RD&D-
PROGRAMME 95

Treatment and final disposal of nuclear waste

Programme for encapsulation, deep geological disposal, and research, development and demonstration

September 1995

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FOREWORD

The Act on Nuclear Activities (SFS 1992:1536) prescribes in Section 12 that a programme shall be prepared for the comprehensive research and development and other measures that are required to safely manage and 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 in the month of September every third year.

The purpose of this fourth programme is to fulfil the obligations described above. The programme takes up where the programme described in RD&D-Programme 92, and in the supplement to it submitted in 1994, leaves off. The emphasis is on implementation of the projects that are required in order to commence deposition of encapsulated fuel in accordance with the plans presented in the aforementioned programme. The programme also covers the supportive research and development activities that are required for the aforesaid projects, as well as follow-up of and research on alternative methods.

This report describes the programme in its entirety. Several important studies have also been completed during the preparation of this RD&D-programme. Thus, for example, the final results of a feasibility study for Storuman Municipality have been published. Additional reports scheduled to be published in the autumn of 1995 include a feasibility study for Malå Municipality, a nationwide survey of preconditions and background for the siting work – General Study 95 – and a template for safety reports – SR 95 – which describes methods for and the outline of forthcoming descriptions of the long-term safety of a deep repository. These reports contain material of great interest for SKB's continued programme.

Stockholm, September 1995

SWEDISH NUCLEAR FUEL AND WASTE MANAGEMENT COMPANY

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RD&D-PROGRAMME 95 – BRIEF SUMMARY

In RD&D-Programme 92, SKB presented a partially new strategy for its activities. The new strategy entailed a focusing and concentration on the implementation of deep disposal of a limited quantity (about 800 tonnes) of encapsulated spent nuclear fuel during the coming 20-year period. Following this initial deposition, the results of the work will be evaluated, and only then will a decision be taken as to how and when regular deposition of the main body of the fuel and other long-lived nuclear waste will take place.

The planning in RD&D-Programme 92 was based on the assessment that available knowledge is sufficient in order to:

- select a prioritized system design for management of the spent nuclear fuel,
- designate candidate sites for the deep repository,
- characterize these sites,
- carry out the necessary safety assessments, and
- adapt the configuration of the repository to local conditions.

Events since the presentation of RD&D-Programme 92 have confirmed and strengthened this assessment. After comprehensive review and commentary, the programme strategy was accepted in all essential respects by the Swedish regulatory authorities and Government.

At the end of 1992, SKB focused and intensified its work on the planning, design and siting of a plant for encapsulation of spent nuclear fuel and of a deep repository. The necessary development work is being coordinated with the planning and design work in the manner described in the Government-requested supplement to RD&D-Programme 92. The same applies to the research and development that is needed to carry out safety assessments and provide a basis for future safety reports.

It has been proposed that the encapsulation plant be situated at the central interim storage facility for spent nuclear fuel, CLAB, at the Oskarshamn Nuclear Power Station. Siting of the deep repository will take place in stages, and the work has been commenced with feasibility studies. These feasibility studies, which are planned for five to ten municipalities, are taking more time than was predicted in 1992. After the feasibility studies, geoscientific site investigations of two sites are planned. After this, one site will be selected for detailed characterization with shaft/tunnels to repository depth. A summarizing account of the nationwide general studies has been requested by the Government and the regulatory authorities. Such an account will be published in a separate report in the autumn of 1995.

The goal is to commence deposition of encapsulated fuel in 2008. However, the time schedule must be flexible to allow enough time for the siting of the deep repository to be completed and for related decisions to be taken. SKB's ambition is to carry out siting and construction of the required facilities in consensus with the concerned municipalities and local populations. The work of carrying out an environmental impact assessment (EIA) in an open and broad process occupies an central role in this context. The Government has stipulated that the county administrative boards in the concerned counties shall have a coordinating function in this EIA process. In its decision regarding SKB's supplement to RD&D-Programme 92, the Government has also clarified certain important questions in the licensing process, for example the link between the encapsulation plant and the deep repository, as well as the fact that the commencement of detailed characterization for the deep repository also implies the start of construction of the deep repository and therefore requires permission under both the Act Concerning the Management of Natural Resources (NRL) and the Act on Nuclear Activities (KTL).

The time schedule is also dependent on the fact that certain knowledge must be available before the next step is taken. Among other things, various choices and applications must be based on comprehensive assessments of the long-term safety of the deep repository. These will be based on data available at the time, whose accuracy will gradually be improved. This means that the time schedule will also be affected by the pace at which the required continued development work can be carried out. SKB believes that the uncertainties surrounding the time schedule can be overcome and that there is a good chance the target date will be reached.

Important development work is planned within the following areas:

- canister fabrication and canister sealing – a testing plant for sealing and non-destructive testing is being considered,
- design of canister insert,
- design of handling equipment for deposition of encapsulated fuel,
- material and methods for backfilling of deposition tunnels and other rock caverns,
- scrutiny of uncertainties and validity of the methods to be used in safety assessments,
- continued development of methodology for definition of scenarios to be described in safety reports.

R&D work aimed at refining knowledge and data for the performance of safety assessments is continuing within such fields as geoscience, chemistry, natural analogues and biosphere, as well as with regard to properties of spent nuclear fuel and buffer materials.

The Äspö Hard Rock Laboratory (HRL) is a central resource for continued development and research on barrier functions, measurement methods and work methods. A comprehensive programme with verifying tests in accordance with the plans presented in RD&D-Programme 92 has been initiated and will continue during the coming years.

Broad international cooperation constitutes an important component of SKB's work. Nine foreign organizations from eight countries are participating in the work at the Äspö HRL under bilateral agreements. An extensive international exchange of information is taking place within other areas as well. Through this cooperation, Sweden is obtaining direct access to world-leading experts in many fields. This contributes to upholding the high quality of the R&D work.

SKB will continue to follow the development of alternative methods for handling, treatment and final disposal of spent nuclear fuel, for example by supporting Swedish research within a certain key areas.

In addition to the technical and safety-related aspects, it is important to continue to develop the forms for communication of knowledge and facts on nuclear waste management in society. SKB will devote considerable efforts to the implementation of the EIA process in conjunction with siting and construction of both the encapsulation plant and the deep repository. This will require broad and objective information presented in a pedagogical fashion and received with an open mind.

CONTENTS

SUMMARIZING OVERVIEW

1 INTRODUCTION

The goal of SKB's radioactive waste management activities is the safe disposal of all radioactive waste products arising at the nuclear power plants and other nuclear installations in Sweden. Furthermore, SKB must safely dispose of all other radioactive waste that arises in Sweden.

Radioactive waste from the Swedish nuclear power programme varies in form and activity content, from virtually inactive trash to spent nuclear fuel, which has a very high activity content. Different waste forms must therefore be managed and disposed of in different ways.

Research on the management and disposal of radioactive waste began on a large scale in Sweden in 1975. The work thus initiated has led over the subsequent 20 years to the development and construction of a system which today manages all radioactive waste generated by nuclear power activities in Sweden, as well as by medical care, research and industry.

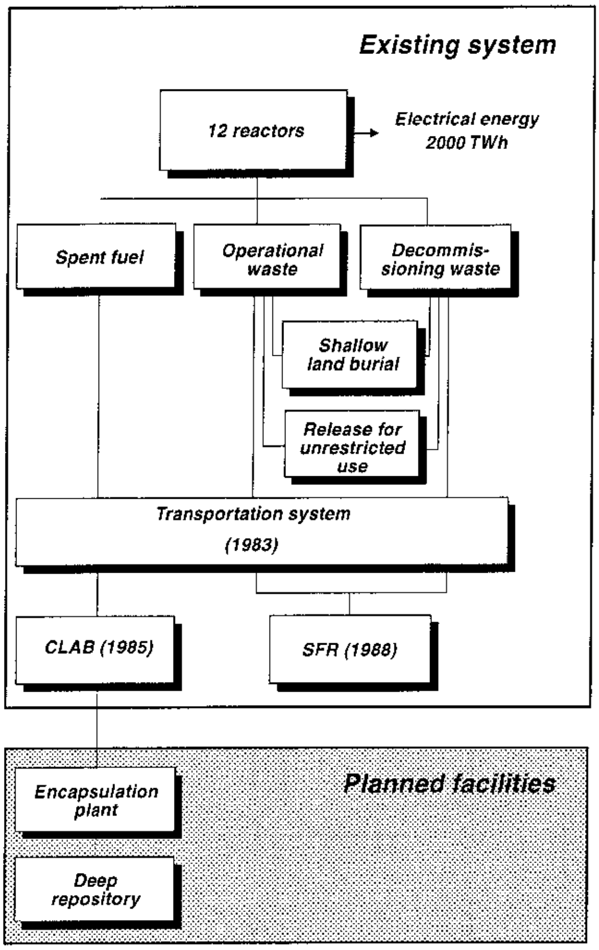


***Figure 1.** The Swedish waste management system.*

Figure 1 provides an overview of the different parts of the Swedish waste management system. They are described in detail in the annual report of the costs of waste management (PLAN 95 is the most recent edition) submitted by SKB.

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

- Short-lived waste is disposed of as soon as possible after arising.
- Spent nuclear fuel is stored for 30–40 years before being emplaced in a deep repository. This limits heat generation in the deep repository.
- Other long-lived waste is disposed of in connection with the deep repository for spent nuclear fuel.

Essential parts of the waste management system are already in operation, namely the central interim storage facility for spent nuclear fuel, CLAB, the final repository for radioactive operational waste, SFR, and the transportation system. Construction of additional storage space in CLAB and SFR is planned just after the turn of the century in order to be able to take care of all spent fuel and waste from the Swedish programme.

What remains to be built of the required system is an encapsulation plant for spent nuclear fuel and a deep repository for long-lived waste, plus the necessary modifications of the transportation system to enable it to ship encapsulated nuclear fuel and other waste to the deep repository. Finally, SFR needs to be expanded to receive decommissioning waste.

2 GOAL

In RD&D-Programme 92, SKB presented its – and thereby the Swedish nuclear power industry's – plans for execution of the deep disposal of the long-lived radioactive waste, including the spent nuclear fuel that arises in conjunction with the operation of the Swedish nuclear power plants. These plans entail the following, in brief:

- The goal is, in compliance with all environmental and safety requirements, to commence deposition in a deep repository of a small portion (about 800 tonnes) of the spent nuclear fuel in the year 2008.

- The preferred alternative is encapsulation in copper canisters. Deep geological disposal is intended to be carried out in accordance with the KBS-3 concept, or a closely-related optimized version of this concept, at a depth of about 500 metres in crystalline rock.

- An encapsulation plant will be built as an addition to CLAB.
- A deep repository will be sited at a suitable location in Sweden where both rigorous safety requirements can be fulfilled and the necessary activities can be carried out with the consent and consensus of the concerned municipality and the concerned population.
- The safety and radiation protection aspects will be thoroughly penetrated and reported before decisions are made on essential binding measures.

This is the same target deadline as that given in RD&D-Programme 92. However, as a consequence of developments since that time, the time schedule for permit applications has been somewhat delayed.

The time schedule for the work with the deep repository and the encapsulation plant is not completely under SKB's control, however. It is also dependent to a high degree on the acceptance which SKB's activities receive in concerned municipalities and on the pace at which different decisions can be taken at both the local and national levels. The schedule is also affected by the local technical and geological conditions that exist on the sites that will be investigated. SKB believes that the uncertainties surrounding the time schedule can be overcome and that there is a good chance the target date will be reached.

The planning in RD&D-Programme 92 was based on the assessment that available knowledge is sufficient in order to select a prioritized system design for management of the spent nuclear fuel, designate candidate sites for the deep repository, characterize these sites, adapt the configuration of the repository to local conditions and carry out the necessary safety assessments. Events since the presentation of RD&D-Programme 92 have confirmed and strengthened this assessment. After comprehensive review and commentary, the programme strategy was accepted in all essential respects by the Swedish regulatory authorities and Government.

At the same time as work proceeds on this main task, SKB will follow and, to a limited extent, fund R&D on alternative lines of development.

3 STEP-BY-STEP DEVELOPMENT AND CONSTRUCTION

In recent years, Swedish environmental legislation has introduced requirements on environmental impact assessment – EIA – of the facility or the system for which a permit or licence is being applied. The background documents for the law state that an EIA shall also shed light on the consequences of alternative methods/designs, including a so-called "zero alternative" for the case that the facility or system for which a permit or licence is being applied for is not realized. In the debate concerning the Swedish nuclear waste programme, criticism is sometimes raised that "no method has yet been chosen", or "SKB is rushing the siting of the deep repository, no method has been developed yet", and so on. But a historical retrospect shows that a gradual narrowing-down of the studied methods for treatment and disposal of the high-level waste has taken place. Furthermore, choices have been made between different fundamental categories of methods. This process of narrowing-down and selecting alternatives has been presented and discussed in the programmes reported at regular intervals and has been based on a broad review and commentary procedure and extensive public scrutiny. Through this process, the principal strategy of the Swedish nuclear waste programme has been developed in consensus between industry, regulatory authorities and the Government. In conjunction with upcoming siting applications for the planned facilities, alternatives will be described and considered for the method, the design and the siting for which the application applies.

The gradual focusing of the programme that has taken place since the Aka Committee report in the 1970s has entailed that the work has, since the mid-1980s, been oriented towards the final goal of deep geological disposal in the Swedish bedrock of the spent fuel without prior reprocessing. Different alternative designs of a deep repository have been studied. The results of these studies have been reported in the programmes published by SKB in 1989 and 1992. The conclusion drawn in RD&D-Programme 92 is that *Deep geological disposal is intended to be carried out in accordance with the KBS-3 concept or closely-related optimized version of this concept, at a depth of about 500 metres in crystalline rock.* This strategy for the first construction stage (see below) has been accepted in all essential respects by the Swedish regulatory authorities and Government.

At present, all spent nuclear fuel is stored in CLAB or at the nuclear power plants. Experience from long-term storage of zircaloy-encapsulated fuel dates back to the late 1950s. This experience shows that storage is possible for at least 50 years, and can probably be extended to at least 100 years if necessary. In so far as storage time and storage capacity are concerned, it is therefore possible to prolong storage at CLAB for several more decades. This will be a natural "zero alternative" in the future EIA work for the deep repository and the encapsulation plant. Supplementary safety assessments (time horizon hundreds of years) are planned for this alternative.

Construction of the deep repository is planned to take place in two stages with a thorough evaluation of the first stage and a new, updated safety account and review before the second stage commences. The first stage is intended to include about 800 tonnes of spent nuclear fuel (about 10% of the expected quantity) and can be completed in about 20 years at the earliest. It will be possible in the subsequent evaluation to take into account all development during these 20 years. If deemed desirable, the already deposited fuel can be retrieved for alternative treatment.

Decisions on siting, construction and operation of the encapsulation plant and deep repository will be taken in steps after licensing review based on a gradually improving knowledge base, where new knowledge can be taken into account at each step. An important component is the EIA process, which will lead to environmental impact assessments (EIAs) for the facilities. This process will involve both SKB and central authorities on the one hand, and the concerned municipalities, county administrative boards and local stakeholders on the other hand. The EIA process has already begun for the encapsulation plant, while for the deep repository it is being prepared for in the feasibility studies and will be carried out to its full extent in conjunction with the site investigations. In reality, a great deal of the work was already conducted in the spirit of the EIA process through the comprehensive public scrutiny of SKB's plans and programmes long before this was made a formal requirement.

4 ENCAPSULATION OF FUEL

The programme for canisters and encapsulation mainly consists of development and fabrication of canisters and planning, design and construction of an encapsulation plant.

The canisters must be designed and fabricated so that they remain intact during a very long time under the conditions that will prevail in the deep repository. In other words, they must not be penetrated by corrosion in the groundwater present in the rock, or be squeezed apart by the mechanical stresses to which they are subjected in the deep repository.

To achieve this, the canister is planned to consist of an insert of e.g. steel, which provides mechanical strength, and an outer shell of copper, which provides corrosion protection. The work of formulating the design requirements for the canister is under way. Requirements during the fabrication of the canister and during handling in the encapsulation plant, transportation and in the deep repository are also being taken into account.

As described in RD&D-Programme 92, encapsulation is planned to take place adjacent to CLAB. The fuel will be received in the encapsulation plant from the storage pools in CLAB. After the fuel assemblies have been checked and dried, they will be placed in the canister. Before the lid on the inner steel container is put in place, the air in the canister will be replaced with inert gas. Then the copper canister will be sealed by attachment of a copper lid by means of electron beam welding. Stringent requirements will be put on the leaktightness of this weld and the ability to test this leaktightness.

In designing the encapsulation plant, great emphasis will be placed on radiation protection for the personnel and the surrounding environment. This means, among other things, that the actual encapsulation procedure will be performed by remote control in heavily radiation-shielded compartments known as hot cells. A large portion of the handling of canisters will also be done by remote control. Experience from CLAB and SFR, as well as from various foreign facilities with similar handling of fuel, will be drawn upon.

4.1 CANISTER DEVELOPMENT

The most important questions surrounding the development of the canister concern material selection, fabrication method, and sealing and testing method. The design of the insert is also of importance for the practical handling of the canisters and to avoid the risk of criticality should the canister become filled with water.

4.1.1 Material selection

Copper has been chosen as a canister material because it does not corrode in oxygen-free water. The life of the copper canister from a corrosion viewpoint is therefore determined by the quantity of dissolved corrosive substances, mainly sulphides, that come into contact with the canister surface. The greatest corrosion depth on a copper canister is conservatively estimated to be about 5 mm in 100,000 years in the groundwater that is expected to be present at great depth in Swedish bedrock. The state of knowledge within the field of corrosion of pure copper is deemed to be good. However, in the event an alloyed copper material should be used in the future, supplementary corrosion studies will be required.

Beside corrosion properties, the creep properties, grain size and weldability of copper are also of importance. These properties are largely dependent on the fabrication method and the choice of copper grade. Verifying investigations of these properties are planned as a basis for the choice of method and grade.

4.1.2 Fabrication

Tests have been conducted of different fabrication methods for the copper canister (and the steel insert) over the past few years. The tests have gradually increased in scale, and the first full-scale canisters were produced in the summer of 1995. Two methods have been tested: roll pressing and extrusion. In the former case, two tube halves are rolled and bent, after which the two halves are welded together with an electron beam weld. In the latter case, a full-length tube is fabricated directly by extrusion. After machining of the copper tube, a bottom is welded on by electron beam welding in both cases before the steel insert is put inside. Further fabrication trials are planned both with the already tested methods and possibly with another method, for instance powder metallurgical fabrication with hot isostatic pressing (HIP) or electrodeposition. The purpose is to show that reproducible and testable canisters can be manufactured in serial production.

4.1.3 Sealing

When the canister has been filled with fuel it will be sealed and the sealing weld checked. Electron beam welding at reduced vacuum is planned to be used for sealing. A trial series of lid welding on full scale has been carried out with good results. Before a final choice of welding method is made, however, modifications of lid and weld design are necessary. Furthermore, development work is needed on the welding equipment to achieve the necessary capacity and reliability.

Development work on non-destructive testing of the weld is proceeding in parallel. The requirements on this equipment are determined by what defects must be able to be detected. Work is currently being done to define acceptable defect sizes. The methods being tested for non-destructive testing are ultrasonic (the pulse-echo method) and radiographic testing. Different types of scanners are being developed to improve the resolution of these methods. Results obtained to date indicate that these methods will be applicable, but that further development work remains to be done.

4.1.4 Full-scale tests

Sealing and inspection of the seal are crucial in order to obtain a leaktight canister. So far tests have been conducted under laboratory conditions. SKB is now considering fabricating a trial series of full-sized canisters in a separate pilot plant. This would then be constructed over the next few years so that the results of the tests can be taken into account in the engineering work for the encapsulation plant.

4.1.5 Insert in copper canister

Different designs are being considered for the insert. Tests have been made with an insert in the form of a steel tube. In order to obtain sufficient margin to criticality (in the event the canister becomes water-filled) in this version, the void around the fuel assemblies must be filled with a particulate material, e.g. glass beads. An alternative design of the insert is currently being studied, where the insert takes the form of a cast container with channels for the fuel assemblies. The insert can be made of cast steel, cast iron or bronze. Trial fabrication of a cast insert is planned. With this design, the criticality problem can be managed without extra filling.

4.2 DESIGN OF THE ENCAPSULATION PLANT

The goal of the ongoing work is that the encapsulation plant should be finished and ready to deliver encapsulated fuel to the deep repository in 2008. The work of designing the encapsulation plant is being pursued step-by-step in accordance with established routines for the construction of power plants and similar industrial facilities. A feasibility study has been carried out and the results reported in an initial step.

The work is currently in the preliminary design phase. The results of this phase will serve as a basis for SKB's decision to apply for a permit to build the facility. The work is being conducted in such a manner that it will be possible to submit the permit application during 1997. In conjunction with the application, SKB must also give an account of how serial fabrication of canisters will take place, and how the canister will meet the requirements made for long-term safety. The date of the application will therefore be dependent on how fast facility design, canister development and the safety assessment for canisters in the deep repository proceed.

An environmental impact assessment (EIA) must be compiled in support of the application. Discussions are held with the county administrative board, municipality and safety authorities about what is to be included in the EIA and how consultation in conjunction with the EIA work is to take place.

5 DEEP REPOSITORY

The programme for siting and construction of the deep repository was presented in RD&D-Programme 92 and its supplement. The time schedule has been modified since site investigations have not yet begun. The task during the period 1996–2001 is to compile supporting material for an application for permission to site and build the deep repository on a specific location. The most important near-term goal is to commence site investigations.

The work with the deep repository encompasses the following:

- background material and plans for design, construction, operation and closure of the deep repository,
- siting studies (general studies, feasibility studies, site investigations) as a basis for future choice of site for the deep repository,

- background material and plans for investigation and evaluation of candidate sites.

5.1 DESIGN OF THE DEEP REPOSITORY

A deep repository is an industrial establishment with facilities both below and above ground. The work with the design of the deep repository aims at achieving good function with respect to safety, environment and technology. Questions being investigated are concerned with the advantages and disadvantages of different repository concepts, construction methods, technology for deposition, closure and retrieval, safeguards, industrial safety and effects on society and the environment.

SKB has begun the planning work by preparing general plant descriptions. These provide examples of some possible ways to design the deep repository with its buildings, land areas, rock caverns, tunnels and shafts. They also contain requirements on and principles for the various functions of the deep repository. A possible schematic design of the deep repository is shown in Figure 2. To a large extent, construction and operation of the deep repository can be based on experience and proven technology from nuclear installations and underground rock facilities. Special attention is devoted to, for example, the impact of the rock construction work on the surrounding rock, methods for manufacture and application of the bentonite buffer, and technology for backfilling and sealing the repository. Studies of crushed rock as an aggregate material instead of sand, which was the principal alternative in KBS-3, indicates that crushed rock, possibly mixed with 10–20% bentonite, can also provide the desired function for backfilling of deposition tunnels etc.

