more fundamental theoretical understanding and description of the leaching process.

The investigations show that radionuclides that have migrated to grain boundaries and to the gap between the zircaloy cladding and the fuel (ie mainly Cs and I) are leached out very quickly. Leaching takes place to a fraction of the inventory correlated with the liberation of fission gas release during operation /2-11, 2-20, 2-22/. This means a rapid selective leaching of from around a tenth of a percent to several percent of the total inventory of the radionuclide.

Under oxidizing conditions, uranium rapidly reaches saturation in a concentration interval of 1-5 ppm for carbonate contents in the range 1-5 mM /2-11, 2-15, 2-24/ (see Figure 2-4.) This experimentally determined solubility limit is about two orders of magnitude lower than the one used for the safety analysis in KBS-3. Pu and other actinides also rapidly reach solubility limits that in general are much lower than that of uranium. In the case of Pu, for example, the equilibrium concentration lies around 0.1-1 ppb /2-24/, ie an order of magnitude lower than the Pu/U ratio in spent fuel (see Figure 2-5). Other radionuclides, such as Sr and Tc, exhibit leaching behaviours that lie between those of Cs and U /2-11, 2-24/. It has not yet been determined whether this is due to segregation of Sr and Tc in the fuel, or whether this is an indication of the continued dissolution of the fuel matrix despite the fact that the solubility limit for uranium has been reached /2-11, 2-21, 2-24/. This could be the case if a secondary uranium phase that controls the solubility of uranium has been formed /2-11, 2-18/.

Under reducing conditions, uranium leaching decreases considerably and generally lies near the detection limit for the analysis equipment /2-18, 2-24/. The leaching of Cs and Sr is also affected by the redox potential in the system. However, the effect is clearly less than for uranium /2-18, 2-20/.

2.3.4 International contacts

In order to provide a forum for a regular informal exchange of experience and ideas, a workshop on leaching of spent fuel is organized annually. Sweden, Canada and the USA take turns hosting the workshop, but representatives of all laboratories working actively with leaching/corrosion of spent UO_2 fuel participate. This workshop provides an excellent opportunity to exchange ideas and results with other laboratories and provides a very good platform for the detailed planning of the Swedish research programme.

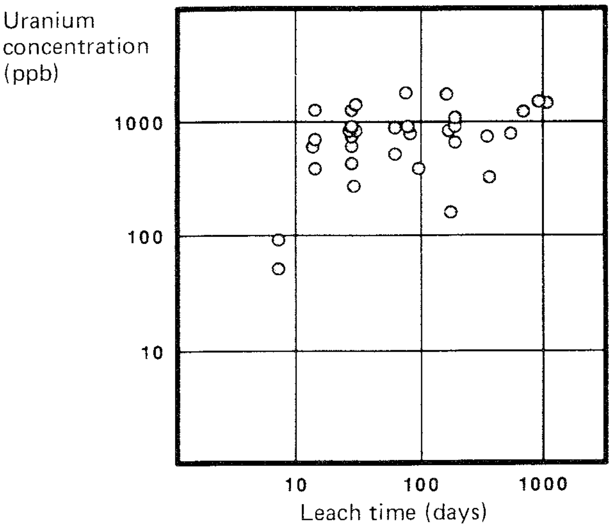


Figure 2-4. Concentration of uranium in solution as a function of leach time. The concentrations refer to a solution that has been filtered to separate particles and colloidal material.

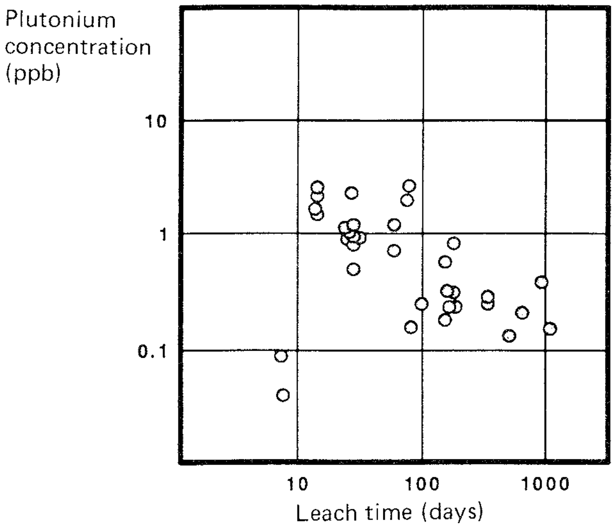


Figure 2-5. Concentration of plutonium in solution as a function of leach time. The solutions have been filtered in the same manner as for Figure 2-4.

2.3.5 1987-1989 research programme

Over the next three years, the work will be concentrated on studies of the fundamental mechanisms for dissolution of UO_2 fuel in pure groundwater systems under oxidizing and reducing conditions. The investigations will gradually be focussed on the more complex realistic repository conditions, also taking into account the effect of corroding canister material, corrosion products and buffer material. A prerequisite for this is a good theoretical understanding of the simpler systems. Around 1990, the work will be concentrated on complex, repository-simulating systems.

There is also extensive international cooperation on the subject of fuel leaching, as mentioned above, in the form of annual informal symposia for information exchange etc, see also Section 7.7.

Only PWR and BWR fuel will be studied during the period. If needed, special studies of MOX fuel may be undertaken in a later phase.

The detailed programme for the coming three-year period is presented below.

Characterization of spent fuel

Ongoing work is focused on investigations of solubility limits, reaction kinetics and the influence of alpha radiolysis. Studies of PWR fuel have also been initiated during 1986. Results obtained thus far have shown that the fuel's burnup, "thermal" history, morphology etc is of importance both for the dissolution kinetics, at least over short periods of time, and for the selective leaching of specific nuclides. During the next few years, a great deal of work will therefore be done on characterization of the fuel before and after leaching in order to distinguish the general mechanisms from specific phenomena dependent on the irradiation history of the individual fuel specimens. This type of information is of special importance for the work on development of predictive models for fuel leaching and will be given priority over the next three years. In order to be able to carry out these investigations efficiently, investments in analysis equipment have been necessary, and certain further investments will probably also be required.

The characterization will be carried out both on BWR and PWR fuel with different thermal loadings. Prior to leaching, the fuel will be characterized with respect to distribution of fission products and actinides in matrix, grain boundaries, inclusions and gap between fuel and cladding. After leaching, the type of corrosion attack and any changes in activity distribution will be recorded. The technology used will primarily be optical microscopy, SEM and STEM/TEM.

Corrosion of spent fuel

The earlier corrosion studies will continue with BWR and PWR fuel, proceeding from the base of the knowledge that has been obtained. The planned investigations will therefore be aimed more specifically at increasing knowledge of the phenomena identified by the early studies as being most important or less well understood. In particular, the investigations will be focussed more on the study of the leaching of special nuclides, which are either important from a radiological standpoint or are related to specific mechanisms for fuel corrosion.

The phenomena that will especially be studied are:

- solubility and saturation effects,
- grain boundary attack on the fuel,
- colloid formation,
- oxidizing/reducing conditions.

General data for actinide and fission product solubilities in groundwater systems will be determined and compiled within the framework of SKB's chemistry programme. In order to be able to understand and model fuel dissolution under oxidizing and reducing conditions, however, it is essential to determine the solubility limits for the fuel matrix, both with regard to uranium and with regard to actinides and other radionuclides. The actinides in particular, which can occur in solid solution with the uranium in the matrix, can have solubilities that deviate from the solubilities of the pure actinide phases.

The data obtained thus far show that uranium rapidly reaches a solubility limit. However, the leaching of certain radionuclides, such as strontium, continues despite the fact that the dissolution of uranium has ceased. At the present time, it is not known whether this continued leaching is caused by preferential leaching of inclusions or regions enriched in certain nuclides, or whether matrix-bound nuclides can continue to be released despite the fact that uranium dissolution has ceased. This could be the case if the conversion of the uranium dioxide matrix continues even after the groundwater has been saturated with uranium, eg by means of oxidation to higher uranium oxides due either to oxygen from the outside or radiolytically produced oxidants. In order to obtain a better understanding of these mechanisms, the programme must, in addition to the above-mentioned characterization of the fuel before and after leaching, include analyses of nuclides that can furnish specific information on the dissolution mechanisms. In addition, special studies of radiolysis are required (see below).

The results of SKB's earlier studies have shown that a large portion of the actinides are liberated from the fuel matrix as colloids. Preliminary characterizations of this colloid fraction have been carried out, but should be supplemented with further studies, primarily to determine the size distribution. Owing to the very low levels of actinides in the leachant solutions (ppb or lower), it is very difficult to make a more detailed characterization. Data from the next few years' studies will decide whether this is necessary. If so, large investments in analysis equipment will probably be necessary. The data generated by the programme thus far pertain for the most part to oxidizing conditions. Since reducing conditions will most probably prevail in the repository environment, it is essential that the present-day database be augmented with

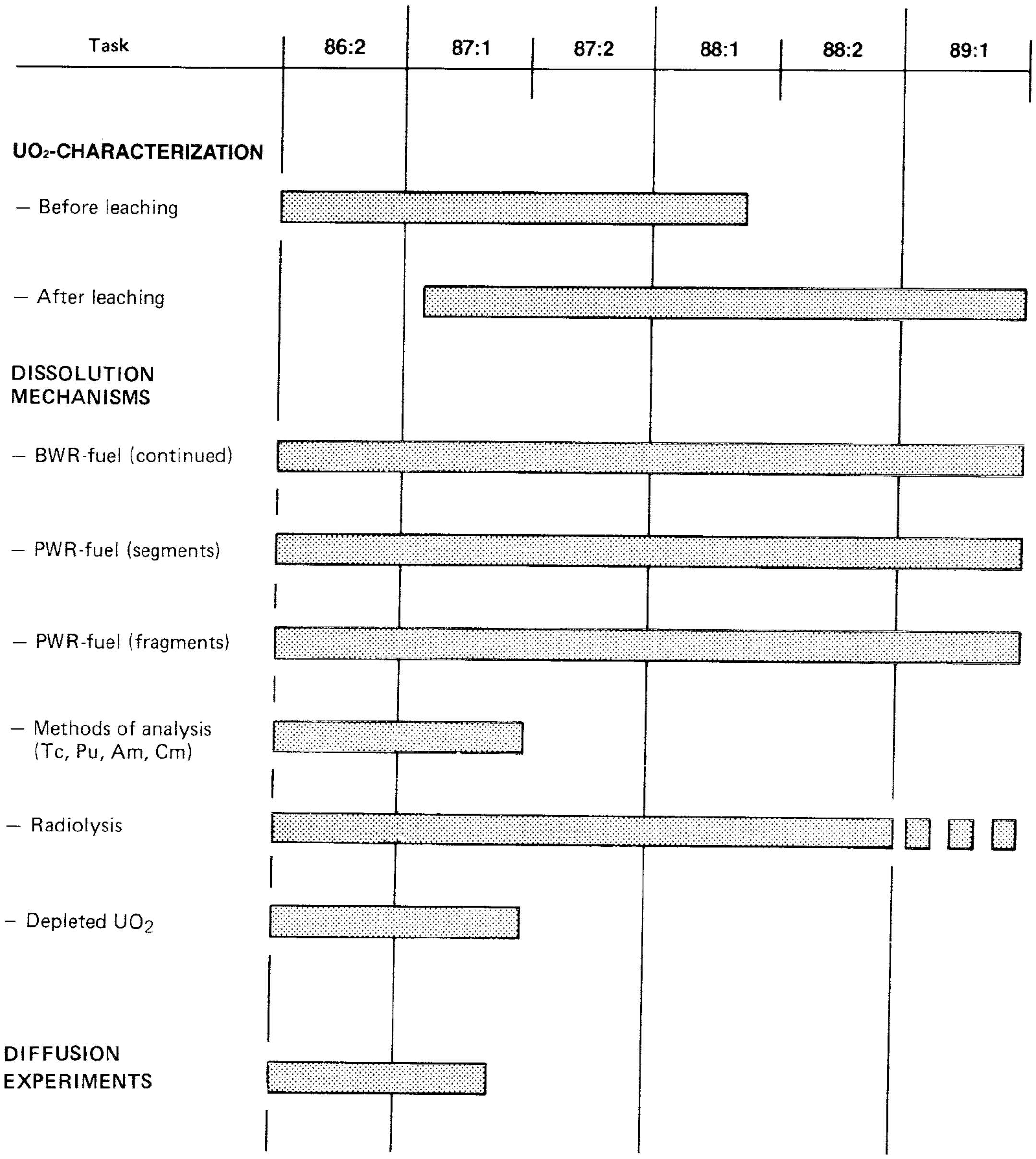


Figure 2-6. Timeschedule for investigations of spent nuclear fuel 1986-89.

data from realistic reducing conditions. Methods for studies of fuel dissolution under reducing conditions are currently being developed, and during the coming three-year period the emphasis will lie on the study of fuel leaching under reducing conditions.

Radiolysis

The field of radiation that surrounds the fuel can cause radiolysis of the water in the near field and create local chemical conditions that deviate greatly from the undisturbed conditions in the rock. This applies especially to the alpha radiolysis caused by the high alpha irradiation of a very thin layer of water close to the fuel surface, which could conceivably give rise to local oxidizing conditions nearest the fuel surface, despite the fact that reducing conditions prevail in the rest of the near field.

The effects of alpha radiolysis on the oxidation and dissolution of UO_2 fuel are poorly understood today. This also applies to the yield etc of radiolysis products in heteorgeneous systems. Considerable work is therefore called for in this area over the next few years.

The studies will primarily be concentrated on the mechanisms for radiolytic oxidation of UO_2 and sensitivity to dose and dose rate. This requires specific experiments, some carried out with unirradiated UO_2 together with external gamma and/or alpha sources. By manipulating the water chemistry, the yield of the individual radiolysis products can be affected in order to obtain information on the mechanisms and kinetics for radiolytic oxidation of UO_2. These experiments must be supplemented with characterization of the oxidation state of the uranium on the surface of the solid phase. In parallel with these experiments, investigations of spent fuel will also be carried out with continuous measurement of eg gaseous radiolysis products.

Model development

The purpose of model development is to obtain a predictive model for leaching of spent fuel over long periods of time. This work has recently been begun and consists in part of theoretical work and in part of specific experimental studies of unirradiated UO_2 intended to supplement the investigations of high-level fuel.

The theoretical work has a thermodynamic part, which describes solubility limits and the formation of new solid phases in the near field, and a kinetic part, which describes the dissolution kinetics of radionuclides that are not solubility-limited.

The kinetic part of the model will be supplemented with specific studies of the influence of critical groundwater components and surface phenomena, for example morphology, on the dissolution kinetics.

2.3.6 1990-1992 research programme

During the latter part of the programme, the emphasis will lie on studies of the influence of other components in the repository system on fuel dissolution. Pilot studies have already been conducted or are being conducted, but in order to be able to draw maximum benefit from the information obtained in these types of studies, the fundamental phenomena occurring at the fuel surface must be understood. Some information on the interaction between bentonite, corrosion products and radionuclides is being obtained from the JSS project's (see Section 7.5) experimental and theoretical studies of glass leaching in the presence of components from the near field. After the completion of the JSS project in 1987, parts of the model developed for glass leaching are expected to be applicable to spent fuel as well. This applies to the model for dissolution kinetics, which is now finished, as well as the model for the interaction between radionuclides and components from the near field. Development work is still underway on this latter part of the model, and the scheduling of similar experimental and theoretical studies for fuel is being held up pending the results of the JSS Project.

2.4 Canister

2.4.1 Background

The high-level waste, whether it be vitrified high-level waste from reprocessing or spent reactor fuel, must be enclosed in an outer canister primarily for two reasons. During its handling in the final repository, the waste must be packaged in impervious containers that prevent the release of radioactivity. After deposition in the repository, it is desirable that no radioactivity should escape from the waste during a certain period of time.

A necessary minimum length of the period of zero release cannot be defined at the present time. Better knowledge of the properties of the waste, the hydrological/geological conditions in the rock and the dispersal of the radionuclides in the geosphere is required in order to determine the optimum period for zero release. Generally accepted estimates cover a very wide span, 1000 - 100 000 years.

Depending on what length of time is aimed at, a number of different canister materials may be appropriate. For practical reasons, the canister materials can be divided into the following classes:

a) Completely or partially thermodynamically stable materials, eg copper.

b) Passive materials, eg stainless steel, titanium, Hastelloy, Inconel, aluminium.

c) Corroding (sacrificial) materials, eg lead, steel.

d) Non-metallic materials, eg ceramics Al_2O_3, TiO_2, cement.

Copper has been the main alternative in the KBS work, with the exception of KBS-1, where titanium-lead was proposed as a canister material. In addition, Al_2O_3 has been studied as an alternative canister material for long-term containment. The corrosion properties and manufacturing technology for a copper canister are relatively well known, even though supplementary investigations must be carried out. During the next few years, however, considerable research will be done on alternative canister materials, ie types b), c) and d). Naturally, the studies of copper will continue with special reference to the knowledge gaps that were identified during the review of KBS-3.

2.4.2 Goal of the R&D activities

The goal of the studies of canister materials is to have assembled sufficient knowledge of both copper and the alternative materials by around 1995 in order to make a final choice of canister material. This naturally presupposes that the parallel investigations of nuclide transport in the geosphere and of fuel leaching provide the necessary data to enable the consequences of a shorter canister life to be judged in a realistic manner.

2.4.3 Present-day state of knowledge

All countries that conduct research and development work aimed at the final disposal of high-level waste from nuclear reactors assume that the waste will be encapsulated in an impervious container prior to final deposition. The period of time during which the canister will retain its integrity varies, but two main lines can be distinguished. In most countries, the goal for absolute containment in the canister is about 1000 years, while Sweden and a few other countries have studied long-term containment (about 100 000 years) as an alternative. The choice of reference material for the canister varies from country to country, but in general it can be said that materials from groups b) and c) have been chosen as the main alternative in most cases.

Most of the research and development work on copper as a canister material has been done in Sweden, and the present-day state of knowledge is described in KBS-3 and its references, see eg/2-15 - 2-27/. Since KBS-3, the research work has advanced along the lines laid down in the reviewing procedure. This means further studies of pitting of copper in a reducing environment, archaeological evidence, inorganic reduction of sulphate to sulphide at low temperatures (<100°C), studies of the creep properties of copper at repository temperatures and method development for both HIPing and electron beam welding. Most of these studies are still under way, but are long-range by nature and no directly applicable results have yet been obtained. However, an evaluation of the corrosion of a canon salvaged from the warship "Kronan" has been carried out. The canon, which has been buried to almost its entire length in clay for over 300 years, exhibits a general corrosion that agrees well with the assessments made in KBS-3 for copper corrosion in a clay environment.

Of the alternative materials, SKB has previously, during the KBS work, studied titanium /2-28 - 2-30/ and Al_2O_3 /2-31/, but most of the information on alternatives to copper comes from laboratories abroad. These materials are reference alternatives in many countries, and considerable research has been devoted to establishing their suitability as canister materials and the expected life of these canisters. Naturally, the Swedish research on materials other than copper should be coordinated with the foreign work and oriented so that it supplements the information being obtained elsewhere. Moreover, the necessary studies, specific for Swedish conditions, must be carried out.

A number of countries have research programmes that are relevant to Sweden since they pertain to similar geological conditions. These investigations provide a good background for the choice of Swedish alternative canister materials. Passive materials are being studied by CEC, France, Canada and the USA, while corroding materials are reference alternatives for CEC, Great Britain, Switzerland and the USA. At the present time, ceramic materials are only being studied to any great extent in Canada, even though some research is being conducted in both Switzerland and Sweden.

Based on consideration of the direction of the international research and previous Swedish work, one alternative from each main category has preliminarily been chosen: titanium, carbon steel and Al_2O_3 (alternatively TiO_2). The state of knowledge for these materials is briefly as follows:

Titanium: For both pure titanium and Ti-12 (0.3% Mo, O,8% Ni) it is improbable that general corrosion could limit the life of the canister in the repository environment /2-29, 2-32/. Uncertainties remain, however, where crevice corrosion and hydrogen embrittlement of titanium are concerned. As far as crevice corrosion is concerned, Ti-12 is much more resistant than pure titanium, while the reverse is true for hydrogen embrittlement /2-32/.

Carbon steel: Conservative estimates of the corrosion rate of steel under reducing conditions show that general corrosion would not prevent steel canisters having lives of more than 1000 years /2-33 - 2-35/. Uncertainties remain concerning local corrosion as well as concerning the influence of hydrogen gas evolution on the corrosion process under reducing conditions.

Ceramics: Studies to date show that the corrosion/dissolution of most ceramic materials takes place extremely slowly in granitic groundwater /2-31, 2-36/. The largest unsolved problem for ceramics as a canister material is the risk of delayed fracturing /2-31, 2-37/.

2.4.4 1987-1992 research programme

During the next three years, work will be concentrated on completing the supplementary studies of copper along the lines laid down in the reviewing procedure. Certain specific investigations of alternative canister materials will also be conducted during the entire six-year period, as mentioned above, see Figure 2-7. The investigations will complement some of the more comprehensive studies being conducted abroad. They

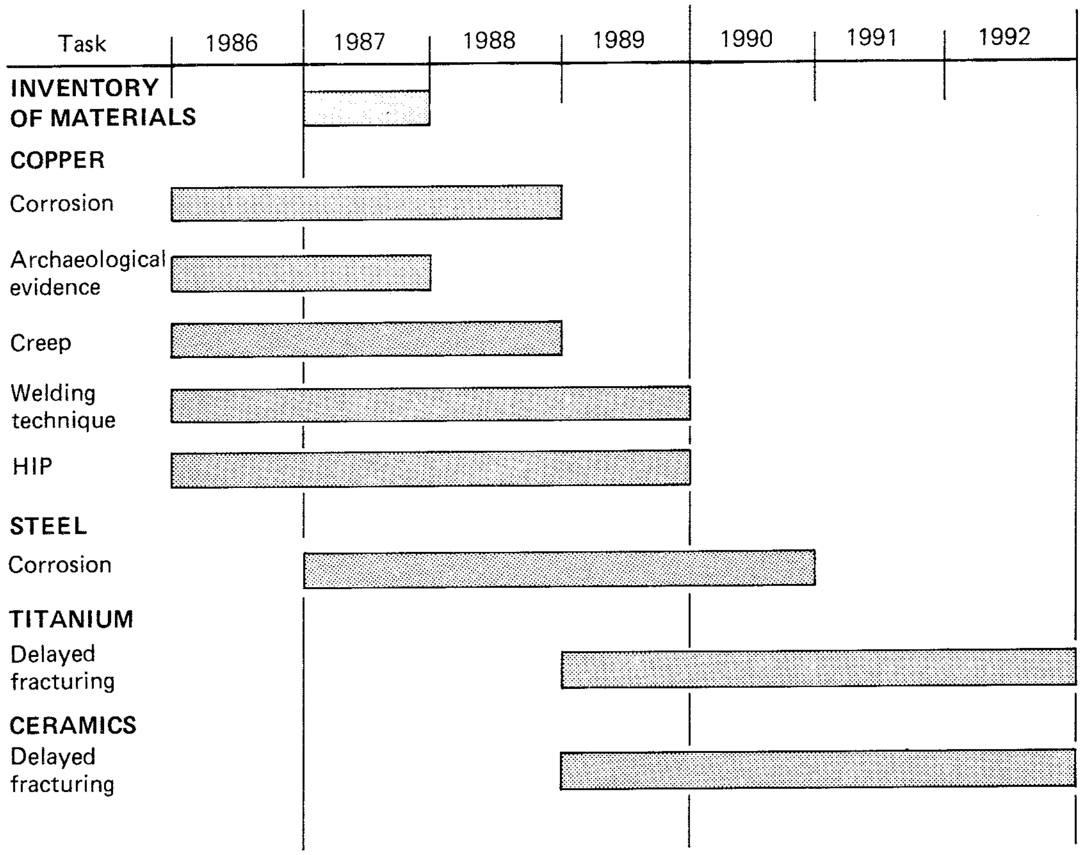


Figure 2-7. Timeschedule for canister studies.

primarily concern local corrosion and integrated performance with the barrier components etc that may be incorporated in alternative repository designs. Work of importance for canister closure as well as R&D concerning non-destructive testing of canisters is also being planned. The latter projects are mainly scheduled for the latter half of the six-year period. Coordination with foreign studies can be provided within the framework of SKB's bilateral cooperation agreements. Important cooperation partners are Switzerland (carbon steel) and Canada (titanium, ceramics).

A research programme for carbon steel was initiated during 1985. A final choice of which alternative canister materials to investigate will be made after a thorough inventory and general review of available materials and composites. This review is planned for 1987, and after evaluation, studies of titanium, ceramics or other alternatives will be commenced in 1988/89.

The more detailed programme for the coming three-year period covers the following subjects, where work on titanium and ceramics is preliminary for the time being, pending a final choice of material.

Copper corrosion

Ongoing investigations are concentrated on supplementary studies of pitting in copper under reducing conditions. These investigations are being combined with further evaluation of archaeological material in order to provide a good basis for the estimate of maximum pitting on copper under repository conditions. In addition, studies are being conducted aimed at determining the reaction rate for the corrosion of copper through inorganic reduction of sulphate to sulphide. This reaction proceeds extremely slowly at temperatures below 100°C, but reliable data are lacking, although geological evidence clearly demonstrates that the reaction rate is extremely slow.

Sealing of copper canister

The investigations for the KBS-3 report showed that both electron beam welding and HIPing are feasible methods to seal the canister, but that certain problems remain for both methods. With electron beam welding, copper with a wall thickness of more than 10 cm can be welded with good results, while certain defects have so far been obtained at the termination of the weld. During the period, work will be devoted to solving these problems. The development of HIPing of copper is also continuing, with the aim of producing a copper material from high-purity copper powder with the same mechanical and corrosion properties as conventionally produced copper.

After encapsulation, the integrity of the canister must be verified. This is particularly important in the joint region. The investigations in KBS-3 showed that non-destructive testing by means of ultrasound is one feasible method /2-27, 2-45/, but that further development will be necessary in order to achieve a satisfactory level of quality control. During the period, efforts will be concentrated on an evaluation of what requirements can be made on the inspection method and on the control of process parameters during canister manufacture in order to ensure a sufficiently low level of defects in the canister joint. If further development of non-destructive testing is required, most of the work will be done during the three-year period starting 1990.

Carbon steel

A relatively good database for general corrosion of steel under repository conditions is available (see eg /2-38 - 2-40/). Moreover, investigations of general corrosion are continuing in Switzerland. However, uncertainties prevail concerning local corrosion (pitting, stress corrosion cracking). The Swedish work is being pursued in cooperation with Great Britain and Switzerland, where stress corrosion cracking in particular is being studied in Switzerland, while development of models for general corrosion and pitting is being done in Great Britain /2-40 - 2-42/. The Swedish research programme will place an emphasis on studies of pitting under realistic repository conditions. In addition, these investigations will be supplemented with specific studies of the influence of hydrogen gas production on the corrosion rate under reducing conditions /2-43/.

Titanium

Previous Swedish investigations, together with Canadian studies, show that a canister of titanium will have a very long life, based on general corrosion alone /2-28, 2-29, 2-32/. The life of the canister will probably be determined by local corrosion. Canada has a large programme for studies of these local corrosion phenomena, both inside and outside the radiation field. Swedish efforts can therefore be concentrated on specific areas, where they complement the more extensive Canadian studies. Investigations of the mechanisms behind hydrogen embrittlement of titanium and Ti-12 are judged to be the most urgent.

Ceramics

Research is being conducted within the Canadian programme on ceramic canister materials as alternatives for long-term containment of the high-level waste /2-36/. In addition to these studies, investigations are being conducted mainly in Sweden, see eg /2-44/, and Switzerland /2-37/. The results from Canada in particular confirm the conclusions drawn from the Swedish KBS work: Many ceramic materials possess excellent chemical stability in groundwater. However, uncertainties still remain concerning delayed fracturing, which could drastically shorten the life of a ceramic canister in groundwater /2-31, 2-37/. This problem is judged to be the most urgent for study. The results of these studies will determine whether further investigations of manufacturing technology and encapsulation technique are needed.

2.5 Buffer and backfill

2.5.1 Background

Buffer in deposition holes and backfill in rock caverns, tunnels and shafts are examples of engineered barriers in the final repository system. The primary function of these barriers is to prevent or limit groundwater flow and to create a chemical and mechanical zone of protection around the canisters.

Sealing measures can be adopted in rock caverns in the form of plugs, or in the host rock in the form of injection grouting.

The barriers are designed to provide a suitable interaction between rock and canisters in a final repository system. The design is controlled by such factors as temperature conditions in the repository, see Section 2.2.

2.5.2 Goal of the R&D activities

The goal is to choose buffer and backfill materials by the mid-1990s and provide an account of their properties of importance for the function of the final repository.

Alternative deposition methods and final repository designs will be considered and systems and methods will be optimized taking into account the geological characteristics of the selected site.

During the first six-year period, material will be presented and properties described so that a choice of deposition method can be made based on

- a clarification of the relationship between different clays, mixed materials, the repository environment and the properties of the materials of importance for the engineered barriers,
- a theoretical model developed for calculation of the mechanical function of the buffer and backfill materials as support and protection for waste canisters,
- developed and tested methods for sealing rock in connection with plugs and deposition holes.

2.5.3 Present-day state of knowledge

In previous KBS work and recent years' studies, interest has been focussed on buffer and backfill materials based on swelling smectite-rich clays. The reference material has been bentonite of the Wyoming type.

In KBS-3, the buffer consists of highly-compacted bentonite that surrounds the copper canister in the deposition hole in the form of moulded blocks. The deposition tunnels are backfilled with bentonite/sand mixture /2-46/. Such materials have been tested in Stripa for several years in the Buffer Mass Test under realistic rock conditions on half scale, both at temperatures up to about 80°C during water absorption and at about 125°C over a period of one year with water-saturated conditions /2-47/. Furthermore, highly-compacted bentonite has been tested as a sealing material in plugs in boreholes, shafts and tunnels. The results show that highly-compacted bentonite is practical to use and very effective for watertight filling of limited spaces in rock with hydraulically conductive fractures /2-6/. The bentonite/sand mixture, used for the overpack above the deposition holes was partially compressed by the swelling highly-compacted bentonite around the canisters, in accordance with expectations.

What is known about bentonite and the geological conditions that have prevailed for a long time in natural formations indicates that long-term stability can be counted on under certain conditions /2-48/. The present-day state of knowledge is, however, insufficient to provide a clear understanding of the theoretical relationships between minerals, chemical and physical stability, water composition and temperature on the one hand and conditions in the clay/water system of importance for barrier performance on the other. This applies in particular to the buffer's rheology for mechanical interaction with canister and rock.

Experience from the Stripa experiments also shows that the method and equipment for compacting of the backfill nearest the roof in tunnels must be further developed in order to achieve a more watertight and less compressive backfill.

Experience from the injection grouting work and knowledge of fracture systems in rock show that known technique and present-day equipment for injection grouting offer limited possibilities for sealing rock. Further development of injection methods and better knowledge of the long-term stability of the grouting material can allow a broader application of sealing measures, particularly in connection with plugs in rock and around deposition holes /2-49/.

2.5.4 1987-1992 research programme

Starting in 1987, a systematic effort will be commenced to verify and clarify the processes, relationships and criteria that determine the properties of different materials. Figure 2-8 illustrates the principle of how a material should be investigated. Through laboratory tests and deeper physical understanding, mathematical relationships can be written describing how different parameters affect material properties. Function in the field is then simulated by calculation models based on such relationships. The final answers will be provided by field trials with well-defined boundary conditions.

This broad knowledge concerning the function of a number of different materials, combined with a raw material inventory, will be used to compile a body of data as a basis for selecting a limited number of buffer materials, see Figure 2-9. The selected materials shall have a defined function and be related to several different deposition methods.

After the choice of buffer materials, knowledge concerning these materials will be further deepened. An optimization of buffer composition and geometric design for the most suitable deposition methods can then be carried out. The optimization will be carried out in conjunction with in-situ tests, after which the final design can be determined.

A target specification should be drawn up to provide support in the inventory and selection of different candidate materials. The target specification should define, within wide frames, the requirements and criteria that can be set up for the materials with regard to certain vital properties and functions, for example:

- Hydraulic conductivity and diffusivity.

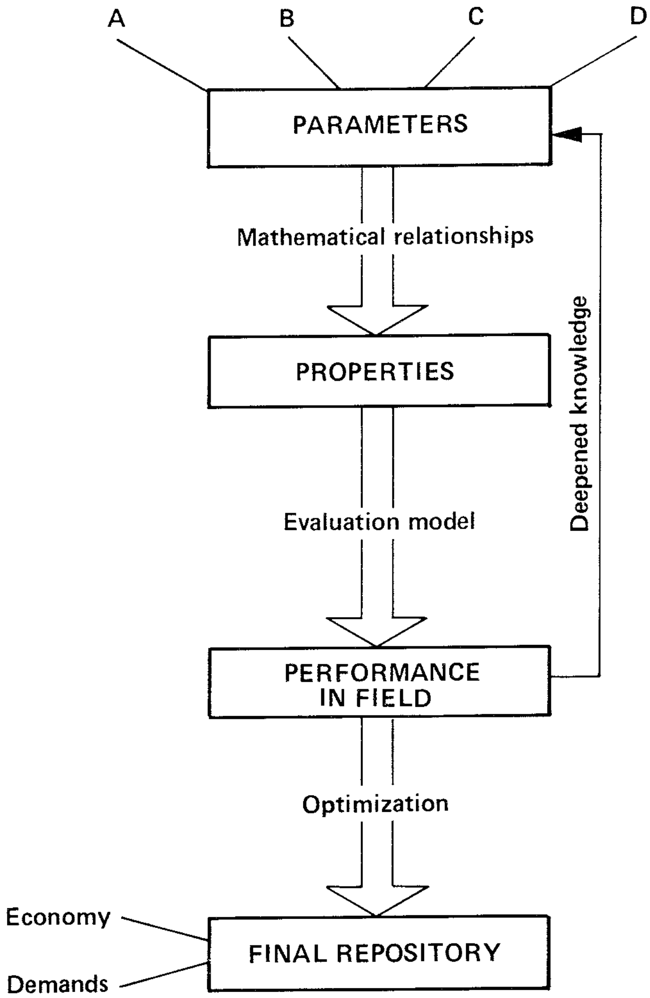


Figure 2-8. General scheme for investigation of buffer material.

- Thermal conductivity.
- Ion diffusivity, ion exchange properties.
- Rheological properties, swelling capacity, swelling pressure.
- Chemical stability (temperature, pH).
- Physical stability (erosion resistance).
- Availability (raw material type, quantities, limits of industrial processing).
- Costs.

The formulation of such specifications should be carried out directly after the turn of the year 1986/87 so that a list of candidate materials containing 3-5 alternatives each for the buffer and backfill materials can be drawn up.

In connection with the formulation of these criteria and the selection of the candidate materials, a research programme will be drawn up aimed at compiling essential data for different alternative buffer materials by 1993.

The following investigations are planned:

General knowledge

- Laboratory determination of hydraulic conductivity with special reference to dependence on density, degree of structural and mineralogical homogeneity, hydraulic gradient, temperature and pore water composition. Experimental determination of diffusivity coupled to density and ion exchange reactions. Determination in the laboratory and the field of thermal conductivity with particular reference to density and structural and mineralogical homogeneity and to the possibility of increasing thermal conductivity by the addition of quartz or graphite.
- Laboratory determination of rheological properties, swelling capacity and swelling pressure. Cf ongoing studies of French clay, Section 7.8.
- Experimental studies of erosion resistance on "molecular" scale and on laboratory scale.
- Inventory of Swedish clay materials. Sampling in the field for material characterization with respect to mineralogy and granulometry.
- Grouting materials and their stability over long periods of time will be studied in accordance with the Stripa phase 3 programme, see Section 7.3.

Models

- Development of mathmatical models and calculation methods for simulation of different processes during and after deposition.
- Theoretical thermodynamic studies and inventory of geological analogues for clarification of chemical stability.

Inventories and alternative studies

- A number of buffer materials and backfill materials will be tested in order to broaden the options for choosing clay materials and for using mixed materials to obtain better properties and economy. As different forms of chemical conditioning of the near field are considered, the stability of the buffer and backfill materials must be verified in reference to the new conditions. Such integrated performance studies will mainly be undertaken during the latter part of the six-year period and continue until the mid-1990s.