A special study has been made of the advantages and disadvantages of different repository depths. The study considers depths down to 2000 metres. The conclusion is that the advantages that can be achieved with a deeper location do not compensate for the growing difficulties encountered in building the repository and in investigating and characterizing the rock.

The continued work of designing the repository includes adapting the layout to the conditions on specific sites as site investigations get under way. Extensive development of technology is needed to arrive at purpose-suited handling equipment for transferring canisters from transport casks in the deposition tunnels and emplacing them in the deposition holes.

Much of the technology for handling of buffer material and canisters will be tested in the Äspö HRL. The effects of the deep repository on society and the environment will be explored in conjunction with the siting studies. Studies performed to date show that it should be possible to adapt the design and operation of the deep repository so that the effects on the environment will be small.

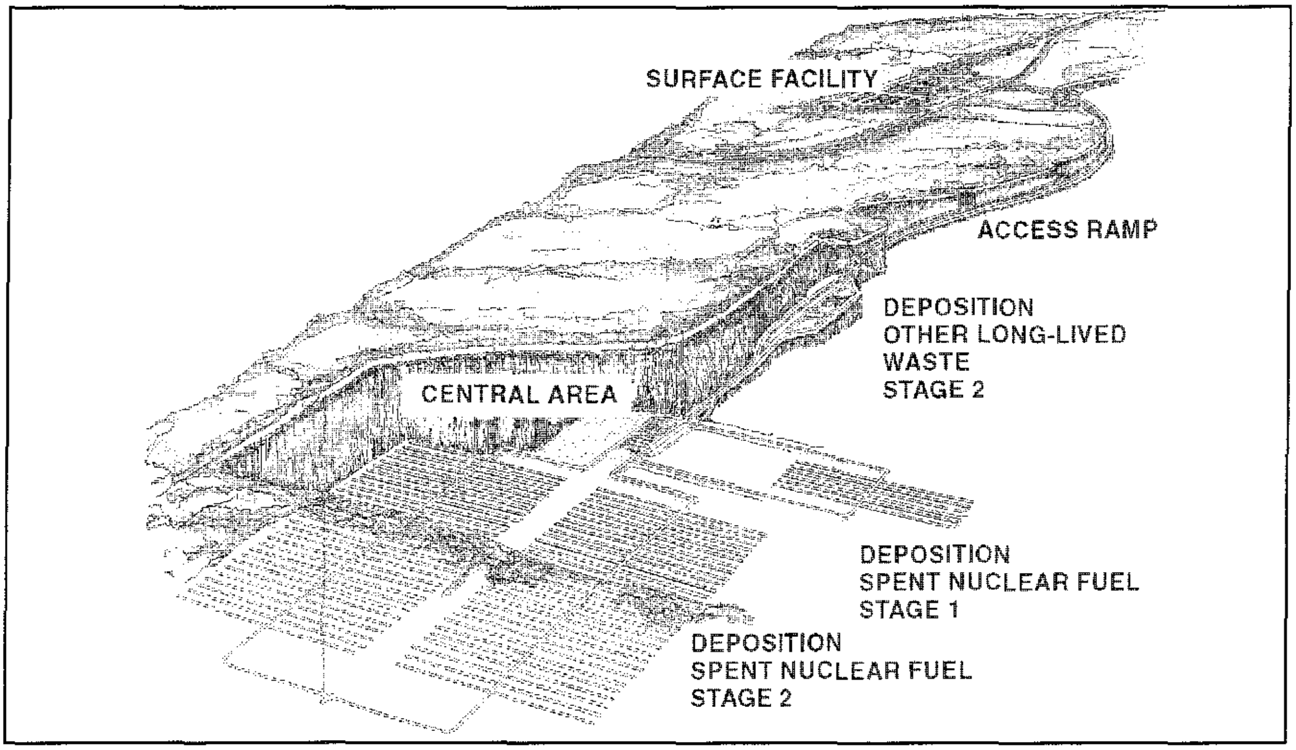
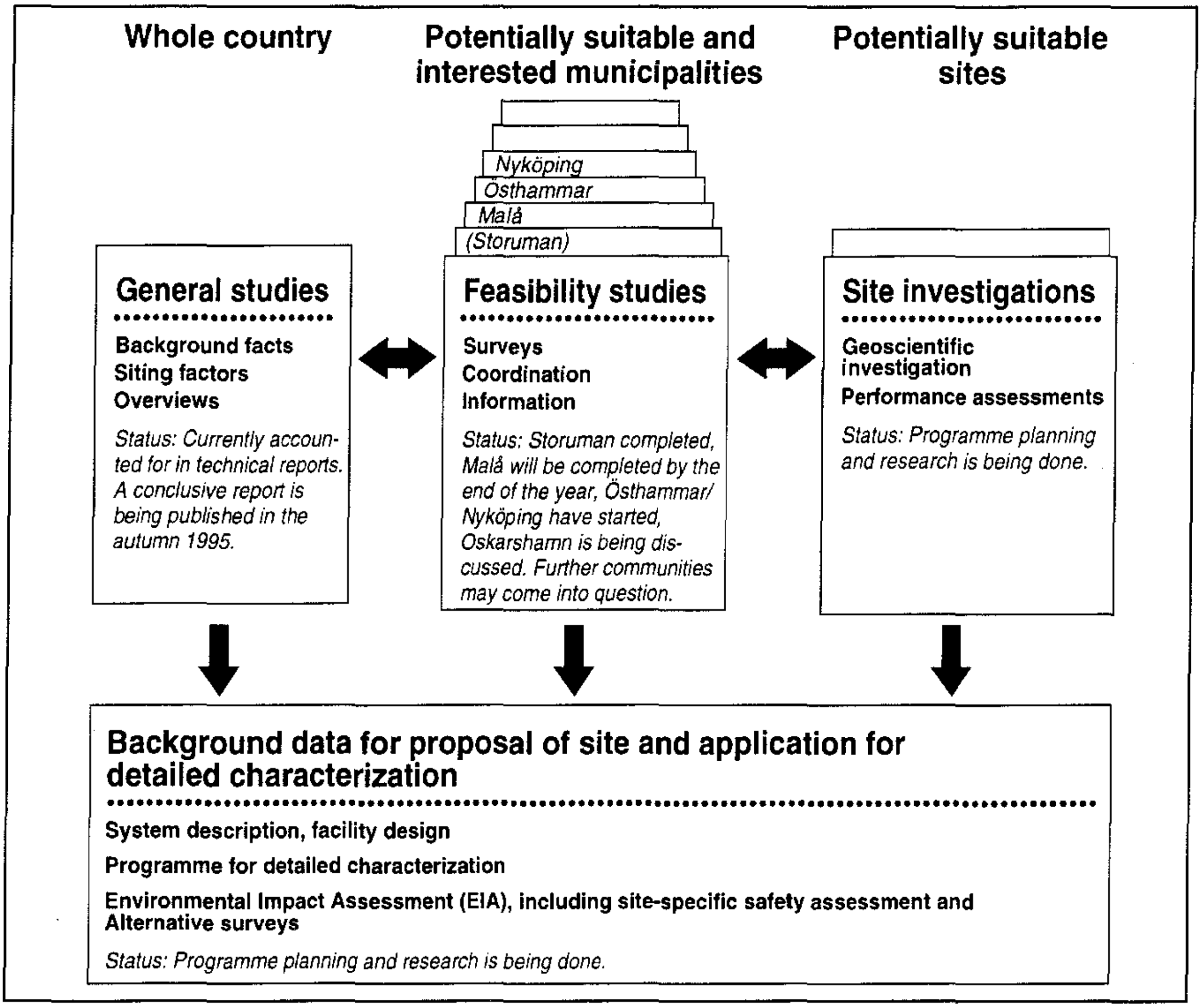


Figure 2. *Schematic drawing of the deep repository.*



Status: Currently accounted for in technical reports. A conclusive report is being published in the autumn 1995.

Status: Storuman completed, Malå will be completed by the end of the year, Östhammar/ Nyköping have started, Oskarshamn is being discussed. Further communities may come into question.

Status: Programme planning and research is being done.

Status: Programme planning and research is being done.

Figure 3. *Main components in the siting work, plus completed and ongoing activities.*

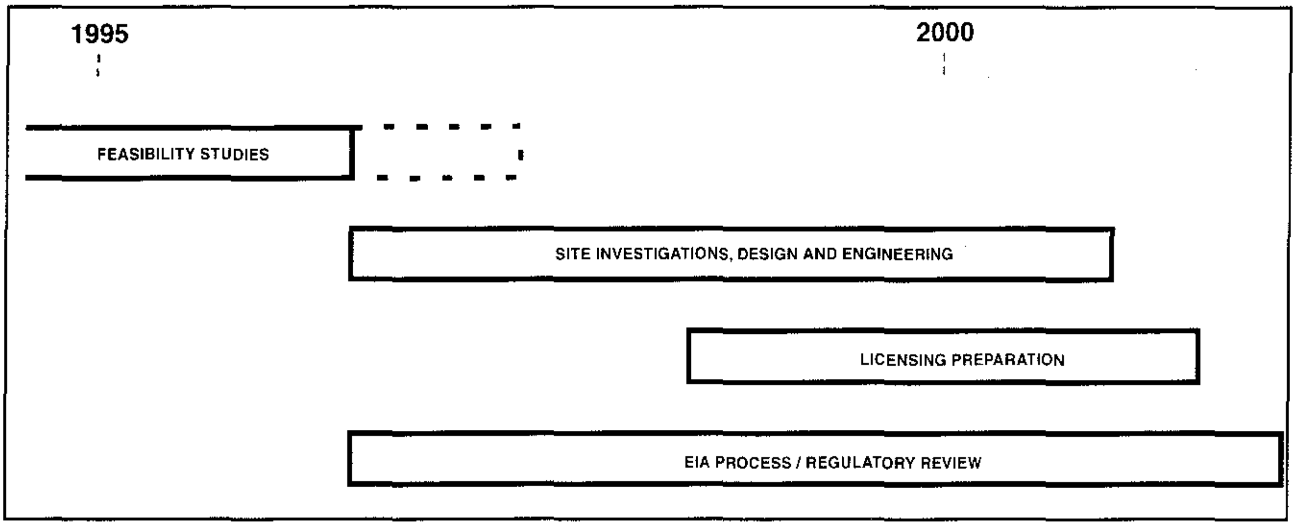


Figure 4. *Schedule for phase 1, siting.*

5.2 SITING STUDIES

SKB intends to obtain background data for the siting of the deep repository by means of

- **feasibility studies** (in 5 to 10 municipalities), aimed at identifying interesting areas for site investigations and illustrating the possible consequences of a deep repository siting in the municipality and the region,
- **site investigations** (on two sites), aimed at providing background data for designing a deep repository with respect to the properties of the site and carrying out an environmental impact assessment with an assessment of long-term safety. Site investigations entail measurements in deep boreholes, among other things.

This work is intended to lead to a proposal to carry out a detailed characterization and construct a deep repository on a site.

Guidelines for the siting studies are the criteria for safety, technology, land and environment, and societal aspects which SKB set forth in RD&D-Programme 92 and its supplement.

In discussions about siting of the deep repository, it is often said that "SKB must find the best site", by which is understood to mean the "best" from a safety viewpoint. However, there is no best site, objectively speaking. The site must meet very stringent safety requirements. A holistic assessment of long-term safety requires access to site-specific data on bedrock conditions. Such data can only be obtained by means of comprehensive investigations on sites selected on the basis of incomplete data. Thus, when it has been demonstrated that safety requirements have been met, it is not meaningful to talk about "even better sites". This has also been pointed out by the Swedish Nuclear Power Inspectorate in its review comments on RD&D-Programme 92.

The main components of the work, and how far the work has progressed, are illustrated schematically in Figure 3.

A time schedule for the siting studies is shown in Figure 4. It is based on the assumption that the feasibility studies can be carried out efficiently from a technical point of view, and that the site investigations can commence in 1997. The timing of the start of the site investigations is critical for the timing of the entire siting programme.

The siting work is supported by general studies, which provide a general background on the fundamental conditions all over the country or parts thereof.

Investigations within the framework of the general studies have been carried out continuously since the mid-1970s. A collective account is published in a separate report in conjunction with this RD&D-Programme 95. A large number of geoscientific and societal factors that are or may be of importance in connection with the siting of the deep repository are described in the report.

The study shows that the fundamental prerequisites with regard to land and rock conditions can be found at many places in most parts of the country. To identify interesting areas for site investigations, a thorough analysis is required of local factors that cannot be judged on a country scale but can best be carried out in feasibility studies on a municipal level. A subsequent holistic assessment of, above all, long-term safety requires access to site-specific data on the bedrock.

The general studies do not provide any direct guidance for identifying areas of interest for locating a deep repository. Their scale is too coarse for that. However, the general studies do provide sufficient information to identify parts of the country which are not of interest for more detailed siting studies. These areas are mainly, for geological reasons, the Scandinavian mountain range, Skåne and Gotland. Areas situated in unusual rock types or where valuable ore deposits are likely to be found are not of interest either. The same applies in areas protected by law, such as national parks, nature conservation areas, and so forth. The general studies and underlying material are also used by SKB in contacts with municipalities to make preliminary assessments of advantages and disadvantages for siting of a deep repository and thereby of the area's interest for feasibility studies by SKB.

5.2.1 Feasibility studies

In the feasibility studies, the prospects for and consequences of a deep repository siting within specific municipalities are examined. The studies are based principally on existing material. SKB needs no formal permits to conduct a feasibility study. However, in practice the feasibility studies are conducted in consensus between SKB and the municipality in question. A feasibility study takes approximately one year to complete and results in a comprehensive body of material which is supposed to provide a good picture of the general prospects for siting of a deep repository in the municipality. Areas that may be of interest for site investigations with reference to their bedrock and soil conditions are identified. Technical and infrastructure aspects with regard to construction and transportation are explored. Possible consequences (positive and negative) for the environment, local economy, business community and society are illuminated.

A feasibility study should thus furnish a broad body of facts for both the municipality and SKB. Both parties can then decide for themselves whether they are interested in starting a site investigation. The same facts are made available to all stakeholders, who thereby have an opportunity to have a say and state their views long before any decisions need to be taken on the siting of the deep repository.

SKB has conducted a feasibility study in Storuman Municipality. The final report was published in February 1995. The feasibility study shows that good prospects may exist for a deep repository in the municipality. The municipality held a (local) referendum on 17 September 1995 regarding the question: "Should SKB be allowed to continue searching for a final disposal site in Storuman Municipality?" The result was 28% Yes, 71% No and 1% Blank votes. Voter turnout was about 73%. This means that SKB will cease its work in Storuman.

Another feasibility study has been under way in Malå since the winter of 1994. A summarizing status report was published in May 1995. The final report is expected to be ready in the autumn of 1995.

In a special survey of a general nature, SKB has examined the prospects for feasibility studies of municipalities with nuclear activities (Varberg, Kävlinge, Oskarshamn, Nyköping, Östhammar). For all municipalities except Kävlinge, the survey showed that feasibility studies are of interest for SKB's part. Such studies have now been started in consultation with the municipalities of Nyköping and Östhammar and are being discussed with the municipalities of Varberg and Oskarshamn. Feasibility studies may be undertaken for several additional municipalities as well.

The feasibility studies have led to extensive discussions, particularly in the concerned municipalities, but also regionally and on the national plane. SKB as well as other concerned parties (authorities, policymakers, the general public) have gained important and valuable experience for the continued work. Difficulties and possibilities in the siting work have been clarified. The work with feasibility studies has taken longer than SKB planned in RD&D-Programme 92, in part because the issue arouses a great deal of discussion right from the start.

The siting of the deep repository is a key issue in Sweden's nuclear waste programme. With the feasibility studies, the concrete work of siting has got under way in various parts of the country. Further persistent and open-minded efforts are needed to arrive at a good solution that meets the requirements of both environment and safety on the one hand and local consensus and understanding on the other.

5.2.2 Site investigations

SKB plans to conduct site investigations within prioritized areas in two of the municipalities where feasibility studies have been conducted. A large body of data will be gathered on each site by means of the following activities:

- Geoscientific investigations in the field.
- Facility design and planning.
- Performance and safety assessments.
- Analysis of societal aspects and land and environment aspects.
- Preparation of an environmental impact assessment in an EIA process.
- Compilation of material for licensing process.

Preparations and planning work are currently under way in all these areas. In part the work is building further on the data gathered in connection with the feasibility studies. The largest efforts during the site investigation phase will be the geoscientific investigations and the performance and safety assessments based on them.

5.3 GEOSCIENTIFIC FIELD INVESTIGATIONS

Even though Swedish bedrock in general offers good conditions for a deep repository, it is the local conditions in the bedrock that will determine the suitability of a site. Before site investigations start, an investigation programme will be presented in a special report. The site investigations are intended to provide a broad geoscientific understanding of the site and its regional environs. They also aim at gathering geoscientific data for a site-adapted layout of the repository and an analysis of the long-term safety of the repository. The most important factors that need to be clarified in the field work are enumerated and discussed in the supplement to RD&D-Programme 92 as well as in the present programme.

The site investigations will be conducted in several stages. The purpose of the initial stage is to verify the feasibility study's assessment of the area's suitability and to identify more precisely in which part of the area the investigations are to be concentrated. Then fracture zones, rock type boundaries and other geological conditions are surveyed in depth with an increasing degree of detail. Measurements and analyses of groundwater chemistry, groundwater movements and rock stresses comprise an important element.

Facility design and safety assessments are carried out in interaction with the investigations. Provided that each stage of the investigations indicates suitable conditions, the programme is carried to completion, providing a comprehensive body of support material for a permit application.

Methods and technology for geoscientific investigations in the field have been included in SKB's programmes for a long time. The development of these methods and technology began with the study site investigations during the 1970s and 1980s at some 10 locations in the country. Prior to designing the investigation programme, the findings of these investigations were re-examined. Furthermore, important method development took place in the international Stripa project. The work for the Äspö Hard Rock Laboratory can be said to have constituted a "dress rehearsal" of the investigation methodology (see section 8). This work has entailed comprehensive testing and coordinated evaluation on a real site and under realistic conditions before the methods are applied to the deep repository project.

6 SAFETY ASSESSMENT

6.1 SAFETY FUNCTIONS

The safety of the repository is dependent on the toxicity and accessibility of the waste. The assessment of the repository's safety is influenced by time in that the quantity of toxic radionuclides declines, and in that the quantification of the repository's safety functions decreases in precision with time. Potential transport pathways for radionuclides to man can change with time, but such changes will take place at different rates for the different parts in the barrier system. Experience shows that essential changes in the biosphere occur on the time scale 100–1000 years. The geological environment deep down in the Fennoscandian Shield, however, exhibits stable conditions on a time scale of millions of years.

Consequently, the feasibility of quantifying the safety of the repository (or the risk from the repository) is dependent on the period of time in which one is interested. The Swedish National Radiation Protection Institute has discussed the influence of the time horizon on radiation protection and finds that:

- Particularly great attention should be given to describing protection for the period up to closure of the repository and during the first thousand years thereafter, with a special focus on nearby residents.
- The individual dose up to the next ice age, i.e. up to about 10,000 years, should be reported as a best estimate with an estimated margin of error. Environmental protection should be described for the same period of time.
- For the period from the next ice age onward, qualitative assessments should be made of what might happen with the repository, including scenarios taking into account the risk of increased releases.

To achieve the desired safety during the construction of a deep repository, during the operating phase and during the long-term containment phase, requirements are put on the function of the repository and its components. The composite function of all the repository's components must together provide adequate safety.

In order to achieve long-term safety, the disposal system is designed to isolate the spent nuclear fuel from the biosphere. This isolation is achieved by encapsulating the spent nuclear fuel in impervious canisters which are deposited deep in the crystalline bedrock on a selected repository site. If this isolation should be broken, the repository has the function of retaining the radionuclides and retarding their transport. Furthermore, transport pathways and dilution conditions in the biosphere can be controlled so that any radionuclides that escape will only reach man in very small quantities.

The materials used in the repository have been selected with a view to the possibility of verifying their long-term stability and safety performance in the repository with experience from nature. For the same reason, the thermal and chemical disturbance which the repository is allowed to cause in its surroundings is limited. The safety philosophy for the deep repository is based on the multibarrier principle, i.e. safety must not be dependent on the satisfactory performance of a single barrier.

The safety functions can be divided into three levels:

Level 1 – Isolation

Isolation enables the radionuclides to decay without coming into contact with man and his environment.

Level 2 – Retardation

If the isolation is broken, the quantity of radionuclides that can reach the biosphere is limited by:

- very slow dissolution of the spent fuel,
- sorption and very slow transport of radionuclides in the near field,
- sorption and slow transport of radionuclides in the bedrock.

Level 3 – Recipient conditions

The transport pathways along which any released radionuclides can reach man are controlled to a great extent by the conditions where the deep groundwater first reaches the biosphere (dilution, water use, land use and other exploitation of natural resources). A favourable recipient means that the radiation dose to man and the environment is limited. The recipient and the transport pathways are, however, influenced by natural changes in the biosphere.

The safety functions at levels 1 and 2 are the most important and the next-most important. They are achieved by means of requirements on the properties and performance of both engineered and natural barriers and on the design of the deep repository. Within the frames otherwise defined, good safety function at level 3 is also striven for by a suitable placement and configuration of the deep repository.

6.2 SAFETY ASSESSMENTS

A number of major decisions and permits are required in order to site, design and build the facilities and systems

Table 1. Forthcoming safety assessments.

	Bases for decision on permit for:	
Safety assessment	**Encapsulation plant**	**Deep repository**
Encapsulation plant SR-I	Siting Construction	
Deep repository SR-D		Siting Construction, incl. detailed geoscientific investigations and some construction
Initial operation (Stage 1)	Start encapsulation – spent fuel Initial operation – Stage 1	Initial operation – Stage 1 – deposition, gradual extension of deposition tunnels
Regular operation (Stage 2)	Supplementary extension Regular operation – Stage 2	Regular operation – Stage 2 – deposition, gradual extension of deposition tunnels
Decommissioning	Decommissioning	Possible supervised storage, closure

required to dispose of radioactive waste, see Table 1. The bases for these decisions include accounts of both radiological safety during operation of the facilities or systems, as well as of safety during the long-term passive deep disposal period that begins when the repository has been sealed.

For this safety accounting, assessments must be performed of the safety of the systems and facilities and of the potential of the different candidate sites to serve as good repository sites. Systematic methods have been developed to carry out the assessments. The radiological safety of the personnel and the environment during the operating phase will be evaluated and reported on in accordance with the practice that has evolved at the nuclear power stations. These assessment methods and reporting principles have also been applied to the transportation system, CLAB and SFR.