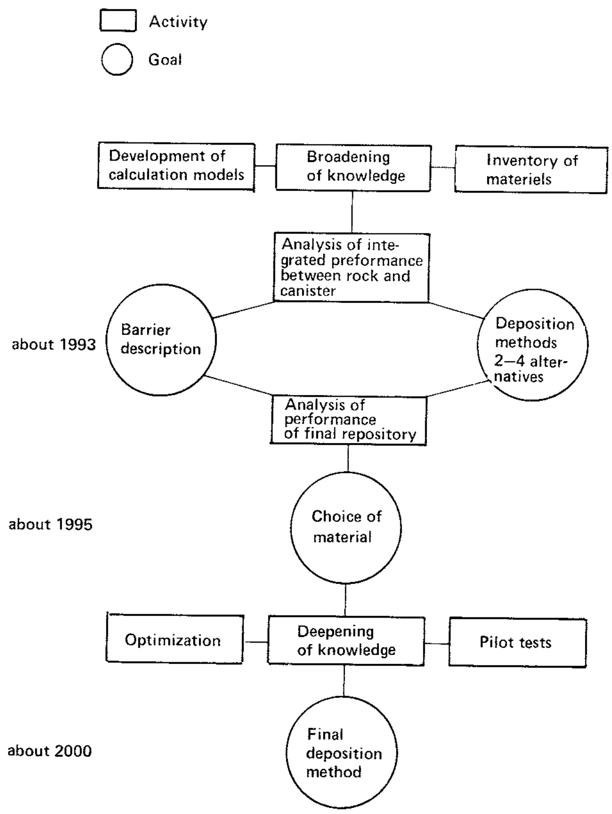


Figure 2-9. Scheme for selection of buffer and backfill material.

3 GEOSCIENCE

The geoscientific research is concerned with properties of the natural barrier (the rock) and acquisition of data for site selection.

Essential goals of this research are to:

- identify factors that can be of importance for the long-term safety of the repository,
- quantify or set limits on the factors that are relevant to safety.

The research includes development of measurement methods and investigation techniques so that:

- fundamental geodata and conditions in different bedrocks can be determined,
- site-specific data on geological and geohydrological conditions within the sites being considered for final disposal of spent nuclear fuel can be described.

Research is planned within the following areas for the period 1987-1992:

- Groundwater movements in the bedrock.
- Stability of the bedrock in a long-range perspective.
- Study-site investigations.
- Underground research laboratory.
- Instrument development.

An account is provided in Part II Chapter 2 and 4 of which factors influence the choice of system and site and what information is required as a basis for the safety assessment. The geoscientific research programme for the next six years has been prepared on the basis of the account provided in Part II. With regard to functional relationships and the background of the research, reference is therefore made to Part II.

3.1 Groundwater movements in the rock

3.1.1 Background

As is evident from Part II, groundwater movements in the bedrock are of essential importance for the safety of a final repository.

Groundwater movements in rock can be studied with different types of physical and mathematical models. Different mathematical models are suitable for studying conditions around a repository under varying conditions.

The model that has heretofore been used for analyses in eg KBS-3 describes the bedrock as a porous medium consisting of units (volumes) with different properties. Certain specific values of hydraulic conductivity are specified for one unit, eg the rock mass, while other values of this parameter are specified for the other units (local fracture zones or regional fracture zones). See Figure 3-1.a. This model has been sufficiently accurate to form a basis for the safety assessment that was carried out for KBS-3. A higher

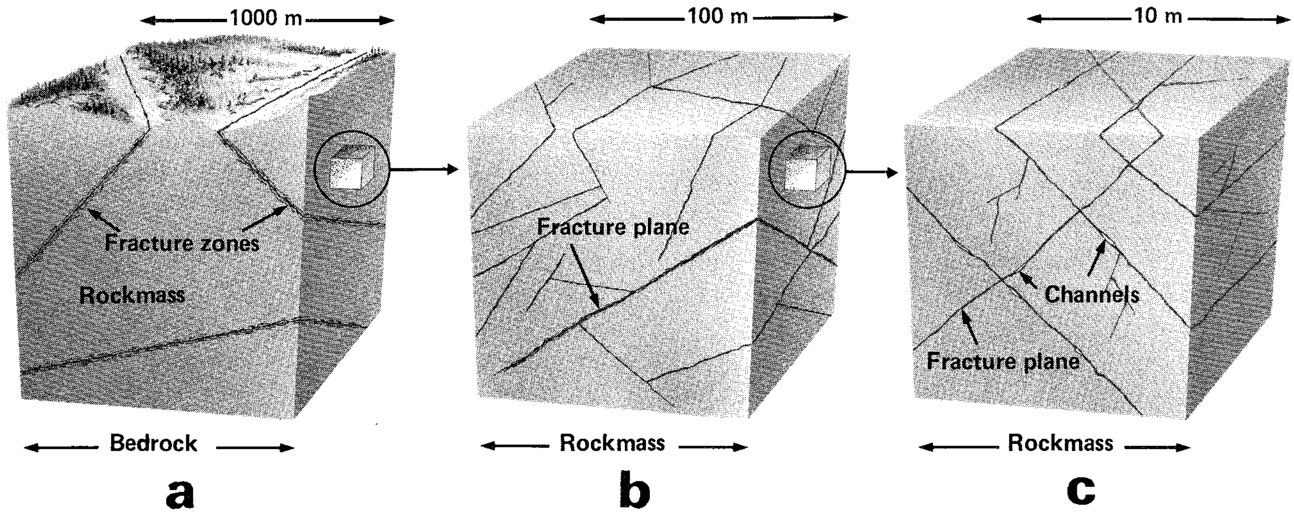


Figure 3-1.a. Model of the bedrock on kilometre scale. The rock is divided into hydraulic units - rock mass and fracture zones. These are treated as porous media with different properties. The flow is distributed over the entire volume and is greater in the fracture zones than in the rock mass.

Figure 3-1.b. Model of rock mass on 100 metre scale. The groundwater flows in networks of fractures. The flow is assumed to be evenly distributed over the entire fracture plane. The flow properties of individual fractures are statistically distributed.

Figure 3-1.c. Model of rock mass on 10 metre scale. The groundwater flows in networks of channels through parts of the fractures.

precision in the safety assessment requires a higher degree of detail in the models.

Since KBS-3, the trend has been towards calculation models that permit more detailed analyses of groundwater movements under different rock conditions. Different alternatives are being dealt with.

One alternative is to describe the bedrock with a model where transport takes place in a network of discrete fractures, Figure 3-1.b. This model requires further data regarding the width, length, frequency and interconnection of the water-bearing fractures as well as the roughness of the fracture faces. The statistical distributions and variations in space of the parameters must be determined. The demands on collection and interpretation of field data and on computer capacity set limits on the size of the networks that can be generated and analyzed. At present, network modelling can therefore only be applied on a local scale, in contrast to the porous model, which can also be applied on a regional scale.

Another alternative assumes that the groundwater flow is unevenly distributed over a fracture plane and takes place mainly in channels. Flow is assumed to take place in "one-dimensional" channels ("pipes") interconnected in a 3-D network, see Figure 3-1.c. This model also requires careful mapping of the flow properties of the rock fractures and is therefore only applicable on a limited scale at the present time.

3.1.2 Goals of the R&D activities

Research on the subject of groundwater movements in the rock is aimed at:

- developing models that describe the flow of groundwater in rock,
- developing and testing methods for location and characterization of fracture zones and water-bearing fractures,
- broadening the database for water-bearing fractures and fracture zones with the data needed in the aforementioned models,
- testing the usefulness of different models and the reliability of the calculation results.

One goal is, in connection with the site-related system optimization during the second half of the 1990s, to be able to quantify the importance of groundwater flow in fracture zones in the vicinity of the final repository. In the detailed investigations of potential final repository sites, it shall be possible to identify and characterize water-bearing fractures and fracture zones of importance to the safety of the final repository.

3.1.3 Present-day state of knowledge

The data collection and modelling that has taken place to date has been of a general nature. The goal has been to demonstrate that it is possible to find rock volumes of sufficient size with a sufficiently low rate of water turnover and that otherwise possess the properties essential for the construction of a final repository. Data on geohydrological conditions have mainly been collected from boreholes in the study-site investigations. Hydraulic conductivity has been measured by means of water injection tests in boreholes at a relatively great distance from each other. These measurements show a large spread of the conductivity in both the rock mass and regional and local fracture zones.

The question is whether measurement sections with high water loss (high conductivity) form part of an interconnected network of fractures or channels of importance for flow and nuclide transport, or whether they constitute local, isolated phenomena of minor importance. Radar measurements /3-2, 3-3/ and hydraulic interference tests /3-4/ can offer a better means to clarify the geometry of the flow paths in the rock mass and to locate regional and local fracture zones in greater detail. It then remains to decide how any averaging is to be done and how individual, good conductors of water are to be described in the model.

In the safety assessment for KBS-3, it was assumed that a radionuclide that reaches a fracture zone at repository depth immediately reaches the surface of the ground. Furthermore, a "respect distance" from the repository to the nearest fracture zone of 100 m was applied. This limits the volume of rock that can be used for waste disposal. In addition, the properties of the fracture zones are of great importance for groundwater flow and probably also for radionuclide transport.

The parameter values used to describe fracture zones have great variation. The thickness and water-bearing properties of the zones can vary considerably, from being virtually impervious to being highly conductive.

More data and refined investigation methodology are needed so that future safety assessments can quantify the transport properties of the fracture zones. A "fracture zone project" is therefore being carried out in order to test and develop methods for location and characterization of fracture zones and collect data on geological, hydraulic and geochemical conditions in fracture zones. The investigations of a fracture zone in Finnsjön began in 1984. The first part of the project has now been concluded /3-3/.

During the summer of 1986, investigations of a fracture zone at Ävrö near the Oskarshamn Nuclear Power Station have also begun. Previously, some data were available on this fracture zone from a borehole drilled at Ävrö. The investigations within these sites are planned to be conducted in parallel, but about one year apart so that experience from Finnsjön can be exploited in the investigation at Ävrö.

Re-evaluation of the earlier study-site investigations, along with supplementary measurements, are expected to provide valuable additional knowledge on the flow and velocity distribution of the groundwater.

A special phenomenon of interest that is also being investigated is natural gas migration through the bedrock. The possibility of nuclide transport through the rock via gas migration is being further explored. Investigations are underway at Finnsjön.

3.1.4 1987-1992 research programme

During the next six-year period, research and development on the subject of groundwater movements in the rock will focus on the following activities:

- Geohydrological method and model development.
- Fracture zone investigations at Finnsjön and Ävrö.
- Documentation of the presence of water in tunnels.
- Investigations of water flow distribution in individual fractures.
- Geohydrology at SFR.
- Geohydrological studies in Stripa, at URL and other international joint projects.

A large portion of the most advanced development work is being conducted within the international projects. These are therefore summarized first (see also Sections 7.3, 7.4 and 7.9), after which other activities are presented.

The URL project

AECL (Atomic Energy of Canada Limited) has established an underground research laboratory in undisturbed granite in Manitoba. Shaft sinking from the present-day 255 m level will continue to the 450 m level.

The scientific programme and results have been published in a number of papers, including /3-5, 3-6/. The experiments that will be conducted at the 450 m level are currently being planned. They relate to rock mechanics tests, including studies of the zone of damage around tunnels and thermomechanical studies. They also relate to sorption tests, studies of borehole and shaft sealing and tests of buffer materials.

The geohydrological description of URL has employed a porous model, see Figure 3-1.a. Prior to the start of shaft sinking, a predictive calculation of the disturbance caused by the shaft sinking was performed. The results show that the calculated pressure changes in the environs of the shaft agree very well with the measured changes /3-7/. Seepage into the shaft was only one fourth of what had been calculated, however.

The Stripa project

Development within the area of geohydrology is an important part of the Stripa project. The research there is being conducted in a granite at a depth of about 350 m. The studies have concerned methods for radar measurement in boreholes, cyclical water injection tests and various types of tracer tests. Large-scale experiments have been conducted to determine how the water moves in the rock mass and for the purpose of model development /3-8/.

The project will continue in a third phase, an essential purpose of which will be to further refine, apply and validate the geohydrological network model, see Figure 3-1.b. Extensive studies will also be conducted to increase understanding of the phenomenon of channelling.

HYDROCOIN

Numeric models for the calculation of groundwater flow can be relatively complex. HYDROCOIN is an international project with fourteen participating organizations aimed at comparison of geohydrological models. The studies include verification, validation against experimental data and sensitivity and safety analyses. The program used by SKB in KBS-3 has been further developed and has shown very good results for the applications that have been compared /3-9/. Data from the study-site investigations have been used as input data in the model analysis. HYDROCOIN is planned to be completed by 1987. Continuation within a project called INTRAVAL is being discussed, see also Chapter 7.9.

Geohydrological method and model development

The methods and models being developed within the international joint projects are of great importance for SKB's own activities. They can be used for such purposes as re-evaluation of investigated study-sites and analysis of conditions at the planned underground research laboratory, see Sections 3.3 and 3.4.

The detailed investigations that are planned to start at the beginning of the 1990s require geohydrological methods and models that permit a rational choice of a suitable site for such detailed investigations. The desired geohydrological properties are first established. The existing database from study-sites is then compared with the need for data deemed necessary in the selection process. Supplementary investigations are then carried out.

For the underground research laboratory, see Section 3.4, it is essential to compile experience from eg URL, Stripa and SFR so that suitable methods and models can be used for the geohydrological description.

The following development work is planned with regard to methods and models:

- Development of improved methods for how data is to be collected and translated into a three-dimensional model that can be analyzed with existing computation programs.
- Development of programs for three-dimensional graphic presentation of data and calculation results.
- Investigation of the correlation between radar reflections and geological and geohydrological conditions.
- Revision of the standard programme for study- site investigations /3-10/.
- Development of test methodology for single-hole and cross-hole measurements.
- Influence of thermal effects on groundwater in the near field around the canister.

The conditions around a final repository should in principle be calculated with numeric models where the influence of stress, flow and temperature are taken into account simultaneously (coupled models). Flow calculations will initially be carried out with uncoupled models, however.

Calculations of groundwater flow in large rock volumes will continue to be carried out with the assumption of a porous medium. With greater computer power, however, a greater heterogeneity can be allowed in the models.

In the Stripa project, coupled stress-flow models are being developed for use in studying conductivity changes adjacent to a tunnel (the skin zone).

A need for coupled thermomechanical calculation models is foreseen for the beginning of the 90s when compilation of data for system selection begins.

More work on coupled near field studies can be foreseen for the period 1990-1992.

Fracture zone investigations

Investigations of the flow and transport properties of fracture zones are continuing at Finnsjön and Ävrö.

In addition to detailed studies at Finnsjön and Ävrö, conducted from the surface, fracture zones will also be studied in a number of tunnels and underground facilities.

Fracture zone studies at Finnsjön

The fracture zone at Finnsjön is inclined about 10 degrees from the horizontal and is about 70 m wide, divided into a number of smaller, parallel fracture zones, see Figure 3-2. The zone has high hydraulic conductivity, which facilitates studies of transport properties. The zone has been identified in boreholes at depths of between 100 and 300 m. An interesting observation is that the composition of the groundwater changes from high salinity below the zone to low salinity above the zone. This indicates that the fracture zone constitutes, at least in part, a barrier against descending surface water. The surrounding bedrock is characterized by a high frequency of water-bearing fractures which together form a network of water-bearing structures. Good hydraulic contact probably exists between the fracture zone and the surrounding bedrock.

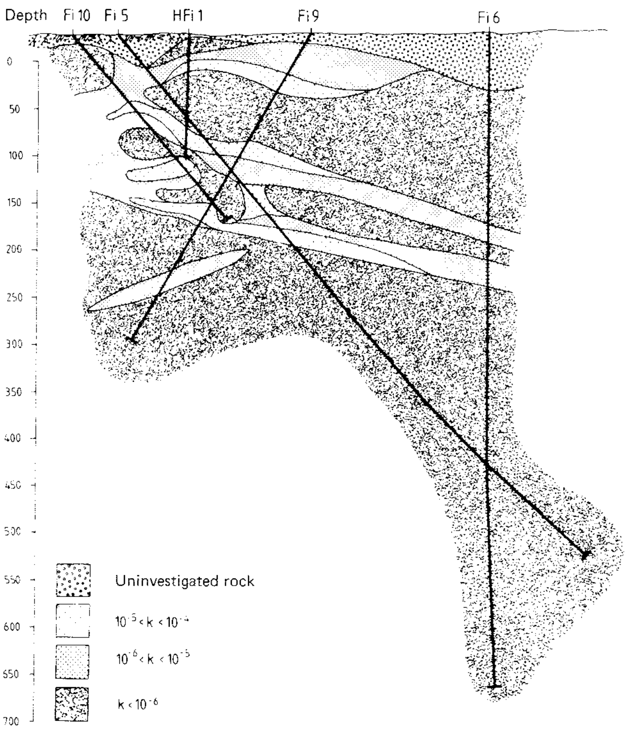


Figure 3-2. Hydraulic conductivity at the fracture zone in Finnsjön.

Further research will be aimed at applying the increased knowledge of the geohydrological and geochemical situation in models that describe and predict the transport properties of the zone.

As the work progresses, modification will be made on the basis of experience gained.

The following stages are foreseen:

Introductory model calculations

Measurements and investigations completed at Finnsjön /3-3/ have provided a general picture of the geohydrological conditions in the rock and the fracture zones. Planned work includes general evaluations of pump tests, the transport velocity of non-sorbing tracers and comparison with measured values. The model will also be used to plan the collection of detailed geohydrological data.

Detailed geohydrological description

The natural water flow in fracture zones will be measured with a dilution probe. A large-diameter percussion drilled borehole will be used as a pump hole for cross-hole measurements. The tests are planned so that detailed information is obtained on the hydraulic properties of the rock mass and the fracture zone. The fraction of hydraulically conductive fractures will be evaluated. Groundwater heads within the zone and between the zone and the rock mass will be measured. Rock stress measurements will be carried out so that any stress anisotropies are interpreted in conjunction with anisotropies in the hydraulic properties.

Predictive models

The model calculations will be refined on the basis of the increased knowledge obtained from the detailed geohydrological description. Predictive models will be set up for travel times for non-sorbing and sorbing tracers.

Tracer tests

Tracer tests will be planned on the basis of the results obtained from the model calculations. The tests will be conducted and sampling will be performed.

Evaluation

The outcome of the tests will be compared with the predictions of the models. Final evaluation will take place after other activities within the fracture zone investigations have been completed. Besides interpretation of the results, an evaluation of methods used for fracture zone investigations will be made. The evaluation will also lead to conclusions concerning the assumptions for the safety analysis. The following questions will be given particular attention:

- Retention of the radionuclides in fracture zones
- Reliability of the investigation methods

- Influence of fracture zones on regional groundwater movements
- Necessary respect distance between final repository and fracture zone.

Fracture zone studies at Ävrö

The fracture zone at Ävrö is estimated to be more than 85 m wide and with an assumed slope of about 40 degrees. This fracture zone is also highly conductive. Due to the probable extent of the zone, its properties can be studied from the surface down to a depth of about 1000 m. The bedrock above the fracture zone differs from the bedrock at Finnsjön in that it probably contains few water-bearing fractures. The fracture zone thereby constitutes a water-bearing structure that is believed to be well-delimited against a low-permeable environment.

The investigations will be conducted in such a manner that experience from Finnsjön will be successively integrated in the planning of the work at Ävrö. Otherwise, similar activities to those at Finnsjön are planned.

Documentation of the presence of water in tunnels

Data will be collected for parameters deemed essential for studies of the water flow with respect to repository design and calculation of nuclide transport, including: Contact area between water and rock, block size distribution, particle size and mineral composition of fracture-filling materials and hydraulic conductivity.

These studies will cover conditions both in the rock mass and in fracture zones. Collection of data is planned to take place in a number of tunnels. Radar measurements will be performed in some of these, which will also provide interpretation experience from radar measurements in different geological and geohydrological environments.

Investigation of flow distribution in individual fractures

The development of the radar technique within the Stripa project has had favorable results and opened up new possibilities for the description of fractures and the location and properties of fracture zones.

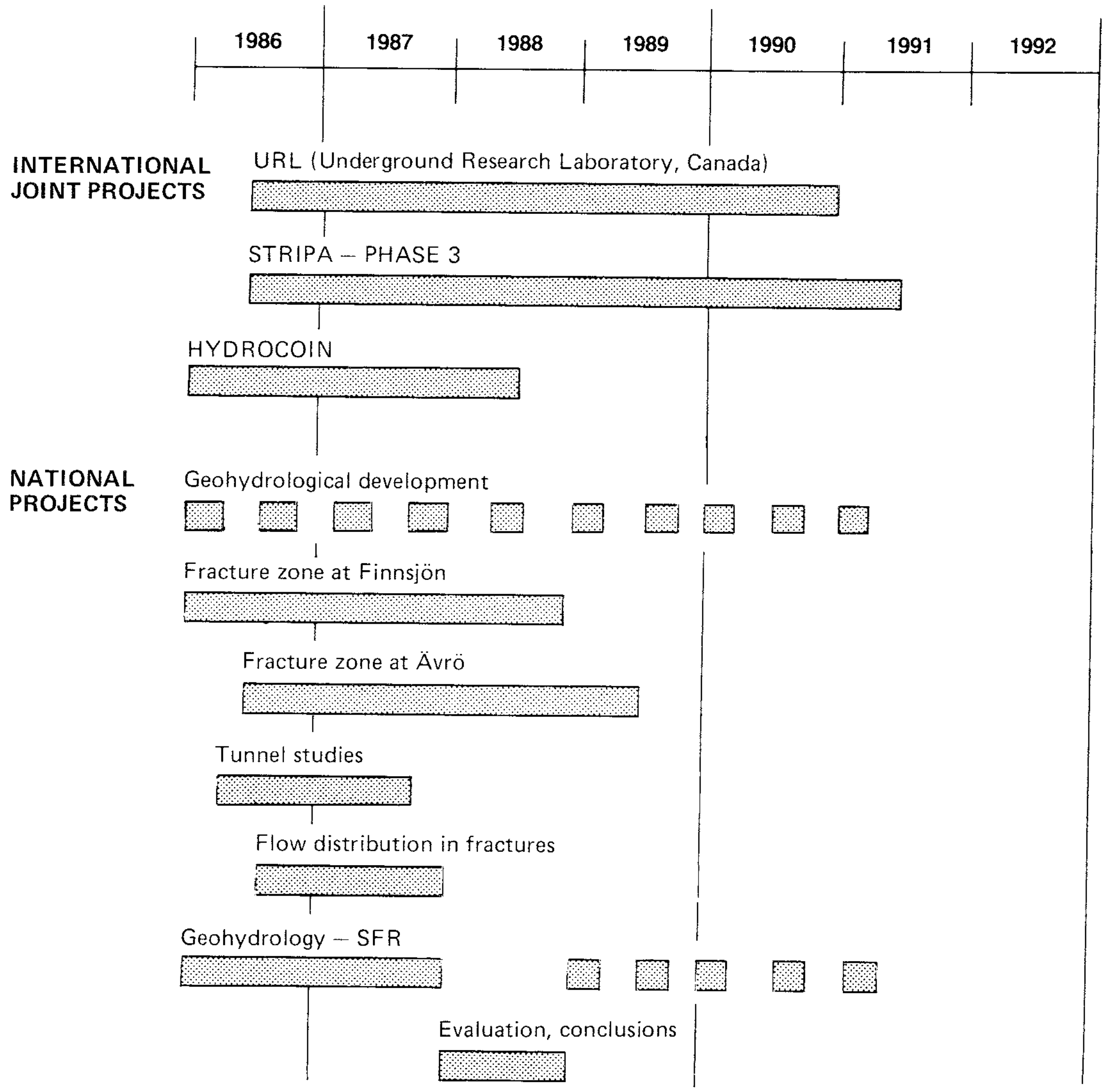


Figure 3-3. Timeschedule for investigations of groundwater movements in the rock.

In order to assess how the flow of water is distributed in a fracture plane, tests are planned for radar mapping of fractures that have been injected with salt water. Salt water possesses higher electrical conductivity than ordinary groundwater and thereby reflects the radar signal differently. A comparison of the fracture's response before and after salt water injection therefore provides a picture of the flow distribution in a fracture plane. Salt water injection will be carried out in the form of a controlled tracer test. Other types of tracer tests are also planned. Taken together, these tests can provide information on the groundwater's velocity distribution, fracture volume and flow porosity.

Geohydrology in SFR

During the planning and construction of SFR, a comprehensive measurement programme has recorded the changes in groundwater conditions caused by rock excavation and drainage. Now that the facility has been mined out, a good picture has been obtained of the actual fracture zones existing in the rock and how they interact. Some of the installed instruments will be kept in place and the measurements will continue until water turnover has reached a steady state. The data obtained can later be used to further refine the geohydrological models. The geochemical composition of the groundwater as a function of time will also be analyzed. The knowledge is deemed valuable for planning of detailed investigations at a final repository and for planning of the underground research laboratory.

Evaluation, conclusions

A summing-up process will be initiated in 1988 to review the state of knowledge on the subject of groundwater movements in the rock. The purpose is to devise an appropriate validation strategy for the planned underground research laboratory, see Section 3.4.

Timeschedule

A timeschedule for research activities concerning groundwater movements in the rock is shown in Figure 3-3.

3.2 Stability of the rock in a long-range perspective

3.2.1 Background

Seismic activity in Sweden is very low by international standards and earthquakes are of low magnitude. Nevertheless, clear regional differences do exist and these can be of importance when considering the long-term aspects for the final repository.

An in-depth analysis of the possible effects of geological processes on a final repository is planned. This will include effects of earthquakes and glaciations. Essential questions are whether recent movements (neotectonism) can lead to new fracturing and whether load changes or rock block movements can decisively alter the geohydrological situation around a final repository.

SKB has already published a large number of reports on the subject of the stability of the bedrock.

Geological aspects are treated in eg /3-11 - 3-15/, seismic aspects in /3-16 - 3-18/, while engineering aspects are mainly treated in /3-19 - 3-22/. The latter reports have mainly revolved around strength problems, while some attention is given to geohydrological factors.

3.2.2 Goals of the R&D activities

The goals are to:

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

3.2.3 Present-day state of knowledge

Studies concerning rock stability are aimed at ascertaining how the geodynamic processes can affect the safety of the repository. Detailed safety assessments /3-23, 3-24/ that consider the probability of new fracturing and its effects show that the impact is limited.

These results are probably not final, but are dependent on what models, data and probabilities are used. Nevertheless, the analysis itself is of value in identifying factors related to the stability of the bedrock that need to be studied in the future from the standpoint of safety.

Otherwise, the state of knowledge can be briefly described as follows:

The Scandinavian land uplift is generally regarded as representing a not-yet-completed rebound from the load of the most recent inland ice sheet. The maximum deformation of the earth's crust caused by the weight of the ice sheet could be accommodated within the elastic range of the rock types. Furthermore, the block structure of the bedrock permits stress-reducing sliding between the blocks. In agreement herewith, the KBS studies have shown that large rock volumes exist with low permeability within the bedrock blocks, despite the fact that they have been subjected to a number of glaciation-deglaciation cycles, and regardless of whether uplift on the site has been small or large. Neither the remaining uplift nor renewed weighing-down by a future ice sheet is therefore expected to cause any significant changes in these conditions.

Against this point of view stands the opinion that the rebound was completed 2000-3000 years ago. Uplift has continued since then for other reasons. The entire uplift region is described as a collapsing dome /3-25/. The region is considered categorically unsuitable for a final repository. This ignores the fact that riverbeds have been detected at a depth of about 100 m below present-day sea level in the Bay of Bothnia

/3-26/, which shows that the earth's crust has not yet resumed its starting level and that there is no dome.

Ten years' studies of displacements in the bedrock that have occurred over the past 12 000 years have yielded considerable knowledge concerning their occurrence. They are preferably or exclusively encountered along major fracture zones that have already existed for a long time. The higher age of the zones is marked by frequently occurring narrow magnetic zones caused by oxidation. Fracture minerals have been encountered which indicate high formation temperatures and thereby an age of more than 600 million years.

Further studies are therefore being focussed on displacements that can be suspected of having occurred where older fracture zones have not existed, to get an idea of the frequency and effects of such events, insofar as they occur at all.

The work so far indicates that recent bedrock movements have occurred as a rule around the time of the retreat of the most recent ice sheet. Such movements have been encountered principally in northern Sweden, where bedrock movements of up to 30 m have been noted. Studies of the age of the displacements are important for determination of their age and frequency. If the connection with deglaciation were coincidental only and the displacements were instead the result of general geodynamic processes, there would be many more than have been found thus far /3-27/. It is also important to try to determine whether the displacements have occurred in a few large or a greater number of smaller steps. In the former case, they may have been accompanied by very large earthquakes.

Research results based on observations from a densified seismic grid in southern Sweden have recently been published /3-28/. To a large extent, the quakes can be shown to have occurred along fracture lines that appear on the surface.

By international standards, earthquakes in Sweden are few and small. They are of no importance in themselves for the safety of the final repository. Nevertheless, the study of small quakes can furnish valuable information on the geodynamic situation in Swedish bedrock both regionally and locally. The frequency and magnitude distribution of the quakes may fluctuate during the waste isolation period, but the deformation picture and general stability can be expected to endure. Aside from special conditions such as ice ages, they are determined by prevailing rock structures and by the movements that have taken place over a long period of time in the earth's active zones and more stable regions. This warrants an observation programme in northern Sweden, especially in view of observed cases of recent rock movements. SKB plans to continue these studies in Lansjärv.

International developments will also be followed with respect to major earthquakes in present-day glaciated regions and their effects on underground facilities in areas of high seismic activity. Experience from tunnels, rock caverns and mines that have been subjected to earthquakes have previously been summarized, along with methods for calculating stresses in and designing underground facilities /3-29/. It is found that the rock facilities can generally withstand even severe earthquakes without appreciable damage.

A hypothesis that should be mentioned in this context is that granitic bedrock exhibits a seismic discontinuity surface which is located in Sweden at a depth of between 0.6 and 1.5 km. Below this surface, the bedrock is expected to have higher strength in relation to the increase in load with depth /3-30/. This hypothesis will be examined more closely in connection with detailed investigations for the underground research laboratory, see Section 3.4.

3.2.4 1987-1992 research programme

The research programme is divided into two parts: Consequence analysis and geodynamic processes.

Consequence analysis

The purpose of the consequence analysis is to:

- compile and evaluate experience of earthquakes in already existing underground facilities,
- set up models of the rock mass and study the effects of earthquakes, glaciation, ice sheet advance, retreat and melting-away and land uplift.

Experience of earthquakes in underground facilities

International experience from regions of high seismicity will be compiled and evaluated. It is of interest to study whether the earthquakes have given rise to new fracturing of the rock mass and whether geohydrological conditions have been affected.

Modelling of the rock mass

Modelling of the rock mass is planned to be carried out in the following stages:

- Validation of numeric models.
- Rock stress measurements in deep boreholes.
- Application of numeric models of varying complexity for general studies.
- Site-specific modelling of the geosphere around a repository.

Validation of the numeric models will be done by means of a well-documented in-situ test, known as the CSM block /3-31/. Two conceptual views stand opposed to each other. In the one case, the rock mass is regarded as completely discontinuous, in the other case as a semicontinuum.

Rock stress measurements will be performed in a hole with a depth of 1000 m. The measurements will employ hydraulic fracturing as well as an overcoring method of some kind. The input data needed for the constitutive model will be estimated at this point with the aid of available classification systems.

Modelling will be divided into stages in which the calculation models are progressively refined. The model will be applied to the Lansjärv area in some introductory calculations. The boundary conditions will be defined by scenarios that are analyzed. The results that are judged to be of essential importance are change in fracture aperture and permanent deformations of the fractures, as well as whether the preconditions for new fracturing exist.

One of the investigated study-sites will be used for site-specific modelling. The existing conceptual model of the site will be transformed into a rock mechanics model, with an evaluation equivalent to that performed for the general modelling.

The results of the modelling of the different load situations will be evaluated with respect to possible geohydrological changes in the rock mass. The preconditions for new fracturing will also be assessed.

The evaluation should also provide guidance as to the degree of accuracy with which future scenarios must be described.

Geodynamic processes

The geodynamic studies are divided into five main categories:

- Structural geology maps.
- Analysis of major earthquakes in the Baltic Shield.
- Neotectonic studies at the Lansjärv fault.
- Detailed recording of seismic activity in southeastern Sweden.
- Evaluation.

Structural geology maps

The National Swedish Land Survey Administration's digital elevation database will be used in an initial phase to create a uniform structural geology map of Sweden's zones of weakness. The scale is 1:2 000 000. The map will be used to demarcate structurally homogeneous areas. Two areas will be studied more carefully on a larger scale, namely the Lansjärv area and the area around Simpevarp. Known earthquakes will be shown on the map with respect to epicentre, depth, quake mechanism and stress field. The relative age distribution of the zones of weakness is of particular interest. The tectonic analysis will take into account the results from the reflection seismics investigations that will be carried out in Sweden over the next few years. The map will be augmented with the knowledge of the earth's crust obtained within the International Lithosphere Program /3-32/ with the Swedish branch PPPL (Present Processes and Properties in the Lithosphere) /3-33/.

Analysis of major earthquakes in the Baltic Shield

Seismic recording of microquakes has taken place since the end of the 1970s /3-28/. The quakes are analyzed with respect to focal depth, source mechanism, stress drop etc. However, the large releases of energy in the earth's crust take place in the major earthquakes. A supplementary study based on an analysis of Swedish earthquake records is expected to make essential contributions to present-day knowledge of deformation mechanisms in the Baltic Shield and facilitate the interpretation of the detailed investigations at Simpevarp and Lansjärv. Large earthquakes with a magnitude M(L) >3.5 will be evaluated with modern methods so that the information from the microquake recording can be compared with the large energy releases in the earth's crust, see Figure 3-4. The parameters deemed to be the most interesting are focal depth, source mechanism and stress drop. The results are expected to contribute to an understanding of where and how stress buildup takes place in the Baltic Shield.

Neotectonic studies at Lansjärv

Seismic activity in Sweden is low at the present time. However, it has been demonstrated that movements have taken place locally in the bedrock since the most recent ice age /3-13, 3-14/. Neotectonic movements have taken place, for example, in the Lansjärv fault.

The goals of the studies in Lansjärv are to:

- assess the mechanisms that have caused present-day carps,
- clarify the extent of any recent fracturing,
- clarify the extent of any ongoing movements.

The work around Lansjärv will be coordinated with the analysis of major earthquakes. These studies are expected to include the following elements:

- Processing and augmentation of geological and geophysical material.
- Seismic recordings.
- Strain measurements.
- Rock stress measurements.
- Fracture mineralogy investigations.
- Evaluation.

The processing of the geological and geophysical material will control the location of the detailed studies in the Lansjärv area. The existing material will be augmented with reflection seismic investigations aimed at locating any horizontal deformations. The hypothesis that rock quality improves substantially at approx 1500 m will be tested.

Seismic recording will be performed with a network of permanent stations. The network will be laid out with a station distance of about 50 km and will therefore provide an accuracy of epicentre determination of within ± 1 km. The permanent network will be augmented with a mobile network during the summer months. The mobile network can record weak, superficial quakes. The accuracy of epicentre determination is estimated to be within ± 100 m.

The possibilities of establishing a precise network for strain measurement will be explored. With modern measuring instruments, the change in distance can be determined to an accuracy of about 0.1 mm/km. This will permit slow creep to be measured by means of recurrent measurements.

In order to facilitate the interpretation of possible source mechanisms and to supplement the stress analysis from focal plane solutions, rock stress measurements will be carried out in the area.

The purpose of fracture mineralogy analyses is to date movements in the fractures. This will shed light on how much the rock mass surrounding the Lansjärv fault has been disturbed.

All investigations will be evaluated in such a manner that comparison will be possible with conditions in southeastern Sweden, see below.

Seismic recordings in southeastern Sweden
Southeastern Sweden is an area of low seismic activity. Future recordings in southeastern Sweden are planned with a denser station network, permitting the detection of smaller quakes than before. Any quakes and source mechanisms in this low-seismic area will be compared with the recordings in the Lansjärv area.

The protogine zone
Present-day knowledge concerning the protogine zone (the margin of the low-seismic area in southeastern Sweden, see Figure 3-4), will be compiled and evaluated.

Evaluation
The results obtained from the various studies within the subject area "Geodynamic processes" will be compiled into a seismotectonic syntesis incorporating existing and new knowledge concerning the mechanisms in the Baltic Shield. This knowledge is of interest for the location of the final repository if it can be shown that the probability of changes in the geohydrology and geochemistry of the rock varies between alternative locations.

Timeschedule
A timeschedule for activities within the subject area "Stability of the rock" is shown in Figure 3-5.

More detailed studies of uplift and ice ages may be warranted at a later date, depending on the results of the consequence analysis obtained within this project.

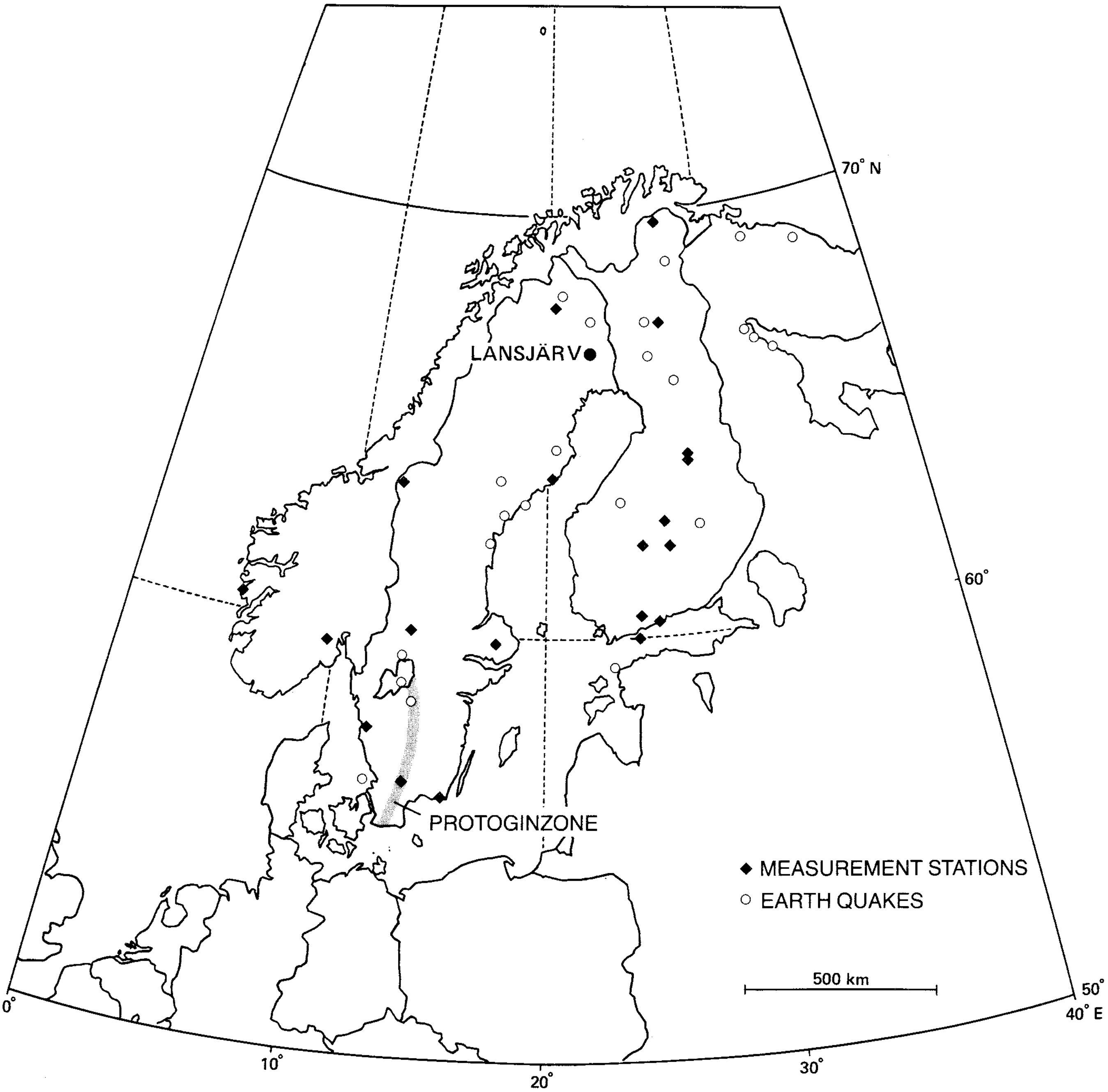


Figure 3-4. Earthquakes with magnitude M_L>3.5 during the period 1962-1985. The map also shows the location of the Protoginzone.

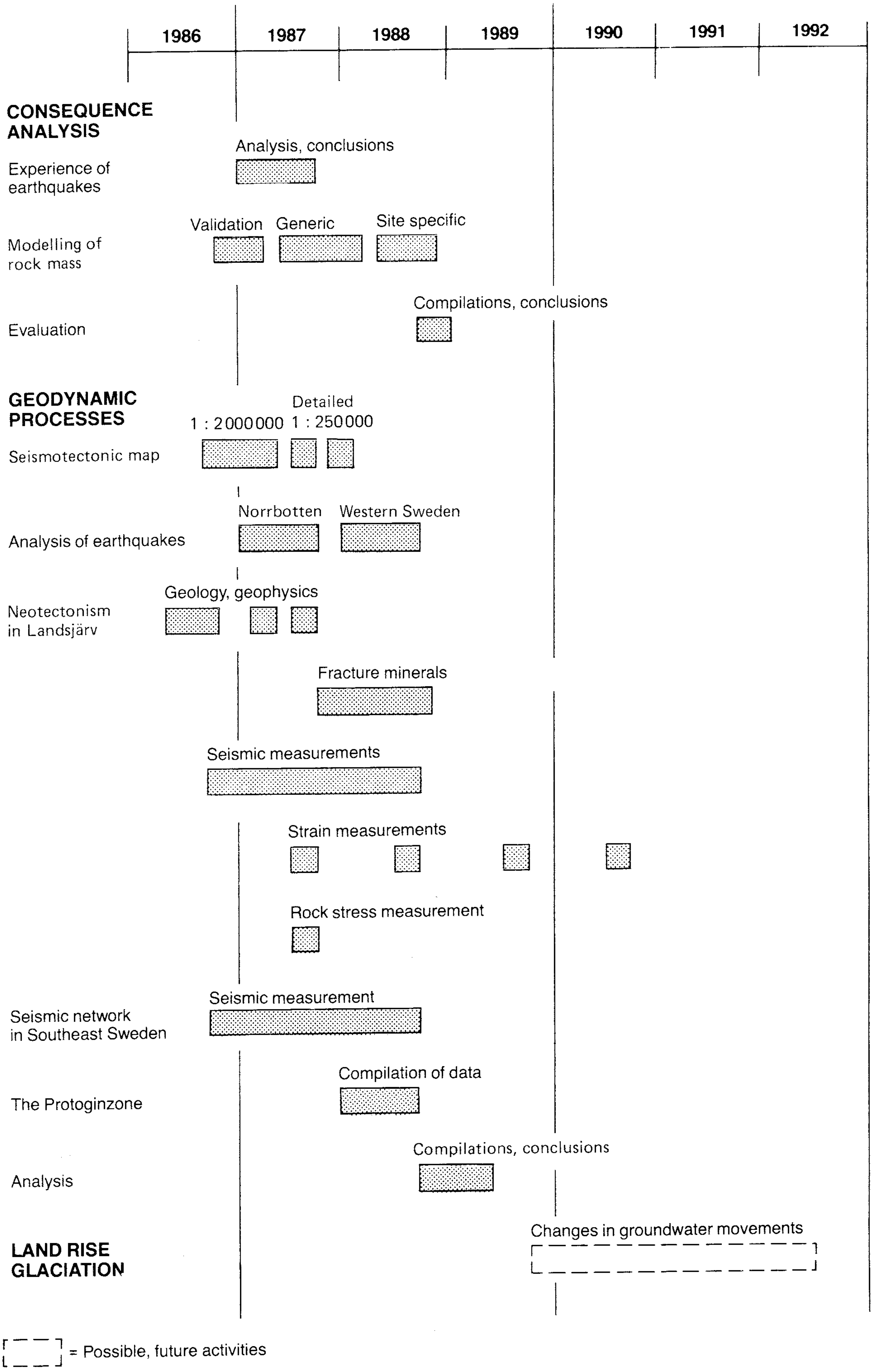


Figure 3-5. Timeschedule for investigations of rock stability.

3.3 Study-site investigations

3.3.1 Background

Study-site investigations are carried out in order to obtain knowledge on geological conditions in different rock types (gneiss, granite, gabbro) and in order to ascertain the geological conditions within rock areas that are conceivable candidates for the final disposal of spent nuclear fuel.

Geological, geophysical, geohydrological and geochemical investigations are carried out both from the surface and from boreholes down to a depth of 500-1000 m, in accordance with an established investigation programme /3-10/.

This standard programme includes four phases (Figure 3-6):

1. Reconnaissance for selection of study-sites.
2. Investigations from the surface.
3. Investigations from boreholes.
4. Evaluation and modelling.

Parts of the investigation programme are changed or augmented in keeping with the development of new methods for measurement and evaluation. As a consequence, the amount of data collected for the different study sites may vary, which may warrant supplementary investigations.

STUDY-SITE INVESTIGATIONS ACCORDING TO STANDARD PROGRAMME ARE DIVIDED INTO FOUR PHASES.

PHASE 1 RECONNAISSANCE

A Map and literature studies
- * Rock blocks bordered by fracture zones in area with flat topography

B Field reconnaissance
- * Overall geological assessment, possibly supplemented by geophysical measurements

C Reconnaissance drilling
- * Geological, geophysical and geohydrological investigations.

PHASE 2 SURFACE INVESTIGATIONS

A Geological surface mapping

B Geophysical measurements
- * Magnetic, electromagnetic, electrical, gravimetric and seismic methods

C Evaluation

PHASE 3 SUBSURFACE INVESTIGATIONS

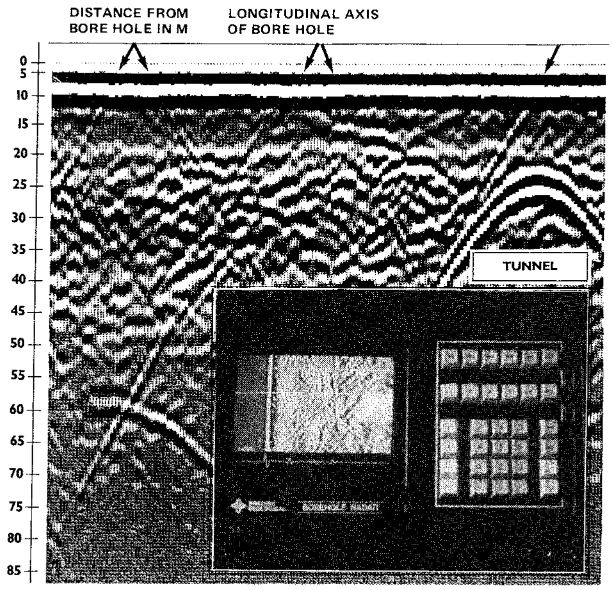
A Percussion drilling
- * determination of fracture zones
- * registration of groundwater tables

B Core drilling of deep boreholes
- * core mapping
- * geophysical logging by means of electrical, radiometric and acoustic methods
- * hydraulic investigations for calculation of hydraulic conductivity and groundwater head
- * hydrochemical investigations for analysis of chemical/physical composition of water

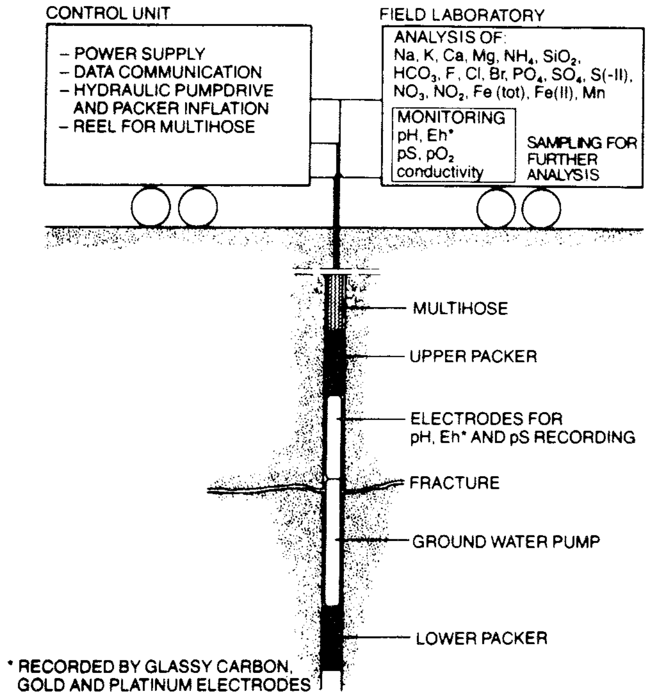
PHASE 4 EVALUATION

A Descriptive models
- * geology, geohydrology and geochemistry

B Numeric models
- * water transport and nuclide transport



Bore hole radar. The arrows mark fractures.



Water chemistry field laboratory.

Figure 3-6. Standard programme for study-site investigations illustrated with examples of investigation methods.

3.3.2 Goal of the study-site investigations

The purpose of the study-site investigations is to broaden and deepen knowledge of the bedrock at different sites in Sweden where geological conditions exist that permit the construction of a final repository for spent fuel and other long-lived waste. The goal is to have collected sufficient material by 1992 to permit the selection of two sites in the country where detailed site characterization can be carried out.

3.3.3 Present-day state of knowledge

The investigations of the Swedish bedrock carried out during the period 1976 - 1986 have started with reconnaissances.

The reconnaissance phase of the standard programme is divided into substages. The introductory inventory, which mainly consists of an examination of existing material such as satellite and aerial photographs, geological and geophysical maps and other geoscientific surveys, has been carried out on a number of occasions. Sometimes the purpose has been to select sites within certain parts of the country, while in other cases sites with special rock types have been sought after. A total of 900 sites have been covered in this survey.

The reconnaissance phase has then continued with detailed studies of several of these sites. General geological and geophysical ground measurements have been carried out to a varying degree as well.

Such geological investigations of varying scope have been carried out on 14 sites, see Figure 3-7. In most cases, a deep reconnaissance hole has been drilled. For the most part, the rock type on these sites is granite or gneiss, while gabbro is found on a couple of sites.

Extensive investigations have been carried out on eight of these sites, known as study-sites, all with granite or gneiss. These investigations correspond to phases 2-4 in the standard programme.

Between 3 and 16 cored holes have been drilled on each site down to a depth of between 500 and 960 m. All drill cores have been mapped in detail, and extensive, geophysical, geohydrological and groundwater chemistry investigations have been carried out in the boreholes. This means that a considerable quantity of data on the rock and the groundwater has been collected on each site. These data have been used in analyses of the safety of a hypothetical final repository within the site. The analyses include description of groundwater flows (direction and velocity) and transport paths for radionuclides. Most sites were investigated and evaluated in connection with KBS-1 and KBS-3 /3-34, 3-1/. Further investigations have been carried out since KBS-3, mainly on the Klipperås site /3-35 - 3-38/.

The study-site investigations have shown that it is possible to find many sites in Sweden that are geologically suitable for the construction of a final repository. The number of sites in granite and gneiss is considered to be sufficient at the present time. Supplementary investigations on some of these study-sites have commenced /3-39/ and will continue during the rest of the 1980s.

Among basic rock types, which have a different mineralogical composition than gneiss/granite, gabbro and closely-related rock types have aroused a certain amount of interest for study. However, they represent a relatively limited fraction of the Swedish bedrock. As regards ultramafic rock types, an introductory inventory showed that such formations in Sweden are too small to warrant further study.

As far as gabbro as a repository host rock is concerned, studies have been made of its occurrence and characteristics. Inventories and limited investigations have been carried out on a number of sites. Reconnaissance holes have been drilled at Gallejaure, where no gabbro was found, and at Taavinunnanen, where geological, geophysical, geohydrological and geochemical investigations were carried out in a 700 m deep borehole /3-40, 3-41/. The gabbro at Taavinunnanen is a well-delineated, approx 40 km^2 large body with a depth of at least 700 m. The hydraulic conductivity in the upper part of the borehole is lower than the average values from investigated gneiss and granite sites. Below a depth of about 500 m, the evaluation produces results equivalent to those from gneiss and granite. Drilling on a third site, Kolsjön in Upland County, has been suspended due to protests.

Outside Sweden, Atomic Energy of Canada Ltd, AECL, has sponsored investigations of a gabbro pluton at East Bull Lake. Extensive investigations, both from the surface and from a number of boreholes, have been carried out /3-42/.

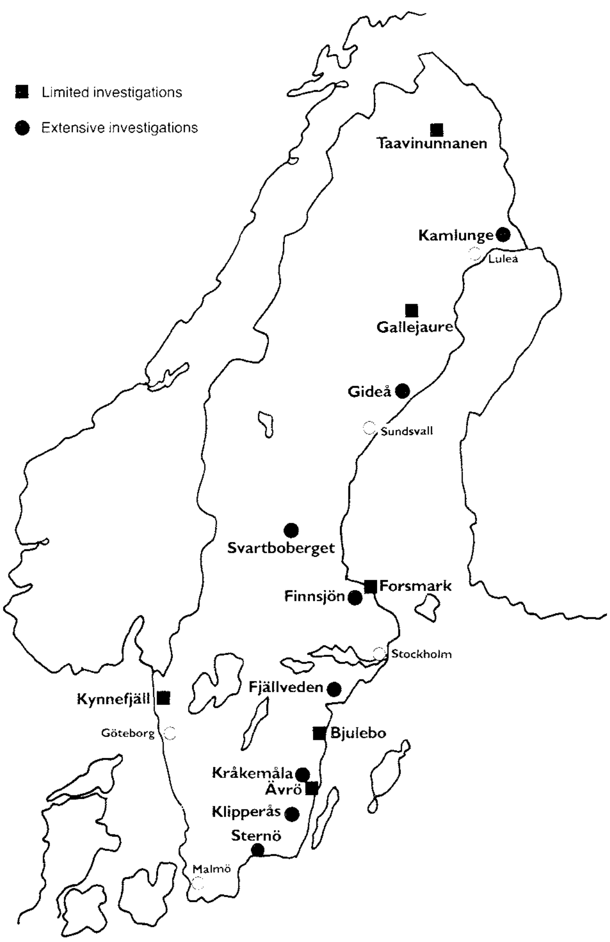


Figure 3-7. Sites where SKB has carried out geological investigations of varying scope.

Present-day knowledge of the properties of gabbro can be summarized as follows:

- *Hydraulic conductivity:* The prevailing assumption of low groundwater flow in gabbro and similar basites is confirmed at the small depths of the investigations conducted. At repository depth (>500 m), however, the hydraulic conductivity measured at present-day accuracy is similar to that for gneiss and granite.
- *Flow porosity and diffusion properties:* The amount of data gathered so far is much too small for conclusions to be drawn.
- *Rock type chemistry and mineral composition:* The prevalence of dark minerals and the low quartz content promote weathering. A high reduction capacity and strong surface sorption of radionuclides can be expected.
- *Fracture minerals:* The gabbro appears to be altered, sealed and fracture-mineral-bearing to a higher degree than granite and gneiss.
- *Strength:* Slightly higher than for gneiss/granite.
- *Thermal conductivity:* Lower than for gneiss/granite, requiring larger repository volumes.
- *Occurrence:* Limited fraction of the Swedish bedrock.
- *Size of the rock bodies:* Only the larger bodies have sizes or depths sufficient for a repository.
- *Homogeneity of the rock bodies:* Often exhibit internal subdivision into layers of highly varying composition. More recent rock types often intersect the gabbro bodies. These dykes have a higher hydraulic conductivity than the gabbro.
- *Ore deposits:* Ores can occur in connection with gabbro.

3.3.4 1987-1992 research programme

During the period 1987-1992, the study-site investigations will primarily involve the following work:

- Supplementary evaluations and investigations on some of the previously investigated study sites in order to further deepen present-day knowledge.
- Completion of reconnaissance of candidate sites for the construction of a final repository.
- If needed, investigations will be carried out on one or more additional sites with gneissic or granitic bedrock during the period 1990-1992.
- Evaluation of reconnaissance material and investigated sites and decision to undertake detailed characterization of a few sites.

In Finland, a site investigation programme has been commenced that resembles the Swedish standard programme in many respects. The actual site investigations are expected to begin in 1987. Since the Finnish bedrock is very similar to the Swedish bedrock, these investigations will be followed closely /3-43/.

Supplementary evaluations and investigations

Since the study-site investigations were carried out in connection with the KBS work, measurement and investigation technology has been refined in a number of respects. It is therefore important to supplement the existing body of data with further evaluations and measurements.

The supplementary work will start with the evaluation of existing material. This will result in a preliminary plan as to which supplementary evaluations and investigations are to be carried out. SKB is currently building up a database where all data from the study-site investigations and other research results will be assembled. This greatly facilitates reexamination and any reinterpretation that may be necessary of the results of previous investigations.

For the most part, the supplementary investigations will be concentrated to a few sites to enable a deeper understanding to be gained. Examples of measurements and methods that may be used in the supplementary investigations are:

- Application of alternative methods for data analysis.
- Expanded tectonic analysis and supplementary fracture mappings.
- Investigations using alternative geophysical borehole methods, such as radar and tube wave.
- Reflection seismics for detecting horizontal structures.
- Rock stress measurements.
- Interference tests.
- Hydraulically conductive fractures; detailed investigations in boreholes provide data for transport modelling.
- Supplementary boreholes; possibly deep large-diameter percussion boreholes whose location is primarily determined to permit the performance of interference tests on a large scale at great depth using existing boreholes for pressure recording. If supplementary geochemical investigations are needed, water samples will be taken at regular interruptions in the drilling.
- Supplementary investigations of groundwater chemistry/geochemistry.
- Analysis of gas formation in the groundwater.
- Sealing-off of hydraulic units in boreholes with packers.
- Modelling, including correlation studies between tectonic, rock-mechanical and geohydrological conceptual models and supplementary calculations.

Supplementary studies will be carried out during the period 1988-1992. The investigations will alternate with periods of evaluation and updating of the investigation plan.

Investigations of gabbro

Appraising the total knowledge acquired concerning final disposal in rock formations, further studies of gabbro are not considered necessary. One reason for this judgement is that it will probably be difficult to find sufficiently large and homogeneous formations of gabbro, which is a relatively uncommon rock type in Sweden.

It has previously been demonstrated that a safe final disposal is possible at a number of sites with gneiss or granite. Further studies should therefore be concentrated on these rock types.

If further investigations of gabbro are nevertheless considered to be needed, they must be initiated as soon as possible so that the results can be taken into account in the summary evaluation at the beginning of the 1990s.

Investigations in gneiss or granite

No further investigations of gneiss or granite on new study sites are planned during the next three years. Current reconnaissance will, however, be completed. One or more sites with gneiss or granite may then be investigated before a decision is taken concerning sites for detailed characterization. Sites near the coast in the southeast part of Sweden are thereby of special interest.

Selection of sites for detailed characterization

Against the background of reconnaissances, investigations on study sites and supplementary investigations, an overall evaluation of the geoscientific suitability of different sites will be carried out at the beginning of the 1990s. This evaluation will form a basis for the selection of two sites for the detailed characterization planned to be carried out during the period 1993-1998. If conditions prove suitable, the site of the underground research laboratory may be one of the sites chosen for detailed characterization. The general, in-depth knowledge obtained from the planned research laboratory is deemed to be of great value in evaluating the geoscientific factors for different sites. Other factors are added to the geoscientific ones to obtain a complete basis for a decision as to where the detailed investigations should be conducted, see also Part II.

Timeschedule

A timeschedule for the activities concerning study-site investigations is shown in Figure 3-8.

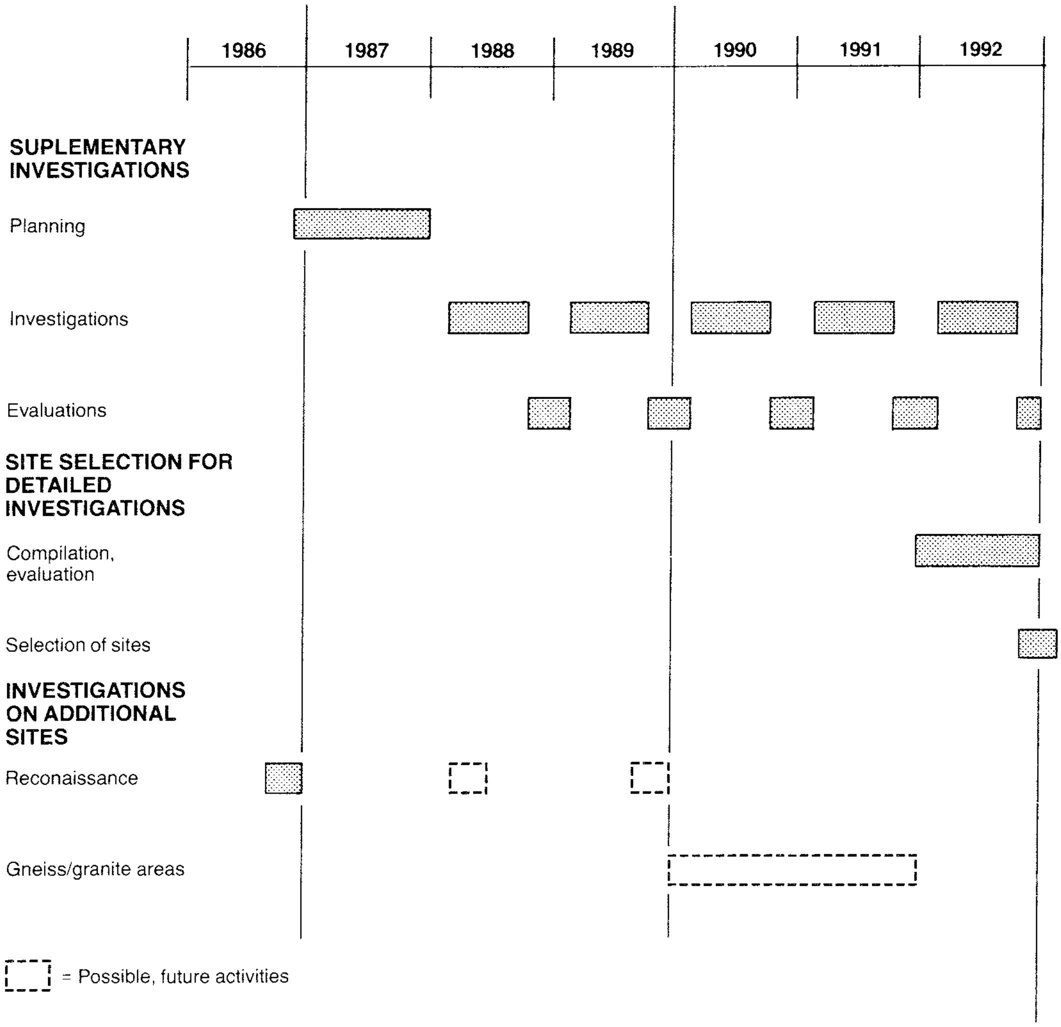


Figure 3-8. Timeschedule for study-site investigations.

3.4 Underground research laboratory

3.4.1 Background

The geological and geohydrological database obtained from the previous study-site investigations are mainly based on airborne geophysical surveys, ground measurements and borehole logging.

The primary purpose of the investigations has been to locate sufficiently large rock volumes of suitable quality.

Data collection from the different sites has been carried out with a high level of ambition. Computer-based calculations have then been carried out in different phases, leading up to a final safety assessment.

Methods and results are described in detail in the KBS-3 report /3-1/ with background reports. A number of parameters have not been possible to quantify definitively. Since the safety assessment is consistently based on conservative assumptions and since factors that act in a favourable direction have not been included, considerable room for optimization of the final repository system is judged to exist.

Whereas the research activities at Stripa will be completed in the early 1990s, it has been deemed to be of very high priority to build an underground research laboratory where continued research can be pursued at a high scientific level to broaden the available body of knowledge.

The research laboratory should be situated in an environment that is geologically and geohydrologically unaffected by previous activities. This will provide an opportunity for many scientific experiments of vital interest for a safety analysis with good precision.

The underground research laboratory is also planned for other purposes than purely geoscientific studies. In preparation for the submittal of a siting application, integrated tests, pilot and in-situ tests may be necessary during the latter half of the 1990s. Such experiments can be conducted in the underground research laboratory. The evaluations of the components of the system - canister, buffer material, rock etc - that are currently being conducted will provide a factual basis for optimization of the final repository system. Development of the repository system may require development and adaptation of technology. Methods for the excavation and construction of a final repository can be tested and demonstrated in an underground research laboratory.

In view of existing services and other infrastructure etc, it is proposed that a location at CLAB (Simpevarp) or in its vicinity be investigated to start with. Previous civil engineering works in connection with the construction of the nuclear power plants at Oskarshamn and CLAB show, together with general regional and geological knowledge, that the Simpevarp area is of interest for more detailed investigations.

In the long-range plan, it has been considered necessary to begin detailed geological characterization on a few sites at the beginning of the 1990s. The preliminary investigation that will be conducted in connection with the establishment of an underground research laboratory will provide good opportunities to develop and test methods for such detailed characterization.

3.4.2 The goals of the underground research laboratory

The goals of the underground research laboratory are to:

- demonstrate that the factors that control the safety of a final repository are understood and can be quantified or delimited,
- validate models and assumptions included in the safety analysis.

The principal activities during the period 1987-2010 are:

- Detailed investigation of the natural barrier (the rock) in bedrock of a final repository character. This includes development of methodology, collection of data and validation of models for groundwater movements and radionuclide transport.
- Pilot in-situ tests for analysis of performance interaction between the repository's engineered and natural barriers.
- Development of appropriate methods for excavation, construction and quality assurance of a repository.
- Demonstration of system, technology and quality assurance.

The following goals are deemed to be the most urgent for the upcoming period, 1987-1992:

- Establish the geoscientific basis required to evaluate whether it is possible to locate an underground research laboratory around Simpevarp and to evaluate the need for detailed investigations for validation.
- Establish a basis for the preliminary facility layout of the research laboratory.
- Establish programmes for shaft sinking or tunnelling and also for monitoring and construction of parts of the facility.
- Make a prediction of the geohydrological and geochemical changes that occur in connection with construction of the research laboratory and compare calculated with measured values.
- Establish a programme for the experiments etc that are to be conducted during the 1990s.

3.4.3 Present-day state of knowledge

Research and development have generated new methods, instruments and calculation tools so that the bedrock can now be defined and quantified in a much more precise manner than has previously been possible. The pace of development is still high.

The new knowledge, which is often formulated in terms of mathematical relationships, must continuously be tallied against actual conditions so that it is possible to determine how realistic the calculated results are.

It is judged to be impossible to fully characterize the rock volume, with a given groundwater situation, that will be affected by the underground research laboratory by means of deterministic methods. An essential task will therefore be to define from what aspects a validation is possible. A clear formulation of these questions is of essential importance for planning and execution of the research programme on the site of the research laboratory.

Research within the geosciences applicable to the final repository has now advanced to such a point that

- The factors that are of vital importance for the long-term safety of the repository have essentially been identified.
- Instruments that permit accurate measurement of many essential parameters have been developed.
- Calculation tools able to describe complex processes have been developed.

There is therefore a good chance that a concerted effort around an underground research laboratory will make essential contributions to the work of effecting a safe final disposal of the Swedish nuclear fuel.

3.4.4 1987-1992 research programme

The detailed investigation of the area around Simpevarp will be divided into stages. The content and final scope of these stages will be determined by the information gathered.

Survey of the area

All available geological and geophysical documentation on a large regional scale will be evaluated .

Airborne geophysical surveys

Measurements of the necessary extent will be performed in order to obtain a regional knowledge of the geology and tectonics of the area.

Preliminary investigations according to modified standard programme

The sites judged interesting for location of the underground research laboratory will be supplemented with detailed geological mapping and ground geophysics.

Drilling

Evaluation will lead to a drilling programme to supplement the conceptual model of the rock mass obtained on the basis of the collected geological and geophysical information.

In connection herewith, a reference area will be established that will remain undisturbed by the activities around the research laboratory from then on. The reference area will be used to distinguish the natural variations in groundwater levels from induced ones.

Borehole logging

Borehole logging will be performed chiefly using the methods previously used in the study-site investigations. The measurements will be supplemented with radar measurements, interference tests and rock stress measurements in order to obtain a detailed picture of the rock mass and its characteristics.

Facility layout

The model of the rock mass obtained will form a basis for a facility layout. The purpose of the layout is not to make use of the best parts of the site for communication between the surface and the research laboratory. The goal is instead to use shaft sinking or tunnelling as a means of large-scale investigation of fracture zones and rock mass. The investigations described above shall be so detailed that it is possible from them to identify a number of areas along the shaft or the tunnel suitable for further studies.

Detailed investigations

The identified areas will be investigated in detail with respect to geohydrology, geochemistry and rock mechanics.

Expectation models

The tunnel or the shaft gives rise to transient and steady-state disturbances in the groundwater situation. The calculated disturbances will be compared with measured disturbances as a basis for testing the validity of the models in different situations.

Civil engineering works

The rock excavation work will be planned so that a continuous follow-up of models is possible. The details of the layout will be adjusted as further knowledge of the rock mass is gained.

The studies to be performed specifically at the underground research laboratory are not expected to commence until the end of the six-year period dealt with in this research plan. A detailed planning of these studies will have to be carried out at a later stage.

Timeschedule

The timeschedule for the planned stages is shown in Figure 3-9.

3.5 Instrument development

3.5.1 Background

Extensive investigations are required for characterization of the properties of the bedrock and groundwater movements. The great depths involved, 500-1000 m, have hereby necessitated extensive development efforts with regard to investigation methods and instruments.

Even before the first geological investigations in 1977, it was decided for the Swedish programme that the deep cored holes should be drilled with a diameter of 56 mm. This greatly reduced drilling costs compared with the use of conventional international borehole diameters of 76 mm or greater. However, it also required active development of instruments for in-situ determination of geological, geohydrological and chemical parameters. The instruments are technically

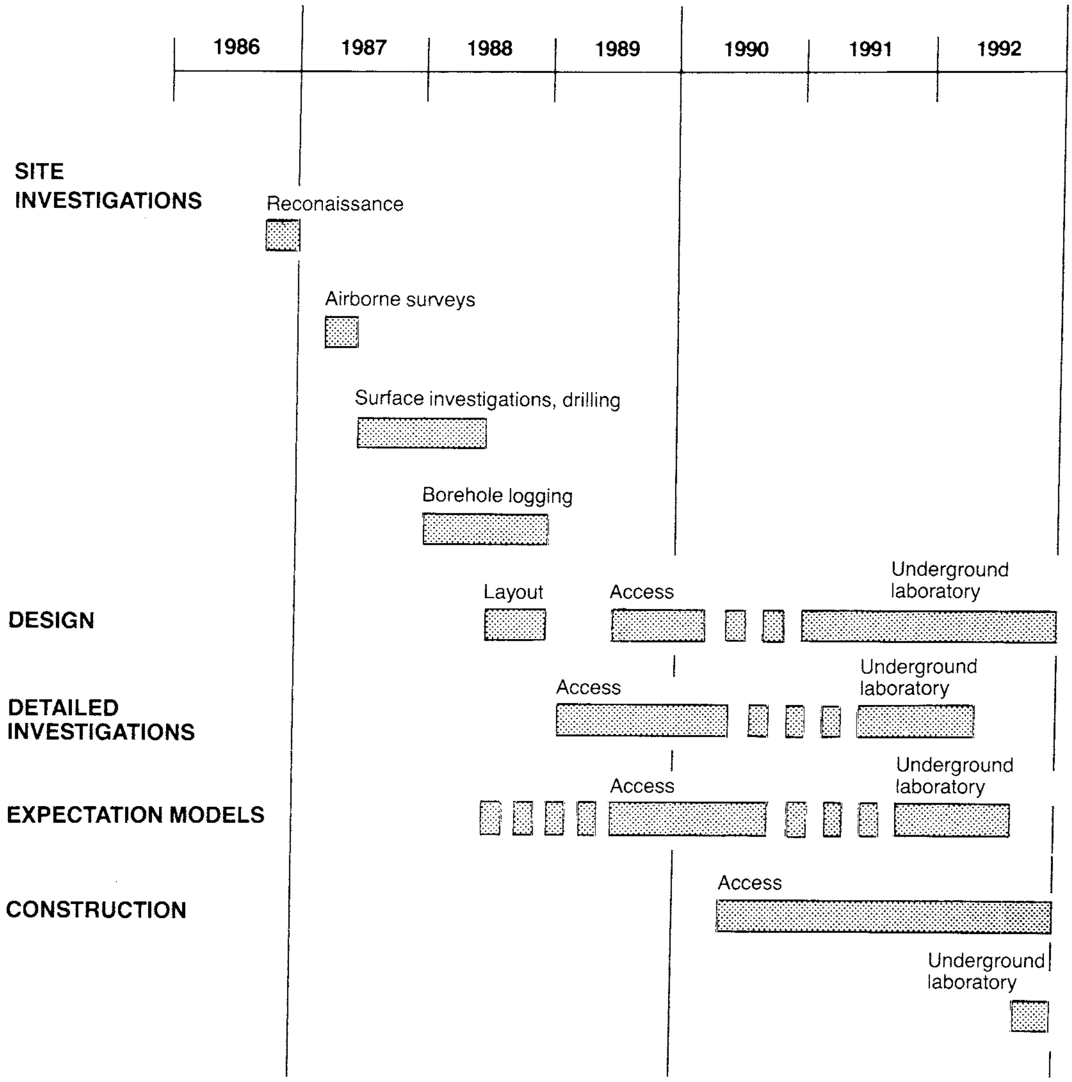


Figure 3-9. Timeschedule for underground research laboratory.

advanced as regards eg electronics and data communications, and they permit rapid measurement with high degree of accuracy down to a depth of 1000 metres. All things considered, the choice of borehole diameter and the development of measurement technique and instruments have provided a system for investigations at great depth in rock that give data of high quality and relatively low cost, by international comparison.