The evaluation of the long-term safety of a deep repository basically follows the same principles as those established for operating safety. Since a deep repository has to function in close interaction with the natural geological environment, however, it has been necessary to develop specific methods to carry out these assessments. The assessment of the safety of the deep repository must project conditions over very long spans of time. The borderline between normal and abnormal conditions can then be difficult to identify.

Safety assessments of entire disposal systems or the assessment of the performance of individual barriers or sub-systems follow an established work sequence:

- Definition of the purpose of the assessment.
- Definition of given assumptions for the assessment, i.e. types and quantities of radioactive waste, the disposal system and its dimensions, and the location and surroundings of the repository.
- Definition of the scope and delimitations of the assessment, and of the safety goals.
- Clarification of both the probable and the less probable or improbable conditions for which the system/facility is to be assessed (scenarios).
- Clarification of the time-dependent processes which are essential for the intended performance of the system/facility in different scenarios.
- Definition of calculation models for quantifying the performance of the repository and the couplings between the models, where possible.
- Quantification of the performance of the repository and essential changes in performance.
- Qualitative assessment of important but non-quantifiable processes or events that can impact on the performance of the repository.
- Discussion of the uncertainties in qualitative and quantitative sub-assessments and evaluation of their validity with respect to the purpose of the overall assessment.

The development in Sweden of a methodology for assessments of long-term safety has been under way since the end of the 1970s and is still being pursued in close international cooperation. The general method development has in the main been concerned with the scenario concept and handling of uncertainty/validity. Specific development of models and data to quantify the processes essential for safety was a dominant activity during the '80s.

A summary of the state of knowledge as a result of a review conducted by experts within the OECD Nuclear Energy Agency, the International Atomic Energy Agency and the European Commission is given in an International Collective Opinion. There it was observed

- that safety assessment methods are available today to evaluate adequately the potential long-term radiological impacts of a carefully design radioactive waste disposal system on humans and the environment, and
- that appropriate use of safety assessment methods, coupled with sufficient information from the proposed disposal sites, can provide the technical basis to decide whether specific disposal systems would offer to society a satisfactory level of safety for both current and future generations.

It was also noted that the collection and evaluation of data from proposed repository sites are tasks on which further progress is needed, and that the methods for safety assessments can and will be refined as a consequence of ongoing activities. SKB shares this opinion.

The principal method development work during the '90s within SKB has been concentrated on developing practical methods for determining scenarios, carrying out model calculations and examining the validity and relevance of the results. In view of the fact that safety reports are to be made on several occasions, discussions have also been held with the authorities on what a safety report should contain and how it can be organized. This work will continue and will be brought into line with the regulations currently being formulated by the Swedish Nuclear Power Inspectorate and the National Radiation Protection Institute.

A fundamental methodology for carrying out safety assessments is presented in the description of the state of knowledge. The detailed account of methods and of the numerical tools which SKB has at its disposal, as well as the account of quality and the confidence which SKB has in these models, has been gathered in a separate report designated SR 95. This has been organized in a way that could serve as a suitable model (template) for the upcoming safety reports. It is being finalized in conjunction with this programme.

7 SUPPORTIVE RESEARCH AND DEVELOPMENT

The supportive R&D activities are aimed at:

- building up a good understanding of the phenomena and processes that can be of importance for long-term safety in the deep geological disposal of radioactive waste,
- refining models for essential processes in the repository,
- building up the necessary databases and comparison material in preparation for the planned site investigations so that the performance and safety of the repository can be evaluated.

In RD&D-Programme 92, SKB concluded that an adequate understanding and capability for quantification of the safety of the deep repository existed in order for SKB to begin siting and construction of the facilities required for deep disposal. The development work that has been carried out since then has gradually taken on a clearer focus on

- methodology for practical site investigation,
- methodology for construction and verification of barriers,
- review of other waste forms than spent nuclear fuel, and
- evaluation of the dependence of safety on extreme events such as ice ages, major earthquakes, intrusion, etc.

These conditions are reflected both in the contents of the account and in the continued programme.

Even though the scope of non-project-bound R&D activities continues to diminish, this does not mean it can be dispensed with. Integrated experiments, practical tests and site-specific bedrock investigations are expected to continue to identify questions and problems that require further deepening of knowledge and databases. Specific needs for deepened understanding can also arise from the need to predict the probable future evolution of the repository without pessimistic simplifications, and the need to better quantify the safety margins in present-day designs.

SKB is anxious to maintain a high level of competence within areas essential to safety assessment and execution of the programme's key areas.

7.1 SPENT NUCLEAR FUEL

SKB's fuel studies have been going on for more than 15 years now. The methods for characterizing the spent fuel and measuring how radioactive materials in the fuel are released in contact with groundwater have undergone considerable development and a large database has been collected. The emphasis of the investigations has gradually shifted from idealized experiments under "pure" conditions to greater realism under the conditions expected in a deep repository.

The findings from the fuel studies have been continuously applied to define the source term in different consequence calculations. The models for how radionuclides are released are still highly simplified, with a large overestimation of the release rate for most radionuclides. SKB's continued efforts will be directed at trying to develop a more realistic release model, where allowance is made for both thermodynamic and kinetic conditions.

7.2 BUFFER AND BACKFILL

Knowledge of bentonite as a buffer material and for possible admixture in the backfill material has been accumulated by means of studies in laboratories and in the field. The state of knowledge is now deemed to be adequate to justify the use of bentonite in the repository. A summary account of data and properties is currently in preparation.

Continued studies will be concentrated on improving knowledge concerning the behaviour of bentonite during wetting, validation and refinement of calculation models, and manufacturing and application technology. Studies concerning the interaction between bentonite and cement are under way, as is scrutiny of the bentonite's influence on living conditions for microbes.

The performance of the bentonite during the wetting phase will be tested in large-scale experiments.

7.3 BEDROCK

With the advent of the Äspö HRL, the studies of the suitability of the Swedish bedrock for deep geologic disposal have been focused on site-specific investigations. The processes that are important for the safety of the deep repository have been identified. Methods have been developed and tested under field conditions for characterizing the rock and measuring the parameters that are needed to quantify these processes.

Models have now been developed to a level that makes it possible to define and minimize various safety-related effects on a deep repository with the aid of descriptions and calculations. Continuing work is aimed at comparing the consequences of different conceptual assumptions. The ambition is also to be able to validate the models used wherever possible. This will continue on the basis of site-specific data accumulation both in Sweden and abroad.

The supportive geoscientific R&D is now focused on broadening and deepening knowledge concerning long-range or general questions, such as:

- examination of how future glaciations may develop and what their effect will be on a deep repository,
- examination of tectonic conditions in a geological time perspective as a point of departure for assessments of the long-term mechanical stability of the deep repository,
- how are the results of site characterization and modelling dependent on the investigation scale,
- studies of the natural variations of the groundwater chemistry around a deep repository in time and space,
- learning to understand how the chemical composition of the groundwater reflects the results of the water's long-term movements in fractures in the bedrock,
- development of databases for conditions in the bedrock at levels deeper than 1,000 m.

Other R&D efforts will be focused on the questions that may come up in connection with the forthcoming site investigations.

7.4 CHEMISTRY

The processes that are important for the performance of the deep repository and for the release, transport and retardation of the radionuclides have been identified. Thermodynamic databases have been developed to provide support for assumptions concerning chemical speciation, solubility, etc. Laboratory measurements have yielded databases for the diffusion of different substances in buffer and rock matrix, as well as for the sorption of these substances in near-field materials or in the rock.

Numerical models have been developed to quantify release, transport and retardation. In part, these models have been structured to be conservatively simplified, which means that if a process cannot be quantified in detail, the calculations should not underestimate the negative consequences of the process for the repository.

The ongoing work is largely focused on further examining various phenomena that could negatively affect the barriers or processes that are important for the intended function of the repository. Examples are the effects of micro-organisms on the canister, groundwater chemistry and transport, formation of colloids and complexes etc. that could hasten the transport of the radioactive substances in the rock. Other efforts are examining the foundations of the sorption concept to enable the transport models to be validated as far as possible.

7.5 BIOSPHERE

Through studies of the transport of radionuclides and other contaminants in the biosphere, a considerable database and modelling capability has been built up within the field. An inevitable uncertainty in predictions over long periods of time arises due to the fact that changes in the biosphere take place at a far greater pace than the changes in the bedrock and in the vicinity of the deep repository.

This means that dose calculations only have a relatively "short-lived" (perhaps 1000-year) relevance. This limits the usefulness of the concept of "dose" as an index of the repository's impact on the human environment. Dose calculations are, however, often used over longer time spans as a means of weighing together conceivable effects of releases of many different radionuclides.

Efforts within the biosphere area are currently being focused on establishing and testing methodology for establishing the properties in site-specific biospheres that are essential for the dose calculations. To start with, a survey of areas that could be recipients for groundwater coming from repository depth is planned. Other efforts are being focused on limiting the uncertainties by trying to delimit the possible changes that will occur with time on the basis of site-specific or regional conditions. Extensive international cooperation is under way to compare different ways to model transport in the biosphere, and to forecast the future evolution of the biosphere.

7.6 NATURAL ANALOGUES

The processes that influence safety in a deep repository are known and can be tested in laboratories or studied through examples in nature. The latter provide an opportunity to study slow processes that occur over very long time spans.

Through observations and measurements of selected natural systems (natural analogues), it has been possible over the past ten years to study and test most of the processes that are expected to influence the performance of the barriers and thereby the safety of a final repository. Examples of such processes are mineral alterations, coprecipitation, corrosion, dissolution processes, matrix diffusion, etc. plus the presence of organic matter, microbes and colloids. Furthermore, the analogues provide an opportunity to study the interaction of several processes with an interdisciplinary approach that is difficult to duplicate in a laboratory.

The studies of analogues to the function of the deep repository will continue in order to test the validity of models and to underpin long-range forecasts.

7.7 OTHER WASTE

Other categories of waste besides spent nuclear fuel will also be disposed of in the deep repository. In order to avoid complicating the chemical conditions in particular, these wastes will be stored in separate caverns. An inventory of quantities, activity content and chemical form has been performed as a prestudy of how the waste is to be packaged and disposed of. The work is now continuing in a second phase with analyses of essential functions and possible scenarios in preparation for safety assessments, decisions on repository layout and design.

8 ÄSPÖ HARD ROCK LABORATORY

The Äspö HRL constitutes an important part of SKB's work to design a deep repository and to develop and test methods for investigating a suitable site. In the autumn of 1986, SKB initiated field work for the siting of the underground laboratory in the Simpevarp area in the municipality of Oskarshamn. Construction was started in the autumn of 1990. The underground portion is a tunnel running from the Simpevarp Peninsula to the southern part of Äspö Island. On Äspö Island, the 3,600 m long tunnel runs in two turns down to a depth of 450 m. The last 400 metres were excavated with a tunnel boring machine (TBM) with a diameter of 5 metres. The first part of the tunnel was excavated by drill-and-blast. The construction work was completed during 1995.

During the pre-investigation phase, 1986–1990, extensive investigations were carried out of the natural conditions in the bedrock both from the ground surface and from an extensive set of boreholes. Predictions were made with respect to the geological, geohydrological, geochemical etc. conditions that would be observed during the construction phase. During the construction phase, 1990–1995, extensive investigations and experiments were carried out in parallel with the tunnelling work. The operating phase commenced in 1995. This programme defines the thrust of the investigations and tests that are planned to be carried out during the operating phase.

The activities at the Äspö HRL have also attracted great international interest. Participation agreements exist with nine foreign organizations.

8.1 GOALS

One of the fundamental motives for SKB's decision to build the Äspö HRL was to create an opportunity for research, development and demonstration in a realistic and undisturbed rock environment down to the depth planned for a future deep repository.

In the planning and design of the activities at the Äspö HRL during the operating phase, priority is being given to projects which aim at:

- increasing scientific understanding of the deep repository's safety margins,
- developing and testing technology which reduces costs and simplifies the final repository concept without sacrificing high quality and safety,
- demonstrating the technology that will be used for the deposition of spent nuclear fuel and other long-lived waste.

8.2 RESULTS

At the start of the work on Äspö, the following stage goals were defined:

- Demonstrate that investigations on the ground surface and in boreholes provide sufficient data on essential safety-related properties of the rock at repository level.
- Refine and verify the methods that are needed for characterization of the rock in the detailed characterization of a site.

The first of these stage goals has been fulfilled now that the construction phase has been completed and the final reports on the investigations and research done in connection with construction are being completed during 1995 and early part of 1996. The results on the whole show that the methods that are available for investigating rock are well-suited to gathering the knowledge and the data on the bedrock at a specific site that are needed to construct a deep repository and demonstrate that it fulfils the safety requirements.

The second stage goal has been fulfilled in part with the work that has been conducted in parallel with the construction. Additional studies that will be concluded during the next few years are being pursued within the framework of this stage goal, including:

- Detailed investigations of the disturbed zone around blasted and drilled tunnels (the ZEDEX project).
- Development of an interactive computer system (Rock Visualization System) for interpretation and presentation of measurement results as well as design of the repository.

8.3 PROGRAMME FOR 1996–2001

Several projects at Äspö are aimed at evaluating the usefulness and reliability of different models that describe the rock's barrier function and at developing and testing methods for determination of parameters included in the models. Studies are also being conducted of the disturbance entailed by construction and operation of a repository in the rock in order to ensure that the disturbance does not have a negative influence on the long-term safety of the repository.

The following ongoing and planned projects are concerned with these questions:

- Detailed characterization of fractures in order to develop models for and data on fracture properties that can be handled in radionuclide transport calculations.
- Field and laboratory experiments aimed at deepening knowledge on the capacity of the rock to retain or retard the transport of radionuclides in fractured rock (Tracer Retention Understanding Experiments).
- Field and laboratory experiments aimed at studying how and at what rate the oxygen present in the repository at closure is consumed by reactions with the rock (REX – Redox experiments on detailed scale).
- Experiments in a specially developed borehole laboratory (CHEMLAB) which permits chemical experiments to be conducted under repository-like conditions with respect to groundwater composition and pressure. The experiments are being conducted to verify the models and check the constants that are used to describe the dissolution of radionuclides in groundwater, the effects of radiolysis, fuel corrosion, sorption on mineral surfaces, diffusion in the rock matrix, diffusion in backfill material, transport out of a damaged canister and transport in a single rock fracture.
- Coordinated evaluation of hydrogeological groundwater flow models and hydrogeochemical mixing models.
- Field and laboratory experiments to investigation to what extent degassing of groundwater at low pressures affects measurements of hydraulic characteristics in tunnels and boreholes situated under ground.

A considerable portion of the work on evaluation of models is being carried out in the internationally composed Äspö Task Force on Groundwater Flow and Transport of Solutes.

The Äspö HRL also provides an opportunity to test, investigate and demonstrate on a full scale various components in the deep disposal system that are of importance for long-term safety. It is also important to show that high quality can be obtained in the design, construction and operation of a deep repository.

The following ongoing and planned projects are concerned with these questions:

- Design, build and test the function of a prototype repository in the Äspö HRL. A full-scale prototype of the deep repository will be built to simulate all stages in the deposition sequence in a realistic environment. It will also provide an opportunity to observe a simulated repository during several years before the time comes to deposit the first canister in the deep repository.
- Test the bentonite buffer's performance in the deep repository environment over a long period of time

(up to 20 years) in order to test models and confirm results from laboratory experiments.

- Test the hydraulic and mechanical properties of different tunnel-back-filling materials and develop and test technology for compaction and retrieval of tunnel back-fill.
- Refine statistic methodology for estimating the portion of the deposition tunnels' length that can be used for emplacement of canisters based on geological, rock-mechanics, hydrogeological and other information from different investigation phases.
- Test injection methodology to verify know-how and technology for grouting/reinforcement of large transmissive discontinuities and strongly water-conducting discontinuities of moderate thickness and extent.

9 ALTERNATIVE METHODS

Deep geological disposal of long-lived radioactive waste is generally accepted among international experts as a good method that can be implemented in a way that satisfies fundamental ethical and environmental requirements. At the same time as the research and development work on direct disposal of spent nuclear fuel is being pursued by construction of facilities for encapsulation and an initial stage of deep disposal, however, good reasons exist to allocate some resources to the follow-up of alternative methods to SKB's main line. This is also in line with the requirements of the Act on Nuclear Activities on a comprehensive programme. Internationally, R&D work is being conducted on both alternative treatment methods for the spent nuclear fuel and on alternative final disposal methods for long-lived waste. Through SKB's extensive international cooperation network, broad insight is ensured in the major programmes that are in progress in other countries. For certain specific lines of development with possible applications in the longer term, however, a limited domestic effort is warranted. In this way Sweden can build up domestic competence in the field which will allow Sweden to gain insight into the broader programmes being pursued in other countries. In the Government decision on RD&D-Programme 92, the Government stipulated that SKB should, in the present programme, give an account of its assessment of the alternative methods that are being considered.

The greatest interest in the scientific and general debate concerning alternative methods to deep geological disposal has been devoted in recent years to transmutation of the long-lived radionuclides in the waste. This method requires reprocessing of the spent nuclear fuel and separation of the long-lived nuclides from the rest of the waste (partitioning). With the aid of nuclear reactions, the long-lived nuclides are then converted (transmuted) to short-lived or non-radioactive elements. The technology exists today for transmutation of a considerable portion of the plutonium that is formed in nuclear fuel. For certain other long-lived elements, transmutation could be made feasible (to a limited extent) through moderate development. However, development of proposed, more advanced methods for transmutation to an industrial scale requires, in certain respects, a technical breakthrough with a long period of work and large resources. The mere fact that transmutation requires reprocessing means that the costs of waste treatment based on transmutation of long-lived nuclides at today's cost level is much higher than the costs of direct disposal of unreprocessed nuclear fuel.

It is difficult to find any economic or short-term safety-related justification for transmutation when compared with present-day industrially established systems for management of spent nuclear fuel (direct disposal and reprocessing/vitrification plus final disposal). Rather, it is found that the radiation doses to the personnel in conjunction with handling and treatment will be much greater for transmutation. Even if the development of transmutation is successful, there will nonetheless be a need for deep disposal of such long-lived waste as inevitably arises from the relatively complicated treatment process.

Other alternatives to geological disposal are not the subject of any direct interest in Sweden or internationally, having been more or less dismissed. Supervised storage is the only exception for the time being. Supervised storage can be carried out in many ways, and is currently being practised in CLAB for the Swedish spent nuclear fuel. However, supervised storage does not fulfil the long-range goal expressed in the law's requirement on final disposal in a safe manner.

Among various alternative methods for geological disposal considered in Sweden, some interest has been expressed in disposal in very deep boreholes. SKB is conducting a limited follow-up programme of this alternative. The current judgement is that extensive and prolonged research would be required to establish a deep repository based on very deep boreholes.

10 DECOMMISSIONING OF NUCLEAR FACILITIES

When a nuclear power plant or other nuclear installation is taken out of service, parts of it are contaminated with radioactivity. Decommissioning and dismantling must therefore be carried out in a controlled manner and the radioactive material must be managed and disposed of as radioactive waste. Decommissioning projects are currently under way in various parts of the world. In most cases, they involve the decommissioning of small research and prototype reactors. In recent years, dismantlement work has also begun on large nuclear reactors, for example in the USA and Germany.

Internationally, extensive cooperation exists within the decommissioning field for the purpose of exchanging experience. SKB is actively involved in such a cooperative programme within the OECD/NEA. At present, this includes 29 plants in ten countries. A few years ago, a thorough analysis of status and development needs within the decommissioning field was done within the programme. No area was identified which requires fundamental development work. A need does, however, exist to translate tested methods to an industrial scale. This is now being done in conjunction with different projects, and the work is being carried out by industrial companies. For this reason, the EU, among others, has cut back its research programme within the field.

No development work directly concerned with decommissioning has been done in Sweden. Extensive experience does, however, exist from various repair and maintenance jobs that is directly applicable to decommissioning, e.g. the thorough decontamination and rebuilding of Oskarshamn 1, and the steam generator replacements in Ringhals 2 and 3. Theoretical studies of the technology and costs for decommissioning the Swedish nuclear power plants have been conducted on several occasions, most recently in 1994. These studies are intended to provide a basis for fee calculations.

No major R&D within the field of decommissioning is planned for the coming six-year period. The work will be concentrated on follow-up of activities abroad and of major Swedish repair jobs. Further, tests will be conducted of handling and possible disposal of large components obtained from previous rebuilding jobs. At the end of the period, it may be time to begin design work on the final repository for decommissioning waste.

1 INTRODUCTION, BACKGROUND

1.1 GUIDELINES FOR RADIOACTIVE WASTE MANAGEMENT IN SWEDEN

The goal of radioactive waste management in Sweden is to dispose of all radioactive waste products generated at the Swedish nuclear power plants and other nuclear installations in the country in a safe manner. Furthermore, all other radioactive waste that arises in Sweden must be safely disposed of.

The following general guidelines were presented in SKB's R&D-Programme 86 /1-1/:

- 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 meet stringent standards of safety and radiation protection and satisfy the requirements of the Swedish authorities.
- The systems for waste management shall be designed so that the requirements on fissile material safeguards can be satisfied.
- The waste problem shall be solved in all essential respects by the generation that utilizes the electricity generated by the nuclear power plants.
- A final 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 worked out inside the country, at the same time as all available foreign knowledge on the subject shall be gathered.
- The regulatory authorities' scrutiny and directives regarding the nuclear power utilities' handling of the waste question shall guide the conduct of the work.
- The activities shall be conducted openly and with good public insight.

These general guidelines did not occasion any special comments on the part of the reviewing bodies. They were reiterated in R&D-Programme 89 /1-2/ and certain parts were then discussed and questioned with respect to the spent nuclear fuel by the National Board for Spent Nuclear Fuel. The Board's viewpoints also occasioned certain comments in the Government's decision on R&D-Programme 89. This led to further deliberation on the part of SKB, and the following conclusion was presented in RD&D-Programme 92 /1-3/:

A broad political and public opinion seems to agree on the following fundamental principles for nuclear waste management in Sweden:

- Sweden already has nuclear waste, and it must be disposed of in a safe manner within the country.

- Future safety should be based on a disposal method that does not require supervision and/or maintenance, since this would entail that generation after generation, far into the future, would have to retain knowledge of the waste and have the will, capability and resources to perform such supervision and maintenance. We know too little about the society of the future to base long-term safety on this assumption.

- While working concretely and resolutely towards realizing the final disposal of all nuclear fuel, it is advisable to retain as much freedom of choice as possible with a view towards the possibility that alternative and somehow superior or simpler solutions may be found, or the possibility that there may be a re-evaluation of the current attitude towards the re-use (reprocessing) of some of the fissile materials (U, Pu) in the fuel.

- The Nordic radiation protection authorities have formulated the following principle: *The burden on future generations shall be limited by implementing, at an appropriate time, a safe disposal option which does not rely on long-term institutional controls or remedial actions as a necessary safety factor* /1-4/. The same requirement is also formulated on an international level /1-5/ and has been generally accepted as a fundamental principle by all countries with nuclear power.

As regards the operational waste from the nuclear power plants and some other waste from research etc., there are already facilities and systems in operation which satisfy the requirements that follow from the general guidelines.

The viewpoints that have been put forth with respect to the value of preserving freedom of choice have been heeded in the current RD&D-Programme.

1.2 APPLICABLE LEGISLATION ETC.

The obligations of the owners of nuclear power reactors with regard to management and final disposal of radioactive waste are set forth in the Act /1-6/ on Nuclear Activities, in the Ordinance on Nuclear Activities /1-7/ and in the Act /1-11/ on the financing of future expenses for spent nuclear fuel etc., as well as in certain permits and guidelines issued by the Government.

The provisions and guidelines entail in brief that the owners of nuclear power plants are responsible for:

- adopting the measures that are needed in order to manage and finally dispose of generated nuclear waste in a safe manner and to decommission and dismantle the nuclear power plants and appurtenant facilities,
- the comprehensive research and development activities that are required to carry out these measures, including studies of alternative management and disposal methods,
- preparing a programme for research and development and other measures every third year starting in 1986, including an account of the research results obtained,
- covering all costs for management and final disposal of the nuclear waste.

1.3 HISTORY

Research regarding the management 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 /1-8/. The research was intensified in conjunction with the enactment of the "Stipulation Act" in 1976/77, when the KBS (Nuclear Fuel Safety) Project was started by the nuclear utilities. The project, which was administrated by SKB, developed two final disposal methods: KBS-1 for vitrified high-level reprocessing waste (1977) /1-9/ and KBS-2 for the final disposal of unreprocessed spent nuclear fuel (1978) /1-10/.

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

When the Financing Act /1-11/ entered into force, PRAV was abolished and the National Board for Spent Nuclear Fuel (NAK, later SKN) was created in its stead. The purpose of this Board was to review, regulate and oversee the activities of the nuclear utilities (SKB) within the waste management field. As from 1 July 1992, SKN's duties were transferred to the Swedish Nuclear Power Inspectorate.

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 /1-12/.

The KBS-3 report was submitted in support of the applications for fuelling permits for the Forsmark 3 and Oskarshamn 3 reactors. The Government granted these permits under the Act on Nuclear Activities /1-6/ in June 1984. A research programme /1-13/ prepared by SKB in February 1984 was also submitted in support of the permit applications. Since then, operating permits for Barsebäck 2, Ringhals 3 and 4 and Forsmark 1 and 2 have also been changed to be based on KBS-3.

In September 1992, SKB presented the third research programme under the Act on Nuclear Activities /1-3/. The results of SKB's research work are reported continuously in SKB's technical reports. Annual summaries are included in the SKB Annual Report /1-14, 15, 16/. A more concise annual account is also presented in SKB's annual Activities report, which is distributed widely.

1.4 RD&D-PROGRAMME 92 – EXPERT REVIEW

After RD&D-Programme 92 had been submitted to SKI in September 1992, the programme was circulated for review and comment to a large number of institutions in Sweden. On the basis of the viewpoints received and its own judgements, SKI compiled a review report and submitted it to the Government in March 1993 /1-17/. In June 1993, KASAM submitted a report with its own commentary on the RD&D-Programme to the Government /1-18/. The Government's decision in regard to RD&D-Programme 92 was handed down in December 1993 /1-19/. In it, the Government stipulated that a supplementary account should be prepared with regard to certain points. SKB submitted such a supplement in August 1994 /1-20/. This supplementary report was circulated for review and comment in the same way as the main report /1-21/ and a Government decision was handed down in May 1995 /1-22/.

Wherever possible, SKB has heeded the comments received on RD&D-Programme 92, including the supplementary report, in the present RD&D-Programme 95.

1.5 WASTE FROM THE SWEDISH NUCLEAR POWER PROGRAMME

Radioactive waste from the Swedish nuclear power programme varies widely in terms of form and activity content, 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 a handling viewpoint, it is practical to distinguish between low-level waste (LLW), intermediate-level waste (ILW) and high-level waste (HLW). LLW can be handled and stored in simple packages, without any special protective measures. ILW must be radiation-shielded for safe handling. HLW requires not

Table 1-1. Waste quantities in the Swedish nuclear waste programme.

Product	Principal origin	Unit	Number of units	Volume in final repository m^3
Spent fuel		canisters	4,500	13,500
Alfa-contaminated waste	LLW and ILW from Studsvik	drums and moulds	2,800	1,700
Core components	Reactor internals	moulds	1,400	9,600
LLW and ILW	Operational waste from nuclear power plants and treatment plants	drums and moulds	55,900	91,000
Decommissioning waste	From decommissioning of nuclear power plants and treatment plants	mainly 20 m^3 ISO containers	8,500	156,400
Total quantity, approx.			**73,100**	**272,200**

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 radionuclides contained in the waste is of great importance. A distinction is made between short- and long-lived waste.

Short-lived waste mainly contains radionuclides with a half-life shorter than 30 years, i.e. it will have decayed to a harmless level within a few hundred years. This waste will be deposited in the final repository for radioactive operational waste, SFR, at Forsmark. Some very low-level and short-lived waste can be deposited on a simple refuse tip (shallow land burial).

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

The waste from the nuclear power plants is usually divided into the following groups with regard to its subsequent handling:

- Spent nuclear fuel.
- Operational waste.
- Core components and reactor internals.
- Decommissioning waste.

The different waste types were described in detail in RD&D-Programme 92 /1-3/, since which time no essential changes have occurred with regard to the different waste types that must be managed and disposed of in Sweden. Current waste quantities for different categories of waste are given in detail in the report PLAN 95 /1-23/ and summarized in Table 1-1.

1.6 EXISTING SYSTEM FOR MANAGEMENT OF RADIOACTIVE WASTE FROM NUCLEAR POWER PLANTS

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 1-1 illustrates schematically 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 and disposal of the radioactive waste products of nuclear power, PLAN 95, which the power utilities have submitted through SKB /1-23/.

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 arisen.
- Spent fuel will be stored for 30–40 years before it is emplaced in the final repository. This will limit heat generation in the final repository.

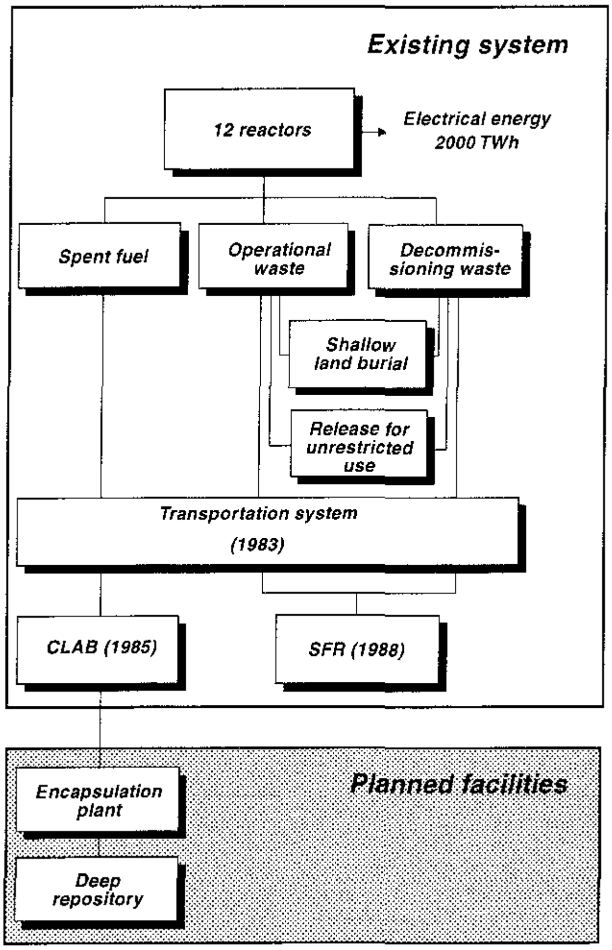


Figure 1-1. *The Swedish waste management system.*

- Other long-lived waste will be deposited of in connection with the final deposition of spent fuel.

Essential parts of the waste management system are already in operation, namely the central interim storage facility for spent nuclear fuel, CLAB, the final repository for reactor waste, SFR, and the transportation system.

SFR has been in operation since 1988. It currently has capacity to accommodate 60,000 m^3 of radioactive operational waste and can be expanded for additional needs. Expansion is also planned to accommodate short-lived low- and intermediate-level decommissioning waste from nuclear facilities.

CLAB has been in operation since 1985. It currently has capacity to store 5,000 tonnes (uranium weight) of spent nuclear fuel, and plans call for this capacity to be expanded to about 8,000 tonnes at the beginning of the next decade.

The transportation system is based on sea transport and consists of a ship, M/S Sigyn, a number of transport containers and terminal vehicles. The system has been in operation since 1982 and has gradually been expanded and augmented to its present-day function and capacity.

The existing facilities and systems are operated with very high availability and good reliability, have a very good working environment and insignificant environmental impact.

What remains to be built of the necessary system is an encapsulation plant for spent fuel, a deep repository for long-lived waste and necessary additions to the transportation system to permit shipment of encapsulated nuclear fuel and other waste to the deep repository. Extensive work is under way for these parts of the system for the purpose of determining a suitable design and site. The plans for this work are described in detail in this report.

Management of the radioactive waste products of nuclear power also includes decommissioning of the nuclear power plants and other facilities when they have been taken out of service and final disposal of the waste from decommissioning, see chapter 14.

2 GOAL OF THE PROGRAMME

2.1 GOAL

In RD&D-Programme 92 /2-1/, SKB gave an account of its, and thereby the concerned nuclear power industry's, planning for deep disposal of the long-lived radioactive waste, including the spent nuclear fuel, that arises in connection with the operation of the Swedish nuclear power plants. In brief, this planning entails the following:

> **The goal** is to begin deposition in a deep repository of a small portion (about 800 tonnes) of the spent nuclear fuel in 2008, in compliance with all environmental and safety standards.
>
> For this an encapsulation plant and a deep repository are required. Furthermore, additions to the existing transportation system are needed to ship the encapsulated fuel from the encapsulation plant to the deep repository. The basic scheme is encapsulation in copper canisters that meet the safety requirements imposed by the deep repository. Deep disposal is intended to be implemented in accordance with the KBS 3 concept or a closely-related optimized version at a depth of about 500 m in crystalline bedrock.
>
> The encapsulation plant will be built as an addition to CLAB. The deep repository will be located on a suitable site in Sweden that enables both the stringent safety requirements to be met and the necessary work to be carried out in consensus with the concerned municipality and the local populace.
>
> The safety and radiation protection aspects will be thoroughly penetrated and accounted for before decisions on essential binding measures are taken.

At the same time as work proceeds on this main task, SKB will follow and, to a limited extent, fund R&D on alternative lines of development mainly conducted in other countries, however. This strategy of SKB's programme, which was described thoroughly in RD&D-Programme 92, is in harmony with the provisions of the Act on Nuclear Activities /2-2/ regarding a comprehensive programme.

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

SKI /2-3/ states that:

...RD&D-Programme 92 meets the basic requirements set forth in Section 12 of the Act on Nuclear Activities on a programme for research and development with regard to objectives, breadth and depth.

SKI can accept that the continued RD&D measures will mainly be concentrated on a method of type KBS-3. ...A KBS-3-like repository should also be able to be designed so that it can offer a reasonable balance between abandonability, retrievability and inaccessibility for the fissile material.

SKI believes that it is a good action strategy to expand the deep repository in stages...

KASAM /2-4/ states that:

KASAM recommends that SKB focus its RD&D activities during the period 1993-1998 on a demonstration-scale disposal with option to retrieve as the first stage in the ultimate management of the spent nuclear fuel.

that this stage encompass 5-10% of the entire estimated fuel quantity from the Swedish reactor programme, and

that KBS-3 is a reasonable choice for the demonstration disposal.

The Government states in its decision of 16 December 1993 /2-5/ regarding SKB's RD&D-Programme 92 that:

The Government finds, in concurrence with SKI, that RD&D-Programme 92 meets the provisions of Section 12 of the Act on Nuclear Activities.

The Government observes that ... the work of depositing spent nuclear fuel and nuclear waste in a deep repository is planned to be carried out in two phases, namely demonstration deposition and final disposal.

The Government finds, in concurrence with SKI and KASAM, that the change of the programme has considerable advantages, even if the long-term properties of the final repository cannot be demonstrated. The Government would particularly like to emphasize that even if the KBS-3 method is a reasonable choice for demonstration deposition, SKB should not commit itself to any specific *handling and disposal method before a coherent and thorough assessment of associated safety and radiation protection aspects has been submitted.*

The continued planning of the measures required to implement the chosen main line requires a number of consequential decisions pertaining to environmental impact assessments, siting, safety accounting, investment, permits under various laws, etc. These decisions must be supported by various kinds of data, which will be obtained through the ongoing work. They may of course also lead to re-evaluation and changes of the chosen strategy.

This RD&D-programme describes the current plans in detail for the coming six-year period and in general for measures necessary in the future.

2.2 GENERAL DESIGN OF THE DEEP REPOSITORY

The following description of the deep repository follows the principles set forth in KBS 3 /2-6/ and RD&D-Programme 92 /2-1/ as well as SKB's PLAN-report /2-7/. A more detailed description of how the facilities may be designed is provided in "Brief preliminary plant description," /2-8/.

The repository is situated at a depth of about 500 m, depending on conditions at the selected site. From tunnels at this depth, deposition holes are bored in which copper canisters with spent nuclear fuel are emplaced and surrounded with bentonite clay – see Figure 2-1. The tunnels can be backfilled with a mixture of bentonite and quartz sand or other suitable material. Closely-related optimized variations of the general scheme described here may be considered.

The deep repository is built in two stages. In the first stage, approximately 400 canisters of spent nuclear fuel (about 800 tonnes uranium weight) are deposited. This initial operating period is planned to start in 2008 at the earliest and last for about 5 years, after which the experience gained will be evaluated. The option then also exists to retrieve the canisters, if this should be deemed necessary for any reason.

If the result of the evaluation is that continued deposition is suitable and acceptable – which is our expectation – the entire repository is built (stage 2) and the activities continue until all waste has been deposited, which is estimated to occur in around 2040. The total quantity of spent nuclear fuel then deposited is estimated to be about 8,000 tonnes, which is the quantity generated by the present-day Swedish nuclear power programme up to the year 2010.

Deposition of "other radioactive waste" is planned in a special part of the repository during stage 2. This waste resembles that deposited today in the Final Repository for Radioactive Operational Waste, SFR, in Forsmark, except that it contains more long-lived radionuclides than the SFR waste. The total quantity of such waste is estimated at 25,000 m^3.

The waste is deposited in three separate repository areas: area for canisters deposited during the initial operating period (stage 1), area for canisters deposited during

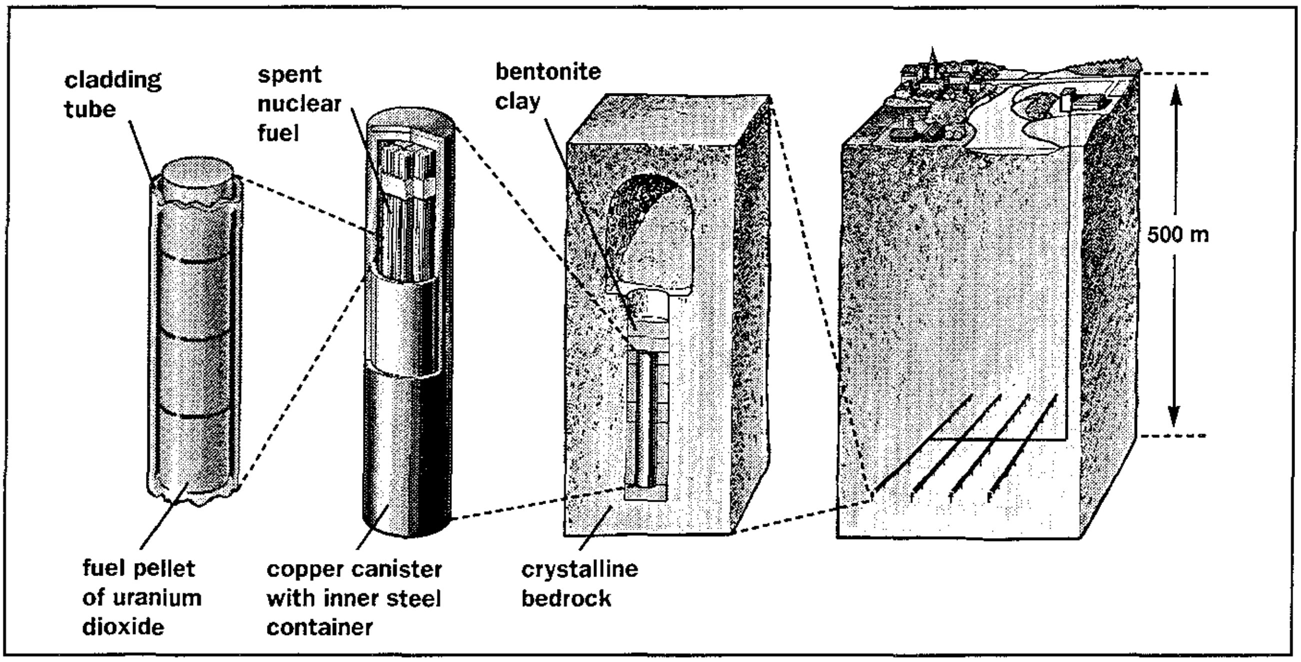


Figure 2-1. *Deep repository in accordance with the KBS-3 concept.*

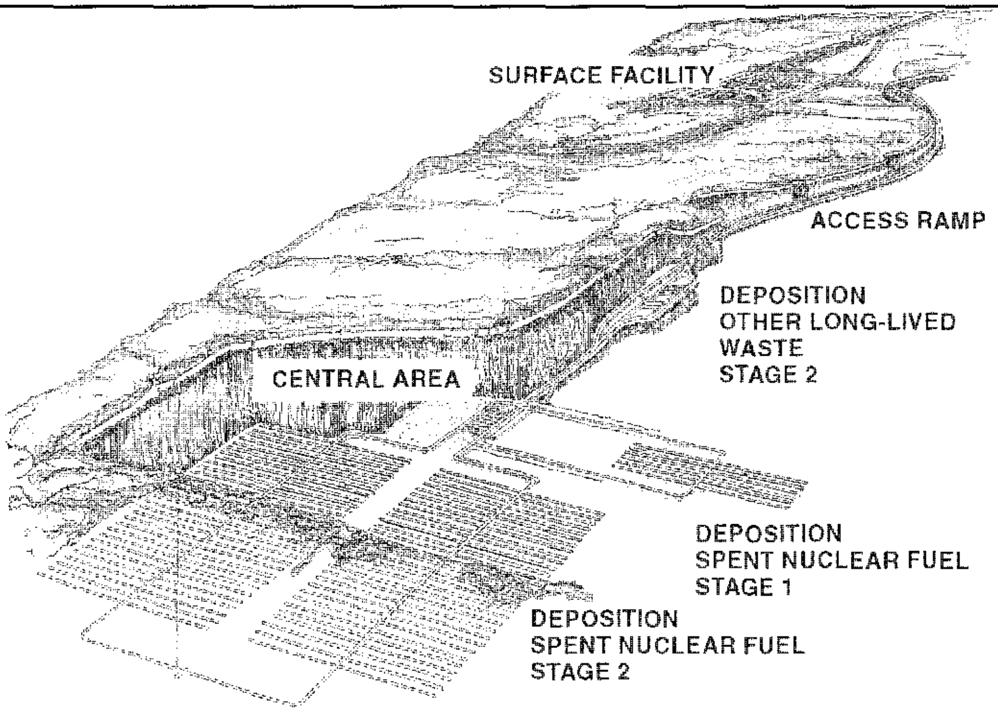


Figure 2-2. *Schematic drawing of the deep repository.*

regular operation (stage 2) and area for other waste (stage 2). Altogether, these repository areas occupy an area of about 1 km^2. Figure 2-2 shows a schematic drawing of the deep repository.

If, on the other hand, the evaluation leads to a decision to terminate deposition after the initial operation (stage 1), the option is then open to retrieve the deposited canisters and place them in interim storage.

3 STEP-BY-STEP DEVELOPMENT AND CONSTRUCTION

In recent years, Swedish environmental legislation has introduced requirements on environmental impact assessment – EIA – of the facility or the system for which a permit or licence is being applied for. The background materials for the law state that an EIA shall also shed light on the consequences of alternative methods/designs, including a so-called "zero alternative" for the case that the facility or system for which a permit or licence is being applied for is not realized. In the debate concerning the Swedish nuclear waste programme, criticism is sometimes raised that "no method has yet been chosen", or "SKB is rushing the siting of the deep repository, since no method has been developed yet", or suchlike. But a historical retrospect shows that a gradual narrowing-down of the studied methods for treatment and disposal of the high-level waste has taken place. Furthermore, choices have been made between different fundamental categories of methods. This process of narrowing-down and selecting alternatives has been presented and discussed in the programmes reported at regular intervals and has been based on a broad review and commentary procedure and extensive public scrutiny. Through this process, the principal strategy of the Swedish nuclear waste programme has been developed in consensus between industry, public authorities and the Government. In conjunction with upcoming siting applications for the planned facilities, alternatives will be described and considered for the method, the design and the siting for which the application applies.

This chapter contains a brief account of the most important steps in method choices already made. Further, the implications of a zero alternative are discussed, along with planned stages for step-by-step construction of the deep repository. Finally, EIA and the EIA process are discussed.

3.1 METHOD SELECTION

3.1.1 Deep disposal in crystalline rock

The development of the Swedish system for management of spent nuclear fuel began in the 1970s with the Aka Committee report, which was published in the spring of 1976 /3-1/. The most important proposals of the Committee were to build an interim storage facility for spent nuclear fuel and a final repository in rock for low- and intermediate-level waste. According to the proposal, the facilities should be located at one of the nuclear power stations or Studsvik, and the waste shipments should be based on sea transport. The proposals led to the construction of CLAB and SFR and the build-up of a sea transportation system during the 1980s.

The Aka Committee also proposed that

- studies should be initiated of the possibility of building a Swedish reprocessing plant,
- studies should be commenced of direct final disposal of the spent nuclear fuel without preceding reprocessing,
- final disposal of radioactive waste should take place in crystalline rock,
- geological studies of sites suitable for final disposal should be initiated.

The Aka Committee report also helped bring the nuclear waste issue into the focus of political debate. The non-socialist Government that was formed after the 1976 election proposed to the Riksdag that a Stipulation Act should be passed to lay down conditions for permits to fuel new nuclear power reactors, and such a law was passed by the Riksdag in 1977 /3-2/. Under the Stipulation Act, responsibility for pursuing development in the area of nuclear waste management was shifted to the owners of the nuclear power plants. They in turn started the KBS project, which was conducted within SKB.