Experience, along with new investigation methods, warrant a continued active development of instruments and measurement technique.

New types of instruments will be developed to permit the use of new investigation methods, while other instruments will be improved to increase the degree of detail in the investigation or standardize sampling. From investigating a limited rock volume around a borehole, the trend is towards instruments that can "see" farther out into the rock or explore conditions between boreholes.

3.5.2 Goals of instrument development

The main goal of instrument development is, hand in hand with method and model development, to see to it that suitable instruments and equipment of high quality are available for the different geoscientific investigations described in other sections. The instrument development work can be broken down as follows:

- Further development of existing equipment, including hydraulic equipment for both single-hole and interference tests, piezometric equipment, chemistry laboratory, borehole radar etc.
- Development of new instruments such as downhole TV, equipment for rock stress measurements and chemistry equipment for "impervious" rock.
- Development of equipment for long-term recording of hydraulic, geochemical and rock mechanics parameters in connection with detailed investigation of a site.

3.5.3 Present-day state of knowledge

The instruments that have been developed to date under contract to SKB, or that are otherwise used in connection with study-site investigations, are described in brief below.

Geophysical measurements from the surface are of the underlying rock volume. Electrical, electromagnetic, magnetic and seismic investigations are carried out along staked-out lines. On sites where rock outcrops are lacking or occur sparsely, these investigations are particularly important.

Geological mapping of drill cores is performed using a microcomputer-based system for data collection and printout of drill core logs. Geophysical loggings are performed in the boreholes, which normally include measurement of the rock's gamma radiation, electrical resistivity, magnetism, acoustic response, the temperature and salinity of the borehole liquid and the direction of the borehole. Collected data are processed and presented on a single graph known as a composite log.

Hydraulic measurement are then performed in the boreholes in order to determine the hydraulic conductivity of the rock mass and the fracture zone. These tests are performed by injecting water into the bedrock from rubber-packer-sealed sections of the borehole. The measurements are mainly performed with the aid of an automated multihose outfit.

The natural groundwater heads in the rock volume are measured by means of piezometric head measurements, whereby several levels in one and the same borehole can be recorded with the aid of a purpose-built instrumentation. Furthermore, a prototype of a dilution probe has been developed, by means of which the natural water movement (groundwater flow) through a borehole can be measured.

Sampling and chemical analysis of groundwater soon proved difficult to do with sufficient accuracy, especially as regards the redox potential of the groundwater, since traces of oxygen in the water leaked into the sample and caused serious disturbances. SKB has therefore developed a sampling system where the groundwater's redox potential (Eh), acidity (pH) and sulphide content (pS) are measured directly in a rubber-packer-sealed borehole section. The water is pumped from there up to a mobile water laboratory so that most of the chemical substances dissolved in the groundwater can be analyzed directly on the site. This laboratory contains a spectrophotometer, an ion chromatograph, titration equipment and a fluorimeter. At present, a special water sampler is being developed that also permits the analysis of gases dissolved in the groundwater.

The instruments and equipment that have been developed and are used within SKB's geoscientific surveys have attracted wide international attention. For further details, the reader is refered to /3-44/.

Instrument development is also being conducted within the framework of the Stripa project. Phase 2 of this project has involved the development of crosshole technique for characterization of a rock volume, which has then also included development of instruments. Thus, equipment for hydraulic crosshole tests with sinusoidal pressure propagation and for characterization of fracture systems in a rock volume with the aid of borehole radar and borehole seismics has been developed /3-44, 3-45, 3-46/. Both the radar and seismic systems will be further refined during phase 3 of the project.

3.5.4 1987-1992 research programme

Instrument development during the upcoming six-year period will take place within the following subject areas:

- Geohydrological instruments.
- Chemical instruments.
- Geophysical instruments.
- Rock mechanics instruments.
- Monitoring systems.

Development of instruments and equipment that can be of interest to SKB is also taking place in eg Canada, Switzerland, the USA and Finland. SKB is following this work and taking note of the results obtained.

Geohydrological instruments

Hydraulic and piezometric equipment

Hydraulic injection tests are performed with two fundamentally similar types of equipment: Multihose outfit and pipe string. Further development of these outfits will mainly consist of devising new measuring probes.

The measurement instruments for piezometric recordings are currently undergoing of extensive modification. Purpose-built pressure calibration equipment should be developed for both the piezometric instruments and the hydraulic testing outfits. This equipment can be used to check the important pressure measurement instruments at regular intervals.

Hydraulic interference tests have so far been carried out on a limited scope. They can be used to determine the geometry of the fracture zones, but above all to investigate the hydraulic properties of the rock mass. For these investigations, existing hydraulic measurement equipment will have to be modified and adapted specially for the purpose.

Instrument and method development for detailed hydraulic investigations from underground facilities or tunnels should be pursued in parallel. The research should be focussed on development of cross-hole measurements for characterization of the hydraulic properties of the local rock mass. In some cases existing equipment can be used, while in other cases existing equipment will have to be modified or new equipment will be necessary.

Dilution probe

A so-called "dilution probe" has been developed for measurement of natural groundwater flow in a fracture or fracture zone penetrated by a borehole. This instrument is used to measure the dilution of a tracer injected into a borehole section, see Figure 3-10. The existing instrument is a prototype for 110 mm boreholes that has performed well. A new instrument for normal borehole diameter is required, while at the same time the possibility of detecting the direction of the groundwater flow should be studied. The method is interesting since it measures the natural groundwater flow.

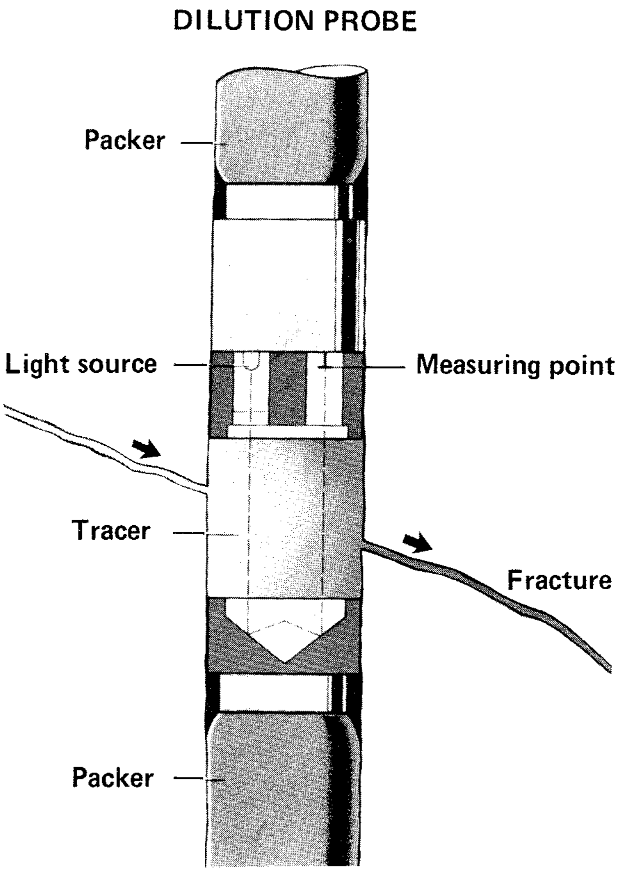


Figure 3-10. Dilution probe for measurement of natural groundwater flow through a screened-off borehole section.

Tracer test equipment
Tracer tests with both non-sorbing and sorbing tracers offer a valuable means for investigating water transport, flow paths, porosity etc. To the extent such equipment requires development of instruments so that the test can be carried out in an effective and standardized manner, such development will take place.

Chemical instruments
Further development of the chemical sampling equipment will include development of an improved and simplified pump unit.

The nearly stagnant water present in the microfractures in the rock mass has been in equilibrium with the minerals in the bedrock for a long time. Its chemical composition is of interest for the analysis of the long-term function of the repository. The water is very difficult to get at, and new equipment will have to be developed for sampling of this water.

Geophysical instruments

Borehole radar
Fundamental development of borehole radar has taken place within the Stripa project. SKB has then further developed the radar to a field-adapted outfit for 56 mm boreholes that has been used with very good results. Development of directional borehole antennas has been initiated. With such antennas, it will be possible to determine the direction of the radar reflections, which has not previously been possible in single-hole measurements. This work will be pursued within the Stripa project.

Further development of the radar equipment will also include development of interpretation programs so that a geometrically correct picture is obtained of the recorded radar reflections.

During construction of the underground research laboratory, investigations from tunnels will be carried out on a relatively large scale. The rader method should therefore be adapted to this purpose. Radar antennas for measurements from the tunnel wall should be developed.

Borehole TV
TV observations from boreholes have previously been difficult to interpret, since the TV screen always shows a distorted picture of the borehole wall. Development of a new borehole TV system is underway. This project includes development of a new camera, digital image transmission to above-ground instruments and presentation of the "unrolled" borehole wall on the TV screen. The equipment is intended to make TV logging of boreholes a practical and effective aid for the orientation of fractures and the like.

Rock mechanics instruments
Measurement of the state of stress in the bedrock has previously only been done on a limited scope on study-sites. Two fundamentally different methods that complement each other are used for these measurements. In the overcoring method, strain gauges are mounted in conjunction with drilling in the lower part of a borehole. They measure how these stresses are relieved when the instrumented section is overcored. By hydraulic fracturing of the rock, the rock stresses can be measured in existing boreholes. The latter method will be further developed, for example so that measurements can be made down to a depth of 1000 m.

Monitoring system
Long-term recordings of geohydrological, chemical and rock-mechanical conditions need to be performed, for example in connection with the underground laboratory and in connection with detailed investigations of different sites. It is important that the boreholes are isolated with rubber packers at an early stage in order to avoid short circuiting between different hydraulic units. Prolonged short circuiting impairs the piezometric pressure head measurements and can be very disturbing to the chemical investigations. Rock mechanics equipment will be installed in other boreholes.

Suitable systems for simultaneous sealing-off and long-term recording of measurement parameters will be developed.

Timeschedule
Activities within the subject area "instrument development" are scheduled as shown in Figure 3-11.

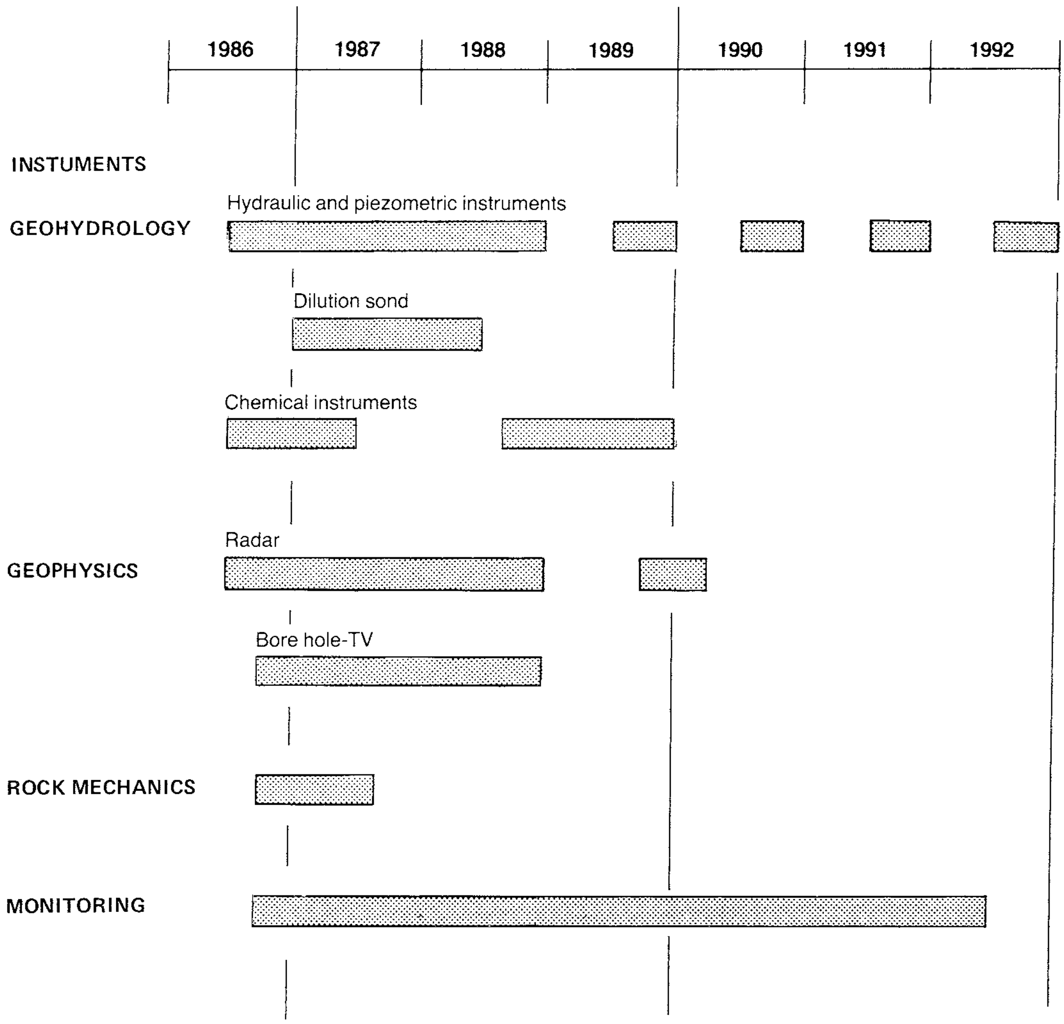


Figure 3-11. Timeschedule for instrument development.

4 BIOSPHERE STUDIES

4.1 Background

Knowledge of how radioactive materials are dispersed in the biosphere is a prerequisite for calculating the radiation dose from releases of radionuclides. In addition to research activities at universities, technical institutes and special research institutions, research on dispersal in the biosphere is also conducted by the two government authorities SNV (the Swedish Environment Protection Board) and SSI (the National Institute of Radiation Protection).

The dispersal calculations in KBS-3 were carried out with a model called BIOPATH and based on data that characterize the different parts of the biosphere and how they interact. With known concentrations of radionuclides in the biosphere and known uses of nature, doses to the population can be calculated. This is done with the aid of models describing how different substances are distributed in the body after ingestion or inhalation and data on the radiation emitted by the different isotopes and how it affects different organs. These models and data have been compiled in a number of internationally accepted recommendations issued by the ICRP.

The biosphere can, however, change on a time scale that is much shorter than the time scale of the retardation and dispersion of any release from a repository at great depth in the bedrock. This lends an unavoidable fundamental uncertainty to the dose calculations. The need for improvements in data and models should be viewed in relation to this uncertainty.

It is debatable whether a characterization of the biosphere in the very long term is at all meaningful, and whether calculations of future doses constitute a suitable measure of repository function. The only realistic alternative to dose as a measure of repository function is to compare the leakage of radionuclides from the repository to the biosphere with the natural release of similar radionuclides from the bedrock.

Present-day acceptance requirements, to limit individual doses and to reduce the total dose to the population to a level that is as low as reasonably achievable, are then replaced with the requirement that the final repository shall not significantly alter the natural radiation environment that originally existed on the repository site. In such a case, biosphere phenomena are of no relevance for the safety assessment.

4.2 Goals of the R&D activities

The biosphere research and the study of how different materials are transported in nature is being conducted by so many different parties, at such a pace and on such a broad basis that SKB cannot reasonably participate actively within all fields. A principal task will be to monitor developments in important fields and make appropriate use of existing and relevant information.

SKB's efforts will be focused on problem areas that are specific to the disposal of radioactive waste in the bedrock and to the acceptance requirements imposed by society on the repository. The biosphere research will only be influenced to a small degree by alternative designs of the final repository.

The goals of further research concerning biosphere dispersal are to:

- attempt to quantify the uncertainties that are introduced into the calculations by the fact that the biosphere is changeable in the relevant time perspectives
- improve data and models within limits that are meaningful in view of the aforementioned uncertainty
- validate the models for biosphere dispersal by investigating natural or man-induced analogue dispersal processes.

4.3 Present-day state of knowledge

During preparation of the KBS reports, a number of biosphere studies were carried out to obtain data and check existing models. These studies mainly concerned the occurrence and uptake in plants of natural radioactive materials, their distribution between water and sediments and their occurrence and transport in beach sediments. Furthermore, a survey was made of the occurrence of radioactive materials in wells in different types of bedrock and of concentrations of radioactive substances in a number of springs in uranium-rich areas. The latter study also included a survey of the rate at which activities in the spring water are reduced downstream of the spring and resulting concentrations in plant material and stream sediments (see KBS-3).

The results of all these studies have, for the most part, confirmed the picture of the transport of the radioactive materials in the biosphere provided by the general literature within the field. However, both the literature and SKB's own investigations indicate large spans of variation for parameters within the biosphere region.

This variation may have many causes, such as differences in water supply, food supply, climate or geochemical conditions. It may also be caused by annual variations during the growing season or variations depending on the slow evolution of a biotope /4-1/. The endeavour to measure this variation and to better be able to quantify it is an important part of the further biosphere studies.

During the KBS studies, conversion factors were calculated for groundwater releases of different nuclides to three types of primary recipient (well, lake, brackish water sea). The factors were calculated with the aid of a compartment model for biosphere dispersal (BIOPATH) and data from the literature, from surveys of recipient areas and from the aforementioned studies. Further detailing of the conversion factors is not deemed to be able to improve the dose calculations significantly due to variation in nature and uncertainties in man's future use of nature.

The BIOPATH model and its database were further developed during this work and certain validations were carried out /4-2/. Further validation and model development is deemed desirable in order to ascertain the most appropriate level of complexity at which the compartments should be defined for different purposes.

4.4 1987-1992 research programme

4.4.1 Variation and uncertainties

Owing to the long travel times through the geosphere, any consequences for man of a final repository for radioactive waste will not manifest themselves until after very long periods of time - for certain designs, only after a period that is longer than the length of time man has existed as a species.

Changes of importance for the safety assessment take place on different time scales:

Time scale	Examples of possible changes.
100 years	Recipient changes such as eutrophication of lakes etc.
10 000 years	Climatic changes such as ice ages etc.
1 million years	Evolutionary changes such as the origin of new species etc.
100 million years	Geological changes such as the formation of mountain chains etc.

Analyses of the span of possible changes and their character are of importance in order to be able to assess the results of the safety analysis and determine what further measures are meaningful. These analyses should be focussed on changes within a time span of 100 - 10 000 years, when effects of recipient changes and climatic changes dominate the picture.

One study is underway to shed light on the natural ageing of the recipients (for example eutrophication of lakes, shallowing of bays) and how parameters of importance for radiation dose change. The study is expected to require detailing and follow-up efforts in 1987. Supplementary studies of the effects of human activities such as land drainage, peat harvesting and the like will be required. The results will also be used to further refine the BIOPATH model, particularly with respect to time-dependent changes.

Evolutionary changes beyond the span reflected by the present-day ecosystems on the earth are not deemed available for meaningful study today.

A follow-up of international activities within this field is essential, since the problems discussed above are general.

4.4.2 Data

Further efforts to build up the biosphere database will primarily be focussed on the isotopes and recipients that dominate the risk picture and on sites where appreciable reductions in present-day uncertainties in dose estimates can be expected.

At the same time, some of the sites selected for geological surveys will be characterized as regards possible primary recipients for groundwater, dilution and runoff conditions, natural activity in soil and surface water etc, cf KBS-3 and /4-3/. The studies permit a description of the original radiological conditions and provide input data for modelling of biosphere transports of radionuclides.

A large portion of the variation in the international database is judged to be a result of unidentified dissimilarities in climate, biotopes and chemical conditions.

In order to reduce this variation if possible, SKB will discuss with SSI and others the possibilities of creating a common Scandinavian database for data of importance to biosphere dispersal of radionuclides. For this, the structure of the database and quality control routines need to be established during 1987-88. Collection of data will continue over a long period of time. Regardless of whether cooperation can be established, a well-documented and analyzed database must be available in time for the safety analyses for the siting application in 1998-2000.

The large body of material on the mobility of heavy metals in Swedish soils and lakes that has been collected by the Swedish Environment Protection Board and the Swedish University of Agricultural Sciences will be utilized in the further studies, as will data from uranium prospecting.

4.4.3 Recipient studies

Radionuclides flowing from the reducing groundwater environment up into the biosphere will pass into oxidizing conditions. The transition often occurs in soils or sediments. The redox transition affects the solubility of many radionuclides and biological activity in the zone. Many of these phenomena are poorly understood, and a general study is planned to be carried out during 1987-88. This study and the results of ongoing sediment investigations in connection with the natural ageing of recipients will then provide a basis for decisions as to further measures. Possible studies concern precipitations or chemical reactions at contacts between groundwater and superficial waters.

As a pilot study, sampling will be performed in one or more distinct areas of groundwater outflow in lake sediments in order to determine chemical and physical dissimilarities with surrounding sediments.

Long-term tests with the addition of special nuclides to well-defined sediments may be required in a final phase in order to study the mobility of certain actinides in the sediments.

4.4.4 Models

Continuous model development is a necessary complement to data collection and data analysis. The development efforts within SKB will be tied to the BIOPATH model and to simplified models for use in connection with probabilistic safety analyses, see Section 6.4.

Attempts to validate dispersal calculations in the geosphere and biosphere will be made through studies of natural analogues. Such large projects will mainly be undertaken in international cooperation. SKB is following the SSI-initiated BIOMOVS project, where a number of groups from different countries will jointly attempt to carry out certain verifications and validations of biosphere dispersal models /4-4/. Studsvik Energiteknik is also participating in this work with the BIOPATH model.

SKB does not intend to initiate its own studies until the thrust and results of the BIOMOVS project show whether the problems specific to geological disposal have been adequately covered. The possibilities of making use of the fallout from the Chernobyl accident to validate biosphere dispersal models are being explored.

4.4.5 Other studies

The properties of the primary recipient that receives the groundwater discharged to the biosphere exert a dominant influence on the dose obtained from a given release. Among different recipients, rock wells have been found to provide the least favourable exposure conditions. The dose from a well is heavily affected by the dilution of radioactivity that occurs in the well. During the period 1987 to 1992, experiments will be conducted to validate different calculation models for this dilution, partly in connection with the fracture zone studies and partly in connection with the excavation of the underground research laboratory.

Radiation doses and associated health effects are being analyzed and assessed on a broad basis by a number of national and international groups. Recommendations are issued by the International Commission on Radiological Protection (ICRP).

SKB will follow this work and its applications to waste management and waste disposal. SKB's own work within the field is expected to be limited and restricted to nuclides of importance to a final repository. The National Institute of Radiation Protection bears a principal responsibility for the national research efforts.

The influence of radiation on organisms other than man is also deemed to lie outside SKB's sphere of interest at the dose levels to which an acceptable final repository is liable to give rise.

Studies of the ability of microorganisms to influence transport conditions for radionuclides and corrosion of canisters are dealt with in Chapter 5.

Development of models and methods for radiological safety at nuclear power stations, CLAB and SFR as well as operating experience at these facilities will be evaluated and applied during the handling phase prior to the final disposal of the spent nuclear fuel.

The risk of release and dispersal of non-radioactive toxic materials will be taken into account. Research may be required as a result of alternative barrier studies or disposal of special waste types.

4.4.6 Timeschedules

The timeschedules for the biosphere research is presented in Figure 4-1. It is judged that the work within this area can be pursued at an unhurried pace. The planning is based on the intention of maintaining a steady level of employment among the researchers used so that their background and expertise will be available if problems should arise. At present, the work is governed by the need to determine uncertainties and ranges of variations so that it will be possible during the 1990s to concentrate increasingly on site-specific and system-specific questions.

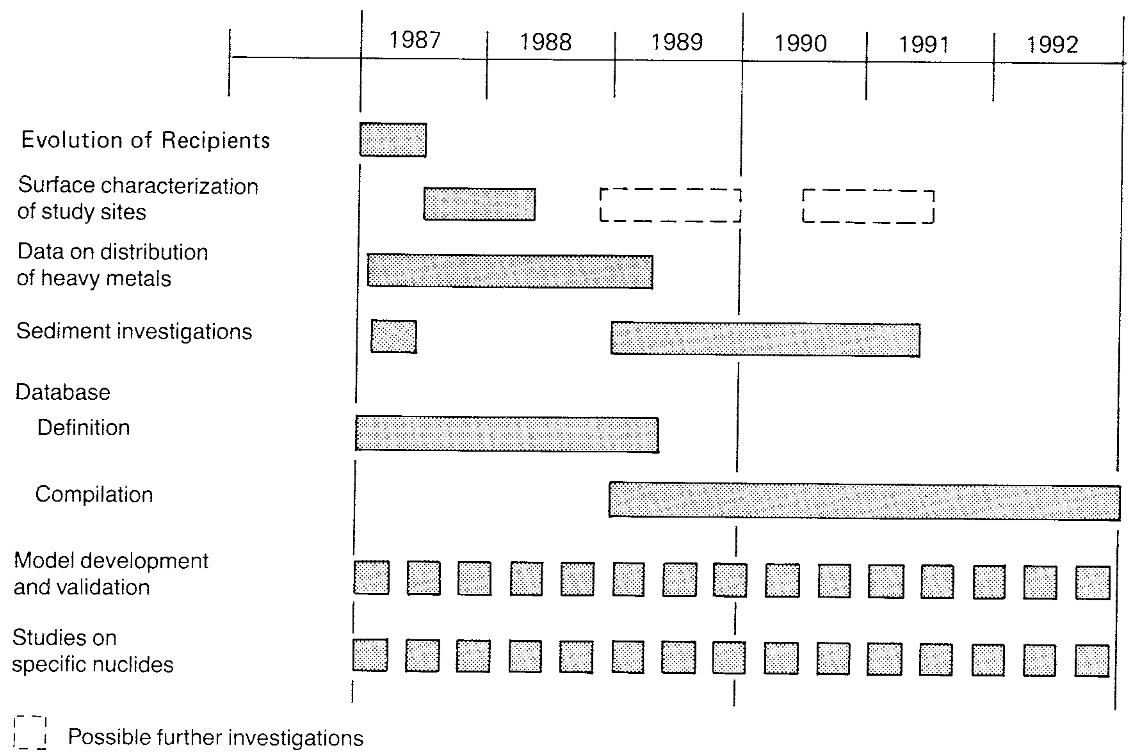


Figure 4-1. Timeschedule for biosphere studies.

5 CHEMISTRY

The chemical parameters that influence the long-term safety of the repository are being investigated within the chemistry programme. The primary goal is to be able to describe the release and transport of radionuclides from the repository and through the rock.

The work consists of collecting fundamental chemical data and developing models and then validating these models by means of tests in the laboratory and field and studies of natural analogues.

The chemistry programme consists of a large number of investigations. They have been broken down into the following subject areas:

- Geochemistry, especially the chemistry of the groundwater in the geosphere and the disturbed near field.
- Radionuclide chemistry, ie the chemistry of the waste's "important" radionuclides in the near field and the geosphere.
- Chemical transport in the near field and the geosphere of radionuclides and inactive species (gas, corrodants, radiolysis products etc).
- Validation of chemical transport models by means of
  - laboratory tests
  - in-situ tests
  - study of natural analogues

The geochemical investigations are closely bound to other geological field investigations in terms of content and timetable.

The content of the chemistry programme is also dependent on the technical proposals for how the radioactive waste is to be treated and disposed of. So far we have presupposed waste forms, encapsulation and repository design as presented in eg KBS-1, 2 and 3. New ideas concerning the treatment and disposal of the waste will require supplementary chemical investigations. The alternative development lines considered and the chemical investigations they warrant are dealt with in the following.

Many of the investigations that are planned or currently underway are, however, of such a general nature that they are applicable to all reasonable proposals for final disposal.

5.1 Geochemistry

5.1.1 Background

Canister corrosion, buffer stability, dissolution of the waste matrix and the mobilitiy of radionuclides in the repository and host rock are influenced to a high degree by the chemical composition of the groundwater. In order to be able to assess the long-term safety of the repository, it is therefore necessary to know the chemical composition of the groundwater and the variations that are possible due to natural causes or the influence of the repository itself.

Moreover, the water's chemical, and in particular its isotope-chemical, composition provides insight into the hydrological conditions in a repository area and support for other investigations of groundwater movements.

The minerals affect the groundwater both chemically and isotope-chemically and are therefore studied in parallel.

5.1.2 Goals of the R&D activities

The geochemical investigations have the following purposes:

- Gather sufficient knowledge of the chemical properties of the groundwaters and minerals that determine canister dissolution, buffer stability, fuel dissolution and radionuclide migration.
- Determine what chemical changes in the natural environment of the near field could be brought about by the repository and any inflowing water of a different composition.
- Obtain geochemical information to support the hydrological model for water flow in the repository.

The first purpose requires continued sampling of water and minerals as well as an increased use of geochemical models to describe the groundwater's Eh, pH and carbonate content. Regular and quantiative analysis of dissolved gases, natural complexing agents and redox-active minerals will be striven for.

The second purpose also presupposes the use of geochemical models, and not just equilibrium models but also reaction models that include heterogeneous reaction systems such as oxidation or actinide reduction by reducing minerals. In addition to theoretical calculations, kinetic investigations in simulated laboratory systems and - if possible - in-situ are also required. Examples of problems of interest are redox reactions in the near field.

The third and final purpose is the most difficult to fulfil. Isotope-chemical analyses are of importance and it is therefore necessary that the sampling be improved as much as possible, for example by completely avoiding the use of drilling water and by sampling between a sealed-off section and the bottom of the borehole during pauses in the drilling. Sampling in underground facilities has also proven advantageous (artesian conditions). An underground research laboratory in a previously undisturbed region provides a unique opportunity for geochemical investigations for all three purposes. Permanent samplers from the surface and in the underground facility can follow the change in water composition with time and the inflow due to drainage pumping.

5.1.3 Present-day state of knowledge

A large number of study-site investigations were carried out as a basis for the KBS-3 report. Groundwater samples were taken regularly and analyzed. Fracture minerals were also mapped, and a more detailed characterization was carried out on a few of the sites.

All water samples were taken with the same equipment and the same sampling strategy, ie two or more boreholes on a site were selected for water sampling after the geohydrological survey. A number of conductive zones in the borehole were isolated with packers and water was pumped up to the surface, where electrochemical measurement of Eh and pH was carried out and a large number of water samples were isolated. The water samples were then sent to outside analysis laboratories.

The same equipment and largely the same methodology was later used at Taavinunnanen and Klipperås. Experience from the investigations is summarized in /5-1/.

A special mobile field laboratory for water sampling and analysis under field conditions was taken into service in 1984. Electrode measurements of Eh and pH are performed down in the sampling zone with a specially developed probe. The most common groundwater components are analyzed directly in the field, as are redox-sensitive trace substances. The drilling water is marked with a dye and the content of residual drilling water is measured on site in the mobile field laboratory. The results are stored in a field computer and sent in regularly for central compilation and evaluation.

Water is sampled at an earlier stage nowadays. A special seismic technique (tube-wave) has been used successfully for rapid location of water-bearing fractures.

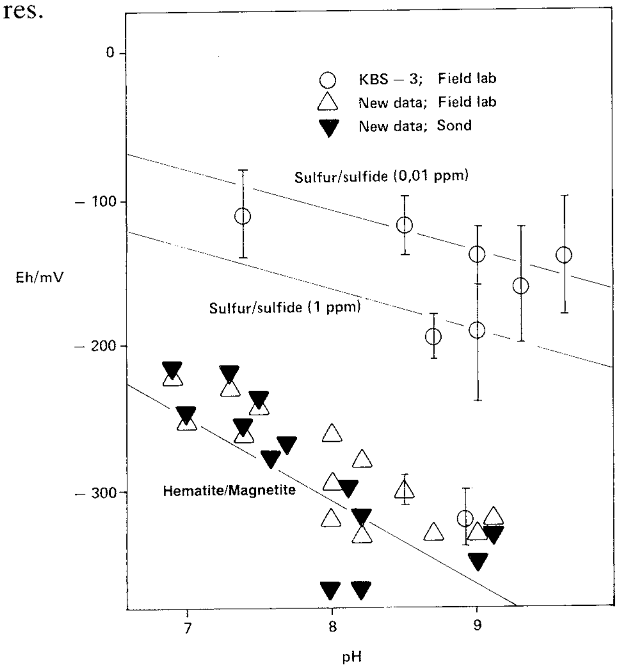


Figure 5-1. Field measurements of Eh and pH in deep groundwaters. The new measurements have been carried out for the most part with a borehole probe (▼) and in the new mobile laboratory (△). Probe and laboratory are interconnected.
The curves are calculated. High values are explained by small quantities of atmospheric oxygen (oxidizes sulphide to sulphur) in previous measurements reported in KBS-3 (○).

The quality of the analysis results has been improved considerably with the adoption of the new technique. Sampling and analysis with the mobile field laboratory have been carried out at Fjällveden, Klipperås and Finnsjön, see Figure 5-1.

The composition of the water is highly dependent on residence time or degree of isolation in the rock. From this standpoint, it would desirable to take samples of all conceivable categories, from highly conductive zones to rock zones with relatively low conductivity. So far, good samples have been obtained from an intermediate range. The ongoing development of early sampling and water-free drilling will hopefully make it possible to take uncontaminated water samples even from highly conductive zones. A new technique will have to be developed for sampling of low-conductive zones.

Evaluation

The groundwater analyses carried out to date have mainly been aimed at finding out the normal water composition at repository depth in granitic bedrock and the deviations that can occur, for example saline groundwater. A great deal of attention has been devoted to groundwater parameters that are of importance for the safety of the repository, eg redox conditions, pH, content of organic and inorganic complexing agents, sulphide, chloride etc.

Chemical relationships that regulate pH and carbonate content as well as redox conditions were described with simple models already in the KBS-3 study. Recently, advanced geochemical models and calculation programs have found increasing use. Such a computer program is EQ3/6, which has been used to interpret redox measurements /5-2/.

Initial attempts have also been made to use geochemical models that include transport of dissolved substances.

The chemical development of the groundwater composition can also be traced in the fracture minerals. It is possible, for example, to see in drill cores from typical inflow areas how young, carbon-dioxide-rich, near-surface groundwater has dissolved calcite minerals in water-bearing fractures. Older deep-lying groundwaters are saturated or even supersaturated with respect to calcite. This is in turn due to the fact that calcium has been supplied or the pH has been raised through the influence of the rock minerals. Vertical flow conditions and chemical groundwater-mineral relationships are indicated in this manner in the fracture minerals /5-3/, see Figure 5-2.

Isotope-geochemical investigations are traditionally used to describe the origin and "history" of the groundwater. The concentration of the stable isotopes oxygen-18 and deuterium in water, as well as carbon-13 in dissolved carbonate, are sampled and analyzed regularly. In addition, the radioactive isotopes tritium in water and carbon-14 in dissolved carbonate are also analyzed.

Oxygen-18 and deuterium show that at least most of the water is of meteoric origin (precipitation).

Owing to its short half-life, tritium can reveal rapid inflow, but its presence is usually a sign of severe

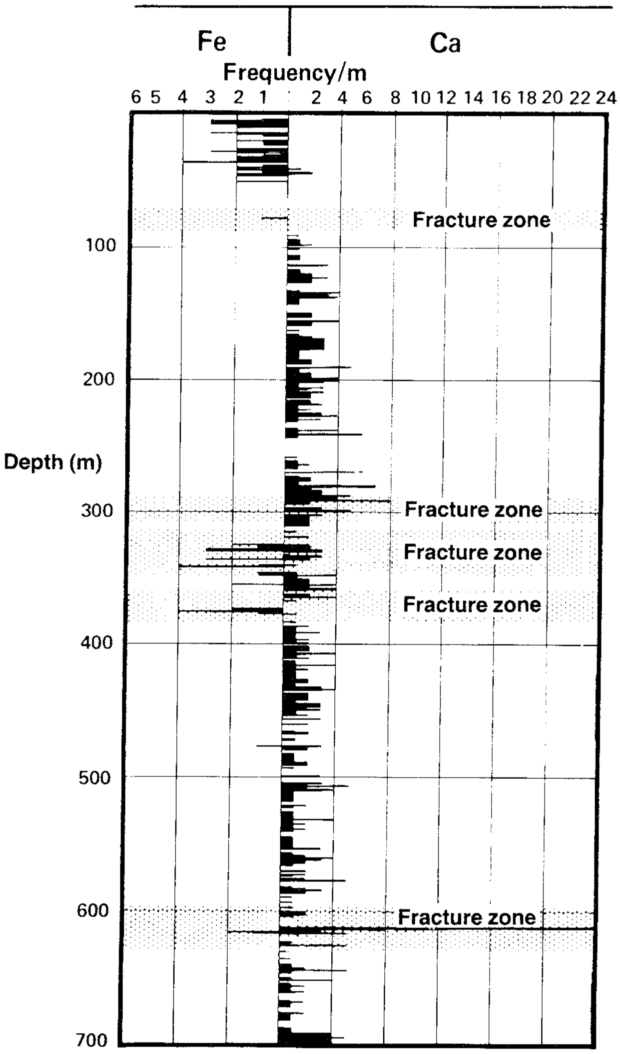


Figure 5-2. Iron oxide hydroxide (rust) and calcite (calcium carbonate) in fracture minerals from drill cores, Klipperås, borehole Kl 12. Oxidizing conditions (rust) and calcite dissolution in the upper 100 m are followed by reducing conditions and calcite precipitation further down. Traces of oxidation are also found in the fracture zones.

sample contamination with drilling water or other near-surface water.