The Stipulation Act required that it be demonstrated "how and where an absolutely safe final disposal of the high-level waste obtained from reprocessing can take place, or" ... "how and where an absolutely safe final disposal of spent, unreprocessed nuclear fuel can take place".

The Aka Committee report and the Stipulation Act together entailed a focusing of the work on deep disposal of the high-level waste in Swedish crystalline rock. This line was accepted by industry, the regulatory authorities and the Government, which subsequently scrutinized the various reports from the KBS project. An initial step in the choice of method was thereby taken de facto.

After the feasibility of safe disposal in accordance with the KBS concept was accepted, alternative concepts for treatment and final disposal of the spent nuclear fuel were once again discussed, for example in the 1986 research programme, pages 17–18 in part I /3-3/. There it is observed that "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.**" Having found that this programme "...meets the requirements set forth in Section 12 of the Act on Nuclear Activities..." and that "...the work should in the main be pursued in accordance with the strategy .... laid down in the programme" /3-19/, the authorities have also accepted this point of departure. This has also been the case with subsequent programmes that have been scrutinized and essentially accepted by the regulatory authorities and the Government.

On the international plane as well, deep geological disposal of the high-level waste is the alternative that is recommended and preferred by industry and government authorities to an increasing degree in nuclear power countries. This is evident not least from the "Collective Opinions" issued by the OECD/NEA's Radioactive Waste Management Committee /3-17, 18/.

3.1.2 Direct disposal without reprocessing

Within the framework of the KBS project, two alternative ways were studied for treatment of the spent nuclear fuel: reprocessing and direct disposal without reprocessing. The first report from the project, KBS-1, dealt with final disposal of vitrified waste from reprocessing /3-5/. Together with a contract for reprocessing of spent fuel with the French company Cogema, this report comprised the supporting material for the applications for permits to fuel the Ringhals 3 and 4 and Forsmark 1 and 2 reactors. Permits to fuel these reactors were obtained after the referendum on nuclear power that was held in the spring of 1980.

The Riksdag decision on the use of nuclear power following the aforementioned referendum limited the number of reactors to the 12 units that were then in operation or under construction. Further, it was decided that these units were to be decommissioned not later than 2010. In addition, a strong cutback in the construction of nuclear power plants all over the world took place in the 1980s, contributing to a sharp reduction in the price of uranium. These factors taken together meant that there was no longer any technical or economical justification for reprocessing of the spent nuclear fuel. Furthermore, political opposition to the reprocessing and reuse of plutonium grew ever stronger, the argument being that plutonium might be diverted to military purposes. The Swedish nuclear power industry therefore decided at an early stage that applications for fuelling permits for the two last reactors in the programme approved by the Riksdag would be based on final disposal of the fuel without reprocessing. The KBS-3 report was prepared and presented in 1983, and with this as a basis the fuelling permits for Forsmark 3 and Oskarshamn 3 were granted in June 1984.

After these fuelling permits had been obtained, other reactors that had obtained fuelling permission under the Stipulation Act also switched to having their permits based on the KBS-3 report /3-6/. This made it possible for the nuclear power utilities and SKB to transfer the right to reprocessing under the contracts with Cogema to other Cogema customers and thereby phase out any further reprocessing of fuel from the Swedish nuclear power plants. As a result, the work was concentrated on direct final disposal without prior reprocessing. A second method choice had thereby been made and accepted by industry, the regulatory authorities and the Government. This has also been noted in previously submitted R&D programmes accepted by the Government.

3.1.3 Alternatives for deep geological disposal

Deep disposal of spent nuclear fuel in Swedish crystalline rock can be designed and executed in a number of different ways. The Act on Nuclear Activities /3-4/ requires that the research programme that is carried out be comprehensive in the sense that different alternatives be studied. Based on the fundamental principles for deep disposal (see further in chapter 4), many different options are available. A number of such options have been studied during the 1980s and 1990s, some very thoroughly. Among the options studied are WP-Cave, Very Deep Holes, Very Long Holes and Medium-Long Holes /3-7, 3-8, 3-9, 3-10/. RD&D-Programme 92 /3-11/ provided a summary account of these studies and drew the conclusion that "the design according to KBS-3 is retained as the main alternative for the continued work. In conjunction with adaptation to local conditions on the selected site, the layout of the repository can be further optimized, whereby technologically closely-related variants can be given further consideration". The basic design has already been described in section 2.2. The strategy has been accepted in all essential respects by the regulatory authorities and the Government.

The principles and conceptual solutions described in the KBS reports have won great respect and recognition internationally. Compared with other alternatives, the KBS-3 design has proved to be very good for the type of bedrock that exists in Sweden and many other countries. Responsible organizations in countries with similar bedrock, e.g. Finland and Canada, have settled on concepts that are very similar to KBS-3.

3.2 ZERO ALTERNATIVE

At present all spent nuclear fuel is stored in CLAB. This storage is planned to last 30–40 years before the fuel is deposited in a deep repository. Experience from long-term storage of zircaloy-clad fuel dates back to the end of the 1950s. This experience shows that storage is possible for at least 50 years and can probably be prolonged to at least 100 years if necessary /3-12, 20/. In other words, as far as storage time and storage capacity are concerned it is possible to continue storing the spent fuel in CLAB for several more decades. This then becomes a natural "zero alternative" in the future EIA work for the deep repository and the encapsulation plant. Supplementary safety assessments (time horizon hundreds of years) are planned for this alternative.

Interim storage of spent nuclear fuel can also take the form of "dry storage" nowadays. Technology for this has been developed and tested in Germany and the United States, among other places /3-13,14/. Dry storage requires less maintenance and supervision than wet storage and can therefore be considered as a secondary "zero alternative" to deep disposal in the unlikely event that a decision is not taken to establish a deep repository within, say, 50 years. Supplementary safety assessment may have to be done for this case as well.

3.3 OVERVIEW OF MEASURES FOR STEP-BY-STEP CONSTRUCTION

A diagram of the major steps in the construction of an encapsulation plant and a deep repository and in the deposition of encapsulated fuel in the deep repository was presented in the supplement to RD&D-Programme 92 /3-15/. This diagram is reproduced in slightly modified and simplified form in Figure 3-1.

The measures that concern the deep repository encompass a time span of about sixty years or longer from the start of feasibility studies up to completed closure of a fully constructed repository. The following stages are distinguished for the **deep repository:**

Siting, which aims at gathering the material needed for decisions on siting (Act Concerning the Management of Natural Resources) and construction (Act on Nuclear Activities) of the repository. The work proceeds in two stages, where the first stage encompasses feasibility studies and general studies and the second stage site investigations. The latter are primarily carried out on two sites, which are chosen on the basis of the feasibility and general studies.

Detailed characterization of one site. This requires a permit under the Act Concerning the Management of Natural Resources (NRL) /3-16/. The work entails some rock construction works, which means in reality that **Construction stage 1** is also begun, which pertains to a facility for deposition of about 400 canisters of spent nuclear fuel from the Swedish programme. The Government's decision on the supplement to RD&D-Programme 92 thus states and clarifies that detailed characterization entails commencement of construction of a nuclear facility, which also requires a permit under the Act on Nuclear Activities

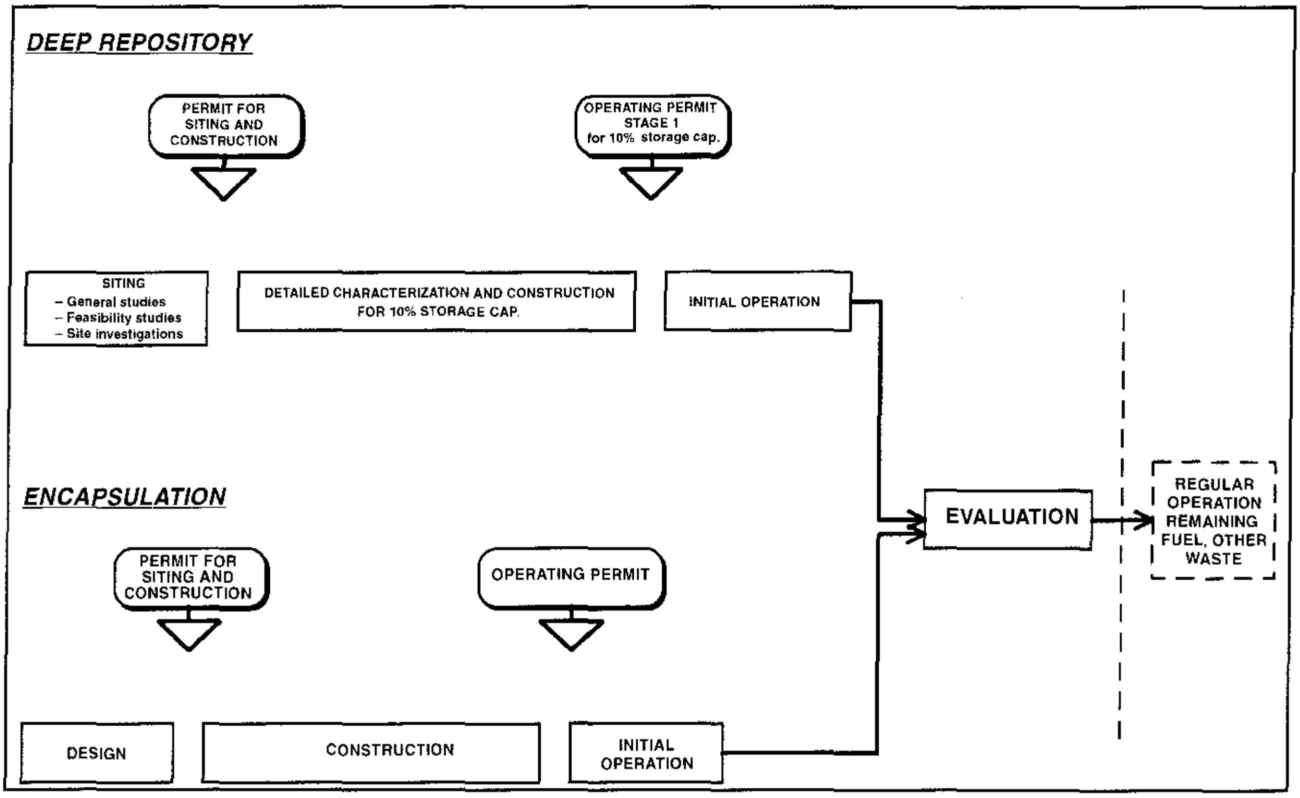


Figure 3-1. Diagram of the major steps in the programme, along with the requisite permits. The upper half of the figure concerns siting, construction and operation of a deep repository, while the lower half concerns the equivalent steps for an encapsulation plant. For each facility, the diagram shows main activities and important permits.

(KTL) /3-21/. The surface facility, common chambers under ground and the first deposition chambers under ground are built during this stage. At the same time, the requisite equipment for deposition of encapsulated fuel and for associated activities is manufactured, delivered and tested.

Initial operation, which comprises deposition of encapsulated spent nuclear fuel, about 10% of the quantity produced by the Swedish nuclear power plants up to 2010, i.e. about 800 tonnes (uranium weight) or about 400 canisters. The deposition chambers are excavated gradually at the necessary pace.

Evaluation. If this turns out favourably for continued deposition of the remaining quantity of spent fuel and other long-lived waste, application is made for the necessary permits for further construction and regular operation.

Construction and regular operation, which comprises the deposition chambers for all remaining spent nuclear fuel and all other long-lived waste. The work includes rock works, construction works and delivery and trial operation of equipment for the parts of the deep repository not included in stage 1. To the extent warranted by experience from initial operation and evaluation, the design of the facility and equipment is modified. The remaining waste is deposited during regular operation. This stage is the longest stage of the entire chain.

Supervised storage in the deep repository for as long as desired. **Closure** of the deep repository. This activity is not indicated in the diagram.

The following stages are distinguished for the **encapsulation plant**:

Siting and Design of the plant, including a final decision on canister design and execution of the necessary development work. The work is carried out in several stages with a gradually increasing degree of detailing up to applications for permits under NRL and KTL, which are planned to be submitted simultaneously.

Construction stage 1, which comprises detailed design and construction of the plant for encapsulation of spent nuclear fuel plus inactive trial operation of the same.

Initial operation, which comprises active trial operation plus encapsulation of about 10% of the spent nuclear fuel, about 400 canisters.

Evaluation. Coincides with evaluation of the initial stage of deep disposal as described above.

Construction and regular operation, which includes construction of a section for encapsulation of other long-lived waste (mainly core components) and encapsulation of remaining spent nuclear fuel and other long-lived waste.

Possible **decommissioning** of the plant and deposition of arising decommissioning waste – not indicated in the diagram.

3.4 ENVIRONMENTAL IMPACT ASSESSMENT AND EIA PROCESS

Permits under the Act Concerning the Management of Natural Resources (NRL) and the Act on Nuclear Facilities (KTL) are required for the siting and construction of an encapsulation plant or a deep repository. These permits are issued by the Government. In addition, approval is required in different stages under various statutes such as the Environment Protection Act, the Radiation Protection Act and possibly the Water Act, as well as a building permit. Under all the above laws, it is nowadays either necessary for a permit application to include an environmental impact assessment (NRL, Environment Protection Act, Water Act), or possible for a competent authority to prescribe that an environmental impact assessment must be performed (KTL, Radiation Protection Act). The authorities may also decide what the EIA must contain, but it is above all in the process by means of which impact assessments take shape that a meaningful EIA develops.

The purpose of an environmental impact assessment is to permit a coherent assessment of the impact of the facility on the environment and on human health and safety, as well as on the management of the country's natural resources. The fundamental scope and contents of an environmental impact assessment are illustrated in Figure 3-2. The EIA is thus a tool that enables an activity to be evaluated from the environmental viewpoint before a permit for the activity is issued, in other words the EIA is a part of the supporting material on which the licensing authority bases its decision on whether to issue a permit and the terms of the permit. Further, the EIA is supposed to enable concerned parties and the public to gain insight into the siting process and give them an opportunity to offer viewpoints. A description of how SKB plans the EIA process was given in a KASAM seminar /3-22/.

Formally, it would be possible for different requirements on EIAs to be stipulated in different laws. However, this would be contrary to the intentions behind the EIA legislation (basis for a coherent assessment). Instead, it is an important function of the EIA process itself

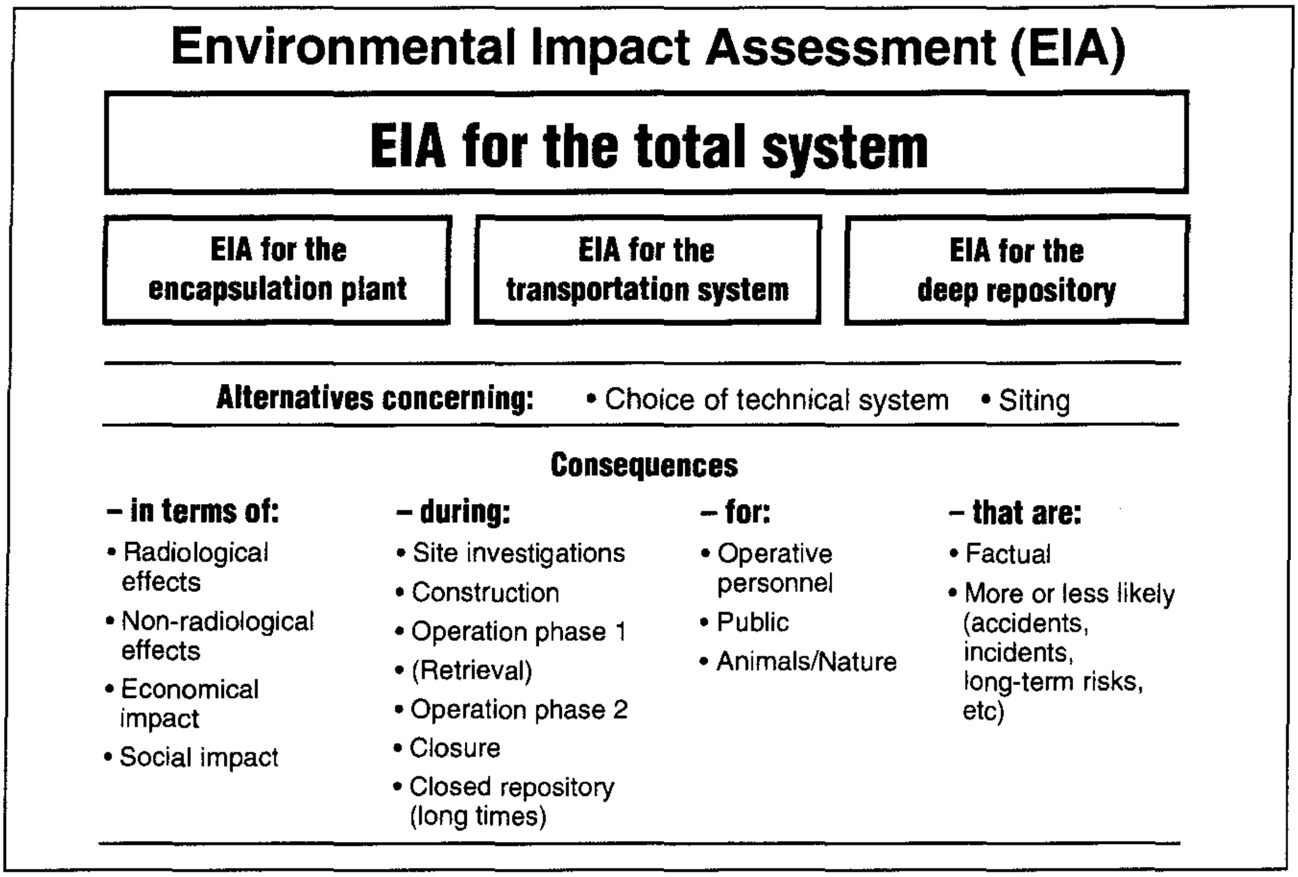


Figure 3-2. *Illustration of structure of environmental impact assessment.*

to create a coherent basis for a decision. According to the ordinance on environmental impact assessments, an EIA shall contain a reasoned account of alternative sitings and designs, plus data on the consequences of failing to adopt the applied-for measures (the "zero alternative").

The legislation does not lay down any further guidelines for how the EIA process is to be carried out. This means that the concerned parties ("the actors") enjoy wide freedom to jointly design the process themselves. SKB has therefore not issued its own detailed description of how the EIA process ought to be carried out. Instead, SKB has, at an early stage, entered into a local dialogue with concerned authorities at the start of the planning and investigation work for the encapsulation plant and the deep repository.

Traditionally, and ever since the introduction of nuclear power, the nuclear power industry has evaluated the safety and environmental impact of its plants and published these evaluations in special reports. In conjunction with the construction of nuclear power plants or other nuclear facilities, for example SKB's final repository for radioactive operational waste (SFR), they have prepared preliminary and final safety reports (PSR and SFR, respectively). These closely resemble the equivalent reports that are prepared for similar facilities abroad. Non-radiological environmental aspects have also been dealt with in the supporting material for decisions on siting and construction. Contacts have been made at an early stage with concerned authorities, municipalities and nearby residents. This has led to valuable experience which will be of use in the siting of the deep repository.

However, the future EIA process will entail a broader and deeper dialogue between all stakeholders. Important actors will above all be those who may have the facility in their midst (the municipality and nearby residents), the enterprise who will build and operate the facility (SKB), as well as supervisory authorities and the county administrative board. It is gratifying that the Government has now agreed to give concerned municipalities resources so that they can participate in a qualified and credible manner in the EIA process.

The formal EIA work has been commenced for the encapsulation plant. A joint consultation group for EIA matters has been formed under the leadership of the county administrative board in Kalmar County. Other participants are Oskarshamn Municipality, SKI (the Swedish Nuclear Power Inspectorate), SSI (the National Radiation Protection Institute) and SKB. A review of alternatives and a general assessment of various environmental impacts has been carried out as an initial step. In parallel, Oskarshamn Municipality has initiated a comprehensive information and joint consultation programme.

Feasibility studies are currently being conducted for the deep repository in several municipalities. Even though these studies are not conducted within a formally defined EIA process, the work nevertheless contains many of the elements that are important in such a process. They are, for example, conducted with openness and great insight and participation from many different interested parties. The set of issues that are examined is of great breadth, and the various stakeholders have a say in which issues are to be taken up.

If the siting studies in a municipality proceed after the feasibility study with site investigations, the work of preparing the environmental impact assessment which the site investigations are supposed to lead to must be begun early. SKB therefore maintains that the forms for the EIA process should be agreed upon among the concerned parties. Since a designated site exists, nearby residents, landowners and competing land-use interests can be identified and allowed insight and influence in the process. Experience from the feasibility study will be of great value to the relevant municipalities. Both the municipal leaders and various interest groups have acquired considerable knowledge in the matter through the feasibility study and are therefore able to safeguard their interests and contribute constructively to a stable and credible process.

The exact design of the EIA process must be agreed upon through discussion between the municipality, SKB and the regulatory authorities. The model and the experience that exist from the EIA work for the encapsulation plant can serve as an important background to the discussion of how the EIA process for the deep repository should best be designed. The Government has also stated that concerned county administrative boards should assume coordinating responsibility. The transportation question should also be explored in conjunction with the EIA work for the deep repository. The shipments may also involve other municipalities than those included in the studies of the encapsulation plant and the deep repository. These "transit municipalities" must be given an opportunity to participate in the EIA work on an equal footing as far as the environmental impact assessment of the shipments is concerned.

An important question in the EIA work both for the encapsulation plant and for the deep repository is the relationship between the two. Thus, for example, the prospects for co-siting must be penetrated in the EIA. Then when a decision is eventually made on the siting of the two facilities, the assessments for one of the facilities will logically be influenced by how far the work has come with the other. A decision will not be made to build one of the facilities unless the work with the other has progressed far enough.

4 DEEP GEOLOGICAL DISPOSAL – PRINCIPLES AND REQUIREMENTS

This chapter discusses the knowledge that is required and certain fundamental principles and requirements for deep geological disposal of spent nuclear fuel in crystalline rock. The results that have been achieved and the state of knowledge on which this programme is based are described more specifically in chapters 5, 6 and 8.

4.1 WHAT KNOWLEDGE IS REQUIRED?

The Swedish nuclear fuel must be finally disposed of in a safe manner. Fulfilling this goal in practice requires knowledge and expertise within a number of fields. It is necessary to know how to

- Handle, condition, transport and dispose of the waste.
- Site and build the necessary facilities.
- Analyze and describe safety aspects and environmental consequences.

For central issues, such as safety assessment, a fundamental understanding of physical and chemical processes is vital. This knowledge must lie at a high international level, even in important details. In large parts, the work today can build on established knowledge and proven experience. In certain respects, new technology and new knowledge must be developed.