Carbon-14 is in principle a suitable method for dating groundwater, but very old deposits of different carbon compounds in the rock (mainly carbonates) can make contributions that are difficult to estimate. The carbon-13 content can be used to some extent for correction.

In several cases, other stable and radioactive isotopes have also been analyzed. A good example is uranium-234, whose relative content (uranium-234/uranium-238) is extremely sensitive to redox conditions.

The isotope-geochemical results were not used to any great extent in the KBS-3 analyses. There are a number of reasons for this. One important reason is the high demands on the purity of the water sample when the radioactive isotopes are sampled - demands which could often not be met previously. There has been a considerable improvement in this respect.

Already today there are examples of results that support conclusions on hydrological conditions. The presence of saline waters in Stripa, Finnsjön and Forsmark (SFR) points towards stagnant conditions. Calcite dissolution in fractures points towards marked inflow at Taavinunnanen. Low contents of carbon-14, tritium and similar radioisotopes point towards a high degree of isolation in a number of cases. It is difficult but desirable to quantify these observations.

New methodology for the analysis of isotopes and interpretation of results is being developed within the Stripa project. More methods, and more unusual ones, are being tested here than in other field investigations /5-4/.

Simulation of natural systems

The minerals in the rock are of great importance for the chemistry of the groundwater. A large number of substances are transferred to the water, and most of the buffering capacity for pH, and to an even higher degree Eh, lies in the minerals. Accessibility and reactivity are of very great importance and are sometimes difficult to appreciate immediately. Reaction kinetics are therefore investigated in simulated systems in the laboratory.

Redox kinetics are of particular importance, ie how oxidants are consumed and actinides reduced.

Near-field chemistry

Geochemical models are used to predict the changes the repository may bring about in minerals and groundwater in the near field. The components of the repository, such as canister and backfill materials, are also included in this evaluation. Highly simplified and conservative assumptions and models were used for KBS-3 to describe the significance of the heating and the development of a possible redox front.

Advanced geochemical models have since been used to evaluate the effects of heating for minerals, water and bentonite clays. This is work that has been done by specialists at the University of Strasbourg. The computer programs EQUIL and THERMAL have been used /5-5 and 5-6/.

5.1.4 1987-1992 research programme

Sampling and analysis of water

Finnsjön and Ävrö

The water sampling is coupled to the field investigations that are being conducted. The mobile field laboratory is being used for sampling in boreholes from the surface. Such work is underway now in 1986 at Finnsjön and is planned to continue at Ävrö. Newly developed technology - large diameter percussion drilling, gas sampling etc - will be introduced as it becomes available.

Underground research laboratory

Preliminary studies are planned to start for an underground research laboratory in 1987. Water sampling will be carried out at an early stage, well separated from other activities so that the undisturbed conditions can be described.

During shaft sinking or tunnelling, the chemical changes will be followed continuously in permanently installed samplers in selected boreholes from the ground surface. This sampling system has not yet been developed, but equipment similar to that used in the URL in Canada could probably be used (Westbay Casing). Water seapage into other boreholes will be prevented.

The possibility of taking good water samples of high quality is very good down in the underground research laboratory, since artesian conditions can be counted on. Samples will be taken from boreholes from tunnels and shafts in a similar manner as is now done in Stripa and Forsmark (SFR). In the underground facility as well, it is important that chemical sampling be started at an early stage.

Permanent samplers will be installed in conductive zones in the underground facility in order to permit changes to be followed with time. It can then be seen if and when eg surface water, sea water or dye-marked drilling water from the above-ground drillings reach the underground facility and this can be compared with hydrological observations and calculations.

Technology for sampling of water underground exists but needs to be developed somewhat. Measurements with an in-situ probe for pH and Eh are highly desirable underground as well. The mobile field laboratory or the equipment included in it can be used to carry out most other analyses in place. In this way, considerably better and quicker analyses can be obtained.

Forsmark - SFR
Sampling in SFR will continue. The analyses will be extended to include parameters that will later also be measured in the research laboratory, ie measurement with pH-Eh probe, analysis of geochemically important trace elements such as iron, aluminium, silicon and sulphide, characterization of organic matter and gas analyses.

It is also possible to use the mobile field laboratory in SFR.

The equipment for underground sampling can be developed in connection with the SFR sampling.

Other sites
Boreholes on previous sites can be used for testing of equipment and for spot collection of large quantities of deep groundwater for special investigations, eg organic matter.

Collection of water from springs within a test site for the purpose of locating any outflow of deep-lying groundwater has been discussed. It is relatively easy to do. Trials are being considered on some previous test site.

Sampling and analysis of fracture minerals
Fracture-mineralogical investigations are striven for on most test sites for the purpose of explaining the water's chemical composition and indicating geohydrological conditions on the site.

Evaluation and reporting of results
The large quantity of water analysis data that is produced will be examined and reduced in the same manner as in the KBS-3 report. Both primary and processed data will be stored in SKB's database system, where previous analysis results are also stored. In addition, the results will be published in reports as before, where the manner in which primary data has been processed will also be described.

For the time being, the results of the fracture mineral analyses will only be presented in report form.

A coherent geochemical evaluation for each study-site in accordance with the guidelines laid down in /5-1/ is striven for. This evaluation should include the following:

- A careful assessment of the relevance of the water analyses on the basis of both hydrological measurements and water analyses.
- A geochemical evaluation of water and mineral composition with the use of advanced geochemical models.
- An assessment, as far as is possible, of the water's origin and residence time on the basis of geochemical information from groundwater and fracture minerals.

Reaction kinetics investigations
Laboratory simulations of the rock-water system for the purpose of determining the rock's reducing capacity and reaction rate are being conducted and will continue. An in-situ test with a similar purpose is being considered.

Near-field chemistry
Geochemical model calculations of developments in the near field, eg water composition and mineral alteration, are being conducted and will continue. A development of coupled models, transport/chemical reactions, has been initiated. If one wishes to assume considerably higher repository temperatures than 100°C, it is necessary to conduct a specific analysis of the importance of this for the near field. This requires, among other things, a database for the temperature range in question, since it is not possible to extrapolate existing data to temperatures much higher than 100°C.

5.2 Radionuclide chemistry

5.2.1 Background

The solubility and mobility of radionuclides are determined by their chemical properties and the chemical environment that prevails inside and outside the repository. Calculations of possible releases to the biosphere in the event of canister penetration are based on data on solubility, sorption and diffusion.

In general, the solubility and mobility of most radionuclides in groundwater are low. Special attention will be devoted to exceptions to this rule and in particular to mechanisms that could alter the picture in an unfavourable direction, eg radiolysis, redox reactions, complexation and colloid formation.

5.2.2 Goals of the R&D activities

The goals of the radionuclide chemistry investigations are as follows:

- Measure and compile the basic chemical data required to describe solubility, inorganic speciation and coprecipitation of radionuclides in and outside the repository.
- Determine possible contents, stability and mobility of dissolved radionuclides in the form of colloids, humic complexes and other aggregates, eg microbes.
- Describe the interaction of radionuclides with rock and backfill material in the form of redox reactions, surface sorption and diffusion.
- Determine the scope and influence of radiolysis in the near field.

The first point is being carried out to a great extent in international cooperation, with an emphasis on measuring solubility constants and compiling a generally accepted and well-documented database. Further measurements are being made where necessary and modern computer technology is being utilized for both storage of data and chemical model calculations. It is desirable that all calculations included in a final account should be carried out with one and the same database, which is also reported.

The second point includes analysis and characterization of the aggregates - eg colloids, humic substances (humic and fulvic acids) - and microbes present in the groundwater. It also includes experiments with the uptake and mobility of radionuclides in such form. Finally, it includes modelling of radionuclide speciation and transport properties, as far as this is possible.

The third point entails both laboratory experiments and model studies aimed at understanding the physico-chemical process of retention in the rock and providing the transport models with retardation constants or submodels for surface sorption and diffusion. It is also important to show that postulated reactions between radionuclides and minerals actually take place, for example reduction of technetium and neptunium.

Regarding the fourth point, good means already exist for calculating the radiation field outside and inside a waste canister as a function of time. There is also a radiolysis kinetics model that provides a means of calculating the scope of radiolysis. New encapsulation concepts require new calculations.

In order to validate the radiolysis model used, radiolysis experiments with uranium dioxide, and preferably also with high-level waste, are required (see Section 2.3.5).

5.2.3 Present-day state of knowledge

Solubility, speciation and coprecipitation

Thermodynamic equilibrium constants that describe the solubility and speciation of radionuclides in the groundwater are being determined at many different places around the world. SKB is cooperating with CEA in France to supplement data for a number of important nuclides /5-7/.

International cooperation is being conducted within the IAEA and the OECD/NEA to review and compile the equilibrium constants. The most important effort, from our point of view, to produce an accurate, consistent and well-documented thermodynamic database for radionuclides is being made by the OECD/NEA /5-8/. A number of international experts are involved in this effort. SKB is supporting the work and following it carefully.

Advanced chemical calculation models such as EQ3/6 and PHREEQE have been introduced and are being used increasingly to describe radionuclide chemistry in groundwater /5-2/.

Solid solutions of different actinides (plutonium, neptunium etc) in uranium greatly reduce their solubilities. The dissolution of actinides in spent fuel is impeded by this means. Moreover, already dissolved actinides can be coprecipitated with uranium if dissolved uranium later becomes supersaturated due to reduction. This coprecipitation phenomenon is well-known and is also expected to appear in other contexts of importance for radionuclide migration, for example when corrosion products are formed or minerals are altered. The difficulty lies in developing a quantitative model. However, there are good prospects for this succeeding for such chemically closely-related substances as the actinides /5-9/. Experimental and theoretical work is underway.

Organic complexes, colloids and microbes

Radionuclides are transported in water in dissolved and in particle-bound form. Knowledge of how low-molecular-weight complexing agents affect the solubility and speciation of the different radionuclides is relatively advanced. Compounds of high molecular-weight, such as humic and fulvic acids, can also form complexes with radionuclides. The importance of these substances for the transport of radionuclides in deep-lying groundwaters is, on the other hand, poorly understood. Since the KBS-3 report was written, such substances have been isolated from superficial waters and used in complexing experiments. A theoretical model for these complexing reactions has also been developed /5-10/.

Sorption of radionuclides on inactive particles appears to be the most important mechanism for radiocolloid formation. A laboratory study has recently been carried out and evaluated /5-11/. The concentration of natural colloids is probably much lower than was assumed in the KBS-3 safety analysis.

Microbes can bind different radionuclides, which will thereby be transported in "particle-bound" form. Microbial processes could conceivably also be of geochemical importance. The question has been explored in connection with repository studies in Switzerland /5-12/ and England /5-13/. A preliminary study of the potential importance of microbe transport has been carried out under contract to SKB /5-14/.

Radionuclide reactions

The need to determine the rock's reducing capacity with respect to oxygen and other oxidants has already been discussed, see Section 5.1.3. It is also urgent to find the rock's redox buffering capacity for oxidized radionuclides and the rate at which the reactions proceed. As a rule, reduction reduces both solubility and mobility.

Attempts to demonstrate this have been underway for some time.

Sorption and diffusion

A large number of experiments with sorption of radionuclides on pieces of rock and diffusion of radionuclides in bentonite clay and into pieces of rock were conducted for the KBS-3 report.

In recent years, laboratory experiments have been conducted with diffusion in rock /5-15 - 5-17/ see Figure 5-3. Efforts have gradually focussed on an understanding of sorption and diffusion on mineral surfaces and a modelling of these processes. Models for surface sorption have, incidently, already been implemented in certain geochemical calculation programs.

Sorption and diffusion of radionuclides in concrete have been studied in depth with an emphasis on conditions in SFR. The special chemical environment in concrete - eg high pH and high calcium content - has been analyzed and described /5-18/.

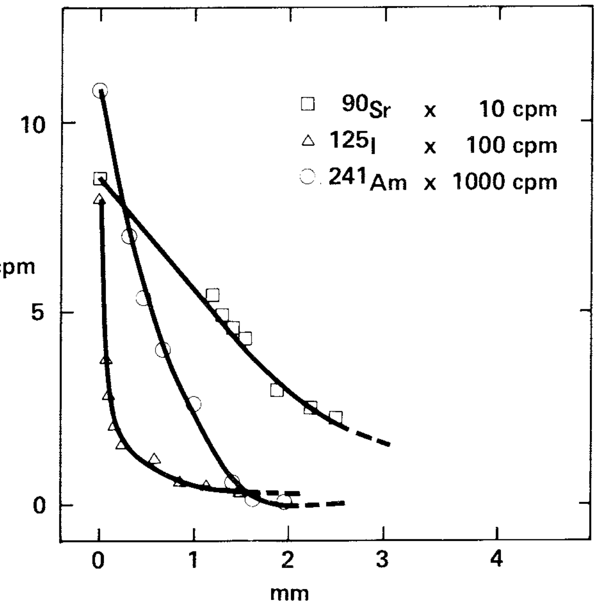
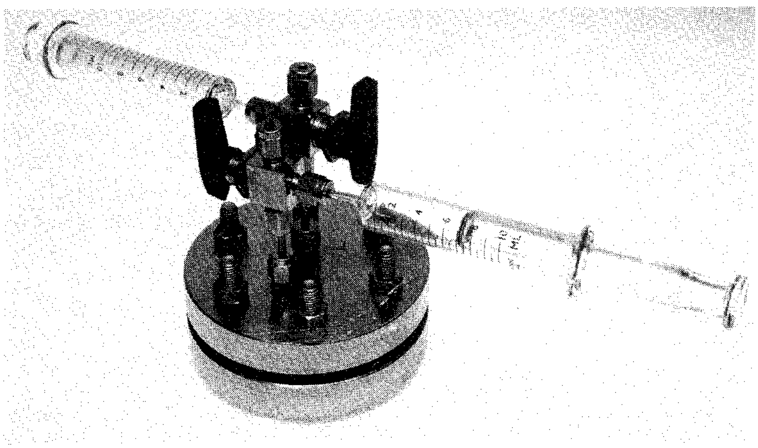


Figure 5-3. Measured penetration of radionuclides in granite from an aqueous solution. The contact times are 164 days for strontium, 421 for iodine and 1 202 days for americium. As expected, strontium penetrates faster than americium. What is remarkable is the insignificant penetration of iodine.

Radiolysis

Radiolysis outside a canister containing spent fuel and radiolysis inside the canister if it is penetrated have been dealt with and analyzed in the KBS-3 report. The estimates were based on calculations of the radiation field outside and inside a canister, an assumed exposed fuel surface and theoretical calculations with a model for radiolysis kinetics. The model had been tested in experiments with gamma and beta radiolysis of water in bentonite clay.

Since then, supplementary calculations have been carried out of the formation of nitric acid and organic compounds /5-19/ and the effect of simultaneous beta and alpha radiolysis /5-20/. Alpha radiolysis experiments have been conducted and compared with theoretical calculations /15-21/, see Figure 5-4. The radiolysis model has worked well and the results obtained thus far support the original assessments in the KBS-3 report. Calculations have also been carried out to shed light on the importance of radiolysis in cemented low- and intermediate-level waste /5-22/.



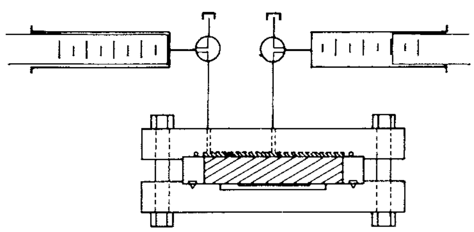


Figure 5-4. Equipment for measuring hydrogen production in alpha-irradiated wet compacted bentonite. The radiation source contains ^{241}Am and gives 30 MBq (nominal activity). The diameter of the active surface is 25 mm.

5.2.4 1987-1992 research programme

Solubility, speciation and coprecipitation

Continued measurements of thermodynamic solubility constants for actinides in the natural water system are foreseen. The emphasis so far has been on the carbonate ion as the most important ligand. An increased interest in other ligands is anticipated, eg phosphate ions.

Continued coprecipitation experiments of three different kinds are foreseen: Fundamental inactive experiments, experiments that simulate natural systems and laboratory experiments with radionuclides. Other types of coprecipitation than with uranium may also be studied.

SKB plans, with the aid of its scientific consultants, to build up its "own" documented database in the field of radionuclides and geochemistry. It is expected to rest on the OECD/NEA's database in all essential respects. The database, as well appropriate calculation programs, eg EQ3/6 and PHREEQE, should be able to be kept generally available /5-23/.

Colloids, humic complexes and microbes

The quantity and nature of such substances in natural groundwaters will be investigated.

In the case of colloids, this means that sampling methods must be developed and suitable analysis methods tried out.

In the case of humic substances, relatively large quantities must be collected for further characterization and experimentation. A separation line will be built up where humic substances that have been collected from large volumes of groundwater can be analyzed and isolated for further experiments.

Further experiments with radionuclides and natural colloids are planned.

Further experiments with radionuclides and natural organic complexing agents will also be conducted. The possibilities of building up a model that describes this type of complexing agents are explored experimentally and theoretically.

A continuation of completed preliminary studies of the importance of microbes is planned. Developments in England in particular will be followed carefully.

In summary, it can be said that the emphasis in the investigations will lie on natural organic complexing agents such as humic and fulvic acids. They are generally of great importance for trace substances in natural waters. Relatively large-scale studies have been initiated.

Building a repository closer to the surface would entail water with a lower ionic strength and a higher expected content of organic compounds. This would then have to be taken into account from the standpoint of colloid and complex formation.

Radionuclide reactions

Laboratory experiments with reduction of redox-sensitive radionuclides such as uranium, neptunium and technetium have been underway for some time. Further experiments with uranium are currently being conducted and an increased effort in this part of radionuclide chemistry is foreseen. In-situ experiments along similar lines are being considered.

Weathering processes are expected to increase the sorption of radionuclides. This will be further explored, if possible.

Sorption and diffusion

Laboratory experiments with sorption and diffusion of radionuclides in the rock minerals will continue, but will now be focussed on obtaining data for the more advanced models for sorption and diffusion, ie surface diffusion, surface complexation, surface reaction etc. Priority will be placed on a better understanding of the phenomena and development of submodels that can be used in the transport models.

The laboratory experiments with sorption and diffusion in concrete will continue with a focus on alternative repository concepts for high-level waste. The influence of the concrete on the environment and chemical and structural changes in the concrete itself must also be further examined.

Bentonite with additives ("getters") has been proposed. An investigation of this involves experiments with radionuclide diffusion and reaction in such a mixture as well as studies of the effects of the additives on the bentonite and other near-field components.

Radiolysis

Further experiments and supplementary model calculations are foreseen. An important development in this field is experiments coupled to the investigations of the spent fuel, see Section 2.3.

A ventilated final repository involves other conditions for radiolysis, which must then be analyzed.

5.3 Chemical transport

5.3.1 Background

Transport calculations for dissolved substances in the near field are essential in the assessment of the performance and safety of the repository. Both the outward transport of dissolved radionuclides and the inward transport of inactive substances that affect the buffer materials, the canister and the waste, are of importance. The outward transport of inactive substances that affect the buffer materials and the rock are of importance as well.

Calculation models for the transport of radionuclides in the far field are necessary tools in the safety assessment.

In addition to the basic geochemical and radionuclide chemistry data, which have already been dealt with in the preceding section, the hydraulic properties of the host rock, the design of the deposition chambers and the components included are important basic data for estimates or calculations of transport in the near field.

Also fundamental for all calculations of radionuclide transport in the far field are the geohydrological models for water flow in fractured rock.

5.3.2 Goals of the R&D activities

The goals are to describe the following:

- Changes in the chemical environment in the near field due to transport-dependent processes.
- Transport of radionuclides out from the near field.
- Migration and retention of radionuclides in the geosphere.

The first point pertains to a whole series of transport-dependent chemical processes that affect corrosion, buffer stability, porosity in surrounding rock and the development of a redox front in buffer or near-filled rock.

New repository concepts have a great influence, eg choice of waste quantity, canister and backfill materials, rock type, repository depth and groundwater conditions.

The second point pertains to the outward transport of radionuclides from the near field. Greater knowledge of the hydraulic properties of the near field, new models for radionuclide release from the waste and choice of alternative repository designs are of decisive importance for developments in this area.

The third point pertains to radionuclide migration in the undisturbed rock.

5.3.3 Present-day state of knowledge

The near field

The transport of the following substances in the near field has been analyzed in connection with the KBS-3 report:

- Corrodants: Sulphide, sulphate and ferrous ions, oxygen.
- Radiolysis products: Oxidants, hydrogen.
- Complexing agents: Carbonate ions, humic and fulvic acids.
- Radionuclides.
- Bentonite reactants: Calcium, potassium.

Analytical solutions have been sufficient for the transport equations that have been set up, which has been confirmed by comparison with more advanced models using an integrated finite difference method /5-24/.

The importance of diffusion resistance in the slowly flowing water in the rock adjacent to the buffer and the canister has been demonstrated /5-24/.

The development of a radiolysis front has been predicted and calculated on the basis of simplified assumptions concerning redox reactions between iron minerals and oxidants generated by radiolysis /5-25 - 5-27/.

The importance of heating for transport has only been analyzed with respect to increased water flow through convection /5-28/. No coupled phenomena (Onsager effects eg thermal diffusion) have been taken into account owing to the very small temperature gradients that have been considered.

The far field

Dispersion in the flow direction, as well as retardation due to surface sorption, K_d, and diffusion of radionuclides into the open microfractures in the rock were dealt with in KBS-3.

This development has since continued. Models of dispersion in the flow direction, for example channelling, /5-29 and 5-30/, are important to validate. The transport of radionuclides in highly fractured rock - fracture zones - has been analyzed theoretically /5-31 and 5-32/. No allowance was made for the retardation of migrating radionuclides in fracture zones in KBS-3.

The development of models that couple transport models and geochemical models has been initiated. Their use is foreseen for both the near and the far field /5-33/.

5.3.4 1987-1992 research programme

The near field

The models for the transport of radionuclides out of the near field will be expanded to take into account chain decay, solubility limits and a more exact description of the geometry of the repository.

Chemical changes in Eh and pH and mineral alterations in the near field will be described with coupled models for transport/geochemistry. The transport of gas out of the near field will be described with models.

The need for the development described above arises above all in connection with analysis of alternative repository designs, other canister materials, for example iron or ceramics, and other backfill materials, for example concrete.

Wherever higher temperatures are involved, the chemical problems they entail should be particularly examined.

The far field

The already initiated development of models that couple transport with an exact description of chemistry, ie geochemistry models, will continue. The goal is to calculate the change in the composition of the water along the flow path so that radionuclide precipitation, dissolution, sorption etc can also be calculated. Multidimensional transport and matrix diffusion will be incorporated. The development of detailed models for surface sorption and diffusion will be made use of and included in the transport models.

5.4 Validation of transport models

5.4.1 Background

In the analysis of repository function and safety, calculation models are used for the escape and transport of radionuclides. These models and underlying conceptual models must be tested - validated - by means of independent tests and observations. For practical reasons, it is necessary to use a mixture of examples where different parts of and aspects of the models are tested. Laboratory tests, in-situ tests and studies of examples in nature - natural analogues - are used for this purpose.

The advantage of simulating natural conditions in the laboratory lies, of course, in the fact that the experimental conditions can be completely controlled. This is of particular importance for tests of radionuclides, which are strongly sorbed and which require radiologically safe handling.

In-situ tests are suitable for validating models of water flow in rock and for cases where it is impossible or difficult to simulate undisturbed conditions in the laboratory, eg diffusion in undisturbed rock and redox processes.

The safety of a final repository must be assessed on a time scale that is inaccessible to planned tests. However, examples of release and migration of radionuclides in nature can serve as objects of study in this respect.

5.4.2 Goals of the R&D activities

The goal is - by means of laboratory tests, in-situ tests and studies of natural analogues - to validate the chemical transport models that are used to describe the release and dispersal of radionuclides from a final repository. A combination of results obtained from the tests and studies mentioned above should cover all validation aspects.

An important aspect of this work is keeping up with new findings and constantly testing existing models on the experimental and investigation results obtained here and elsewhere. Similarly, the needs of the transport models shall govern the choice of validation investigation.

5.4.3 Present-day state of knowledge

Laboratory tests

Drill cores taken so that they contain a natural water-bearing fracture have been used since the end of the 1970s for hydrodynamic flow tests and migration tests with radionuclides /5-34/. The results have been analyzed with transport models that include mixing, diffusion in open micropores, surface sorption and dispersion /5-35/.

In-situ tests

The goal of tracer tests in situ has primarily been to study groundwater flow. This is an important task, since the size and distribution of the water flow governs to a high degree the processes that are important for the safety of the repository, see Sections 3.1 and 3.3.

Migration tests with real or simulated radionuclides have been difficult to execute and interpret. Even weakly sorbing substances can be retarded so strongly that a high flow, short migration distance or long observation time is required.

Cross-hole tests with sorbing radionuclides or radionuclide-like substances from the ground surface have been conducted in Studsvik /5-36/ and Finnsjön /5-37/. The flow here has been increased by pumping in the sampling hole. The results have been interpreted with transport models and reported in KBS-3.

In-situ tests with both sorbing and non-sorbing substances have been conducted in a single fracture in Stripa within the OECD/NEA project. Despite the relatively short migration distance, it was necessary to overcore the fracture and analyze the surface in order to determine the transport of the sorbing substances. The results of the tests have been reported /5-38/.

A large-scale test with non-sorbing tracers, known as the 3D-test, is also being conducted in Stripa within the framework of the international OECD/NEA project /5-39/.

Tracer tests with non-interacting tracers in Stripa have also been conducted entirely on behalf of SKB. The water flow in a small but well-defined rock mass is being investigated in hydraulic cross-hole tests /5-40/.

Since 1982, a series of in-situ tracer tests of a somewhat different nature have been conducted in Stripa in order to investigate the diffusion properties and accessibility of the interconnected micropore system in undisturbed rock. Non-sorbing tracers are injected under low pressure in a relatively thin borehole well away from the disturbed zone around the tunnel. Two such tests have been executed and analyzed /5-41 and 5-42/. The results are reported in KBS-3. The final test in the series, which began in 1982, has now been discontinued for sampling and analysis.

In summary, in-situ tests have been performed both with non-sorbing tracers and with sorbing radionuclide-like substances. The results have been used to validate transport models. The use of internal and external laboratory tests and in-situ tests for validation of models for radionuclide transport is being followed up systematically.

Natural analogues

A conclusion drawn from reviews of previously conducted studies is that there is no analogue that simulates in all respects the conditions in a final repository. It is, however, possible to discern natural processes that are the same /5-43/.

The Oklo reactor in Gabon in Africa was investigated relatively thoroughly by international experts under the auspices of the IAEA. The results of these and more recent investigations were analyzed for the purpose of evaluating the radiolysis and its effect on the immediate environment and the release of radionuclides from the "fuel" /5-44/.

A further review and compilation of the investigation material from Oklo has been done /5-45/. Particularly remarkable is the fact that the "fuel" has been affected so little. Furthermore, actinides and rare earth metals have stayed put, while technetium, alkali metals and alkaline rare earth metals have, not unexpectedly, been mobile. Some of these latter elements have been retained by surrounding sandstone.

The thorium deposit at Morro do Ferro in Brazil has previously been investigated mainly with respect to dispersal of radionuclides in the biosphere /5-43/. Sweden (SKB) has participated here together with the USA, Brazil and Switzerland (NAGRA).

Drill cores from Kråkemåla (Sweden), Grimsel and Böttstein (Switzerland) have been investigated in cooperation with Swiss NAGRA. The goal has been to determine the mobility of uranium perpendicular to a water-bearing fracture in granitic rock. In the Swedish samples from Kråkemåla, it can be seen that uranium has been mobile within 3 cm of the fracture /5-46/.

5.4.4 1987-1992 research programme

Laboratory tests

Tests with radionuclide migration in open fractures that have been overcored and taken into the laboratory will continue. Efforts will be made to simulate the natural chemical environment to as great an extent as possible, ie carbonate-controlled pH and oxygen-free, reducing conditions.

Increased activities are foreseen to validate models for consumption of oxidants, reduction of actinides, coprecipitation and bacterial action.

In-situ tests

Tests with non-interacting tracers are foreseen within the framework of the fracture zone investigations, in the Stripa project and in the underground research laboratory, see Sections 3.1, 3.4 and 7.3.

Tests with sorbing substances are being considered. The rock's reducing properties with regard to oxygen and redox-sensitive radionuclides may be the subject of in-situ investigations, depending on the outcome of preliminary investigations.

Natural analogues

In cooperation with England (UKDOE), Switzerland (NAGRA) and Brazil, an investigation of natural analogues is being conducted in Poços de Caldas in Brazil /5-47/. The work was commenced in May 1986 and is planned to last three years. SKB is responsible for the project management, see further Section 7.6.

Domestic uranium mineralizations will be investigated extensively to provide a body of data so that the Poços de Caldas project can be supplemented with further investigation in Sweden in a few years. Preliminary studies have shown that the comparable Swedish analogues are not as simple and clear, but on the other hand, rock and groundwater conditions are more similar to our repository conditions.

The joint Swedish-Swiss studies supported by SKB and NAGRA of the distribution of natural radionuclides around open fractures in drill cores from granitic rock will probably continue. Discussions are being held.

The uranium mineralizations in the Alligator Rivers area in Australia /5-43 and 5-49/ and at Cigar Lake in Canada /5-49/ have been proposed by the respective host countries as suitable objects for international natural analogue studies. Both of the deposits exhibit interesting features. The uranium ore at Cigar Lake, for example, is located down in the rock isolated by a shell of secondarily formed clay. In Alligator Rivers, the uranium with associated substances is located near the ground surface and consequently participates in ongoing transport processes, where particles and probably also humic substances participate.

At present, we are awaiting the results of the preliminary investigations and planning of the Alligator Rivers and Cigar Lake projects. A future Swedish participation is possible.

6 SAFETY ASSESSMENT

6.1 Background

Before the safety of a final repository can be assessed, the repository site and engineered barriers must be defined and their interaction with each other and the environment identified. In this way, the performance of the repository and its constituent components can be defined for different selected external circumstances (scenarios). An assessment of the performance of the repository expressed in relevant terms with respect to functional and safety requirements is called a safety assessment, see Fig 6-1.

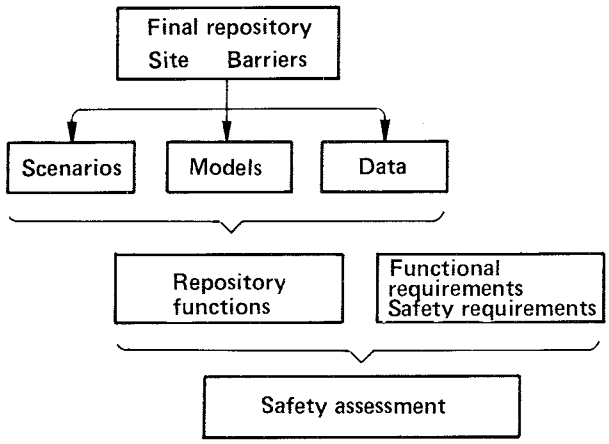


Figure 6-1. General scheme for functional and safety analyses.

The purpose of the performance assessment will change during different phases of the development and licencing of a final repository for spent fuel. In an early phase, the performance of the subsystems in the repository are evaluated in order to permit priorities to be assigned to research and development measures. Eventually, a balance must be found between the safety barriers; the system must be optimized with respect to performance and cost at an acceptable safety level. During the licencing phase, it must be formally and finally demonstrated that the system fulfils the demands of society and the regulatory authorities on safety. Different purposes make different demands on the performance assessment.

After a presentation of the goals in Section 6.2, scenario selection and scenario analysis as well as acceptance criteria are discussed in Section 6.3. The development of models and a database for assessment of the performance of the repository is dealt with in Section 6.4, and the performance and safety assessments intended to be carried out over the next six-year period are dealt with in Section 6.5.

6.2 Goals of the R&D activities

In an early phase, development of the repository concept was conducted in parallel with the feasibility studies required by law. The strategy chosen for the performance assessment in KBS-1 and KBS-3 allowed simplifications to be made as long as they did not lead to underestimation of the radiological consequences of the existence of the repository.

Since the KBS-3 report, the goals of the development work conducted for the performance and safety assessments have been reformulated. The new goals take aim at the final selection of a repository site and the designing of the repository itself.

The overall goals are to:

- perform a final safety assessment of the actual repository,
- be able to carry out more realistic assessments in order to better quantify the safety margins.

The development work is aimed at preparing the ground for:

- assigning priorities to research and development work,
- evaluating a number of possible repository sites and a number of non-site-specific design principles as a basis for a ranking,
- optimizing the repository design for the finally chosen site. For this, the near-term research activities must be aimed at compiling the databases and models required for different alternative designs,
- judging the uncertainties in the predictions of repository performance, radiological consequences and overall safety, and assessing the sensitivity of the results with respect to variation in design parameters and uncertainty in the database.

6.3 Scenarios and acceptance criteria

In order for a relevant performance assessment to be carried out, the external conditions relevant to the purpose of the assessment, the design of the repository and the site must be defined.

Scenarios can be chosen to represent changes in:

- environmental conditions that can affect the performance of the repository, eg glaciations or human intrusion into the repository,
- natural conditions or the use of natural resources that can influence the radiological consequence assessments, eg drying-up of the Baltic Sea (due to seabed uplift) or large-scale changes in diet.

Scenarios can also represent extreme situations or the loss of an individual safety barrier (eg certain scenarios described in KBS-3).

Scenarios must be chosen in view of the purpose of the assessment so that adequate cases are presented as regards both the consequences for safety and the probability of their occurring. SKB's work with scenario selection and scenario definition will be pursued with regard to the international cooperation that has recently been initiated within the OECD/NEA, and in consideration of the reviews of alternative system designs that are planned.

A systematic review of scenarios relevant for Swedish conditions and for system designs studied thus far will be performed during 1987.

Responsibility for development and definition of acceptance criteria for final repository facilities lies primarily with the regulatory authorities and society. The formulation of the criteria can greatly influence both means and methods for the safety assessments. Examples of essential questions are:

- At what level (components-total system) will the acceptance criteria be set?
- How will the concept of probability be incorporated in the criteria?
- How will small dose contributions and population doses be handled?
- How will the long time spans be handled?
- How will the concept of uncertainty be handled?
- How will the optimization requirements of the radiation protection guidelines be applied?

SKB will follow national and international developments within the area and will, in consultation with the authorities, create a basis for criteria definition. At the present time, no specific activities can be defined for the coming six-year period.

6.4 Models and data for performance and safety assessments

6.4.1 Background

A very long period of time can be expected to pass between the deposition of the spent fuel and any leakage from the canisters that might possibly result in environmental impact. It is therefore necessary to rely on calculations and assessments of repository performance based on short-term experiments and mathmatical modelling of processes of interaction.

A very important ingredient in SKB's performance analysis development is the model work pursued at different levels. The term "model" is used here for all stages of development: A conceptual model is often developed into a mathematical calculation model, which is then developed into a computer program. Here, the word "model" will usually be synonomous with the word "computer program". Three different levels can be distinguished (the distinctions may sometimes be difficult to make):

- Detailed, research-related models of different processes and phenomena pertaining to fields such as hydrology, geochemistry, materials science and their interaction (research-related models).

Program	Area of application	Characteristics
HYPAC/GWHRT	Geohydrology	3-D, homogeneous medium, double porosity Forced convection Various boundary conditions Finite elements
QEQCAL	Near-field migration	Design-specific, one canister Diffusion through the clay barrier to rock fractures
LCHCAL	Near-field migration	Chain decay Solubility limits
NUCDIF	Far-field migration	1-D, matrix diffusion Single nuclide Boundary condition: congruent dissolution Semianalytical
TRUCHN (TRUMP)	Near-field and far-field modelling	General 1-D, 2-D or 3-D Chain decay Arbitrary boundary condition Integrated finite differences
BIOPATH	Biosphere modelling and dose calculations	Compartment theory

Figure 6-2. Independent analysis models used in SKB's function analysis work.

- Models of total radionuclide transport in the repository's near field, far field and in the biosphere (assessment models).
- Models for uncertainty and sensitivity analyses (probabilistic performance assessment models in the sense that probability distributions can be defined for input data in order to represent uncertainties).

The fundamental research, collection of data and detailed modelling constitute the scientific foundation on which the analysis work rests. The detailed research models are often too complicated and deal with a far too narrow area to be used in overall assessments of repository performance. On the other hand, the results of research models can be used in many cases as input data to assessment models.

SKB's centralized database is also of great importance for the performance assessment development work. The system is based on the database program MIMER and is implemented on a VAX-11/750 delivered by Digital Equipment. The database gives the analyst immediate access to geoscientific and barrier-related data from the study-site investigations and laboratory studies for further evaluation and statistical processing. The latter is particularly important for simplified assessment models and uncertainty analyses in which highly processed data with distributions are used.

6.4.2 Present-day state of knowledge

The development and use of detailed research models and corresponding collection of data are described in connection with the corresponding subject areas. Assessment models that were used in the KBS work and that will also be used in the future are described in Figure 6-2. Several of these can also be regarded as research models.

At the beginning of 1985, SKB initiated the development of a probabilistic performance assessment model, a computer program package called

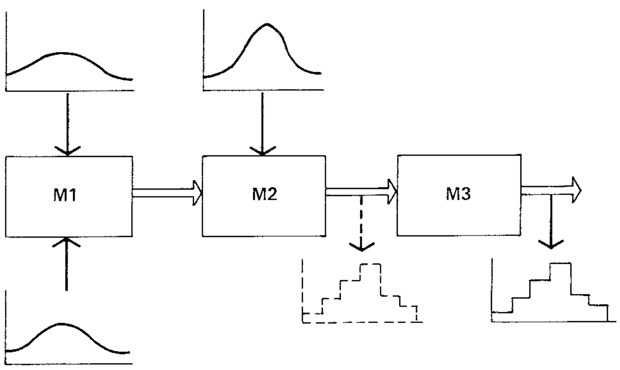


Figure 6-3. Schematic illustration of the function of PROPER. A number of coupled submodels (M1, M2 and M3) are provided with input data by means of random sampling from distributions. Data between submodels consists of time series. Statistics in the form of histograms or the like can be obtained.

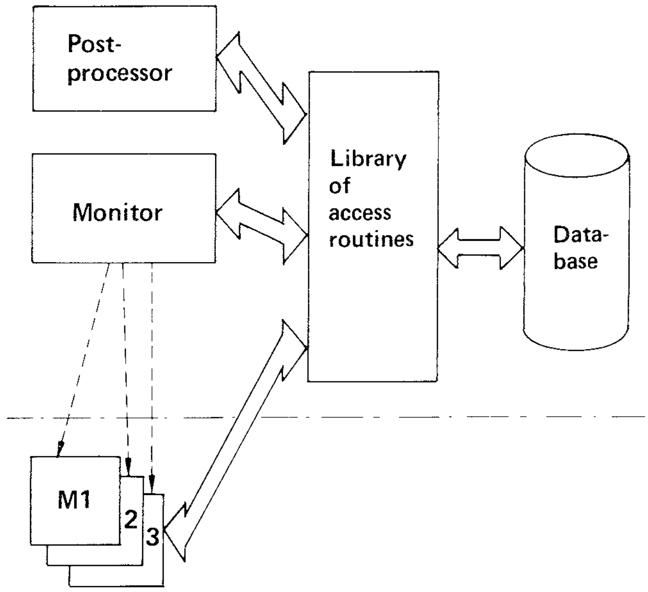


Figure 6-4. PROPER's structure. The monitor, which is the actual control program, controls the calculations with different submodels. The results are processed in the postprocessor.

PROPER, intended to serve as a tool for the prioritization of research and development work, evaluations in the site selection process, safety assessments etc.

The system is primarily intended for assessments of the performance of the repository as regards release and transport of radionuclides from the encapsulated fuel to the biosphere. High demands have been imposed on the flexibility of the system in terms of the possibility of coupling together an arbitrary selection of assessment models from some type of model library. Input data are defined in the form of probability distributions in order to represent uncertainties. The calculation results are processed statistically for evaluation of their uncertainty and for sensitivity analyses, see Figure 6-3.

An initial version of the program package is nearly finished. It consists of a control program, the monitor, and a number of assessment models or submodels, see Figure 6-4, which can be coupled together relatively arbitrarily without changing any program code. Uncertainties in the input data are translated to uncertainty in the results by means of Monte Carlo technique, which means that the assessment models must be slightly simplified or otherwise adapted.

Standardized, structured programming has been used in the development work in an endeavour to facilitate documentation and maintenance of the system and to make it portable between different computers.

The submodels that currently exist in the library each deal with a separate aspect - geohydrology, the near field, the far field and the biosphere - based on the KBS-3 design of the repository. In addition to these, there are models developed for use in an NEA-initiated comparison study, see Section 7.10.

Naturally, the analysis system is not bound to the KBS-3 design, but also works in principle for alternative designs with other submodels.

The development work also includes

- validation of the conceptual correctness of the models,
- numeric verification of the models' algorithms,
- use of quality assurance procedures in the program development work.

Direct validation through comparisons between results obtained from models and observations of natural phenomena is primarily done at the research model level. This work is described in other chapters.

The transport models NUCDIF and TRUCHN, which are used in KBS-3, have been used in a verification study within the framework of the INTRACOIN project, initiated and led by the Swedish Nuclear Power Inspectorate /6-1/. HYPAC/GWHRT is currently being verified in a similar project for hydrology models, HYDROCOIN /6-2/.

In an endeavour to maintain good quality assurance in the program development work for PROPER, a special programming standard has been produced. Further procedures and documentation are under development.

6.4.3 1987-1992 research programme

The most important development activities during the period 1987-1992 are presented below. The work will be pursued with the aim of producing a set of models by the beginning of 1989 for a generic pilot assessment. This will require the following activities:

- testing, verification, validation/calibration, documentation of the first generation of assessment models (mostly further development of current models) and of the PROPER monitor and evaluation routines,
- sensitivity assessment procedures for PROPER,
- improved result presentation for PROPER,
- principle studies of the second generation of assessment models (provides an opportunity for comparisons).

It is believed that a new set of models can be developed so that they can be used for site evaluation in 1992. In order to achieve this goal, development work is required during the second half of the period on:

- site-specific second-generation assessment models including tests, documentation, validation-calibration, verification etc,
- further improved result presentation for PROPER.

At the present time, the assessment models have certain weaknesses that require the use of safety margins in the analyses. The geohydrology models are based on treatment of the fractured rock as a porous medium. The transport models deal only with individual canisters. Moreover, the models that are designed especially for PROPER do not take chain decay into account. Some justified criticism has also been levelled at the excessively detailed modelling of the biosphere for long periods of time, see Chapter 4. The following is therefore planned for the next generation of models:

- *Geohydrology:*
  - Better treatment of fractured medium.
  - Possible site-specific models.
  - Use of geostatistics.
- *Radionuclide transport:*
  - Models for the whole repository.
  - Inclusion of chain decay (for PROPER).
- *The biosphere:*
  - For times <10 000 years - compartment model.
  - For times >10 000 years - comparison with natural erosion and turnover of radionuclides.

In the further development of assessment models, heavy emphasis will be laid on the speed of the computation programs for use in PROPER. Validation can seldom be done directly, but must be carried out by means of some kind of calibration procedure where the calculation results are compared with the results obtained from other models that have been validated.

In order to achieve the above goals, supportive development work is also required on:

- numerical methods in general,
- documentation,
- adminitrative routines and quality assurance procedures such as authorization of code changes, standardized testing and documentation etc,
- routines for utilization of data from the database,
- statistical routines of the kind: precision measurement, variance reduction, correlation handling and automated sensitivity assessment; specially for PROPER.

The development work will also help to build up general experience to facilitate modelling and calculations on quite different repository concepts, if necessary.

6.5 Execution of performance and safety assessments

During the period 1987 to 1992, assessments will primarily be carried out for evaluation and comparison of alternative designs of the barrier system and potential sites for detailed investigations.

As is evident from the above, the PROPER system is expected to able to be fully utilized for these purposes from about 1989. Deterministic analyses will also be carried out with the larger assessment models.

In parallel with the alternative studies, performance analyses of components and subsystems will be utilized to steer the R&D work into areas that dominate the uncertainty.

In the safety assessments, certain nuclides are found to dominate the risk picture, while others are uninteresting. A number of nuclides will be systematically analyzed during the six-year period in order to see whether they can be dismissed as uninteresting on the basis of generic, non-site- specific or non-system-specific data. Examples of candidates for such studies are carbon-14, selenium-79, zirconium-93, technetium-99, tin-126, iodine-129 and cesium-135.

7 INTERNATIONAL COOPERATION

Development work within the field of nuclear waste management is being pursued to a great extent in international collaboration and exchange. Most countries with a nuclear power programme of any size have made up plans for the management of different forms of radioactive waste and have begun the research and development that is considered to be needed. Activities on an international plane are therefore being conducted today on a large scale in the form of experiments, model development, site investigations, data compilations etc within the field of nuclear waste management, of which the Swedish efforts necessarily constitute only a small part.

The extent to which Sweden is able to derive direct benefit from the work being done in other countries is primarily dependent on the following two factors:

- Technical and geological similarities in repository design and site.
- Timeschedules for the execution of research programmes, large-scale tests and demonstration projects as well as the construction/operation of final repositories.

The benefit that Sweden can derive from other countries' research may lie on several different planes:

- Contributions to method and model development.
- Broadened and strengthened databases.
- Exploration of other alternatives for repository and barrier design, material selection etc.
- Contributions to reinforcing public confidence in the system through eg demonstration trials and large-scale tests.

An important part of SKB's programme is therefore to follow and take advantage of the research and development that is being conducted in other countries in a well-planned and effective manner.

This task is made easier by the great interest shown internationally in the work being conducted in Sweden. A detailed review of the international research and SKB's follow-up of it is provided in /7-1/. A summary of the most important programmes with a bearing on Swedish waste management is provided in this chapter. An overview of the different joint international projects in which SKB is directly involved is also provided.

7.1 Foreign R&D of importance for SKB's programme for spent fuel disposal

USA

The USA plans to build two final repositories, the first in salt, basalt or tuff and the second possibly in crystalline rock. The timetables in the USA are controlled to a high degree by the "Nuclear Waste Policy Act" /7-2/.

The Act states that the federal government is responsible for the final disposal of high-level waste and spent fuel. DoE, the Department of Energy, is responsible for building the final repository.

The Act contains detailed directives describing how site selection is to proceed and when the different phases of the process are to be completed. The first repository must be able to receive waste no later than 31 January 1998.

As far as Sweden is concerned, the programme for disposal in crystalline rock is of the greatest interest. This part is currently being reassessed and it has recently been decided to postpone planned site investigations until the mid-1990s. Sweden has good contacts with the USA regarding the programme for crystalline rock and Swedish experts are participating in the programme.

The entire American nuclear waste management programme is very extensive. The methodology for site selection and site evaluation of the "first repository", as well as model development, studies of the waste forms and the safety assessments, are of value for Sweden, even if the host medium should be another. Established contacts exist between Swedish and American experts in a number of areas: fuel leaching, geochemistry, geotechnics, model development etc.

Canada

AECL (Atomic Energy of Canada Ltd) is the federal organization that is in charge of Canada's nuclear power programme. AECL is also responsible for research and development on the conditioning and disposal of nuclear fuel waste. The provincially owned power utility Ontario Hydro is responsible for interim storage and transportation of spent nuclear fuel. The division of responsibilities between the federal government and the provincial governments when it comes to the final repository has not yet been defined. Canada's programme for final disposal consists of three phases:

- Concept assessment.
- Site selection.
- Demonstration of disposal vault.

The first phase is currently underway. In a 10-year programme, research is being conducted in order to establish a scientific basis for geological disposal and for technical criteria for site selection and repository design. In 1988, a proposal for a disposal method will be presented to the authorities for review and assessment. An extensive review is foreseen, including public hearings, leading to a final assessment of the proposed concept in 1990-91. Actual site investigations and site selection are expected to take place during the 1990s. Once a site has been selected, a 20-year demonstration period is planned, concluding with expansion of the demonstration facility to a disposal vault which will be taken into operation after the year 2010.

The bedrock in Canada closely resembles the Scandinavian bedrock. Consequently, many of the geological investigations in Canada are of interest to Sweden. Of particular interest is the URL (Underground Research Laboratory) project which is currently underway and where a shaft is being sunk to a depth of about 450 m in the bedrock. SKB has preliminarily agreed with AECL to participate in the URL see Section 7.4. Canada is also well advanced in the field of chemistry and in studies of spent fuel.

Finland

According to Finnish law, responsibility for nuclear waste management in Finland lies with the nuclear power producers. The two power utilities IVO and TVO have formed a joint company, YJT, to coordinate the necessary research and development activities.

For spent nuclear fuel, the policy is to attempt to secure agreements whereby the spent fuel can be sent abroad for final disposal. In the case of the Loviisa reactors, such an agreement exists with the Soviet Union. Other nuclear fuel is to be temporarily stored and finally disposed of in Finland. A facility is being built in Olkiluoto for interim storage. It is scheduled to be completed at the end of 1987. A site for a final repository will be selected around the year 2000, and the repository will be put into use around 2020.

A list of 101 potential sites for a final repository obtained from an inventory was presented in early 1986. Preliminary investigations on 5-10 of these sites are planned during the period 1986-1992. These will be followed by detailed investigations on 2-3 sites up to the year 2000, when the final site will be chosen. Further investigations will be conducted on this site up to the time of a licence application around the year 2010.

Due to the close similarities between the Swedish and the Finnish bedrock, an exchange of information is particularly valuable.

France

Responsibility for final disposal of nuclear waste in France lies with an independent body, ANDRA within Commissariat à l'Energi Atomique, CEA. The research and development work is being conducted primarily by CEA. Salt, shale and clay formations as well as crystalline rock are being considered as host media for the underground test facility. According to the plans, a site is to be chosen by 1987-88. If the choice falls on crystalline rock, this will be of great interest for Sweden. SKB has concrete cooperation with CEA within the fields of radionuclide chemistry and buffer/backfill, see Section 7.8.

West Germany

West Germany intends to dispose of its high-level waste in a salt formation at Gorleben. No other site is currently being considered. An extensive investigation programme is being conducted at Gorleben, including driving of two shafts down to repository depth. These investigations are expected to be completed by the beginning of the 1990s. It would then be possible to take a repository into operation at the end of the 1990s.

The geological studies in salt are of little interest for Sweden. However, along with Sweden, West Germany is the country that has most systematically explored the direct disposal alternative. The results of these studies were reported in the spring of 1985 in an extensive study, PAE, Projekt Andere Entsorgungstechniken /7-3/. The PAE project is being carried further, aimed at a demonstration on full scale of certain elements, eg canister fabrication and handling of encapsulated fuel. SKB is following the work on direct disposal in West Germany through information exchange with the PAE project.

Switzerland

According to the Atomic Energy Act in Switzerland, the nuclear power utilities are supposed to present a plan for safe final disposal of radioactive waste. The Swiss federal government and the Swiss nuclear power utilities have jointly formed NAGRA (Nationale Genossenschaft für die Lagerung Radioaktiver Abfälle) in order to manage the radioactive waste.

NAGRA recently published its study - Projekt Gewähr - /7-4/, an equivalent of the KBS-3 report. High-level waste will be disposed at great depth in crystalline rock. An experimental station in rock, corresponding to the Swedish Stripa mine, has been built at Grimsel in the Alps.

The timeschedules are still vague. Site selection is planned around the year 2000, and the final repository is planned to be taken into service around the year 2020.

SKB has close contacts with NAGRA and the Swiss programme. Direct cooperation and coordination of research is taking place within the fields of glass leaching, canister materials and natural analogues, see also Sections 7.5, 7.6, 2.3 and 2.4.

Great Britain

During the 1970s, a programme of geological investigations for disposal in granite formations was initiated in Great Britain . In December 1981, further activities within this programme were postponed for at least 50 years on the grounds that it had been demonstrated that final disposal was possible in principle and that high-level waste can be temporarily stored without any problems for such a period of time. Consequently, no further decisions on final disposal of HLW are expected within the next few decades. R&D in Great Britain is therefore now being devoted solely to technology for vitrification, storage and model studies. Great Britain is also participating actively in the Stripa project, the Poços de Caldas project and the NEA's seabed disposal studies, see Sections 7.3 and 7.6.

CEC

The CEC is conducting an extensive and well-coordinated programme within the field of nuclear waste management. Interesting programmes are being carried out for modelling of nuclide migration and for safety analyses, among others.

Studies in an underground experimental facility built in clay in Mol are being conducted under the auspices of the CEC. Studies at the French repository facility and Gorleben, West Germany, are also being coordinated.

International organizations

Overall international cooperation takes place within the UN's International Atomic Energy Agency, IAEA, and within the OECD's Nuclear Energy Agency, NEA. These organizations provide natural forums for an exchange of information through expert meetings, symposiums and conferences on different subjects. A number of important joint projects are also being conducted under the auspices of the OECD/NEA, of which the Stripa project is one example. SKB is participating actively in the activities of both of these organizations. For example, SKB is represented in the OECD/NEA's Radioactive Waste Management Committee, which serves as a reference group for all NEA activities in the field of radioactive waste management, see Section 7.10.

7.2 SKB's cooperation agreements with foreign organizations

In view of current timetables and available bedrock, the countries that can make contributions of importance to Sweden in the field of nuclear waste management are, as has been made evident above, above all Canada, the USA and France. In addition, continued cooperation is foreseen with Switzerland and Finland, among other countries, within different R&D fields. Development work in West Germany may provide useful experience on the encapsulation of spent fuel and handling technology.

At the present time, SKB has formal bilateral agreements with the following organizations in other countries:

- USA - DoE (Department of Energy).
- Canada - AECL (Atomic Energy of Canada Ltd).
- Switzerland - NAGRA (Nationale Genossenschaft für die Lagerung Radioaktiver Abfälle).
- France - CEA (Commissariat à l'Energie Atomique).
- CEC - EURATOM.

Information exchange without formal agreements also exists with

- West Germany.
- Belgium.
- Great Britain.
- Japan.
- Finland and the other Nordic countries.

The formal agreements are similar in their construction and cover information exchange and cooperation within handling, treatment, storage and final disposal of radioactive waste. Exchange of up-to-date information (reports) as well as results and methods obtained from research and development are main points in the agreements. The arrangement of 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 within the framework of the agreements takes place at approximately one-year intervals.

As a rule, special agreements are concluded within the framework of the general agreement in connection with exchanges of personnel of long duration or extensive direct project cooperation. These agreements give specialists within the field of nuclear waste management greater opportunities for contacts leading to a fruitful exchange of up-to-date information.

7.3 The Stripa project

7.3.1 Background

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

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

The aim of this cooperation was to develop technology for measuring certain properties of the Stripa granite, eg thermomechanical, geophysical and geochemical properties. The results of this programme have been published in a large number of reports /7-5/.

The high international class of the Swedish-American research, and the great interest on the part of the OECD member countries in continued research, resulted in an expanded international cooperation in the Stripa Project. It was started in May 1980 as an autonomous OECD/NEA project with SKB as the coordinating party. Phase 1 was carried out during the period 1980-85, followed by phase 2, which commenced in 1983 and is expected to be concluded for the most part in 1986.

Research has been conducted within the following four main areas:

- Geohydrological investigations of the Stripa granite and migration tests with nuclides in simple and complex fracture systems.

- Chemical investigations of the groundwater in the Stripa granite.
- Technique for detecting and characterizing fracture systems in granite.
- Study of bentonite clay for use as a backfilling and sealing material in a fractured bedrock.

7.3.2 Results

The results of the Stripa Project have been reported at two seminars arranged by the OECD/NEA /7-6, 7-7/ and in a number of technical reports published by the project /7-8 - 7-16/. So far, results have been reported from phase 1 and certain preliminary results from phase 2.

The research has shown, among other things, that a series of different types of investigations and measurements are required - including specially designed geophysical and hydrological investigations - in order to be able to determine the extent and location of the planes of weakness in the rock. Methods have also been developed for determining the migration tendency of absorbing and non-absorbing tracers in single fractures and in complex fracture systems. An extensive programme of water sampling, including chemical analyses of the groundwater in Stripa, has been carried out as a complement to the migration tests. The results of these experiments have contributed new knowledge on the chemical character and origin of the groundwater in granite.

As regards the engineering aspects of designing a repository, the experiments with bentonite clay as a backfill material, under temperature conditions similar to those expected to prevail in a repository located in rock, have confirmed previous laboratory experiments and theoretical calculations. The borehole, shaft and tunnel sealing tests carried out within the framework of phase 2 have now reached their final phase. The purpose of these tests is to determine the sealing properties of the bentonite clay.

7.3.3 Goal of phase 3 of the Stripa Project

The results of phases 1 and 2 have shown that decisive steps have been taken in the development of methods and technology for detailed investigations of the rock on a potential repository site, as well as in finding engineering solutions for sealing of the rock mass. Future work is aimed at applying experience gained thus far to an undisturbed granitic rock volume. In addition, the measurement technology developed will be coupled to a mathematical modelling effort so that theoretically calculated values can be compared with values measured in the field. Further development of technology for field measurements will be pursued in parallel with this.

In the engineering field, the next step is to find suitable methods for injection grouting and determine the long-term properties of materials for sealing of fractures etc.

7.3.4 The programme for phase 3 of the Stripa Project

Based on the aims outlined above, the management of the Stripa Project has recommended to each of its member countries that a phase 3 of the project be carried out during the period 1986-1991. A programme has been drawn up /7-17/. Phase 3 of the Stripa Project is a direct continuation and is based on the work carried out within phases 1 and 2, but new research activities will also enter in. An undisturbed granitic rock volume (approx 125 m x 125 m x 50 m) will be investigated, see Figure 7-1. A mathematical model for groundwater flow will be developed and compared with values measured in the field. Previously obtained results show that models that treat the rock as a porous medium cannot describe in detail the conditions prevailing in a fractured granitic rock volume of the size in question. The mathematical model to be tested is based on a combined deterministic and statistical description of the groundwater flow in a discrete fracture pattern in three dimensions.

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

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

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

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

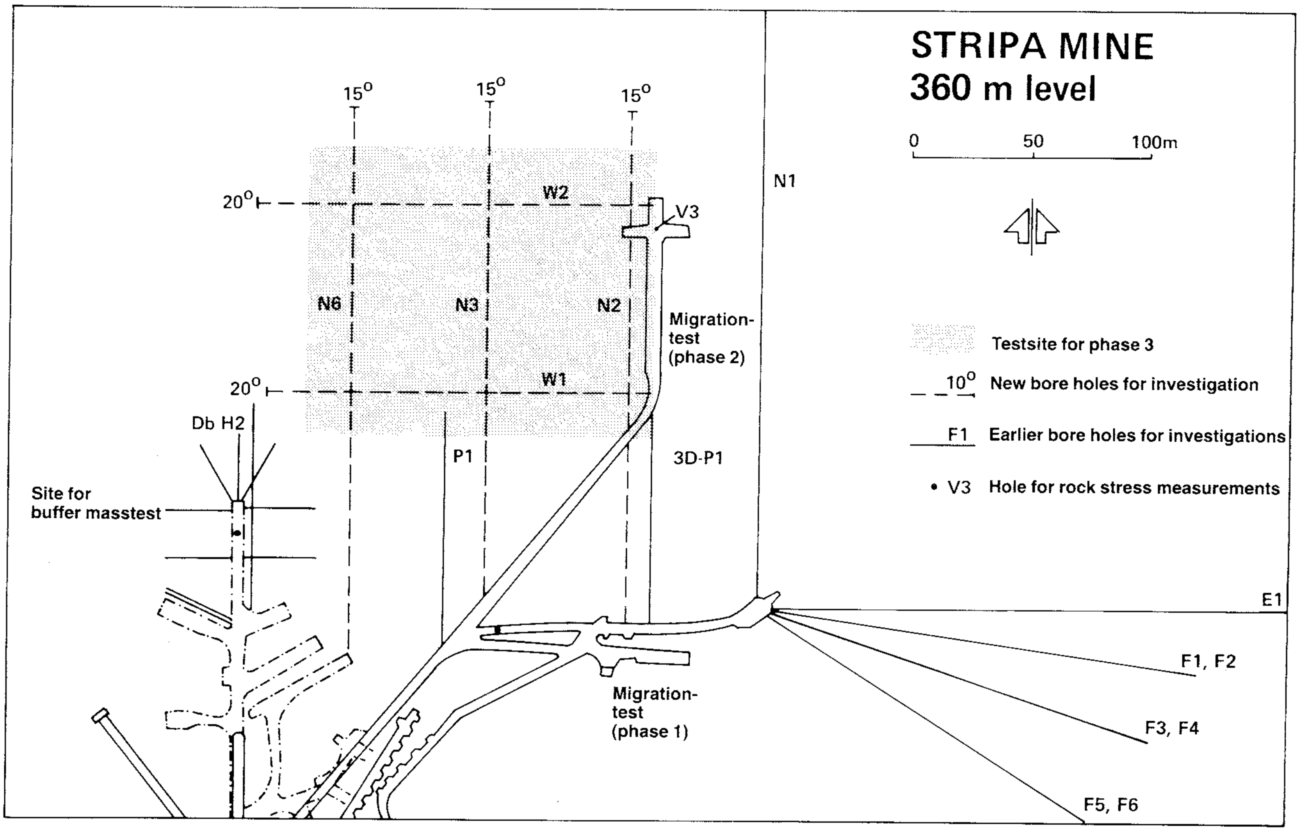


Figure 7-1. Schematic illustration showing the test site for the planned geohydrological investigations in Stripa phase 3.

7.4 The URL Project

The URL Project is one of the most important components in Canada's waste management programme. An underground research laboratory will be built 450 m below the surface, /7-18/.

The goals of the project are to:

- explore ways to interpret airborne, surface and borehole measurements,
- analyze geohydrological and geochemical conditions in undisturbed bedrock,
- carry out a large-scale geohydrological shaft sinking experiment,
- study how the rock mass reacts to rock removal,
- study how the rock mass reacts to varying load and temperature,
- test buffer and backfill materials and carry out and test shaft and borehole sealing,
- study transport phenomena in a fractured rock mass,
- study final repository systems with several components at normal and elevated pressures and temperatures.

The URL has been located in a large granite formation in southeast Manitoba, the Lac du Bonnet batholith. The site was chosen in 1979 and geological investigations started in 1980.

A very extensive geohydrological characterization was carried out and the groundwater pressure was recorded regularly in nearly 200 measurement points. Shaft sinking to the 250 m level was begun in 1983. The geohydrological and geochemical changes were recorded continuously. Advance calculations of pressure changes and water seepage into the shaft agree well with measured values.

During 1987-88, shaft sinking will continue to a depth of 450 m, where experimental tunnels will be built. The shaft will be sunk through a fracture zone.

Characterization of the rock will take place both during and after shaft sinking. The shaft walls will be mapped and photographed during the excavation process. Furthermore, instruments that record displacements and water pressure will be installed.

The experimental programme after the shaft has been completed is still in the planning stage. The large experiments are expected to start in the early 1990s.

7.5 The JSS Project

The JSS Project started in 1982. It is a joint project between CRIEPI (Japan), NAGRA (Switzerland) and SKB for studies of radioactive glass. The goals of the project were originally to

- determine whether radioactive glass displayed different behaviour in any respect on contact with water than a chemically identical non-radioactive glass,

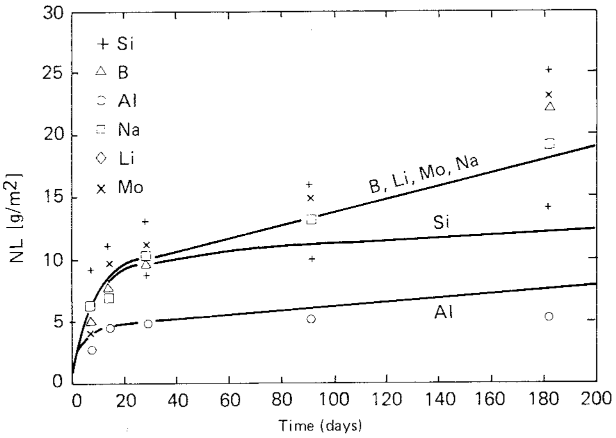


Figure 7-2. Comparison between leaching results (points) from radioactive glass in deionized water (static test, temp. 90°C, glass area/liquid volume = 10 m^{-1}) and model calculations (curves). NL = Normalized mass loss for the element in question.

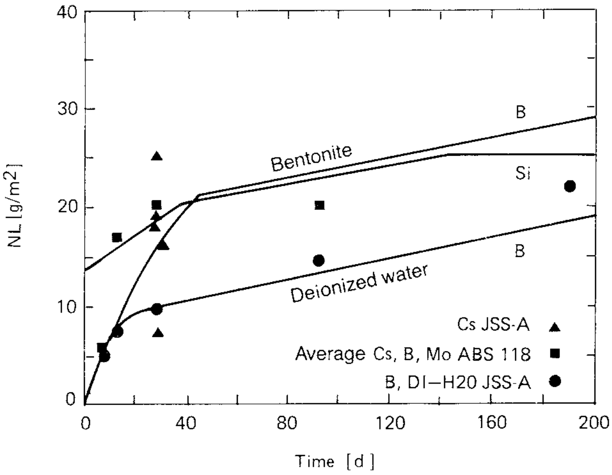


Figure 7-3. Same comparison as in Figure 7-2, but with bentonite present.

- build up an independent database for the glass that was to be delivered in the future from COGEMA under existing reprocessing agreements.

These investigations were carried out in phases I-III of the project, which have now been virtually completed and their results published /7-19 - 7-23/. The data obtained have been of such high quality that they have been deemed suitable to serve as a basis for development of a predictive model for glass leaching under repository conditions. The project was therefore extended in the autumn of 1984 with a phase IV to include the development work for such a model. Supplementary experimental data have also been gathered during this phase for the reactions with both water and other components in the waste package, ie bentonite and corrosion products from steel. The model, which consists of a geochemical part, PHREEQE /7-24/ and a kinetic part is described in the final report for phase IV /7-25/ and in detail in reference /7-26/. Preliminary results for phase IV show that the model development is very promising /7-27/ (experimental results) and /7-28, 7-29/ (modelling). The available experimental results for reactions with both water and water/bentonite can be described well already at the present stage of development, see Figures 7-2 and 7-3.

The kinetic part of the model contains experimentally determined data for reaction rates. Of these data, the reaction rate under conditions close to saturation concentrations is of decisive importance for the accuracy of the long-range forecasts made with the aid of the model. After phase IV, which is now in the process of being reported, it is clear that better data for these long-term reaction rates are required for reliable predictions of the leach resistance of the glass over long periods of time. This has led to the continuation of the project in a concluding phase, phase V, for the period up to and including 1987.

7.6 The Poços de Caldas Project

This project entails studies of natural analogues for the release and dispersal of radionuclides from a final repository. The investigations are tied to two closely-situated sites in the Poços de Caldas district in Minas Gerais, Brazil: The thorium deposit in Morro do Ferro and the Osamu Utsumi uranium mine, C-09, see Figure 7-4. Section 5.4.4 deals with the overall plan for SKB's studies of natural analogues for radionuclide migration.

Sweden (SKB), Great Britain (UK DOE), Switzerland (NAGRA) and Brazil (Rio de Janeiro University, CNEN and NUCLEBRAS) are participating in the project.

The project will last three years under an agreement drawn up between SKB, UKDOE and NAGRA, who are the direct sponsors. Brazil is serving as the host and is contributing some equipment and labour. SKB is in charge of the project management.

The introductory phase started in May 1986 with drilling and sampling in the Osamu Utsumi mine.

Morro do Ferro

Morro do Ferro constitutes a 140 m high hill in the landscape. The minerals are heavily weathered and the groundwater table is low. Thorium is bound to lenses of clay minerals. The total quantity of thorium has been estimated at 30 000 tonnes. Of this total, a fraction of 7.3 x 10^{-7} is mobilized per year, mostly in the form of erosion. A small fraction is carried away with the groundwater (5 x 10^{-10} per year). Besides thorium, there are unusually rich deposits of rare earth metals. The possibility of mining thorium, and recently rare-earth metals, has been considered, so prospecting holes and a mined test tunnel into the rock already exist /7-30 and 7-31/.

A large portion of the runoff is collected in a small stream that flows past a small farm further downstream.

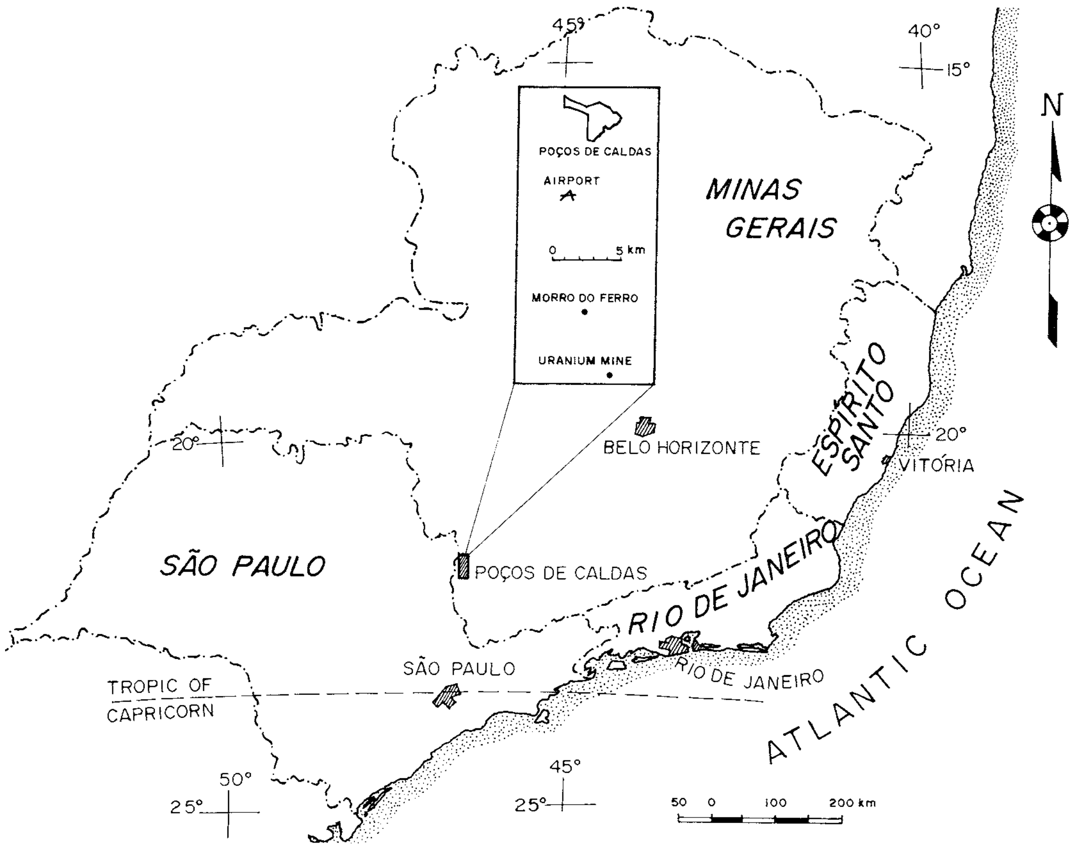


Figure 7-4. Map showing location of Poços de Caldas and Morro do Ferro, Brazil.