4.1.1 Handling, conditioning, transport and disposal of the waste

Handling and transport of nuclear waste and spent nuclear fuel are based on known technology. Practical experience has existed for several decades in both Sweden and other countries. Encapsulation of spent nuclear fuel in the manner planned by SKB has not, however, been carried out in practice. Design, fabrication and sealing of canisters is therefore a key area in the programme. The comprehensive development work in this area is described in greater detail in chapters 6 and 7.

For natural reasons, transport of encapsulated spent nuclear fuel has not been carried out in practice. However, encapsulated fuel is better protected and has a much lower radiation level and lower heat output than the spent fuel that is transported today between the nuclear power plants and CLAB. Nuclear fuel has been transported by road and/or rail for many years in a number of countries. Taken together, this means that the method for transport to the deep repository of the canisters with fuel can be based in all essential respects on established knowledge. What is needed is adaptation of the technical design. See further chapters 8 and 9.

Handling of the canisters at the deep repository includes a number of operations:

- Reception and transport of cask with canisters.
- Transfer of canisters to handling machine in deposition tunnel.
- Emplacement of canisters at deposition positions.

Of these operations, handling of canisters in deposition tunnels and emplacement of them in deposition positions is the new and important one. Qualified design and engineering work needs to be carried out in order to develop appropriate handling equipment. Other handling of waste in the deep repository can be done by adaptation of already established technology. Chapters 8 and 9 provide a more detailed account of the state of knowledge and programme for deep repository technology.

Buffer and backfill materials are also needed in the deep repository. It must be possible to

- Manufacture and apply the bentonite buffer in the deposition holes.
- Backfill the deposition tunnels.
- Seal the entire repository.

Development of the methods to be used for these purposes comprises an important part of the nuclear waste programme. The work has been in progress for a long time. Experiments and tests were conducted within the Stripa Project during the 1980s and further work will be carried out in the Äspö Hard Rock Laboratory. Results, state of knowledge and programme are described in greater detail in chapters 5 and 8–12.

4.1.2 Siting and construction of the necessary facilities

Siting, particularly of a deep repository, is a multifaceted and controversial activity. It involves both technology and safety aspects on the one hand and community planning, politics and public-opinion aspects on the other. The concrete experience and knowledge that exists relates to previous establishments of controversial facilities of a similar nature in Sweden and abroad. SKB and the owners of the nuclear power plants have long experience from different types of siting, including the establishment of CLAB, SFR and the Äspö Hard Rock Laboratory. However, no such previous experience is fully applicable to the deep repository.

Following the publication of RD&D-Programme 92 /4-1/, a concrete siting process was initiated. Background material (general studies) has been compiled and siting investigations (feasibility studies) have been carried out /4-2/ or commenced. The siting process and siting criteria have, in accordance with the requirements imposed by the Government /4-3/, been described more thoroughly in the supplement to RD&D-Programme 92 /4-4/.

The feasibility studies have led to extensive discussions, especially in the concerned municipalities, but also regionally and on the national plane. SKB as well as other concerned parties (authorities, policymakers, the general public) have gained important and valuable experience for the continued work. Difficulties and possibilities in the siting work have been clarified. The work with feasibility studies has taken longer than SKB planned in RD&D-Programme 92, in part because the issue arouses a great deal of discussion right from the start.

The development work has gradually led to the creation of a solid platform for continuing to gather the information that is needed as a basis for siting of the deep repository. The process and the criteria have been clarified by SKB and accepted by the regulatory authorities and the Government. In its decision /4-5/, the Government has also clarified the licensing procedure. Furthermore, the Government has decided to allocate funds to concerned municipalities for participation in the process. The concrete siting work has got under way in the form of feasibility studies at various locations in the country.

The siting of the deep repository is a key issue in the nuclear waste programme. It should be possible to arrive at a good solution through continued thorough, persistent and open-minded siting work. Simultaneously with this RD&D-Programme, SKB is publishing a consolidated account of the general studies /4-6/. State of knowledge and plans concerning siting are described in chapters 8 and 9. To house the encapsulation plant, SKB is planning an addition to CLAB, since this offers several obvious advantages. During the ongoing EIA work, alternative sitings will also be analyzed, such as adjacent to the deep repository, see chapter 7.

Extensive knowledge and experience can be drawn on when it comes to constructing the necessary facilities (encapsulation plant and deep repository). Experience from the construction of nuclear power plants and CLAB can be utilized in designing and building the encapsulation plant and the surface facilities at the deep repository. Furthermore, substantial know-how exists in Sweden from the construction of underground rock facilities for mining, power production, oil storage and defence. SKB has direct experience from the rock facilities at CLAB, SFR and the Äspö HRL. All of this provides a broad and solid knowledge base. Special development initiatives are needed on some important points, mainly methods and technology for geoscientific site investigations and detailed characterization of a selected site. This has been included as a large and important part of SKB's programme for a long time. A "dress rehearsal" of the methodology can be said to have been held through the works for the Äspö HRL. These entail testing and evaluation on a real site and under realistic conditions before the methods are applied in the deep repository project. An account of the state of knowledge regarding rock investigations and construction of the facilities is given in chapters 6 and 8. The programme for the Äspö HRL is described in chapter 12.

4.1.3 Safety assessments and environmental impact assessments

In order to be allowed to execute the planned final disposal scheme, SKB must thoroughly analyze and account for safety aspects and environmental consequences. Traditionally, and ever since the introduction of nuclear power, the nuclear power industry has evaluated the safety and environmental impact of its plants. Previously, in conjunction with the construction of CLAB and SFR, SKB has prepared preliminary and final safety reports. Non-radiological environmental aspects have also been dealt with in the supporting material for decisions on siting and construction of these facilities. A large and valuable body of experience therefore exists which can be drawn on in the work with safety assessments and environmental impact assessments. In the preparation of the environmental impact assessments, extensive consultation is supposed to take place between applicants, local stakeholders and central authorities. See also section 3.4.

To develop methods and gather scientific data as a basis for an assessment of the long-term safety of a deep repository, SKB has long been conducting a comprehensive R&D programme. Important areas in this programme are:

- characterization of spent fuel and studies of the durability of the fuel in groundwater,
- durability of canisters in a deep repository,
- performance of bentonite buffer,
- chemical composition of the groundwater and groundwater movements in the rock,
- chemical conditions and reactions in a deep repository,
- stability of the rock,
- radionuclide transport in the deep repository, bedrock and biosphere,
- dose calculation.

The principles for radiation protection and safety are described in section 4.2 below. The repository's safety functions and functional requirements are described summarily in 4.3.

The state of knowledge within the parts of the programme that pertain to the background data for assessment of long-term safety is described in chapter 5. A special report (SR 95 /4-11/) describes a template for how future safety reports will be structured and the methods and calculation tools that SKB has at its disposal today for carrying out assessments of long-term safety.

A programme for continued R&D within this area is presented in chapters 10, 11 and 12.

4.2 PRINCIPLES FOR RADIATION PROTECTION AND SAFETY

4.2.1 General

Radioactive waste must be handled in keeping with established principles for protection against ionizing radiation /4-7, 8/.

- The activity must be justified, protection must be optimized and the individual must be protected by dose limits.
- The radiation protection considers human health and nature with regard to conditions for biological diversity and utilization of natural resources.
- The radiation protection must be independent of whether the doses arise today or in the future, or if they are emitted inside or outside national boundaries.
- The radiation protection in management and long-term disposal of radioactive waste must be equivalent to that in other radiological activities, e.g. other portions of the nuclear fuel cycle.

In view of the long period of time which must be taken into account when planning a deep repository, specific guidelines have been proposed for a final repository /4-9/:

- The repository shall not be dependent for its long-term safety on monitoring and maintenance by future generations. This is not to say, however, that the repository cannot be monitored for a period after disposal of the waste or closure of the repository.
- The repository shall not be designed so that it unnecessarily impairs future attempts to change the repository or to retrieve the waste.
- The long-term safety of the repository shall be based on passive multiple barriers so that the degradation of one barrier does not substantially impair the overall performance of the disposal system.
- During a reasonably predictable period of time, the radiation doses to individuals caused by expected releases shall be lower than 0.1 mSv/y, after which the radionuclide flow from the repository shall be limited to a level corresponding to naturally occurring flows.
- Probabilities and consequence of unexpected extreme events shall be judged in comparison with the risk of injury in the critical group at the above individual dose limit.

The safety of the repository is dependent on the toxicity and accessibility of the waste. The assessment of the repository's safety is influenced by time in that the quantity of toxic radionuclides declines, and in that the uncertainty in the quantification of the repository's safety functions increases with time. The concept "reasonably predictable period of time" refers primarily to the time-dependent uncertainty in the performance of the repository. Potential transport pathways for radionuclides to man can change with time, but such changes will take place at different rates for the different parts in the barrier system. Experience shows that essential changes in the biosphere occur on the time scale 100–1000 years. The geological environment deep down in the Fennoscandian Shield, however, exhibits stable conditions on a time horizon of millions of years.

Consequently, the feasibility of quantifying the safety of the repository (or the risk from the repository) is dependent on the period of time in which one is interested. SSI has discussed the influence of the time horizon on radiation protection /4-10/ and finds that:

- Particularly great attention should be given to describing protection for the period up to closure of the repository and the first thousand years thereafter, with a special focus on nearby residents.
- The individual dose up to the next ice age, i.e. up to about 10,000 years, should be reported as a best estimate with an estimated margin of error. Environmental protection should be described for the same period of time.
- For the period from the next ice age onward, qualitative assessments should be made of what might happen with the repository, including deliberations regarding the risk of increased releases.

SKB intends to utilize these guidelines in forthcoming accounts of radiation protection and safety for different scenarios for a deep repository on different time scales.

4.2.2 Safety functions of the repository

To achieve the desired safety during the construction of a deep repository, during the operating phase and during

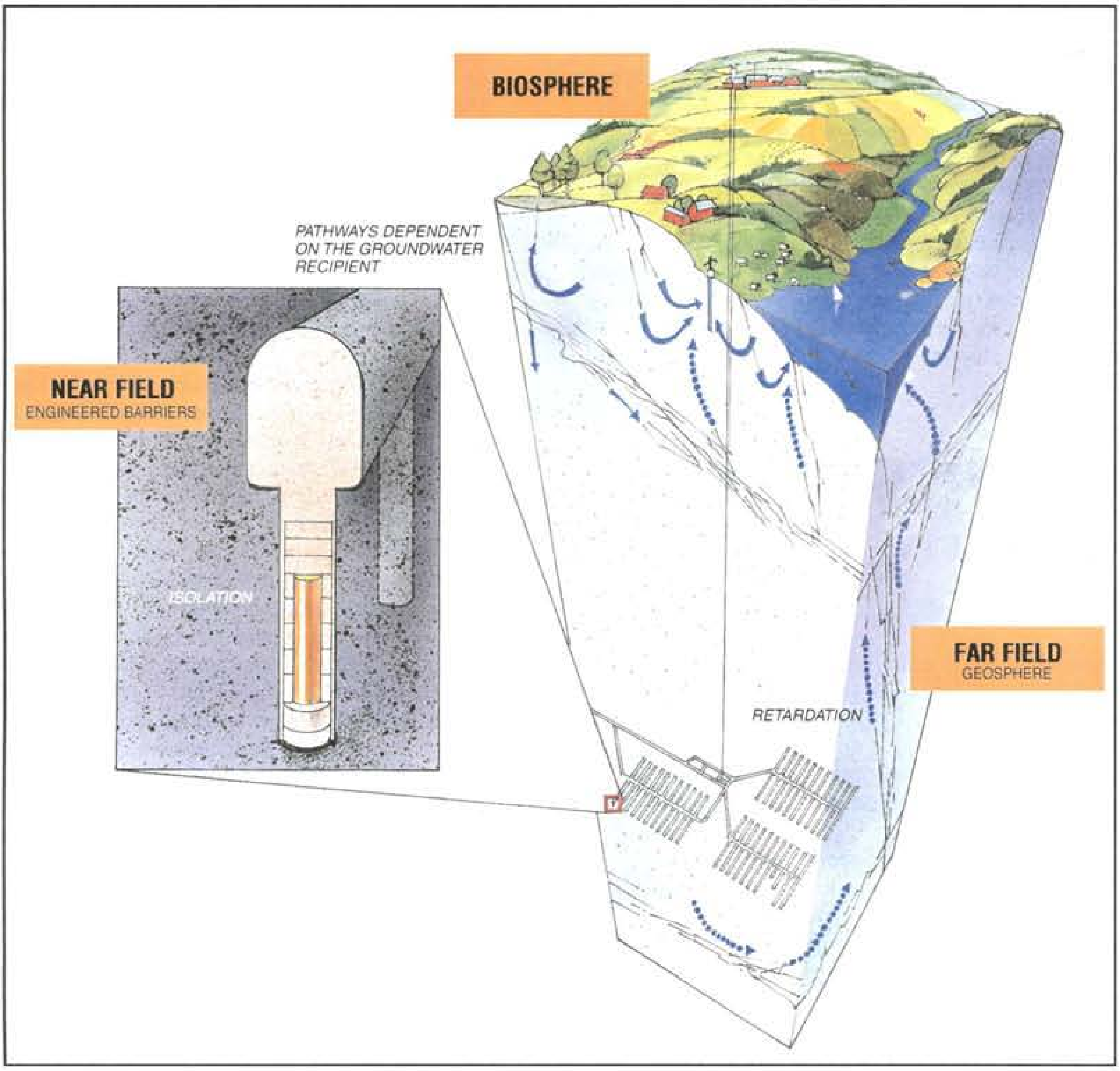


Figure 4-1. *Parts of the deep disposal system and their most important safety functions.*

the long-term containment phase, requirements are made on the function of the repository and its components. The integrated function of all the repository's components must together provide adequate safety in the activities.

In order to achieve long-term safety, the disposal system is designed to **isolate** the spent nuclear fuel from the biosphere. This isolation is achieved by encapsulating the spent nuclear fuel in impervious canisters which are deposited deep in the crystalline bedrock on a selected repository site. In addition, the repository has the function of **retaining** the radionuclides and **retarding** their transport if this isolation should be broken. Furthermore, by proper site selection and suitable adaptation of the repository to the actual site, transport pathways and dilution conditions in the biosphere can be influenced so that any radionuclides that escape will only reach man in very small quantities. Figure 4-1 shows the different parts of the disposal system and their primary safety functions.

The materials used in the repository have been selected with a view to the possibility of verifying their long-term stability and safety performance in the repository with experience from nature. For the same reason, the thermal and chemical disturbance which the repository is allowed to cause in its surroundings is limited. The safety philosophy for the deep repository is based on the multi-barrier principle, i.e. safety must not be solely dependent on the satisfactory performance of a single barrier. The safety functions are affected by site selection, layout, and by the design and sizing of the engineered barriers. The functions can be divided up into three levels:

Level 1 – Isolation

As long as the waste is isolated, the radionuclides can decay without coming into contact with man and his environment.

Level 2 – Retardation

If the isolation is broken, the quantity of radionuclides that can reach the biosphere is limited by:

- very slow dissolution of the spent fuel,
- sorption and very slow transport of radionuclides in the near field,
- sorption and slow transport of radionuclides in the bedrock.

Level 3 – Recipient conditions

The transport pathways along which any released radionuclides can reach man are controlled to a great extent by the conditions where the deep groundwater first reaches the biosphere (dilution, water use, land use and other exploitation of natural resources). A favourable recipient means that the radiation dose to man and the environment is limited. The recipient and the transport pathways are, however, influenced by natural changes in the biosphere.

The safety functions at levels 1 and 2 are the most important and next-most important. They are achieved by means of requirements on the properties and performance of both engineered and natural barriers and on the design of the deep repository. Within the frames otherwise defined, good safety function at level 3 is also striven for by a suitable placement and configuration of the deep repository.

4.2.3 Safety functions of the barriers

The guidelines for final disposal of spent nuclear fuel discussed in Sweden /4-9, 10/ define safety goals for the deep repository as a whole. This provides an opportunity to design the function of different barriers, within the framework of the multibarrier principle, so that the necessary safety can be achieved in a reliable and effective manner. The functional requirements are also affected by the goal that radioactive waste management should be conducted in a balanced manner with respect to operational and long-term safety.

The conditions in different barriers that contribute towards defining the safety functions are described below.

Isolation

At the depths being considered for a deep repository according to KBS-3, mass transport normally takes place only with groundwater. Special transport pathways, caused by e.g. human intrusion, must be examined separately. Isolation is achieved by encapsulating the spent fuel in leaktight canisters. To give the canisters a stable and favourable environment, they are emplaced in deposition positions in a tunnel system at a depth of about 400–700 m in the rock and surrounded with a plastic clay material with low permeability to groundwater.

The ability of the canister to isolate the spent fuel is influenced in practice by

- the design and quality of the engineered barriers,
- site-specific conditions,
- repository depth and the design of the repository and its near-field.

To ensure adequate isolation of sufficient duration, acceptance levels or requirements must be stipulated for, above all

- the canister materials and dimensions as well as inspection methods to verify canister quality,
- the chemical and physical properties of the buffer material,
- the methods for conditioning and application of the buffer and inspection methods to verify its application,
- the geometry of the deposition holes and the hole-making methods,
- the mechanical, chemical and hydraulic conditions in the immediate surroundings of the deposition hole,
- the geohydrochemical conditions in the repository area,
- the stability of the host rock,
- the radiation and temperature levels in the repository.

The isolation can be broken by an undetected defect from fabrication, by internal or external mechanical stresses, or by internal or external corrosion. The goal is that the isolation should be able to resist the cumulative effects of corrosion, buffer swelling and hydrostatic head during the approximately 100,000 years required until the potential hazardousness of the spent fuel has reached the level of natural uranium. The repository should also be able to retain its isolation in the face of rock movements in the repository caused by anticipated stress redistributions. The number of possible canister failures resulting from changes and loads expected to occur in connection with a future ice age should be limited.

Retardation

If the isolation should be broken due to the fact that a canister is damaged, fuel will come into contact with water, whereby radionuclides can be dissolved. Radionuclides that have been released from the fuel matrix can be transported through the defective canister via the buffer material to the mobile groundwater in the rock, and from there further through the bedrock to recipients in the biosphere. The mass flow is determined by the transport and retardation processes that act in the near field and surrounding bedrock.

The dissolution process is affected by

- the spent fuel and its properties, i.e.
    - the inventory and properties of the radionuclides
    - the properties of the fuel matrix,
    - the temperature and radiation field in and around the canister,
- the engineered barriers, i.e.
    - the nature of the canister damage,
    - the canister material and the buffer material, and
    - any building material in the near field
- site-specific conditions
    - groundwater chemistry such as redox conditions and salinity.

Transport mechanisms and retardation mechanisms in the near field and adjacent host rock can be affected by

- the design of and properties of the engineered barriers,
- the design of deposition holes and tunnels,
- the impact on nearby rock of the methods of rock extraction,
- the topography of the repository site, its geological structures and their hydraulic connection to the engineered barriers in the near field,
- the sorption of the nuclides on available solid surfaces.

Within the framework of the design that is required to create and maintain good isolation between the fuel and the groundwater, the conditions in the repository's natural and engineered barriers should be chosen so that the solubility of the radionuclides is limited and their transport retarded.

The solubility limitation assumes a definition of acceptable ranges as regards the chemical composition of the groundwater and a limitation of the influence of materials and impurities in the near field. The large-scale transport of radionuclides through the rock is controlled by the groundwater movements in the repository area, available surfaces for sorption and matrix diffusion along the transport pathways, and the geohydrochemical conditions in the area.

The requirements on the engineered barriers are formulated as limitations of chemical parameters (e.g. redox potential, stability of the bentonite) and transport parameters (e.g. hydraulic conductivity of the buffer, temperatures). The requirements on the repository's host bedrock are formulated as safety-related siting factors and met by adaptation of the repository to local geological structures.

Recipient conditions

If the isolation should be broken, radionuclides that do not decay and are not fixed in the rock will reach the biosphere. A favourable recipient will limit the potential radiation dose to man from the radionuclides that reach the biosphere.

The transport pathways along which radionuclides can reach man are mainly dependent on dilution, water use and land use at the points where the deep groundwater from the repository first reaches the biosphere. Thus, potential radiation doses can be further limited by means of a suitable choice and utilization of the repository site.

However, many changes of importance for the transport pathways in the biosphere are highly complex and take place over a much shorter time span than corresponding changes in the geosphere. A safety function that is based on favourable conditions in the recipient is therefore not as dependable and long-lasting as safety functions based on the bedrock and/or the engineered barriers.

4.3 BARRIER FUNCTIONS – REQUIREMENTS

4.3.1 General

A deep repository for radioactive waste should be designed with a view towards safety, constructability and effectiveness with respect to costs and resources. The safety of the repository can be influenced by choice of deposition method, site choice and adaptation of the repository's design and layout to the properties of the site, by choice of technology and inspection methods for construction of the repository, and by choice of materials, design and sizing of the engineered barriers around the radioactive waste. Other factors that also influence safety are the properties of the radioactive waste and radionuclides contained in it. The availability of suitable rock in Sweden and the properties of the water constitute premises for how the repository is to be designed.

The safety functions of the repository and how they are affected by various processes and conditions in the barriers are discussed in section 4.2. This section summarizes the requirements that are made, or may come to be made, on site/layout and on the engineered barriers, as well as on the methods for their fabrication/application and their inspection. One point of departure for the formulation and quantification of requirements is previous performance and safety assessments. The state of knowledge for understanding and quantifying the processes on which the requirements are based is presented in chapter 5, sections 5.3–5.8. The state of knowledge concerning processes essential to the function and fabrication of the canister has been compiled in chapter 6.

The requirements on the barriers must be quantified once design and fabrication methods have been established. This work is under way for the canister, and the status of the work is described in chapter 6. The times at which material specifications, designs or dimensions are established must be coordinated with the planning of fabrication and handling of the engineered barriers. The quantitative requirements presented in RD&D-Programme 95, especially in chapters 6 and 8, are to be regarded as tentative and may be modified during the course of the continued design process.

The coupling between the characterization of the site and progressive decisions regarding how the site is to be utilized and how the layout of the repository is to be made with regard to safety and constructability will be discussed in a planned special report on the programme for site investigations.

Logically, it should be possible to derive the functional requirements on different barriers directly from the quantitative safety goals for the repository (expressed e.g. in dose limits). However, in the case of repositories with multiple barriers, such a derivation does not give unequivocal requirements on the individual barriers. The requirements on the individual barriers will therefore be formulated primarily on the basis of:

- parameter limitations to make it possible to rule out or neglect certain processes,
- available technology,
- cost and reliability optimization.

Considerations of how convincingly the function of different barriers can be proven and how sensitive different barriers are to variations in the surrounding environment will influence the strived for balance between the protective effects of the barriers.

4.3.2 Repository site and rock as barrier

The site should be selected so that it has good conditions with respect to:

Level 1 – isolation

- mechanical stability of the rock,
- chemical environment in groundwater/rock with respect to the canister and the buffer,
- presence and transport of substances corrosive to the canister,
- prevention of future intrusions and alternative uses,
- groundwater.

Level 2 – retardation

- limitation of radionuclide solubility and transport to the biosphere
- chemical environment in groundwater/rock with respect to fuel dissolution and buffer,
- groundwater.

Level 3 – recipient conditions

- groundwater dilution and food chains.

4.3.3 Canister

The canister must be designed and fabricated so that it

Level 1 – isolation

- is leaktight at deposition,
- can resist the chemical action of
  - oxygen and other oxidants that are introduced during the repository's construction and operating period,
  - substances that can normally occur in reducing groundwaters,

- limits the effects resulting from
  - external and internal corrosion caused by radiolysis products,
  - internal corrosion caused by residual oxygen and water,

- can resist mechanical stresses caused by
  - hydrostatic head at repository depth,
  - the swelling pressure from the buffer material,
  - extra loads during an ice age,
  - rock movements caused by stress redistributions as a consequence of the repository's construction.

Level 2 – retardation

- does not unnecessarily and in a detrimental manner affect
  - the normal properties of the surrounding rock,

  - the stability of surrounding buffer material,
  - the rate of dissolution of fuel if the isolation is broken,
  - transport of radionuclides through buffer and rock,
- as far as possible limits and retards the outward transport of radionuclides from fuel to buffer even if the isolation is broken.

4.3.4 Buffer

The buffer should give the canister a favourable environment for maintaining the isolation, comprise a protective layer between the canister and the rock with respect to mechanical and chemical forces, and, if the isolation of the canister is broken, limit and retard the escape of radionuclides from the repository.

For these purposes the buffer should:

Level 1 – isolation

- completely envelop the canister for a long period of time – "remain in the deposition cavity",
- bear the canister centred in the deposition hole,
- prevent groundwater flow and thereby retard the inward transport of corrodants,
- dissipate heat from the canister,
- resist chemical transformation for a long time,
- not jeopardize the abilities of the canister and the rock to fulfil their functional requirements,
- protect the canister by comprising a plastic protection against rock movements.

Level 2 – retardation

- prevent flow of groundwater and thereby retard transport of radionuclides,
- resist chemical alteration for a long time,
- completely envelop the canister for a long time – "remain in the deposition cavity",
- permit generated gas to escape,
- filter colloids.

4.3.5 Design of the repository and the near field

The favourable properties of the site for preventing and retarding the release of radionuclides to the biosphere should be utilized optimally by adaptation of the layout and depth of the repository to local conditions. Tunnels and deposition holes should be situated in the repository rock so that rock formations unfavourable for safety or construction are avoided.

The repository should be designed and construction carried out so that corrosion of the canister is limited with respect to microbial activity and oxygen and other oxidants introduced during the repository's construction and operating period.

The repository's geometric layout should be chosen in consideration of local rock stresses, temperature limitations and water flow paths. Construction and other works should be carried out so that the barrier properties of the host rock are not unnecessarily degraded.

Backfilling of tunnels and rock chambers should be done to give the rock back some mechanical support and to limit the volume increase of swelling bentonite in deposition positions in deposition tunnels. Plugging of tunnels and shafts should be done to limit the transport capacity of groundwater along the pathways opened up during excavation. Before the surveillance and control of the repository is discontinued, the repository must be sealed to prevent access. Materials used during the construction and deposition phases must be checked with regard to the consequences of their remaining in the repository after closure.

The design of the repository must also permit subsequent retrieval of the waste if this is deemed desirable in the future. At the same time, international requirements on physical protection of the fissile material – safeguards – must be met.

5 STATE OF KNOWLEDGE - LONG-TERM SAFETY

Based on the principles and basic requirements on the barrier system presented in chapter 4, this chapter describes the state of knowledge within the various areas that are of importance for the long-term safety of the deep repository. This overview of the state of knowledge has in some portions been made relatively comprehensive in recognition of the viewpoint expressed in the review of RD&D-Programme 92, that it was difficult to judge SKB's programme without having an idea of how SKB views the state of knowledge. This does not mean that the account is exhaustive in all respects. A more detailed and exhaustive account is given in various areas in SKB's technical reports, in the supporting documentation for safety assessments, in SKB's Annual Reports and in a large number of reports from e.g. Stripa, Äspö and the natural analogue projects.

The chapter begins with a survey of methods for safety assessment and for selection of scenarios that can affect the deep repository. This is followed by an account of the state of knowledge for the spent nuclear fuel, for the buffer and backfill materials and for the bedrock. The properties of the Swedish bedrock with respect to deep geological disposal are described in considerable detail. The intention is to provide a full description of the state of knowledge as a background to ongoing feasibility studies and forthcoming site investigations, as well as to experimental activities at the Äspö Hard Rock Laboratory. Specific chemistry questions, which pertain to several barriers, have been collected in their own section, as have the studies of natural analogues. Also, the state of knowledge for description of the biosphere is presented in a separate section. The concluding section deals with questions concerning, among other things, long-lived waste that is to be disposed of by deep geological disposal in a manner similar to the spent fuel. Canister-related questions are dealt with in chapter 6.

In each section, an attempt is made to define the relevant issues that require further R&D and that will be addressed in future RD&D work.

5.1 METHODS FOR SAFETY ASSESSMENT

5.1.1 General

On the basis of the experience that has been gained through research, experiments, studies of natural analogues etc., and on the basis of previously performed performance and safety assessments, preliminarily optimized disposal systems can be designed for final disposal of radioactive waste. To demonstrate the safety of a disposal system, the processes that are essential to the safety of the repository must be identified, and their change with time analyzed. This must be done in consideration of site-specific conditions, the chosen repository design and layout, and for the design, materials and dimensions chosen for the engineered barriers.

Regardless of whether the assessment covers the entire repository or just parts of it, or whether it is intended to shed light on a specific function or the total safety of the repository, it must be carried out systematically. A complete assessment includes:

- Definition of the purpose of the assessment.
- Definition of given assumptions for the assessment, i.e. types and quantities of radioactive waste, the disposal system and its dimensions, and the location and external environment of the repository.
- Definition of the scope and delimitations of the assessment, and of the safety goals.
- Clarification of both the probable and the less probable or improbable conditions for which the system/facility is to be assessed (scenarios).
- Clarification of the time-dependent processes which are essential for the intended performance of the system/facility in different scenarios.
- Definition of calculation models for quantifying the performance of the repository and the couplings between the models, where possible.
- Quantification of the performance of the repository and essential changes in performance.
- Qualitative assessment of important but non-quantifiable processes or events that can affect the performance of the repository.
- Discussion of the uncertainties in qualitative and quantitative sub-assessments and evaluation of their validity with respect to the purpose of the overall assessment.

The work procedure for performance and safety assessments is shown in Figure 5.1-1 and has previously been presented in RD&D-Programme 92 – Supplement.

In order to enable the assessments to be carried out in a systematic and traceable fashion, the methods for the different steps have been discussed within Sweden, in SKB's cooperation with the major nuclear power countries, and in the international cooperation. By "methods" is meant here both the general systematics that are applied in the work, and the tools – numerical models – that are used to quantify the safety-related processes in the repository. Most of the methods that are employed today have been developed over many years, mainly during the 1980s, and are continuing to be developed.

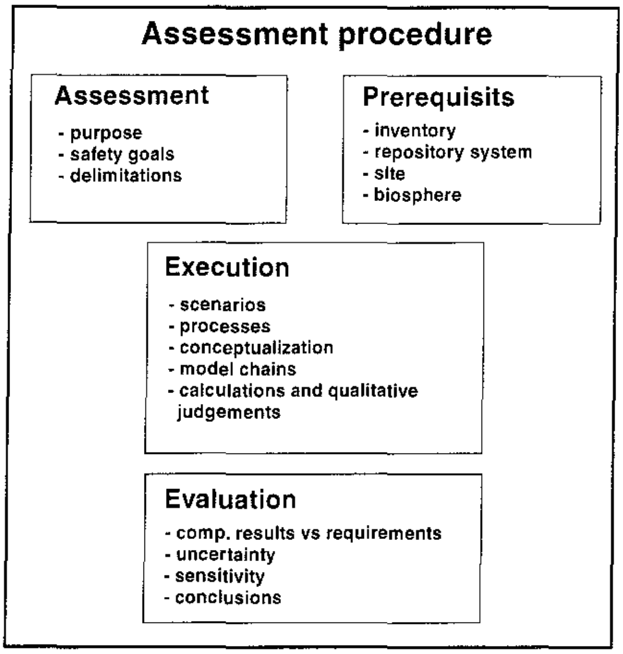


Figure 5.1-1. Block diagram for how major performance assessments and safety assessments are carried out.

A large survey of systematics and tools for safety assessments was carried out in October 1989 at a symposium arranged by the IAEA, the OECD/NEA and the CEC in Paris /5.1-1/. The findings of this symposium were evaluated and discussed in the arranging organizations' expert groups, and the results summarized in an International Collective Opinion /5.1-2/. There it was observed

- that safety assessment methods are available today to evaluate adequately the potential long-term radiological impacts of a carefully design radioactive waste disposal system on humans and the environment, and
- that appropriate use of safety assessment methods, coupled with sufficient information from the proposed disposal sites, can provide the technical basis to decide whether specific disposal systems would offer to society a satisfactory level of safety for both current and future generations.

It was also noted that the collection and evaluation of data from proposed disposal sites are major tasks on which further progress is needed, and that the methods for safety assessments can and will be further developed as a consequence of ongoing research work. SKB shares these viewpoints.

In response to the comments and opinions offered on RD&D-Programme 92 and the supplement that was published in 1994, SKB has, for RD&D-Programme 95, made a compilation of the methods which are available to SKB today for carrying out safety assessments. This compilation is available in a separate report, SR 95 /5.1-3/.

Since SKB plans to give accounts of safety on a large number of occasions, see chapter 10, it has been deemed desirable to establish a standardized format for how long-term safety is to be presented. Such a format would both facilitate a progressive updating of safety accounting in various phases and facilitate comparisons between assessments for different sites or under different work phases. For these reasons, SR 95 has been written in such a way that it can serve as a future template for how long-term safety is to be accounted for and comprise an account of currently available methods and numerical tools, including their applicability and quality.

SR 95 begins with a survey of the purposes of a safety report during different phases in the development of a deep repository and the methods available for carrying out the assessments, after which the currently prioritized repository design is presented. The application of SKB's scenario methodology to this design is then presented, along with the safety-related scenarios (calculation cases) with processes of chemical or physical interaction. A detailed examination is made of the tools, i.e. numerical models and conceptual assumptions, available to SKB today and their applicability and quality. The methodology for model couplings and the performance of the calculations are illustrated with material based on the prioritized design and on a site-specific geoscientific body of data from the Äspö HRL and surrounding biosphere.

It should be observed that neither the scenario survey nor the model calculations in SR 95 are complete. They constitute an illustrative method description. In particular the reported set of scenarios (calculation cases) comprise parts of the safety report that are in the process of being developed in preparation for the permit application for the encapsulation plant. As the process of designing the facilities for encapsulation and deep disposal progresses, premises, data and calculations will be revised.

Certain fundamental methodology questions have, however, been taken up for discussion in this RD&D-Programme, see further the sections

5.1.2	Conceptual and numerical models
5.1.3	Numerical coupling between models
5.1.4	Uncertainties and validity
5.2	Scenarios

All numerical models presented in SR 95 have been developed and continue to be developed on the basis of the evolving understanding of the processes included in the models. The state of knowledge within these areas and methods for collection and processing of data are described in the barrier- or subject-specific sections 5.3–5.9 and in chapter 6.

5.1.2 Conceptual and numerical models

Different calculation models comprise important tools in the work with performance and safety assessments. As the computation capacity increases, increasingly powerful tools are being developed for both deterministic and statistical analysis of conditions and processes of importance for safety and performance.

As is evident from the assessment procedure, the processes which can transport radionuclides from the repository to the biosphere are identified at an early stage. On the basis of previously conducted performance and safety assessments, a good understanding has been built up of the processes that are important. Extensive work has been done to clarify these processes and their parameters, and how they are to be conceptualized and quantified in numerical models.

Different views on conceptual models and their role in the safety assessments were presented and discussed in November 1993 in a workshop arranged by the OECD/ Nuclear Energy Agency (NEA) /5.1-4/. A hierarchical structure showing how models can be regarded in relation to natural laws and theories is shown in Figure 5.1-2.

SKB uses the following terminology when describing models:

conceptual model	describes the assumptions and relationships that are utilized to simulate the events or conditions to be modelled:
– **structural model**	describes the geometric or dimensional conditions that are required for modelling
– **process model**	describes how time-dependent processes are simulated and their boundary conditions,
mathematical model	describes a mathematically formulated approximation of the conceptual (structure/process) model,
numerical model	defines a numerical approximation for quantitative calculations with the mathematical model,
data	defines the parameters/ quantities included in the mathematical or numerical model,
computer code/model	defines the algorithm (for the numerical model) that is implemented on a computer and that is used to generate calculation results.

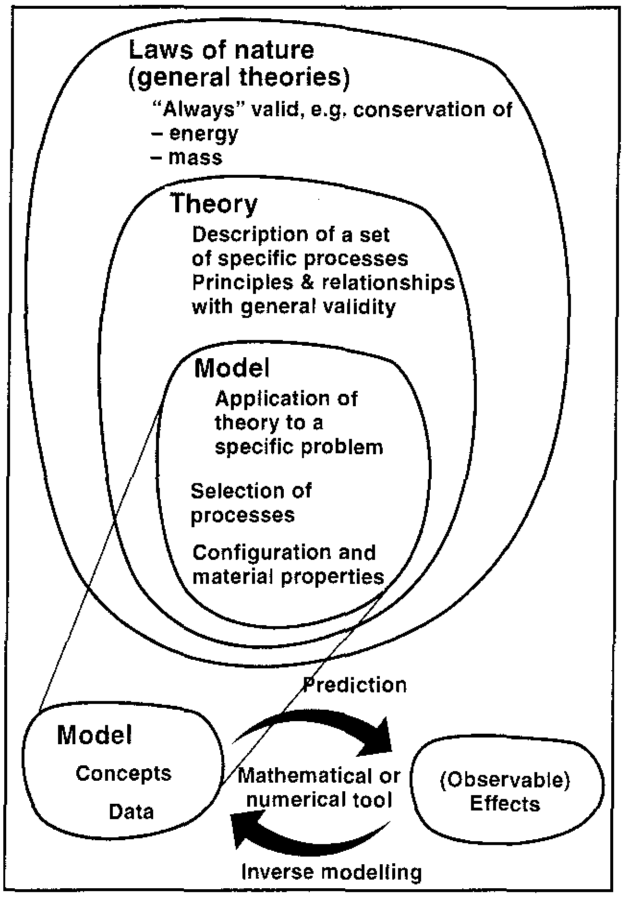


Figure 5.1-2. Schematic structure of natural laws, theories and models /5.1-4/.

A calculation model – mathematical, analytical or numerical – is used to

- improve the understanding of a scientific problem,
- analyze which parameters are essential for solving a calculation problem with given assumptions, and for making forecasts in time and space.

SR 95, chapters 10 and 11 /5.1-3/, contains a survey of the state of knowledge for the calculation steps included in an assessment, or the system parts with more or less coupled processes that must usually be evaluated in order to be able to assess the long-term safety of the repository. They have been divided up as follows:

Thermal development
Rock performance
Canister performance
Bentonite performance
Chemical speciation
Groundwater movements
Nuclide transport near field
Nuclide transport far field
Biosphere dispersion
Dose calculation

The safety-related processes and the methods for their quantification are examined there. Any simplifications and pessimistic (conservative) assumptions are discussed. To the extent alternative methods are available for describing a process, the essential differences in conceptualization or modelling are discussed.

Knowledge and experience concerning how well a given numerical model is able to describe the reality we register in the field are discussed in specific sections in the description of the models. Separate validity documents have been prepared for the transport codes NAMMU (far field) and NUCTURAN (near field) and for the biosphere code BIOPATH. In these documents, data essential to the concept of validity have been compiled for the code version in question under the following headings:

- Fundamental theory
- Conceptual model
- Numerical methods
- Verification
- Validation
- Program documentation

The purpose of these validity documents is to determine whether it is possible in practice to standardize the reporting of experience from application of the model and of how reliable different models are for their purpose. Such a standardization would make it simpler to compare experience of the area of application and validity of different alternative models. If these validity documents prove to be useful, most of SKB's more important numerical model tools will be documented in this way.

The knowledge basis for the phenomena that are simulated in the process models – e.g. diffusion, sorption, colloid transport, etc. – is discussed in the sections that describe the barriers 5.3–5.5, or in the chemistry section 5.6.

In addition to the processes discussed in SR 95, other processes may also have to be modelled in order to analyze specific scenarios. For example, the impact of an ice age, or the risks to ore prospectors if they should unknowingly drill through the repository. The assessment models have not been standardized for such odd processes that are not generally utilized in design work or safety assessments. Description and scrutiny of methods employed to quantify or limit the effects of such processes must be done separately.

SKB is now entering a phase when safety assessments and safety reports are directly linked to permit applications and decisions. Models and methods may hereby have to be adapted to the site that is being assessed or to the specific decision the assessment is intended to support. Such adaptation will be done individually for each safety assessment, see chapter 10.

The state of development for characterizing a site and representing it with a geological structure model on the basis of site investigations is discussed in chapter 7.

5.1.3 Numerical coupling between models

Most of the calculations in a safety assessment consist of chains or networks of computer models that are linked together. A handling system called PROPER was developed for such calculations during the 1980s. The system also permits probabilistic assessments.

But with the development of menu interfaces and the ability of computers to handle increasingly complex model chains, PROPER's management system, based on text files, appears outmoded today. A graphics-based management system is therefore being developed at the present time, under the working name MONITOR-2000.

MONITOR-2000 will offer the following advantages compared with today's system:

- Quality assurance will be simplified and improved, in part because there is less risk of mistakes, and in part because the quality of the documentation is better.
- As a consequence of the improvement of the documentation, the format of the reports will be able to be made clearer and more standardized.
- A specially trained operator will no longer be needed to carry out calculations with complex model networks. Everyone who works with modelling will be able to handle even the complex calculations.
- Considerable time can be saved in the work of defining and documenting model calculations. Because these operations will no longer be a bottleneck in the procedure, in terms of either time or manpower, more calculation cases will be able to be carried out.

The development work is planned to be finished in November 1995, which means that MONITOR-2000 can be used in future safety assessments.

To enable the numerical models to be used in coupled model chains, new models will gradually be adapted to the requirements in PROPER as regards handling of input data and formats for data transfer between models.

5.1.4 Uncertainty and validity

A comprehensive analysis must be performed of the uncertainties in the assessment in order to obtain an idea of the assessment's ability to describe reality. The uncertainties introduced into the assessment at the different steps in the analysis sequence described above will be of varying character and quantifiable to a varying degree.

A general survey of our understanding and handling of the uncertainties with reference to their role in the safety assessments is performed in SR 95 chapter 3 /5.1-3/ with background reports. Uncertainties in data and models for the safety assessments is discussed in the account given for the different knowledge areas in SR 95 chapters 10 and 11. Fundamental uncertainties in our understanding of safety-related phenomena and processes and of how they are conceptualized in mathematical models is dealt with in the following sections 5.3–5.9.

Uncertainties associated with scenarios are discussed in connection with the application of the scenario methodology to the disposal system which is described in SR 95 chapter 9.

The assessment of whether knowledge and technology for handling uncertainties is adequate, or whether it must be further refined, is closely linked to how simplifications, pessimistic assumptions and safety margins are handled in each specific assessment. In the same way as for other methodology, a need for supplementary measures connected with each evaluation and account of safety is expected to exist with regard to uncertainties.

5.2 SCENARIOS

5.2.1 General

The purpose of the scenario methodology is to identify and describe scenarios to be evaluated in the safety assessment. To do this, a systematic approach is needed for identifying how the repository will develop with time. The development of the repository is dependent in part on the external conditions or events that can affect the disposal system, and in part on the internal processes that may occur due to the waste, materials present in barriers and host rock, and other materials/contaminants that may be brought down into the repository.

The work of studying and evaluating different approaches for identifying relevant scenarios has been going on for many years. A survey of scenario methodology was published in 1992 by the OECD/Nuclear Energy Agency /5.2-1/. Work has been pursued in parallel in Sweden and other countries to identify the features in and around the repository, and the possible events and processes (Features, Events and Processes) that can make it necessary for specific scenarios to be defined. This material is currently being compiled within the NEA.

The specific question of how human intrusion can affect the safety of the repository has also been dealt within by the NEA /5.2-2/. The value of, and methods for, preserving information on the repository for long periods of time has been studied in Nordic cooperation /5.2-3/. SKB and Swedish government authorities are participating in this joint international work.

The initial step in a safety assessment, after having defined the system to be dealt with, is to identify the scenarios that are of such importance for the performance of the repository that light must be shed on them in the safety report. The scenarios should cover a broad spectrum of possible pathways of development, and together they should provide perspective on the safety margins provided by the system. The different steps in the process of devising these scenarios must be documented to facilitate scrutiny and future surveys and updates. High demands will be made on the completeness of the material and thereby on ensuring that all relevant questions have been examined.

5.2.2 Principal steps in the methodology of devising scenarios

The work of structuring the process of devising scenarios started as a joint research project between SKI and SKB in 1988 and has been described in /5.2-4/. The Features, Events and Processes (FEPs) that are conceivable in a waste repository were sorted there into two groups, either the Process System, consisting of "internal FEPs" which define the performance of the repository (including variations occasioned by parameter deviations) or a group of "External FEPs", each of which can influence the Process System and thereby give rise to different scenarios.

The Process System is defined as a systematic compilation of the phenomena (FEPs) that are needed to describe barrier performance and the mechanisms for radionuclide transport. In order to forecast the development of the repository via the Process System, it must be possible to quantify FEPs thoroughly by means of measurement data, modelling or estimates.

The methodology for devising scenarios has the following principal steps:

- Identification of the Process System plus visualization and documentation.
- Identification of initiating external events or extreme cases.
- Choice of scenarios and calculation cases to treat in the safety assessments.