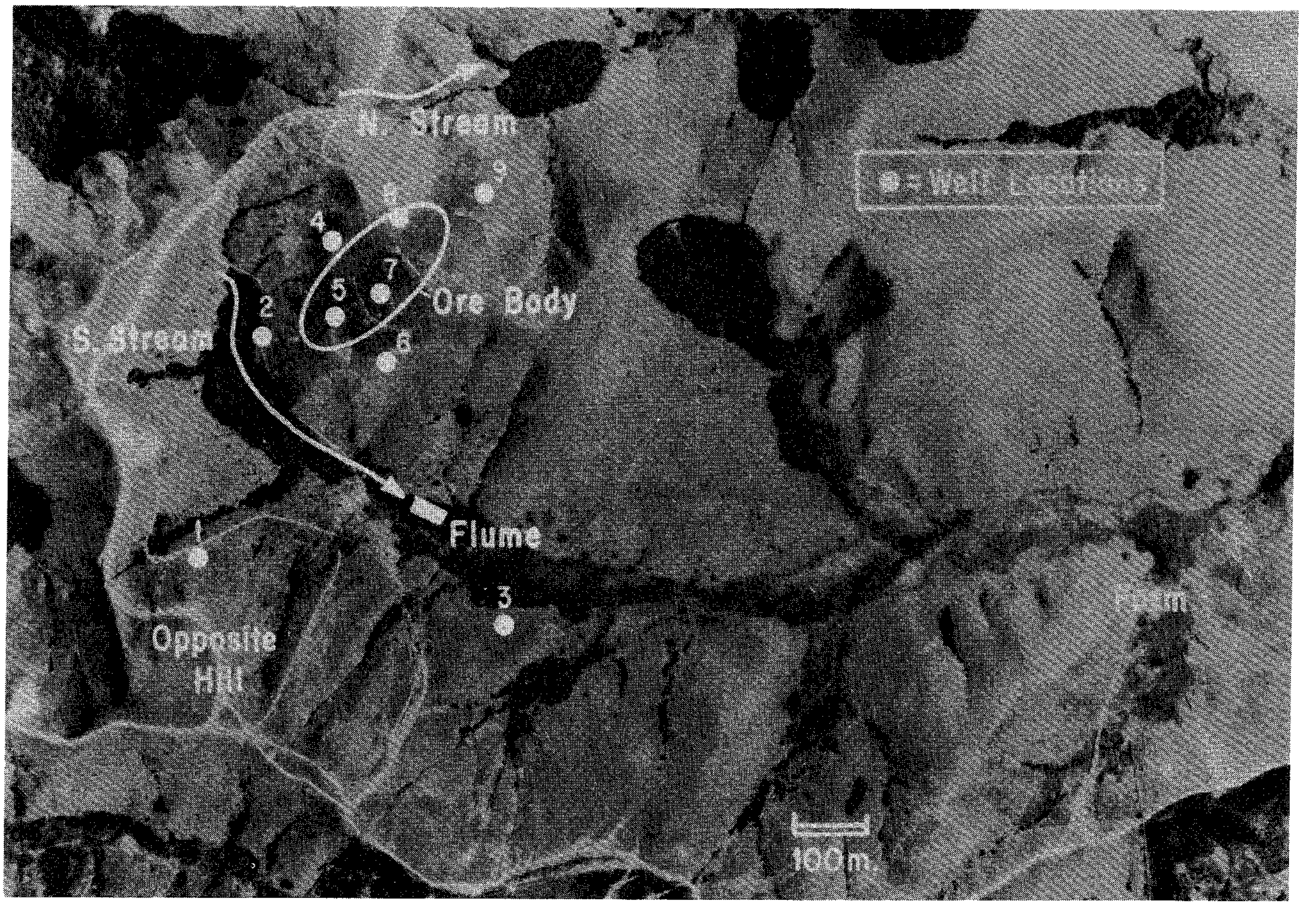


Figure 7-5. Aerial photograph of Morro do Ferro with previous sampling sites marked.

	Thorium	Neodymium	Lanthanum	Cerium	Number of samples
Ore body	5 150 ± 490	2 320 ± 240	4 340 ± 410	9 360 ± 1 220	101
Areas out-side ore body	140 ± 20	380 ± 30	890 ± 50	1 220 ± 90	104
Swamp area downstream	130 ± 15	260 ± 30	550 ± 50	890 ± 70	40

Figure 7-6. Distribution of thorium and rare earth metals in Morro do Ferro. The concentrations are given in mg/kg.

The natural radioactivity level is high. Gamma radiation is 100 - 250 mGy per year within an area of 30 000 m². The concentration of Ra-228 in the ground is so high that leaves from plants in the area can be autoradiographed /7-34/.

The thorium deposit was discovered in the beginning of the 1950s. During the 1960s and a few years into the 1970s, radiobiological studies were conducted in cooperation between the Catholic University in Sao Paulo and the New York Medical Centre. The release and dispersal of thorium, its radioactive daughters and the rare-earth metals have been studied since 1979. SKB and NAGRA participated in the programme during the period 1982-1984. These studies were primarily concentrated on dispersal in the biosphere and uptake in people living nearby /7-31 and 7-32/, see Figure 7-6. The transport of radionuclides and radionuclide-like substances with the groundwater down in the rock has been studied relatively little so far /7-33/.

The Osamu Utsumi Mine

The Osamu Utsumi C-09 uranium mine is an open-pit mine and is an important uranium mine in Brazil /7-34/. Operations have temporarily been shut down. NUCLEBRAS, which operates the mine, has given its permission for investigations and is also contributing personnel.

The uranium exists in the form of precipitations adjacent to very clearly marked redox fronts, which in turn follow the water-bearing fracture system. The conditions for investigating redox transitions in connection with fracture-bound water flow in crystalline rock and accompanying uranium precipitation are the best imaginable.

The Poços de Caldas Project

The ongoing project is divided into two subprojects: Project 1 at the C-09 uranium mine and Project 2 at Morro do Ferro. The two subprojects deal with the following:

1 Determination of speciation and chemical transport of natural radionuclides and rare-earth metals in a fracture flow system in crystalline rock under oxidizing and reducing conditions.

2 Formation and mobility of colloid-borne radionuclides in natural groundwaters (here, humic substances are also included in the term "colloids").

The most important goals of the subprojects are as follows:

1 – Validate equilibrium models for different water-mineral systems.

– Understand the mechanisms for the dissolution and precipitation of uranium and other elements around the redox front.

– Compare retention factors from in-situ measurements with laboratory values.

– Determine the occurrence and extent of diffusion in microfractures in the rock.

– Determine the influence of microbes and microbial processes on radionuclide migration.

2 – Characterize and determine the concentration of natural colloids and organic complexes in the groundwater.

– Determine the fraction of thorium, radium and rare-earth metals that are transported in the form of colloids and organic complexes.

The first year is primarily being devoted to a preparatory investigation of the C-09 mine, including drilling, sampling and analyses of the most important samples. During the second year, sampling will be concentrated to Morro do Ferro. Most of the water and mineral analyses are planned for the second year, see Figures 7-7 and 7-8.

The third year is intended to be devoted to summarizing, interpretation and reporting of results.

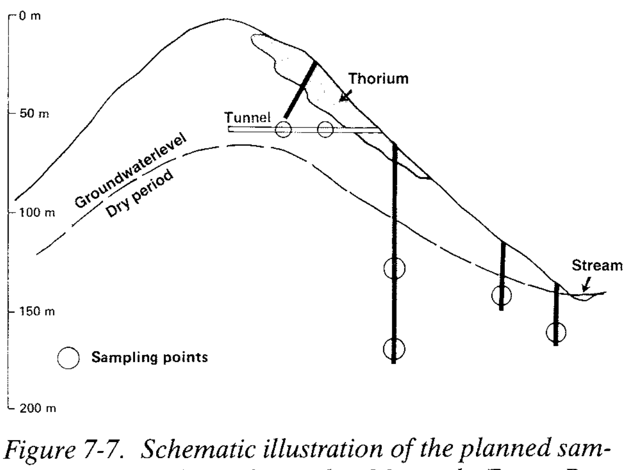


Figure 7-7. Schematic illustration of the planned sampling in boreholes and tunnel in Morro do Ferro, Brazil.

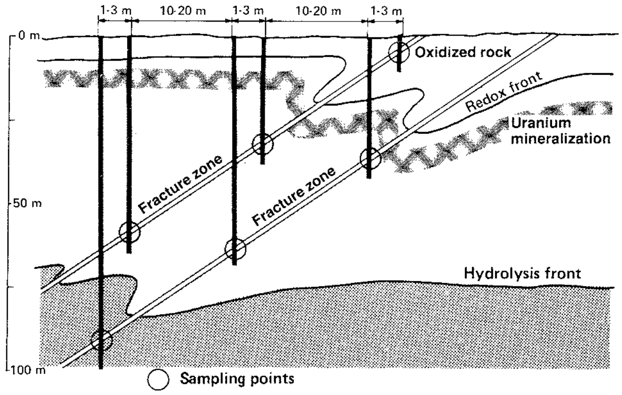


Figure 7-8. Schematic illustration of the sampling holes in the uranium mine C-09, Poços de Caldas, Brazil.

7.7 Fuel leaching - Workshops

Studies of the leaching/corrosion of high-level fuel are only being conducted at a few laboratories in the world. Moreover, the experimental work is time-consuming and complicated, since it has to be carried out in a hot cell. It is therefore essential that the researchers who are working with these investigations be given an opportunity for informal information exchange with above all, foreign colleagues in order to discuss results, experimental problems and planned studies. The Spent Fuel Workshops that were started on the initiative of SKB in 1981 have become an effective forum for this exchange of information.

These workshops, of which a total of five have now been held, are currently being organized annually according to a rotating schedule where Sweden, Canada and the USA alternate as hosts. Invitations primarily go out to representatives of the laboratories in these three countries that have been conducting research on spent fuel the longest. Representatives from other countries who are studying spent fuel as a waste form have also participated, mainly from France and West Germany.

7.8 Cooperation with CEA, France

7.8.1 Clay

CEA and SKB have coordinated certain research concerning smectite-rich clay so that comparisons can be made between our reference material and French clay. Studies are being made of changes in the properties of the clays with respect to temperature and radiation effects and of rheological properties based on measurements in the laboratory.

Studies of water absorption in French highly-compacted clay and of chemical conditions due to contact between clay and steel in heaters with a temperature of up to 170°C are being conducted in a joint experiment in the Stripa mine. The experiment supplements previous investigations within the Buffer Mass Test in the Stripa Project /7-16/.

The experimental programme is in progress and will be wound up during 1988.

7.8.2 Chemistry

Within the framework of the bilateral cooperation agreement between CEA and SKB, experiments are being conducted to collect basic data on the chemistry of the actinides in groundwater, ie solubility, redox chemistry and complexation with carbonate ions etc.

The CEA laboratories have excellent facilities for experiments with actinides, such as plutonium and neptunium. Experiments with uranium and thorium are mainly being conducted at the Department of Inorganic Chemistry at the Royal Institute of Technology in Stockholm.

Swedish researchers have participated in the planning and execution of the experiments in France. Researchers from CEA have participated in the work at the Department of Inorganic Chemistry at the Royal Institute of Technology in Stockholm. Experience of the cooperation is very good and the programme is now being extended to encompass complexation between actinides and humic substances. This also entails a Swedish participation with researchers from Tema Vatten ("Theme Water") at the University of Linköping.

7.9 Other international projects

SKB is participating in several other international cooperation projects besides those mentioned above. The most important are HYDROCOIN, INTRAVAL and BIOMOVS.

HYDROCOIN

This project is headed by the Swedish Nuclear Power Inspectorate (SKI) and consists of an international comparison and verification of different computer programs for the calculation of groundwater flow. The project started in 1981 and encompasses 14 organizations in 11 different countries. The work is planned to be completed during 1987. SKB is participating with the models that were developed and used for our work with KBS-3 and SFR. A detailed account of the HYDROCOIN project is provided in /7-35/.

The studies cover:

- the importance of the quality of the numerical solution methods for the calculation results
- the ability of models to describe field measurements
- an account of how the modelling of various physical problems influences the final result.

The studies are being conducted on three levels.

The primary goal of level 1 is to verify the numerical accuracy of the different computer programs. There are seven test cases and SKB has carried out calculations on four of these cases.

Level 2 aims at validating models against field or laboratory investigations. There are five test cases and SKB has carried out calculations on one of these. This test case concerns thermal convection and conduction around a cylindrical heater.

Level 3 aims at sensitivity analyses of seven calculation cases. SKB will carry out a sensitivity study for the model calculations previously carried out for Fjällveden, which is one of the specified cases /7-36/.

INTRAVAL

A follow-up of the HYDROCOIN project and the previous INTRACOIN project /7-37/ is planned by SKI. The new project is called INTRAVAL and aims at a validation of computer programs for nuclide transport. A definition and planning phase is currently underway, in which SKB is participating. The results of selected laboratory experiments, field experiments, studies of natural analogues and simulations are intended to be utilized to validate geosphere transport models. A special group has been formed to discuss the organization and contents of the project. The last meeting of this group is scheduled for November 1986. The work of the group will result in a report on which a decision as to the continuation of the project will rest.

BIOMOVS

This project is headed by the National Institute of Radiation Protection (SSI) and consists of an international comparison and verification of computer programs for radionuclide transport in the biosphere. The project started in 1985 and Studsvik's computer model BIOPATH, which is used by SKB, is being included in the comparison through the participation of Studsvik Energiteknik. SKB is not participating actively, but is following the project and is greatly interested in the results.

7.10 Cooperation within the OECD Nuclear Energy Agency

One of the OECD/NEA's principal areas for cooperation is radioactive waste management in the member countries. These questions are dealt with by the Radioactive Waste Management Committee (RWMC), where SKB is represented through Tönis Papp. Some work is carried out in joint international projects, and work groups are formed to facilitate information exchange or prepare material as a basis for joint decisions or coordination.

Seminars and workshops are arranged within important areas to document and discuss the state of development and the direction of future work, see eg /7-38/.

The groups and projects within the area of radioactive waste management where SKB is providing personnel or funding are listed below.

Groups

PAAG (Performance Assessment Advisory Group) functions in an advisory capacity to RWMC in matters pertaining to cooperation in terms of means and methods for performance and safety analyses of final disposal systems.

Member from SKB: Tönis Papp (Chairman).

The Advisory Group on In Situ Research and Investigations functions in an advisory capacity to RWMC in matters pertaining to the activities at the various underground research laboratories.

Member from SKB: Bengt Stillborg.

The PSAC (Probabilistic Safety Assessment Code) Users Group is a cooperation group between those who develop and those who use mathematical models for probabilistic analyses of repository systems. The emphasis lies on coordinating the development and comparing the quality of the models.

Member from SKB: Nils Kjellbert.

The Cooperative Program 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 in the world.

Member from SKB: Hans Forsström. SKB is also sponsoring a programme coordinator, Shankar Menon, Studsvik Energiteknik AB.

Projects

Stripa - see Section 7.3. Project manager and person in charge of project administration is Bengt Stillborg.

Members from SKB: P-E Ahlström (Chairman of Joint Technical Committee), Hans Carlsson (member of Joint Technical Committee) and Bengt Stillborg (project manager).

ISIRS, (International Sorption Information Retrieval System), is building up a database and serves as an information centre for the sorption of nuclides of interest within the waste management field.

Member: Bert Allard, University of Linköping, sponsored by SKB.

The NEA's Chemical Thermodynamic Data Base System analyzes and controls the quality of base data for essential nuclides for the buildup of a database.

Swedish participants: Bert Allard, University of Linköping, and Ingmar Grenthe, Royal Institute of Technology, sponsored by SKB.

In addition, the NEA arranges 3 - 4 R&D workshops every year in which SKB personnel or consultants actively participate.

8 ORGANIZATION AND EXECUTION

8.1 SKB's functions and organization

Svensk Kärnbränslehantering AB - SKB (Swedish Nuclear Fuel and Waste Management Company) - has been commissioned by its owners, the Swedish nuclear utilities, to develop, plan, construct and operate facilities and systems for the management and disposal of spent nuclear fuel and radioactive waste from the Swedish nuclear power plants.

SKB is owned by Forsmarks Kraftgrupp AB (FKA), OKG AB, Sydsvenska Värmekraft AB (SVAB, owned by Sydkraft AB) and Vattenfall (The Swedish State Power Board).

Within the framework of its commission from the above nuclear power utilities, SKB will also be responsible for the extensive research and development included in the programme presented here.

SKB is organized in three divisions:

- Research and development.
- Planning and systems analysis.
- Facilities.

In addition there are staff units for public relations and for accounting and administration. A special group is responsible, in collaboration with SwedPower, for coordination of consulting services to foreign customers.

Overall responsibility for the execution of the research programme lies with the R&D division. This division currently has a director and ten academically trained specialists responsible for research within different subject areas.

8.2 Role of the regulatory authorities

Within the field of radioactive waste management, there are three regulatory authorities who have direct responsibility for matters dealt with in this research programme.

The main function of the National Board for Spent Nuclear Fuel (SKN) is to oversee the implementation of the programme for the management and disposal of spent nuclear fuel and the decommissioning of facilities in the nuclear power programme. SKN shall thus exercise supervision over how SKB executes the comprehensive research activities that are called for in the Act on Nuclear Activities. Furthermore, SKN shall review and assess this R&D programme as well as the annual PLAN reports, which present plans and calculated costs for the waste management system. The means that SKN will use in following, reviewing and assessing the system and site selection process described in this R&D programme have not yet been defined. SKN also conducts some supplementary research on different final disposal methods.

The Swedish Nuclear Power Inspectorate (SKI) is responsible for state supervision of, among other things, the technical safety of nuclear installations and systems. In order to build up a knowledge base for this regulatory function, SKI conducts some research of its own within the field of waste management. A number of the projects initiated or sponsored by SKI are directly related to SKB's activities and needs.

The National Institute for Radiation Protection (SSI) is responsible for state supervision of radiation protection matters at, for example, nuclear installations. This includes supervision of radiation protection for both personell and the public. Like SKI, SSI conducts its own research, which in many cases is directly related to SKB's activities and needs.

In order to coordinate the research conducted by the regulatory authorities in the field of waste management, a Consultative Committee for Nuclear Waste Management (KASAM) has been formed.

Certain other authorities also have functions that concern nuclear waste, for example the Swedish Environment Protection Board, but this is of relatively little relevance to the present research programme.

The above regulatory authorities and SKB consult regularly with each other on matters of the above nature in order to cover the boundary regions between their areas of responsibility. Some projects are also conducted with funding shared between regulatory authorities and SKB.

8.3 Execution of the R&D activities

In order for the R&D activities to be effective, defined goals and delineated frames are required. At the same time, the planning must be flexible enough so that the R&D programme can be continuously adapted to the results obtained both domestically and internationally. This means that SKB, which is directly responsible for the programme, is also responsible for successively adapting the programme to the state of knowledge existing at different points in time.

The R&D measures will be executed mainly through contracts awarded by SKB to research institutions, consultants, industrial enterprises or other Swedish and foreign groups possessing the necessary competence. The task for SKB's own staff is primarily to plan, initiate and coordinate the work and to compile and document the results and see to it that they are applied. Another important task is to keep track of national and international developments within relevant fields of research. This is a prerequisite for being able to manage the contracts and the work so that appropriate and effective contact networks are created and the necessary competence and quality is achieved and maintained.

Special reference groups exist within some specialist areas. These groups include SKB's own specialists along with researchers from universities, industry, consulting agencies and other bodies. Goals, strategies, contents and results of different projects are regularly reviewed and assessed in these reference groups. Review and assessment provides a basis for continuous revision of the work and allocation of priorities.

One goal of the R&D work is to assemble the necessary data to enable a site-specific siting application to be submitted around the year 2000. This requires analysis and evaluation of various alternatives for the design and siting of the final repository.

The performance of the components of the repository is affected both by their own characteristics and by the environment defined by the surrounding geology and other components in the repository. The integrated performance of the components in the repository is decisive for the choice of a future repository system. In order to get the right balance of research and development work on different alternatives, special groups for the evaluation of integrated performance are being organized within SKB. These groups will include representatives of relevant fields. The groups will define the analyses that are to be done and the models that can be used and then evaluate the results and their relevance with respect to uncertainties in data and models. Safety, cost estimates, technical feasibility and development potential of different alternatives will play a prominent role in these evaluations.

In the KBS studies, the integrated performance assessments were carried out in campaign form in connection with the compilation of the main reports, in which the persons in charge of all the different fields participated. In the future R&D work, the integrated performance assessments for the various alternatives will be carried out with varying intensity in parallel with special studies for the individual components. This will permit a continuous steering of the special studies into relevant areas and a successive reallocation of priorities between the different alternatives studied.

For natural reasons, the integrated performance assessments at an early stage will be of a more qualitative and general character than during the 1990s, when final system selection and optimization is planned to take place.

In order to permit scientific review and discussion of the research results, the results will, as before, be widely distributed internationally. This will be done through publication in SKB's own technical reports and in scientific journals, through participation in conferences and through an open and extensive exchange of information via contacts. An annual summary will be published in the SKB Annual Report.

An important and necessary feature of the R&D programme is the exchange of information and the opportunities for bilateral cooperation that follow from the agreements that have been signed with corresponding organizations in other countries, see Chapter 7.

8.4 Financing

SKB's research activities are financed in accordance with the "Act on the Financing of Future Expenses for Spent Nuclear Fuel etc" (SFS 1981:669) with money from the funds that are being accumulated through a special fee levied on nuclear power production. The funds are administered by the National Board for Spent Nuclear Fuel (SKN), which also disburses research money to SKB.

8.5 Information

As has been pointed out in another context, SKB strives for great openness and public insight into its activities. This applies in particular to the research work. The demands of society and the public on information and insight into all activities that have to do with the management and disposal of radioactive waste have increased sharply in recent years. In an effort to satisfy these increasing demands, SKB will expand its resources to furnish easily available information to interested persons above and beyond its normal technical reporting activities.

SKB will furnish information on plans, works in progress and results of the activities occasioned by this research programme.

REFERENCES PART III

Chapter 2

2-1 **Handling and Final Disposal of Nuclear Waste**
Alternative disposal methods.
Background report to R&D programme 86.
SKB Sept 1986.

2-2 **Final storage of spent nuclear fuel KBS-3.**
Volume I General. 4.5 Final repository for spent fuel
SKBF/KBS, Stockholm 1983.

2-3 **PUSCH R, NILSSON J and RAMQVIST G, 1985**
Final Report of the Buffer Mass Test
Volume 1: Scope, preparative field work and test arrangement.
Stripa Project Technical Report TR 85-11, July 1985, SKB, Stockholm.

PUSCH R, BÖRGESSON L and RAMQVIST G, 1985
Final Report of the Buffer Mass Test
Volume II: Test results.
Stripa Project Technical Report TR 85-12, July 1985, SKB, Stockholm.

PUSCH R, 1985
Final Report of the Buffer Mass Test
Volume III: Chemical and physical stability of the buffer materials.
Stripa Project Technical Report TR 85-14, November 1985, SKB, Stockholm.

2-4 **KNUTSSON S, 1983**
On the thermal conductivity and thermal diffusivity of highly compacted bentonite.
SKBF/KBS Technical Report TR 83-72, October 1983.

2-5 **PROJEKT GEWÄHR 1985**
Endlager fur Hochactive Abfälle: Bautechnik und Betriebsphase.
NAGRA PROJEKTBERICHT NGB 85-03 (1985).

2-6 **PUSCH R, 1985**
The borehole, shaft and tunnel sealing test, in Radioactive Waste Disposal; In situ experiments in Granite, OECD/NEA, Proceedings of the 2nd NEA/Stripa Project Symposium, page 132, Paris.

2-7 **Boliden WP-Contech AB, 1985**
NAK WP-Cave Project. Report on the research and development stage, May 1984 to October 1985.
SKN Report 16 (1985).

2-8 **KATAYAMA B, 1976**
Leaching of Irradiated LWR Fuel Pellets in Deionized and Typical Ground Water.
Report: BNWL-2057. Battelle Pacific Northwest Laboratory, Richland, WA.

2-9 **EKLUND U-B and FORSYTH R S, 1978**
Leaching of Irradiated UO_2 Fuel.
KBS Technical Report 70, Stockholm.

2-10 **WILSON C N, 1985**
Results from NNWSI Series 1 Spent Fuel Leach Tests.
Report: HEDL-TME 84-70.
Westinghouse Hanford Co., Richland, WA.

2-11 **OVERSBY V M and WILSON C N, 1986**
Derivation of a Waste Package Source Term for NNWSI from Results of Laboratory Experiments, in: Scientific Basis for Nuclear Waste Management-IX, ed. L.O. Werme, p. 337, the Materials Research Society, Pittsburgh, PA.

2-12 **SCHRAMKE J A, SIMONSON S A and COLES D G, 1984**
A Report on the Status of Hydrothermal Testing of Fully Radioactive Waste Forms and Basalt Repository Waste Package Components.
Report: SD-BWI-TI-253, Rev. O.
Battelle Pacific Northwest Laboratory, Richland, WA.

2-13 **GRAY W J, McVAY G L, BARNER J O, SHADE J W and COTE R W, 1984**
Evaluation of Spent Fuel as a Waste Form in a Salt Repository, in: Scientific Basis for Nuclear Waste Management-VII, ed. G.L. McVay, p. 437, North-Holland Publ. Co., New York.

2-14 **VANDERGRAAF T T, 1980**
Leaching of Irradiated UO_2 Fuel.
AECL Technical Record, TR-100.

2-15 **JOHNSON L H, 1982**
The Dissolution of Irradiated UO_2 Fuel in Groundwater.
AECL Report, AECL-6837.

2-16 **JOHNSON L H, BURNS I, JOLING H H and MOORE C J, 1981.**
The Dissolution of Irradiated UO_2 Fuel under Hydrothermal Conditions.
AECL Technical Record, TR-128.

2-17 **JOHNSON L H and JOLING H H, 1982**
The Dissolution of Irradiated Fuel under Hydrothermal Conditions, inø Scientific Basis for Nuclear Waste Management-IV, ed. S.V. Topp, p. 321, North-Holland Publ. Co., New York.

2-18 STROES-GASCOYNE S, JOHNSON L H, BEELEY P A and SELLINGER, D M, 1986
Dissolution of Used CANDU Fuel at Various Temperatures and Redox Conditions, in: Scientific Basis for Nuclear Waste Management-IX, ed. L.O.Werme, p. 317, the Materials Research Society, Pittsburgh, PA.

2-19 SHOESMITH D W, SUNDER S, JOHNSON L H and BAILEY M G, 1986
Oxidation of CANDU UO_2 Fuel by the Alpha-Radiolysis Products of Water, in: Scientific Basis for Nuclear Waste Management-IX, ed. L.O. Werme, p. 309, the Materials Research Society, Pittsburgh, PA.

2-20 JOHNSON L H, BURNS K I, JOLING H H and MOORE C J, 1983
Leaching of Cs-137, Cs-134 and I-129 from Irradiated UO_2 Fuel.
Nucl. Techn. 63 470.

2-21 Systemstudie Andere Entsorgungtechniken, Technischer Anhang 9.
Auslaugungsversuche an unbestrahlten und bestrahlten Kernbrennstoffen in Salzlaugen.
KWU AG, October 1984.

2-22 FORSYTH R S, SVANBERG K and WERME L O, 1984
The Corrosion of Spent UO_2 Fuel in Synthetic Groundwater, in: Scientific Basis for Nuclear Waste Management-VII, ed. G.L. McVay, p. 179. North-Holland Publ. Co., New York.

2-23 BRUNO J, FORSYTH R S and WERME L O, 1985
Spent UO_2 Fuel Dissolution. Tentative Modelling of Experimental Apparent Solubilities, in: Scientific Basis for Nuclear Waste Management-VIII, p. 413, the Materials Research Society, Pittsburgh, PA.

2-24 FORSYTH R S, WERME L O and BRUNO J, 1986
The Corrosion of Spent UO2 Fuel in Synthetic Groundwater.
J. Nucl. Mat. 138 (1986) 1.

2-25 LÖNNERBERG B, LARKER H and AGESKOG L, 1983
Encapsulation and handling of spent nuclear fuel for final disposal.
SKBF/KBS Technical Report TR 83-20, May 1983.

2-26 The Swedish Corrosion Research Institute and its reference group.
Corrosion resistance of a copper canister for spent nuclear fuel.
SKBF/KBS Technical Report TR 83-24, April 1983

2-27 SANDERSON A, SZLUHA T F, TURNER J L and LEGGATT R H, 1983
Feasibility study of electron beam welding of spent nuclear fuel canisters.
SKBF/KBS Technical Report TR 83-25, April 1983.

2-28 HENRIKSON S and de POURBAIX M, 1979
Korrosionsprovning av olegerat titan i simulerade deponeringsmiljöer för upparbetat kärnbränsleavfall. Slutrapport.
(Corrosion testing of unalloyed titanium in simulated deposition environments for reprocessed nuclear fuel waste. Final Report).
SKBF/KBS Technical Report TR 79-14, May 1979.

2-29 MATTSSON H and OLEFJORD I, 1984
General corrosion of Ti in hot water and water saturated bentonite clay.
SKB/KBS Technical Report TR 84-19, December 1984.

2-30 MATTSSON H and OLEFJORD I, 1986
ESCA investigation of the reaction products formed on titanium exposed to water saturated bentonite clay, in: Scientific Basis for Nuclear Waste management-IX, ed.: L.O. Werme, p. 483, Materials Research Society, Pittsburgh, PA.

2-31 The Swedish Corrosion Institute and its reference group.
Aluminium oxide as an encapsulation material for unreprocessed nuclear fuel waste - evaluation from the viewpoint of corrosion,
SKBF/KBS Technical Report TR 80-15, March 1980.

2-32 IKEDA B M and McKAY P, 1985
The corrosion of titanium grades 2 and 12, in: AECL Technical Record TR-350, p. 135.

2-33 The NAGRA Working Group on Container Technology.
An assessment of the corrosion resistance of the high-level waste containers proposed by NAGRA.
NAGRA Technical Report 84-32, February 1984.

2-34 SIMPSON J P, SCHENK R and KNECHT B, 1986
Corrosion rate of unalloyed steels and cast irons in reducing granitic groundwaters and chloride solutions, in: Scientific Basis for Nuclear Waste Management-IX, ed.: L.O. Werme, p. 429, Materials Research Society, Pittsburgh, PA.

2-35 **MARSH G P, TAYLOR K J, BLAND I D, WESTCOTT C, TASKER P W and SHARLAND S M, 1986**
Evaluation of the localized corrosion of carbon steel overpack for nuclear waste disposal in granite environments, in: Scientific Basis for Nuclear Waste Management-IX, ed.: L.O. Werme, p.421, Materials Research Society, Pittsburgh, PA.

2-36 **ONOFREI M, RAINE D and BROWN L, 1985**
Ceramic materials for advanced containment, in: AECL Technical Record TR-350, p. 194.

2-37 **FETT T, KELLER K and MUNZ D, 1985**
Determination of crack growth parameters of alumina in 4-point bending tests.
NAGRA Technical Report 85-51.

2-38 **SIMPSON J P, 1983**
Experiments on container materials for Swiss high-level waste disposal projects. Part I.
NAGRA Technischer Bericht 83-05.

2-39 **SIMPSON, J P, 1984**
Experiments on container materials for Swiss high-level disposal projects. Part II.
NAGRA Technical Report 84-01.

2-40 **TAYLOR K J, BLAND I D and MARSH G P, 1984**
Corrosion studies on containment materials for vitrified high-level nuclear waste.
AERE-G2970.

2-41 **SHARLAND S M and TASKER P W, 1985**
A mathematical model of crevice and pitting corrosion: Part I - The physical model.
AERE Report TP.1123.

2-42 **SHARLAND S M, 1985**
A mathematical model of crevice and pitting corrosion: Part II - The mathematical solution.
AERE Report TP.1124.

2-43 **NERETNIEKS I, 1986**
Some aspects on the use of iron canisters for HLW, in: Scientific Basis for Nuclear Waste Management-IX, ed.: L.O. Werme, p. 411, The Materials Research Society, Pittsburgh, PA.

2-44 **BERGMAN B and FORBERG S, 1985**
Ceramic containers for spent nuclear fuel. I. Homogeneous sealing of rutile containers at low temperatures, in: Scientific basis for Nuclear Waste Management-VIII, eds.: C.M. Jantzen, J.A. Stone and R.C. Ewing, p. 421, The Materials Research Society, Pittsburgh, PA.

2-45 **Tekniska Röntgencentralen AB.**
Feasibility study of detection of defects in welded copper.
SKBF/KBS Technical Report TR 83-32, April 1983.

2-46 **Final storage of spent nuclear fuel KBS-3.**
Volume III Barriers. 9. Buffer and backfill material.
SKBF/KBS, Stockholm, 1983.

2-47 **Same as /2-3/**

2-48 **ANDERSON D M, 1984**
Smectite alteration. Proceedings of a Workshop convened at the Shoreham Hotel Washington, D.C. December 8-9, 1983.
SKB/KBS Technical Report TR 84-11, November 1984.

2-49 **PUSCH R, ERLSTRÖM M and BÖRGESSON L, 1985**
Sealing of rock fractures. A survey of potentially useful methods and substances.
SKB Technical Report TR 85-17, December 1985.

Chapter 3

3-1 **Final storage of spent nuclear fuel KBS-3.**
Volumes I-IV.
SKBF/KBS, Stockholm, 1983.

3-2 **OHLSSON O, FALK L, SANDBERG E, CARLSTEN S,MAGNUSSON, K-Å, 1985**
Results from Borehole Radar Reflection Measurements, p. 190-202, Proc 2nd NEA/Stripa Project Symp, OECD/NEA, Paris.

3-3 **AHLBOM K, ANDERSSON P, EKMAN L, GUSTAFSSON E, SMELLIE J, TULLBORG E-L, 1986**
Preliminary Investigations of Fracture zones in the Brändan Area, Finnsjön Study Site.
SKB Technical Report 86-05, February 1986.

3-4 **BLACK J H, 1985**
Crosshole Investigations. Preliminary Results of Single-Borehole Hydraulic Tests and Early Crosshole Sinusoidal Measurements, p. 214-229, Proc 2nd NEA/Stripa Project Symp, OECD/NEA, Paris.

3-5 **AECL 1985**
The Geoscience Program
Proc 17th Information Meeting of the Nuclear Fuel Waste Management Program.
AECL TR-299.

3-6 **AECL 1986**
General Meeting.
Proc 20th Information Meeting of the Canadian Nuclear Fuel Waste Management Program.
AECL TR-375.

3-7 **HANCOX W T, WHITAKER S H, 1986**
An Innovative Approach to Characterizing Sites for Nuclear Fuel Waste Disposal.
Proc 26th Annual Conf, Canadian Nucl Ass.
Toronto June 8-10.

3-8 **OECD, 1985**
Proc 2nd NEA/Stripa Project Symp,
OECD/NEA, Paris.

3-9 **THUNVIK R, BRAESTER C, 1980**
Hydrothermal Conditions around a Radioactive Waste Repository.
SKBF/KBS Technical Report TR 80-19, December 1980.

3-10 **AHLBOM K, CARLSSON L, OLSSON O, 1983**
Final Disposal of Spent Nuclear Fuel - Geological, Hydrogeological and Geophysical Methods for Site Characterization.
SKBF/KBS Technical Report TR 83-43, May 1983.

3-11 **MÖRNER N A, 1977**
Rörelser och instabilitet i den svenska berggrunden (Movements and instability in the Swedish bedrock).
KBS Technical Report TR 18, August 1977.

3-12 **RÖSHOFF K, LAGERLUND E, 1977**
Tektonisk analys av södra Sverige, Vättern - N Skåne (Tectonic analysis of southern Sweden, Vättern - N Skåne)
KBS Technical Report TR 20, September 1977.

3-13 **HENKEL H, HULT K, ERIKSSON L, 1983**
Neotectonics in Northern Sweden - Geophysical Investigations.
SKBF/KBS Technical Report TR 83-57, May 1983.

3-14 **LAGERBÄCK R, WITSCHARD F, 1983**
Neotectonics in Northern Sweden - Geological Investigations
SKBF/KBS Technical Report TR 83-58, May 1983.

3-15 **FLODÉN T, 1977**
Tectonic Lineaments in the Baltic from Gävle to Simrishamn.
KBS Technical Report TR 59, December 1977.

3-16 **KULHANEK O, WAHLSTRÖM R, 1977**
Earthquakes of Sweden 1891-1957, 1963-1972.
KBS Technical Report TR 21, September 1977.

3-17 **RINGDAL F, GJÖYSTDAL H, HUSEBY, E S, 1977**
Seismotectonic Risk Modelling for Nuclear Waste Disposal in the Swedish Bedrock.
KBS Technical Report TR 51, October 1977.

3-18 **BÅTH M, 1979**
Fracture Risk Estimation for Swedish Earthquakes.
SKBF/KBS Technical Report TR 79-27, October 1979.

3-19 **PUSCH R, 1977**
The Influence of Rock Movement on the Stress/Strain Situation in Tunnels or Boreholes with Radioactive Canisters Embedded in a Bentonite/Quartz Buffer Mass.
KBS Technical Report TR 22, August 1977.

3-20 **STEPHANSSON O, 1977**
Deformationer i sprickigt berg (Deformations in fractured rock).
KBS Technical Report TR 29, September 1977.

3-21 **PUSCH R, 1978**
Inverkan av glaciation på en deponeringsanläggning belägen i urberg 500 m under markytan (Influence of glaciation on a repository situated in crystalline rock 500 m below the surface of the ground).
KBS Technical Report TR 89, March 1978.

3-22 **STEPHANSSON O, MÄKI K, GROTH T, JONASSON P, 1978**
Finit elementanalys av bentonitfyllt bergförvar (Finite element analysis of bentonite-filled rock repository).
KBS Technical Report TR 104, July 1978.

3-23 **PELTONEN E, RYHÄNEN VH, SALU J-P, VIENO TK, VUORI S J, 1986**
Concept and Safety Assessment for Spent Fuel Disposal in Finland.
Int Symp on the Siting, Desing and Construction of Underground Repositories for Radioactive Waste.
Hanover, March 1986, IAEA-SM-289/28.

3-24 **VUORI S, PELTONEN E, VIENO T K, 1986**
Safety of the Disposal of Spent Fuel and other LWR Wastes in Hard Bedrock p. 583-590.
9th FORATOM Congress (ENC 86).
Geneva, June 1986.

3-25 **MÖRNER N A ed, 1980**
The Fennoscandian Uplift in Earth Rheology, Isostasy and Eustasy.
John Wiley & Sons, New York.

3-26 **TULKKI P, 1977**
The Bottom of the Bothnian Bay, Geomorphology and Sediments.
Marine Research Inst, Finland, report no 241.

3-27 **TALBOT C, SLUNGA R, 1986**
The Pattern of Active Faults in the Baltic Shield.
GFF, Stockholm (in print).

3-28 **SLUNGA R, 1985**
The Seismicity of Southern Sweden 1979-1984.
Final Report.
FOA Stockholm (1985).

3-29 **MASSARCH R, 1983**
Inverkan av jordbävningar på underjordsanläggningar. (Influence of earthquakes on underground facilities).
Dept. of soil and rock mechanics, Report 16, Royal Inst. of Technology. Stockholm, 1983.

3-30 **BÅTH M, 1985**
Superficial Granitic Layering in Shield Areas.
Tectonophysics 118, 75-83.

3-31 **RICHARDSON A M, BROWN S M, HUSTRULID W A, RICHARDSON D L, 1986.**
An interpretation of Highly Scattered Stress Measurements in Foliated Gneiss.
Proc Int Symp Rock Stress and Rock Stress Measurements. Stockholm 1-3 Sept 1986, CENTEK Luleå, p. 441-447.

3-32 **PRICE R A, FLINN E A, 1981**
International Lithosphere Program,
Episode No 3, p. 13-17.

3-33 **MÖRNER N A ed 1986**
PPPL - a Part of the Swedish ILP.
Report 1986. Stockholms University.

3-34 **KBS, 1977**
Handling of spent nuclear fuel and final storage of vitrified high-level reprocessing waste. KBS-1 Volumes I-V.
KBS, Stockholm 1977.

3-35 **OLKIEWICZ A, STEJSKAL V, 1986.**
Geological and Tectonic Description of the Klipperås Study Site.
SKB Technical Report TR 86-06, October 1986.

3-36 **SEHLSTEDT S, STENBERG L, 1986**
Geophysical Investigations at the Klipperås Study Site.
SKB Technical Report TR 86-07, July 1986.

3-37 **GENTZSCHEIN B, 1986**
Hydrogeological Investigations at the Klipperås Study Site.
SKB Technical Report TR 86-08, June 1986.

3-38 **TULLBORG E-L, 1986**
Fissure Fillings from the Klipperås Study Site.
SKB Technical Report TR 86-10, July 1986.

3-39 **BJARNASON B, STEPHANSSON O, 1986**
Hydraulic Fracturing Rock Stress Measurements in Borehole Gi-1, Gideå Study Site, Sweden.
SKB Technical Report TR 86-11, April 1986.

3-40 **GENTZSCHEIN B, TULLBORG E-L, 1985**
The Taavinunnanen Gabbro Massif. A Compilation of Results from Geological, Geophysical and Hydrogeological Investigations.
SKB Technical Report TR 85-02, January 1985.

3-41 **LARSSON S-Å, TULLBORG E-L, 1984**
Fracture Fillings in the Gabbro Massif of Taavinunnanen, Northern Sweden.
SKB Technical Report TR 84-08, August 1984.

3-42 **McCRANK G F D, STONE D, EJECKAM R B, KAMINENI D C, SIKORSKY R I, McEWEN J, 1985**
Surface and Subsurface Geological Investigations of the East Bull Lake Pluton, Research Area 7, 1.
AECL TR-299, p. 143-164.

3-43 **Industrins Kraft AB, 1985**
Slutförvaring av använt kärnbränsle.
Rapportsammandrag, Platsundersökningsprogrammet.
(Final disposal of spent nuclear fuel. Summary of reports, Site investigation programme)
Industrins Kraft AB (TVO), Finland 11 p.

3-44 **ALMÉN K-E, ANDERSSON O, FRIDH B, GUSTAFSSON E, HANSSON K, JOHANSSON B-E, NILSSON G, OLSSON O, SEHLSTEDT M, AXELSEN K, WIKBERG P.**
Site Investigations - Equipment for Geological, Geophysical and Hydrochemical Characterization.
SKB Technical Report TR 86-16.

3-45 **HOLMES D C, SEHLSTEDT M, 1985**
Crosshole Investigations - Design of the Hydraulic Testing System p. 203-213. Proc. 2nd NEA/Stripa Project Symp,OECD/NEA, Paris.

3-46 **OLSSON O, FORSLUND O, LUNDMARK L, SANDBERG E, FALK L, 1985**
The Design of a borehole Radar System for Detection of Fracture Zones, p. 172-189, Proc. 2nd NEA/Stripa Project Symp, OECD/NEA, Paris.

3-47 **COSMA C, 1985**
Detection of Fractured Zones by Crosshole Seismics, p. 160-171, Proc. 2nd NEA/Stripa Project Symp, OECD/NEA, Paris.

Chapter 4

4-1 **AGNEDAL P O, ANDERSSON K, EVANS S, SUNDBLAD B, THAM G, WILKENS A B**
The dynamics of lake, bog and bay - consequences of exposure to uranium related to final storage of spent nuclear fuel.
Studsvik Energiteknik AB
SKB/KBS Technical Report 84-17, December 1984.

4-2 **BERGSTRÖM U-B, EDLUND O, EVANS S, RÖJDER B, 1983**
BIOPATH - A computer code for calculation of the turnover of nuclides in the biosphere and the resulting doses to man.
Studsvik/NW-82/261.

4-3 **SUNDBLAD B, LANDSTRÖM O, AXELSSON R**
Concentration and distribution of natural radionuclides at Klipperåsen and Bjulebo, Sweden.
Studsvik Energiteknik AB.
SKB Technical Report TR 85-09, October 1985.

4-4 **JOHANSSON G**
Minutes from the first BIOMOVS Coordinating Group Meeting in Boden October 30, 1985.
SSI Report 85-24.

Chapter 5

5-1 **SMELLIE J, LARSSON N-Å, WIKBERG P and CARLSSON L**
Hydrochemical Investigations in Crystalline Bedrock in Relation to Existing Hydraulic Conditions. Experience from the SKB Test-Sites in Sweden.
SKB Technical Report TR 85-11, November 1985.

5-2 **NORDSTROM D K and PUIGDOMENECH I**
Redox Chemistry of Deep Groundwaters in Sweden.
SKB Technical Report TR 86-03, April 1986.

5-3 **TULLBORG E-L**
Fissure Fillings from the Klipperås Study Site.
SKB Technical Report TR 86-10, June 1986.

5-4 **NORDSTROM D K, ANDREWS J N, CARLSSON L, FONTES J C, FRITZ P, MOSER H and OLSSON T**
Hydrogeological and Hydrogeochemical Investigations in Boreholes - Final Report of the Phase I Geochemical Investigations of the Stripa Groundwaters.
Stripa Project Technical Report TR 85-06, July 1985.

5-5 **FRITZ B, KAM M and TARDY Y**
Geochemical Simulation of the Evolution of Granitic Rocks and Clay Minerals Submitted to a Temperature Increase in the Vicinity of a Repository for Spent Nuclear Fuel.
SKB/KBS Technical Report TR 84-10, July 1984.

5-6 **FRITZ B and KAM M**
Chemical Interactions between the Bentonite and the Natural Solutions from the Granite near a Repository for Spent Nuclear Fuel.
SKB Technical Report TR 85-10, July 1985.

5-7 **GRENTHE I, RIGLET CH and VITORGE P**
Studies of Metal-Carbonate Complexes. Composition and Equilibria of Trinuclear Neptunium and Plutonium Carbonate Complexes.
Inorganic Chemistry, 25 (1986) 1679.

5-8 **MULLER A B**
International Chemical Thermodynamic Database for Nuclear Applications.
Radioactive Waste Management and the Nuclear Fuel Cycle, 6 (1985) 131.

5-9 **BRUNO J, GRENTHE I and MUÑOS M**
The UO_2-La $(OH)_3$ Coprecipitation as an Analogue for the UO_2-Pu $(OH)_3$ System, in Scientific Basis for Nuclear Waste Management IX, p 715, the Materials Research Society, Pittsburg, PA (1986).

5-10 **MARINSKY J, MATHUTHU A, BICKING M and EPHRAIM J**
Complex Forming Properties of Natural Occurring Fulvic Acids.
SKB Technical Report TR 85-07, July 1985.

5-11 **OLOFSSON U and ALLARD B**
Formation and Transport of Americium Pseudocolloids in Aqueous systems.
SKB Technical Report TR 86-02, March 1986.

5-12 **McKINLEY I G, WEST J M and GROGAN H A**
An Analytical Overview of the Consequences of Microbial Activity in a Swiss HLW Repository.
NAGRA TR 85-43, December 1985.

5-13 **WEST J M, HOOKER P J and McKINLEY I G**
Geochemical Constraints on the Microbial Contamination of a Hypothetical UK Deep Geological Repository.
British Geological Survey Report FLPU 84-8, August 1984.

5-14 **ENGVALL A-G and HALLBERG R**
Förstudie av mikroorganismers delaktighet i radionuklidmigration
(Preliminary study of participation of micro-organisms in radionuclide migration).
Report June 1985.

5-15 **SKAGIUS K and NERETNIEKS I**
Porosities and and Diffusivities of some Non-sorbing Species in Crystalline Rocks.
SKB Technical Report 85-03, February 1985.

5-16 **SKAGIUS K and NERETNIEKS I**
Diffusivity Measurements and Electrical Resistivity Measurements in Rock Samples under Mechanical Stress.
SKB Technical Report TR 85-05, April 1985.

5-17 **SKAGIUS K and NERETNIEKS I**
Diffusion Measurements of Cesium and Strontium in Biotite Gneiss.
SKB Technical Report TR 85-15, December 1985.

5-18 **ALLARD B, ELIASSON L, HÖGLUND S and ANDERSSON K**
Sorption of Cs, I and Actinides in Concrete Systems.
SKB/KBS Technical Report TR 84-15, September 1984.

5-19 **CHRISTENSEN H**
Formation of Nitric and Organic Acids by the Irradiation of Groundwater in a Spent Fuel Repository.
SKB/KBS Technical Report TR 84-12, July 1984.

5-20 **CHRISTENSEN H and BJERGBAKKE E**
Effect of Beta-Radiolysis on the Products from Alfa-Radiolysis of Groundwater.
SKBF/KBS Technical Report TR 84-03, July 1984.

5-21 **ERIKSEN T and CHRISTENSEN H**
Hydrogen Production in Alfa-Irradiated Bentonite.
SKB Technical Report TR 86-04, March 1986.

5-22 **CHRISTENSEN H and BJERGBAKKE E**
Radiolysis of Concrete.
SKBF/KBS Technical Report TR 84-02, March 1984.

5-23 **JENNE E A ed.**
Chemical Modelling in Aqueous Systems. Speciation, Sorption, Solubility and Kinetics.
American Chemical Society Symposium, Series 93 (1979).

5-24 **ANDERSSON G, RASMUSON A and NERETNIEKS I**
Migration Model for the Near Field. Final Report.
SKBF/KBS Technical Report TR 82-24, November 1982.

5-25 **NERETNIEKS I**
The Movement of a Redox Front Downstream from a Repository for Nuclear Waste.
SKBF/KBS Technical Report TR 82-16, April 1982.

5-26 **NERETNIEKS I and ÅSLUND B**
The Movement of Radionuclides Past a Redox Front.
SKBF/KBS Technical Report TR 83-66, April 1983.

5-27 **NERETNIEKS I and ÅSLUND B**
Two Dimensional Movements of a Redox Front Downstream from a Repository for Nuclear Waste.
SKBF/KBS Technical Report TR 83-68, June 1983.

5-28 **NERETNIEKS I**
Some Notes in Connection with the KBS Studies of Final Disposal of Spent Fuel.
KBS Technical Report TR 120, September 1978.

5-29 **RASMUSON A**
Analysis of Hydrodynamic Dispersion in Discrete Fracture Networks using the Methods of Moments.
SKB Technical Report TR 85-13, June 1985.

5-30 **RASMUSON A and NERETNIEKS I**
Radionuclide Transport in Fast Channels in Crystalline Rock.
Water Resources Research (in print).

5-31 **NERETNIEKS I and RASMUSON A**
An Approach to Modelling Radionuclide Migration in a Medium with Strongly Varying Velocity and Block Sizes along the Flow Path.
Water Resources Research 20 (1984) 1823.

5-32 **RASMUSON A and NERETNIEKS I**
Radionuclides Migration in Strongly Fissured Zones. The Sensitivity to some Assumptions and Parameters.
SKB Technical Report TR 85-14, August 1984.

5-33 **RASMUSON A**
Modelling of Coupled Chemistry and Chemical Transport for a Final Repository of Nuclear Waste in Granitic Bedrock.
Report March 1986.

5-34 **ERIKSEN T**
Radionuclide Transport in a Single Fissure.
A Laboratory Study of Am, Np and Tc.
SKBF/KBS Technical Report TR 84-01, January 1984.

5-35 **MORENO L, NERETNIEKS I and ERIKSEN T**
Analysis of some Laboratory Tracer runs in Natural Fissures.
SKBF/KBS Technical Report TR 84-04, March 1984.

5-36 **LANDSTRÖM O, ANDERSSON K and TULLBORG E-L**
Migration Experiments in Studsvik.
SKBF/KBS Technical Report TR 83-18, January 1983.

5-37 **GUSTAFSSON E and KLOCKARS C-E**
Study of Strontium and Cesium Migration in Fractured Crystalline Rock.
SKBF/KBS Technical Report TR 84-07, September 1984.

5-38 **ABELIN H, NERETNIEKS I, TUNBRANT S and MORENO L**
Final Report of the Migration in a Single Fracture. Experimental Results and Evaluation.
Stripa Project Technical Report TR 85-03, May 1985, SKB, Stockholm.

5-39 **Stripa Project TR 85-07.**
Annual Report 1984
SKB July 1985

5-40 **ANDERSSON P and KLOCKARS C-E**
Hydrogeological Investigations and Tracer Tests in a Well-Defined Rock Mass in the Stripa Mine.
SKB Technical Report TR 85-12, September 1985.

5-41 **BIRGERSSON L and NERETNIEKS I**
Diffusion in the Matrix of Granitic Rock. Field Test in the Stripa Mine. Part 1.
SKBF/KBS Technical Report TR 82-08, July 1982.

5-42 **BIRGERSSON L and NERETNIEKS I**
Diffusion in the Matrix of Granitic Rock. Field Test in the Stripa Mine. Part 2.
SKBF/KBS Technical Report TR 83-39, March 1983.

5-43 **SMELLIE J ed.**
Natural Analogues to the Conditions around a Final Repository for High-level Radioactive Waste. Proceedings of the Natural Analogue Workshop held at Lake Geneva, Wisconsin, USA (October 1-3, 1984).
SKB/KBS Technical Report TR 84-18, December 1984.

5-44 **CURTIS D and GANCARZ A**
Radiolysis in Nature. Evidence from the Oklo Natural Reactors.
SKBF/KBS Technical Report TR 83-10, February 1983.

5-45 **CURTIS D**
The Chemical Coherence of Natural Spent Fuel at the Oklo Nuclear Reactors.
SKB Technical Report TR 85-04, March 1985.

5-46 **SMELLIE J A T, MACKENZIE A B and SCOTT R D**
Part I. An Analogue Validation Study of Natural Radionuclide Migration in Crystalline Rock using Uranium Series Disequilibrium Studies.
Part II. A Comparison of Neutron Activation and Alpha Spectroscopy Analyses of Thorium in Crystalline Rocks.
SKB Technical Report TR 86-01, February 1986.

5-47 **Proposed Program of Investigation at Poços de Caldas, Minas Gerais Brazil.**
May 1986.

5-48 **KULLMAN F, LÖFROTH B and SMELLIE J**
Uranium Mineralisations in Sweden. A Compilation Report for Potential Natural Analogue Study Sites.
SGAB Report IRAP 86008, February 1986.

5-49 **Natural Analogues Working Group Meeting**
Brussels, November 5-7, 1985.
CEC Report EUA 10315.

Chapter 6

6-1 **INTRACOIN**
Final Report Level 1: Code Verification.
Swedish Nuclear Power Inspectorate Report SKI 84:3 (1984).

6-2 **HYDROCOIN**
Progress Report No 2: January-June 1985.
Hydrocoin Project Secretariat Report, 1985.

Chapter 7

7-1 **Handling and final disposal of nuclear waste.**
Internationell och utländsk verksamhet.
Underlagsrapport ill FoU-program -86.
(International and foreign activities.
Background report to R&D programme '86. In Swedish)
SKB September 1986.

7-2 **Public Law 97-425 - January 7, 1983.**
Nuclear Waste Policy Act of 1982.

7-3 **Systemstudie Andere Entsorgungstechniken, Abschlussbericht Hauptband.**
Kernforschungszentrum Karlsruhe (Dec 1984).

7-4 **Projekt Gewähr 1985.**
NAGRA Projektbericht NGB 85-01 - NBG 85-08 (Jan 1985).

7-5 **Swedish-American Cooperative Program on Radioactive Waste Storage in Mined Caverns in Crystalline Rock.**
Technical Information Reports No. 1-54 with various authors.
The most recent report was written by Binnall and McEvoy and is designated LBL-12670, SAC-54, UC-70. It was published in October 1985 and contains a complete list of all SAC reports.

7-6 **Geological Disposal of Radioactive Waste In Situ Experiments.**
Proceedings of the NEA Workshops in Stockholm 25th - 27th October 1982.
OECD/NEA Paris 1983.

7-7 **Radioactive Waste Disposal - In Situ Experiments in Granite.**
Proceedings of the 2nd NEA/Stripa Project Symposium in Stockholm 4-6 June 1985.
OECD/NEA Paris 1985.

7-8 **Stripa Project TR 81-02.**
Annual Report 1980.
SKBF/KBS 1981.

7-9 **Stripa Project TR 82-01.**
Annual Report 1981.
SKBF/KBS 1982.

7-10 **Stripa Project TR 83-02.**
Annual Report 1982.
SKBF/KBS 1983.

7-11 **Stripa Project TR 84-01.**
Annual Report 1983.
SKBF/KBS 1984.

7-12 **ABELIN H et al**
Final Report of the Migration in a Single Fracture. Experimental Results and Evaluation.
Stripa Project TR 85-03, May 1985, SKB, Stockholm.

7-13 **NORDSTROM D K et al.**
Hydrogeological and Hydrogeochemical Investigations in Boreholes - Final Report of the phase 1 geochemical investigations of the Stripa groundwaters.
Stripa Project Technical Report TR 85-06, July 1985, SKB, Stockholm.

7-14 **Stripa Project TR 85-07.**
Annual Report 1984.
SKB, July 1985.

7-15 **CARLSSON L and OLSSON T**
Hydrogeological and Hydrogeochemical Investigations - Final Report.
Stripa Project Technical Report TR 85-10, July 1985, SKB, Stockholm.

7-16 **PUSCH R, NILSSON J and RAMQVIST G, 1985:**
Final Report of the Buffer Mass Test - Volume I: Scope, preparative field work and test arrangement.
Stripa Project Technical Report TR 85-11, July 1985, SKB, Stockholm.

PUSCH R, BÖRGESSON L and RAMQVIST G, 1985:
Final Report of the Buffer Mass Test - Volume II: Test results.
Stripa Project Technical Report TR 85-12, July 1985, SKB, Stockholm.

PUSCH R
Final Report of the Buffer Mass Test - Volume III: Chemical and physical stability of the buffer materials.
Stripa Project TR 85-14, November 1985, SKB, Stockholm.

7-17 **Tentative Program for the Stripa Project Phase 3 1986-1991.**
January 28, 1986, SKB.

7-18 **AECL - The Geoscience Program**
Proc 17th Int Meeting of the Nuclear Fuel Waste Management Programme.
AECL TR-299, (1985).

7-19 **HERMANSSON H-P, BJÖRNER I-K, CHRISTENSEN H and YOKOYAMA H, 1984**
JSS Project Phase I: Static leaching in distilled water, silicate water and simulated groundwater at 90°C with and without granite. Studsvik's final report.
JSS Project Technical Report TR 84-01, SKB, Stockholm.

7-20 **BART G, AERNE E T, GÖRLICH W, GRAUER R, LINDER H, MOKOS M, Z'BERG D and ZWICKY H U, 1984**
EIR final report of JSS glass corrosion programme Phase I.
JSS Project Technical Report TR 84-02, SKB, Stockholm.

7-21 **JSS Project Phase I:**
A summary of work performed at Studsvik Energiteknik AB and at Swiss Federal Institute for Reactor Research (EIR).
JSS Project Technical Report TR 84-03, SKB, Stockholm.

7-22 JSS Project Phase II:
Final report of work performed at Studsvik Energiteknik AB and at Swiss Federal Institute for Reactor Research.
JSS Project Technical Report TR 85-01, SKB, Stockholm.

7-23 JSS Project Phase III:
Static leaching of radioactive glass at 40°C and leaching under dynamic conditions.
JSS Project Technical Report TR 86-01, SKB, Stockholm.

7-24 Code developed by US Geological Survey,
see eg D L Parkhurst, D C Thorstensen and L N Plummer (original PHREEQE), Water-Resources Investigations 80-96, US Geological Survey, Reston, VA, USA (1980).

7-25 JSS Project Phase IV:
Reactions between radioactive glass, water, bentonite and steel corrosion products; Experiments and model.
JSS Project Technical Report TR 86-02, SKB,Stockholm.

7-26 GRAMBOW B, 1986
A model for leaching of HLW glass under repository conditions.
JSS Project Technical Report TR 86-03, SKB, Stockholm.

7-27 HERMANSSON H-P, BJÖRNER I-K, CHRISTENSEN H, OHE T and WERME L O, 1986
Static leaching of fully radioactive waste glass at 90°C in the presence of bentonite, granite and stainless steel corrosion products, in: Scientific Basis for Nuclear Waste Management-IX, ed.: L O Werme, p 179, The Materials Research Society, Pittsburgh, PA.

7-28 GRAMBOW B B, HERMANSSON H-P, BJÖRNER I-K and WERME L, 1986
Glass/water interactions with and without bentonite present - Experiment and model, in: Scientific Basis for Nuclear Waste Management-IX, ed.: L O Werme, p 187, the Materials Research Society, Pittsburgh, PA.

7-29 GRAMBOW B, HERMANSSON H-P, BJÖRNER I-K, CHRISTENSEN H and WERME L
Reaction of nuclear waste glass with slowly flowing solutions, presented at American Ceramic Society's Third International Symposium on Ceramics in Nuclear Waste Management, Chicago, Ill. April 27 - May 1 1986 (in print).

7-30 WEDOW H, 1967
The Morro do Ferro thorium and rare-earth deposit, Poços de Caldas District, Brazil, USGS Bull. 1185-D (Washington DC, US Geological Survey).

7-31 EISENBUD M, KRAUSKOPF K, PENNA FRANCA E, LEI W, BALLARD R, LINSALATA P and FUJIMORI K, 1984
Natural analogues for the transuranic actinide elements.
Environ. Geol. Water Sci. 6, 1 (1984) 1.

7-32 LINSALATA P, EISENBUD M and PENNA FRANCA E, 1986
Ingestion estimates of Th and the light rare earth elements based on measurements of human feces, Health Physics 50, 1 (1986) 163.

7-33 MIEKELEY N, DOTTO R M, KUCHLER I L and LINSALATA P, 1985
The importance of organic compounds on the mobilization and bio assimilation of thorium in the Morro do Ferro environment, in: Scientific Basis for Nuclear Waste Management VIII, Materials Research Society, Pittsburg PA.

7-34 SANTOS R
Geology and mining development of the C-09 uranium deposit.
IAEA-AG-162/28, Vienna, 1976.

7-35 HYDROCOIN.
Progress Report No 3.
SKI, Stockholm, (1986).

7-36 CARLSSON L, WINBERG A, GRUNDFELT B
Model Calculations of the groundwater flow at Finnsjön, Fjällveden, Gideå and Kamlunge.
SKBF/KBS Technical Report TR 83-45, May 1983.

7-37 INTRACOIN; FINAL REPORT LEVEL 1
Code verification.
SKI 84:3, September 1984.

7-38 System Performance Assessment for Radioactive Waste Disposal.
Proceedings of an NEA workshop,
OECD/NEA, 22-24 October 1985, Paris 1986.

Appendix

EXPERT REVIEW OF KBS-3. STATEMENTS AND COMMENTS RELEVANT FOR R&D PROGRAMME 86.

In its licence to load the Forsmark 3 and Oskarshamn 3 reactors with nuclear fuel, the Government has prescribed that the R&D programme shall also include an account of how the viewpoints and comments offered in the expert review of KBS-3 have been taken into account or are intended to be taken into account.

The viewpoints that have emerged in connection with the review deal with the presentation of evidence demonstrating that the described design is feasible and satisfies the requirements of society on safety, and with proposals for ways to achieve more effective system designs or better performance and safety assessments.

The review has constituted a valuable basis for both the R&D programme presented in 1984 in connection with KBS-3 and the existing 1986 R&D programme.

As a consequence of the Government's judgement that the KBS-3 method is acceptable with respect to safety and radiation protection, further activities in the R&D programme are mainly aimed at a comprehensive evaluation of various alternative ways to design the final repository.

Aside from certain measures concerned with individual features of the KBS-3 method, no further development of the KBS designs will be commenced until a broad review of the alternatives has been completed.

This means that certain measures proposed by reviewers concerning, for example, further technology development and optimization of the barrier system will be postponed, while others, for example concerning alternative designs or materials, will be included in various types of alternative inventories at an early stage.

Part II of the 1986 R&D programme outlines the necessary R&D activities to permit selection of a site and design of a final repository by the year 2000. Such activities that fall during the period 1987-1992 are then described in detail in Part III under the various subject headings. Activities that pertain to engineered barriers and their function are particularly oriented towards the goal of carrying out a broad review of alternatives. Activities related to the geosciences, the biosphere and chemistry are primarily oriented towards a generally applicable further development of models or databases and will only be partially oriented towards the alternative reviews mentioned above.

The comments and viewpoints of the reviewers have often resulted in contacts or cooperation being established with other groups. There contacts have then in turn influenced the structure of the R&D programme. The extensive international contact network that has been built up over the past 10 years also provides good opportunities for cooperation, exchange of experience and division of labour between SKB and foreign groups, see Chapter 7 in Part III. Such cooperation is reflected, for example, in the planned research activities for canister and buffer materials.

In the face of the large safety margins applied in the KBS-3 analyses, a large number of reviewers expressed a wish for realistic calculations of repository performance based on probable parameter values. This wish will be taken into account in the evaluations that precede the selection of site and system and in the final optimization. Another prerequisite for optimization is a further development of models and databases, which has also been recommended by many reviewers.

Comments made in the review of KBS-3 of importance for the present R&D programme have been tabulated below. A guiding principle in this tabulation has been to select comments that either point to areas where deeper knowledge is needed, propose alternative designs or methods or point out uncertainties with a bearing on the safety of the repository.

Comments within the same area are presented in brief under a single heading, and the reviewers who have taken up the matter are indicated by a source reference. The third column provides a reference to the sections in Part III of the R&D programme where the issue is dealt with. After the table, a list is presented explaining the abbrevations for the various reviewers.

Often, the reviewers take up the same problem area from different angles and express their viewpoints in different ways. As a result, the wording of the heading is often relatively broad. The source references do not include all reviewers who have touched upon a matter. In many cases, only those who have been most explicit in their comments have been referred to.

The purpose of the table is to make it easier to quickly find the text sections that deal with the most common review comments and those of the greatest relevance to the R&D programme.

Review comments on KBS-3

Subject area	Reviewers	Sections in R&D programme 86 Part III
ENGINEERED BARRIERS		
Fuel matrix and dissolution		
Studies of fuel dissolution/leaching	NAK, SKI, FOA, IAEA, TAC	2.3.5
Modelling of fuel dissolution	SKI, Liljenzin, Langmuir	2.3.5
Radiolysis	Liljenzin, Studsvik	2.3.5, 5.2.4
Canister and canister corrosion		
Studies of pitting/crevice corrosion	SKI, Beijer, KTH, CEA, AERE	2.4.4
Inorganic reduction sulphate/sulphide	TAC	2.4.4
Development of electron beam welding	NAK, SKI, IAEA	2.4.4
Development of hot isostatic pressing	NAK, CTH, IAEA	2.4.3
Non-destructive testing	NAK, SKI, LuH, CEA, IVA, AERE	2.4.4
Creep studies	KTH	2.4.3
Buffer and backfill		
Field tests	SGI, SKI, Studsvik	2.5.3
Properties of bentonite	SKI, NAK	2.5.4
Temperature sensitivity of bentonite	SGU, KTH, SKI, NAS	2.5.4,7.8.1
GEOSCIENCES		
Geohydrology		
Further development of flow models	SKI, AERE, RE/SPEC, LTH, KTH, IVA, IAEA, NEA, NAS	3.1.4, 7.3
Hydraulic conductivity	SKI, AIB, UU, IVA, RE/SPEC, SGU, NFR, KVA, IAEA,NEA, NAS	3.1.4
Kinematic porosity	SKI	3.1
Water turnover	SGI, KTH, IVA, Studsvik	3.1
Flow dispersion in fractured rock	NAK, KTH, LTH	3.1
Orientation of fractures – anisotropy	RE/SPEC, SKI, CEA	3.1, 3.5.4, 7.3
Importance of fracture zones	TAC, NAK	3.1
Geophysical methods for tracing fracture zones	West, SKI	3.1.4, 3.3.4, 7.3
Study-site investigation		
Regional studies of tectonics, geohydrology	SKI, TAC, Wickman, SGU	3.3.4
Interference tests	SKI, NAS, SGU	3.3.4, 3.5.4
Rock mechanics calculations	SKI, SGI, IVA, LU, KTH, SGU, TAC, CEA	3.2.4, 3.3.4
Investigations to a depth of at least 1000 m	NAK, CTH, SGU	3.3
Site-specific verification of model calculations	TAC, IAEA, NEA	3.4.4
Ultramafites	CTH	3.3.3
Instruments		
Radar investigations	West, SKI	3.1.4, 3.3.4, 3.5.4, 7.3
Oriented cores or TV logging	SKI	3.5.4
In-situ measurement of redox conditions	NEA, IVA, CEA	3.5.4, 5.1.4
Rock mechanics		
Investigations of a boundary layer at 1.4 km	Båth, UU	3.2.4
Rock mechanics models	AIB, Massarsch	3.2.4
Thermomechanical studies	CEA, SKI, RE/SPEC	3.1.4
Thermal convection	SKI	3.1.4
Nationwide tectonic map	NAK, AIB, NFR, LU	3.2.4
Influence of earthquakes on the repository	KTH, LTH, Massarsch, UU, CEA	3.2.4
Influence of ice sheet on the repository	SKI, LTH, KTH, Wickman, IAEA	3.2.4
Postglacial zones of movement	SKI, NAS	3.2.4

Subject area	Reviewers	Sections in R&D programme 86 Part III
BIOSPHERE		
Time-dependent parameters	NRPB	4.4.1
Database	Lidén, SU, NFR, Studsvik	4.4.2
Sediment studies	Dyrssen, NRPB	4.4.3
CHEMISTRY		
Geochemistry		
Sampling and analysis of groundwater	Langmuir, Dyrssen, IVA, NEA	5.1.4
Groundwater dating	Langmuir, Beijer, SGU, IAEA, NEA, LU	5.1.3
Geochemical modelling	SKI, Langmuir, RE/SPEC, NAK, Beijer, Liljenzin, Jacks, Dyrssen, Wickman, SNV, UmU, NEA, CEA	5.1.4
Natural redox conditions	Langmuir, SIKOB, Jacks, KTH, IVA, IAEA, NEA, CEA	5.1.4, 3.5.4
Saline groundwater	Jacks, Dyrssen, IAEA, NEA	5.1.3
Geogas	AIB, SNV, CEA, LTH	5.1.4, 3.1.4
Analysis of fracture minerals	Wickman, NEA, CEA	5.1.4
Radionuclide chemistry		
Solubility and complexation (inorganic)	SKI, Langmuir, Beijer, Liljenzin, NAS, Studsvik	5.2.4
Reduction and precipitation	Beijer, Liljenzin, Studsvik, IAEA	5.2.4
Organic complexes, colloids and microbes	SKI, Langmuir, Liljenzin, Dyrssen, Studsvik, IAEA, NAS, CEA, TAC, SNV, KTH	5.2.4
Sorption models	SKI, AERE, Langmuir, NAK, Liljenzin, KTH, CTH, IVA, NRPB	5.2.4
Diffusion in microfractures in the rock	SKI, Beijer, TAC, CEA	5.2.4
Radiolysis	SKI, KTH, TAC	5.2.4, 2.3.5
Chemical transport		
Migration model for the near field	NRPB	5.3.4
Importance of heating in the near field	SKI	5.3.4
Gas evolution in the near field	SKI	5.3.4
Redox effects in the near field	SKI, Jacks, Studsvik, TAC	5.3.4
Coupled models transport-geochemistry	SKI	5.3.4
Validation		
Migration tests in the laboratory	Studsvik	5.4.4
Migration tests in situ	NAK, SGU, Studsvik	5.4.4, 3.5
Natural analogues	Beijer, Wickman, KTH, Stusvik, IAEA	5.4.4, 7.6
SAFETY ANALYSES		
Scenario description	NRPB, NEA, FOA	6.3
Probablistic analyses, uncertainties and sensitivity	NAK, FOA, IAEA, NAS, TAC, CEA	6.4.3

List of reviewers

AERE	AERE Harwell, Theoretical Physics Division, Great Britain
AIB	Allmänna Ingenjörsbyrån AB (NAK)
Beijer	Beijerinstitutet (NAK)
Båth	Marcus Båth (SSI)
CEA	Commissariat a l'Energie Atomique, France
CTH	Chalmers Tekniska Högskola (Chalmers University of Technology), Göteborg
Dyrssen	David Dyrssen (NAK)
FOA	Försvarets Forskningsanstalt (Swedish Defence Research Institute)
IAEA	International Atomic Energy Agency, Vienna
IVA	Ingenjörsvetenskapsakademin (the Royal Swedish Academy of Engineering Sciences)
Jacks	Gunnar Jacks (NAK)
KTH	Kungliga Tekniska Högskolan (Royal Institute of Technology), Stockholm
KVA	Kungliga Vetenskapsakademin (the Royal Swedish Academy of Sciences)
Langmuir	Don Langmuir (SKI)
Lidén	Kurt Lidén (NAK)
Liljenzin	Jan-Olof Liljenzin (NAK)
LTH	Lunds Tekniska Högskola (Lund Institute of Technology)
LU	Lunds Universitet (University of Lund)
LuH	Högskolan i Luleå (University of Luleå)
Massarsch	Rainer Massarsch (NAK)
NAK	Nämnden för hantering av använt kärnbränsle (National Board for Spent Nuclear Fuel)
NAS	The US National Research Council of the National Academy of Sciences
NEA	OECD Nuclear Energy Agency, Paris
NFR	Naturvetenskapliga Forskningsrådet (the Swedish Natural Science Research Council)
NRPB	National Radiological Protection Board, Great Britain
RE/SPEC	RE/SPEC (SKI)
SGI	Statens Geotekniska Institut (the Swedish Geotechnical Institute)
SGU	Sveriges Geologiska Undersökning (Geological Survey of Sweden)
SIKOB	SIKOB AB (SKI)
SKI	Statens Kärnkraftinspektion (Swedish Nuclear Power Inspectorate)
SNV	Statens Naturvårdsverk (Swedish Environment Protection Board)
Studsvik	Studsvik Energiteknik AB
SU	Stockholms Universitet (University of Stockholm)
TAC	The Technical Advisory Committee to the AECL, Canada
UU	Uppsala Universitet (University of Uppsala)
UmU	Umeå Universitet (University of Umeå)
West	G F West (SKI)
Wickman	F E Wickman and M Gillberg-Wickman (NAK)