Identification of the Process System and visualization

The first step is to identify the Process System in text and by visual methods so that all known couplings between component processes are shown. Identification of the FEPs included in the Process System can be done in several ways, and tests have been conducted with different methods during 1991–1994. The following two methods in particular have been used:

- Influence diagrams /5.2-5/
- The Rock Engineering System (RES) method /5.2-6/

Influence diagrams

In an influence diagram, all FEPs are represented by boxes. Couplings/interactions between different FEPs

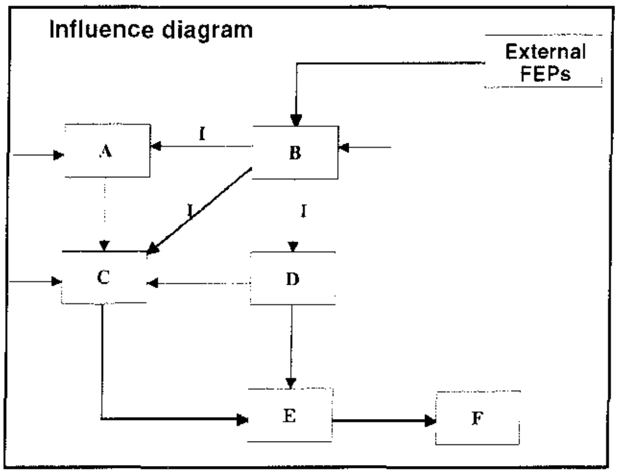


Figure 5.2-1. Schematic illustration of an influence diagram where an initiating event (External FEP) influences the processes.

are illustrated by arrows between these boxes, see Figure 5.2-1. Each box and arrow in the diagram has an identification code and is documented in databases which are directly accessible from the software in which the influence diagram is produced.

The influence diagrams permit a detailed analysis of how different FEPs are linked to or influence other FEPs in the Process System. The methodology has been tested in a study on deep disposal of "Other long-lived waste than spent nuclear fuel" /5.2-5/. The conclusions of this study were that it is fully possible to carry out the systematic analysis of the Process System's different FEPs and to represent this in an influence diagram or in several sub-diagrams for different sub-systems. The databases that are simultaneously produced contain specifications of all influences and notations of the assessments made for each influence. Visually, however, the influence diagrams are complex and do not provide the quick overview of the Process System that would be desirable.

The RES method

The RES method entails identifying the repository's most important sub-systems with their features and representing them on the diagonal in a matrix. The other boxes in the matrix will now represent interactions between these sub-systems, i.e. of the processes that are involved, and the matrix comprises the Process System.

So as not to make the matrices too big (since processing of the matrix would then be too complex), the Process System is divided into smaller parts, see Figure 5.2-2. An example of the contents of a sub-matrix for the far field part of a deep repository is shown in Figure 5.2-3.

Work is currently under way on coupling the various interaction boxes in the sub-matrices to databases in a manner similar to what has previously been done for the influence diagrams in the aforementioned study concerning "Other long-lived waste".

More detailed descriptions of influence diagrams and the RES method, plus comparisons between them, are given in /5.2-7/.

The current scenario work is concentrated on the RES method.

Identification of initiating external events or extreme cases

Through the Process System's RES matrix, it is possible to

- make a survey of the potential pathways that exist for various internal disturbances to propagate through the system via the interaction boxes,
- examine how different External FEPs can influence the Process System and how a possible disturbance can be propagated through the system (the RES matrix may have to be modified for larger disturbances),
- provide a graphic description of how this chain of coupled processes (interaction pathways) affects long-term safety.

This information, together with the external initiating events (External FEPs) that lie outside the Process System, provides a number of scenarios that can be interesting to examine in quantified safety assessments.

However, it is necessary to be aware of the fact that both the creation of FEP lists for influence diagrams and the choice of diagonal elements in RES matrices are dependent on our understanding of the disposal system, and that both the identification of normal repository

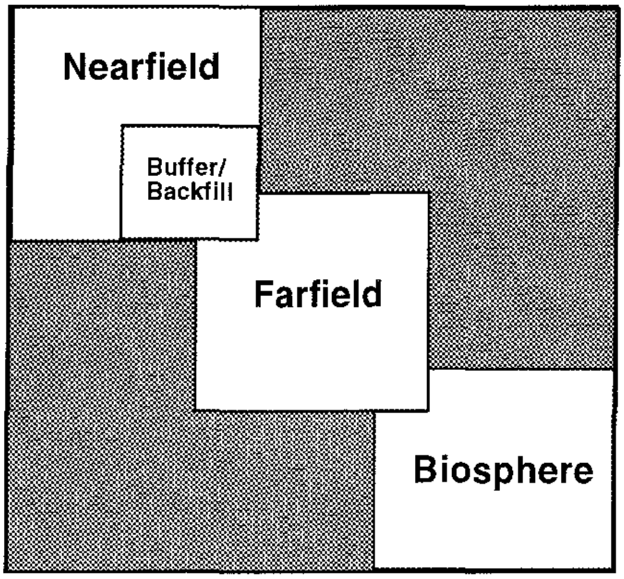


Figure 5.2-2. Example of division of the total system into sub-matrices.

August 16, 1995

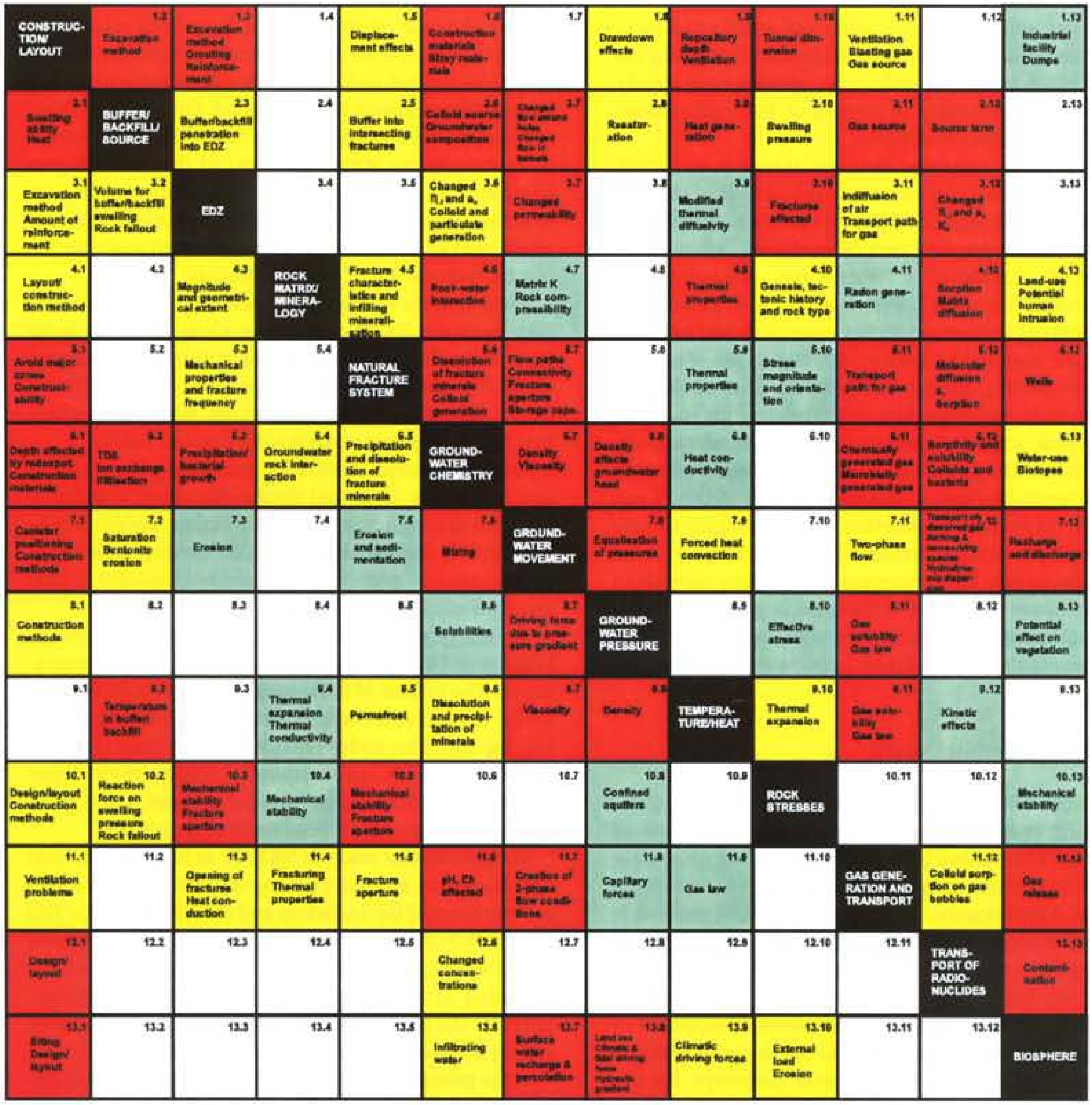
FAR FIELD

process system - far field 1

🟥 Interaction which should be part of the performance assessment

🟨 Interaction present - influences on other parts of the process system in a limited or uncertain way and/or under special circumstances

🟩 Interaction present - influences on other parts of the process system can be neglected



CONSTRUCTION/ LAYOUT	1.2 🟥 Excavation method	1.3 🟥 Excavation method Grouting Reinforcement	1.4	1.5 🟨 Displacement effects	1.6 🟥 Construction materials Stray materials	1.7	1.8 🟨 Drawdown effects	1.9 🟥 Repository depth Ventilation	1.10 🟥 Tunnel dimension	1.11 🟨 Ventilation Blasting gas Gas source	1.12	1.13 🟩 Industrial facility Dumps
2.1 🟥 Swelling ability Heat	**BUFFER/ BACKFILL/ SOURCE**	2.3 🟨 Buffer/backfill penetration into EDZ	2.4	2.5 🟨 Buffer into intersecting fractures	2.6 🟥 Colloid source Groundwater composition	2.7 🟥 Changed flow around holes Changed flow in tunnels	2.8 🟨 Resaturation	2.9 🟥 Heat generation	2.10 🟨 Swelling pressure	2.11 🟥 Gas source	2.12 🟥 Source term	2.13
3.1 🟨 Excavation method Amount of reinforcement	3.2 🟨 Volume for buffer/backfill swelling Rock fallout	**EDZ**	3.4	3.5	3.6 🟨 Changed f_r and a_r Colloid and particulate generation	3.7 🟥 Changed permeability	3.8	3.9 🟩 Modified thermal diffusivity	3.10 🟥 Fractures affected	3.11 🟨 Indiffusion of air Transport path for gas	3.12 🟥 Changed f_r and a_r K_d	3.13
4.1 🟨 Layout/ construction method	4.2	4.3 🟨 Magnitude and geometrical extent	**ROCK MATRIX/ MINERALOGY**	4.5 🟨 Fracture characteristics and infilling mineralisation	4.6 🟥 Rock-water interaction	4.7 🟩 Matrix K Rock compressibility	4.8	4.9 🟥 Thermal properties	4.10 🟨 Genesis, tectonic history and rock type	4.11 🟩 Radon generation	4.12 🟥 Sorption Matrix diffusion	4.13 🟨 Land-use Potential human intrusion
5.1 🟥 Avoid major zones Constructability	5.2	5.3 🟨 Mechanical properties and fracture frequency	5.4	**NATURAL FRACTURE SYSTEM**	5.6 🟥 Dissolution of fracture minerals Colloid generation	5.7 🟥 Flow paths Connectivity Fracture aperture Storage capa.	5.8	5.9 🟩 Thermal properties	5.10 🟩 Stress magnitude and orientation	5.11 🟥 Transport path for gas	5.12 🟥 Molecular diffusion & Sorption	5.13 🟥 Wells
6.1 🟥 Depth affected by redoxpot. Construction materials	6.2 🟥 TDS Ion exchange Infiltration	6.3 🟥 Precipitation/ bacterial growth	6.4 🟨 Groundwater rock interaction	6.5 🟨 Precipitation and dissolution of fracture minerals	**GROUND-WATER CHEMISTRY**	6.7 🟥 Density Viscosity	6.8 🟥 Density affects groundwater head	6.9 🟩 Heat conductivity	6.10	6.11 🟥 Chemically generated gas Microbially generated gas	6.12 🟥 Sorptivity and solubility Colloids and bacteria	6.13 🟨 Water-use Biotopes
7.1 🟥 Canister positioning Construction methods	7.2 🟨 Saturation Bentonite erosion	7.3 🟩 Erosion	7.4	7.5 🟩 Erosion and sedimentation	7.6 🟥 Mixing	**GROUND-WATER MOVEMENT**	7.8 🟥 Equalisation of pressures	7.9 🟨 Forced heat convection	7.10	7.11 🟨 Two-phase flow	7.12 🟥 Transport of dissolved gas Sorbing & sorptivity [illegible] Hydrodynamic dispersion	7.13 🟥 Recharge and discharge
8.1 🟨 Construction methods	8.2	8.3	8.4	8.5	8.6 🟩 Solubilities	8.7 🟥 Driving force due to pressure gradient	**GROUND-WATER PRESSURE**	8.9	8.10 🟩 Effective stress	8.11 🟥 Gas solubility Gas law	8.12	8.13 🟩 Potential effect on vegetation
9.1	9.2 🟥 Temperature in buffer backfill	9.3	9.4 🟩 Thermal expansion Thermal conductivity	9.5 🟨 Permafrost	9.6 🟨 Dissolution and precipitation of minerals	9.7 🟥 Viscosity	9.8 🟥 Density	**TEMPERA-TURE/HEAT**	9.10 🟨 Thermal expansion	9.11 🟥 Gas solubility Gas law	9.12 🟩 Kinetic effects	9.13
10.1 🟨 Design/layout Construction methods	10.2 🟨 Reaction force on swelling pressure Rock fallout	10.3 🟥 Mechanical stability Fracture aperture	10.4 🟩 Mechanical stability	10.5 🟥 Mechanical stability Fracture aperture	10.6	10.7	10.8 🟩 Confined aquifers	10.9	**ROCK STRESSES**	10.11	10.12	10.13 🟩 Mechanical stability
11.1 🟨 Ventilation problems	11.2	11.3 🟨 Opening of fractures Heat conduction	11.4 🟨 Fracturing Thermal properties	11.5 🟨 Fracture aperture	11.6 🟥 pH, Eh affected	11.7 🟥 Creation of 2-phase flow conditions	11.8 🟩 Capillary forces	11.9 🟩 Gas law	11.10	**GAS GENERATION AND TRANSPORT**	11.12 🟨 Colloid sorption on gas bubbles	11.13 🟥 Gas release
12.1 🟥 Design/ layout	12.2	12.3	12.4	12.5	12.6 🟨 Changed concentrations	12.7	12.8	12.9	12.10	12.11	**TRANS-PORT OF RADIO-NUCLIDES**	12.13 🟥 Contamination
13.1 🟥 Siting Design/ layout	13.2	13.3	13.4	13.5	13.6 🟨 Infiltrating water	13.7 🟥 Surface water recharge & percolation	13.8 🟥 Land use Climate & tidal driving force Hydraulic gradient	13.9 🟨 Climatic driving forces	13.10 🟨 External load Erosion	13.11	13.12	**BIOSPHERE**

Figure 5.2-3. Sub-matrix of the far field in a deep disposal system.

performance and extreme scenarios will contain a measure of expert judgement.

Choice of scenarios and calculation cases to treat in safety assessments

The choice of scenarios to be ultimately included in the safety assessments is made with reference to the questions which the safety assessment is intended to answer. The knowledge and sensitive disturbance pathways discussed above provide guidance in the choice.

The final list of scenarios and calculation cases selected to provide a complete picture of the "threats" to the repository's safety (external and internal FEPs) will also be dependent on "expert judgement". This is a consequence of the fact that neither the background data for nor the understanding of the process that are dealt with in various scenarios permit each scenario to be evaluated with the same accuracy and equally extensive quantification. However, the background underlying the scenario choice will be able to be reported more clearly and be more traceable as a result of the methodology developed as described above.

Besides the scenarios that are intended to depict, through various systematic approaches, realistic possible developments of the repository's safety, other types of scenarios will also be examined, often called "What-If Scenarios", "Worst-Case Scenarios" or "Bounding Scenarios". For example, it is possible to carry out calculations under the assumption that a release from the near field winds up directly in the biosphere without passing through the bedrock, or to exclude in calculations e.g. dispersion or diffusion in the rock matrix. These scenario types are aimed, as the names indicate, at shedding light on the safety-related importance of different barriers or retardation mechanisms. Even though the scenario descriptions are often highly simplified and physically unreasonable, they can provide an upper boundary for the consequences. These unrealistic scenarios are often used to illustrate in a simple manner how robust or how sensitive the safety of the repository is to uncertainties in different barriers or processes.

5.2.3 Ongoing work

The work of establishing practical systematics and traceability in the scenario work continues. The status of the work is described in SR 95 /5.1-3/, where a survey is made in section 3.3 of different ways to establish the scenario systematics. In chapter 9, the RES method is applied to the disposal system that is now being defined in preparation for the siting process and for permit applications for the encapsulation plant.

The systematics in the scenario work is supposed to make it easier to evaluate whether the choice of scenario covers the important development pathways for the repository, and whether the processes essential to safety have been identified. SKB believes that this can be achieved by means of many methods. A crucial criterion for the choice of methodology is whether it meets the stipulated requirements, how practical it is to apply and what kind of overview it provides. Method development within the scenario field will continue both nationally and internationally. Results and experience may lead to changes in the recommended methodology or applications.

5.3 SPENT FUEL

In order for radioactive materials to escape from the repository, a leak must have occurred in a copper canister, for example due to corrosion or mechanical stress. Water can then come into contact with the fuel and water-soluble radionuclides can be released from the fuel. In the case of nuclides that have been released to some proportion from the uranium matrix during reactor operation, such as iodine, this can take place without the fuel itself necessarily being affected. Otherwise, release of radioactivity requires that the fuel either be dissolved or corrode in the water. The goal of the research programme is to investigate how rapidly radionuclides are released from the fuel under different conditions that might prevail in a deep repository, and to describe the release with the aid of suitable models.

Investigations of the fuel's durability in groundwater have been conducted in Sweden since 1977. An overview of results and data obtained within the framework of SKB's programme in recent years is provided in /5.3-1/, together with a comparison with the database that has been gathered during the past ten years.

Several different models for calculating fuel dissolution have been discussed during the years. The hypotheses range from strongly conservative, highly simplified models for calculations in conjunction with safety assessments, to attempts at phenomenologically correct description of fuel dissolution.

The simplest hypothesis is to completely disregard the kinetics of the fuel dissolution and regard it as instantaneous. The release of radionuclides will then be controlled by the individual solubilities of the fission products and the actinides under repository conditions. This description defines an extremely conservative upper boundary for the releases from the canister, and it gives a far-from-correct picture of the fuel dissolution.

An attempt was made in SKB 91 to take into account the dissolution kinetics by using the release of strontium as a measure of the oxidation and dissolution of the fuel matrix /5.3-2/. This model was also very conservative, since the rate of release for strontium that was used was measured in the presence of oxygen from the atmosphere. In the deep repository, only oxidants produced by radiolysis will be present after a few hundred years.

In the model used by AECL Canada, it is assumed that the fuel matrix remains stable and that the solubility of the fuel itself controls the release of radionuclides /5.3-3/. This model is probably the most realistic one in the longer time perspective. Due to the higher actinide content of light-water fuel, compared with CANDU fuel, the effects of radiolysis, particularly α-radiolysis, should be further investigated before a similar model is applied to our conditions.

This section provides a brief account of the importance of a number of important factors such as irradiation history, the mechanism of matrix oxidation, groundwater chemistry, redox conditions, sorption on the buffer mass etc. for leaching of spent nuclear fuel, and thereby also for modelling of the fuel dissolution.

5.3.1 Corrosion of spent fuel

Analytical methods

An experimental programme has been conducted at the Studsvik fuel laboratory since 1982. Short pieces of fuel and cladding have been exposed to corrosion in synthetic groundwater under oxic and anoxic conditions. The filtered solution, the material on the filter and material dissolved in the acid used to rinse the leach vessels have been analyzed. The analysis programme has included laser fluorescence (U), alpha spectrometry (Pu, Cm), gamma spectrometry (gamma-emitting fission products) and radiochemical separation and beta spectrometry (Sr, Tc). The results have provided a good understanding of fuel corrosion, and a summary of the results in the programme has been published /5.3-1/.

The possibility for multi-element analyses provided by mass spectrometry with an inductively coupled plasma source (ICP-MS) can replace all other previously used methods and furthermore provide data for other radioactive elements of smaller radiological importance. Analyses of these radionuclides can be of great importance for understanding the corrosion processes. An ICP-MS instrument has been in operation at Studsvik since 1992. Since the isotope composition in the fuel can vary from sample to sample depending on enrichment, burnup and decay, considerable data processing has been done of sample-related variables /5.3-4/.

The new technology allows uranium contents to be measured with good precision and accuracy under both oxic and anoxic conditions. The same applies to Np and Pu under oxic conditions. For anoxic conditions, on the other hand, precision is lower due to the low concentrations of these actinides. Direct analysis of Am and Cm in the leachate has given unsatisfactory results due to poor measurement statistics and uncertainties in the background level /5.3-5/.

The results from measurements of relative release rates for caesium and technetium in the corrosion tests performed to date are shown in Figure 5.3-1.

Area determination

In SKB's previous fuel corrosion work, leach rates have been expressed as fraction of inventory in the aqueous phase. This provides a general picture of the fuel dissolution process. However, the leach rate is highly dependent on the exposed area of the fuel, which is in turn dependent on several factors related to the fuel's irradiation history. The area of the fuel that is accessible to penetrating groundwater is an essential parameter for determining the corrosion rate in absolute terms. Experiments for determining specific fuel area with BET technology are currently under way. Reproducible values for the fuel area in the in the range 70–120 cm^2/g have been obtained. However, attempts to relate these values to fuel burnup /5.3-6/ do not reveal clear relationships.

Matrix dissolution

In order to be able to predict the release of radionuclides from spent fuel, it is of great importance to clarify how and to what degree this release is related to the dissolution of the UO_2 matrix. This is particularly true for strontium, since this element has been suggested as an indicator of matrix dissolution. Arguments have been offered for and against this hypothesis, however /5.3-7/.

Observations of the release rate for ^{90}Sr indicate a dependence on the migration and segregation that has taken place during irradiation /5.3-1/. Attempts to identify such segregation by means of electron microprobe analysis have not succeeded, however /5.3-8/. It has been suggested that the underlying mechanism is migration of ^{90}Sr's parent nuclides ^{90}Br and ^{90}Rb /5.3-9/. This is supported by the fact that significant quantities of Rb have been detected on surfaces of CANDU fuel with the aid of X-ray photoelectron spectroscopy /5.3-10/.

To test this hypothesis, the migration of Sr was studied by imposing a steeper than normal temperature gradient to the fuel in a power bump test /5.3-11/. Then the concentrations in solution were measured in a series of short leaching experiments and compared with reference samples. The results of both ICP-MS and radiochemical/radiometric methods are shown in Table 5.3-1.

The release rates for Cs, Rb and Sr for reference samples and for samples from the power bump test are shown in Figure 5.3-2.

The results show that rubidium migrates in the fuel, but to a lesser degree than caesium and iodine. No strontium migration of significance, within experimental uncertainty, has been detected. Of the other fission products studied (Mo, Tc and Ba), only molybdenum shows a significantly higher release at higher power density. It is possible that this was caused by oxidation of the fuel during sample preparation.

Flow reactors have been used in a number of studies of the kinetics of dissolution of sparingly soluble solids

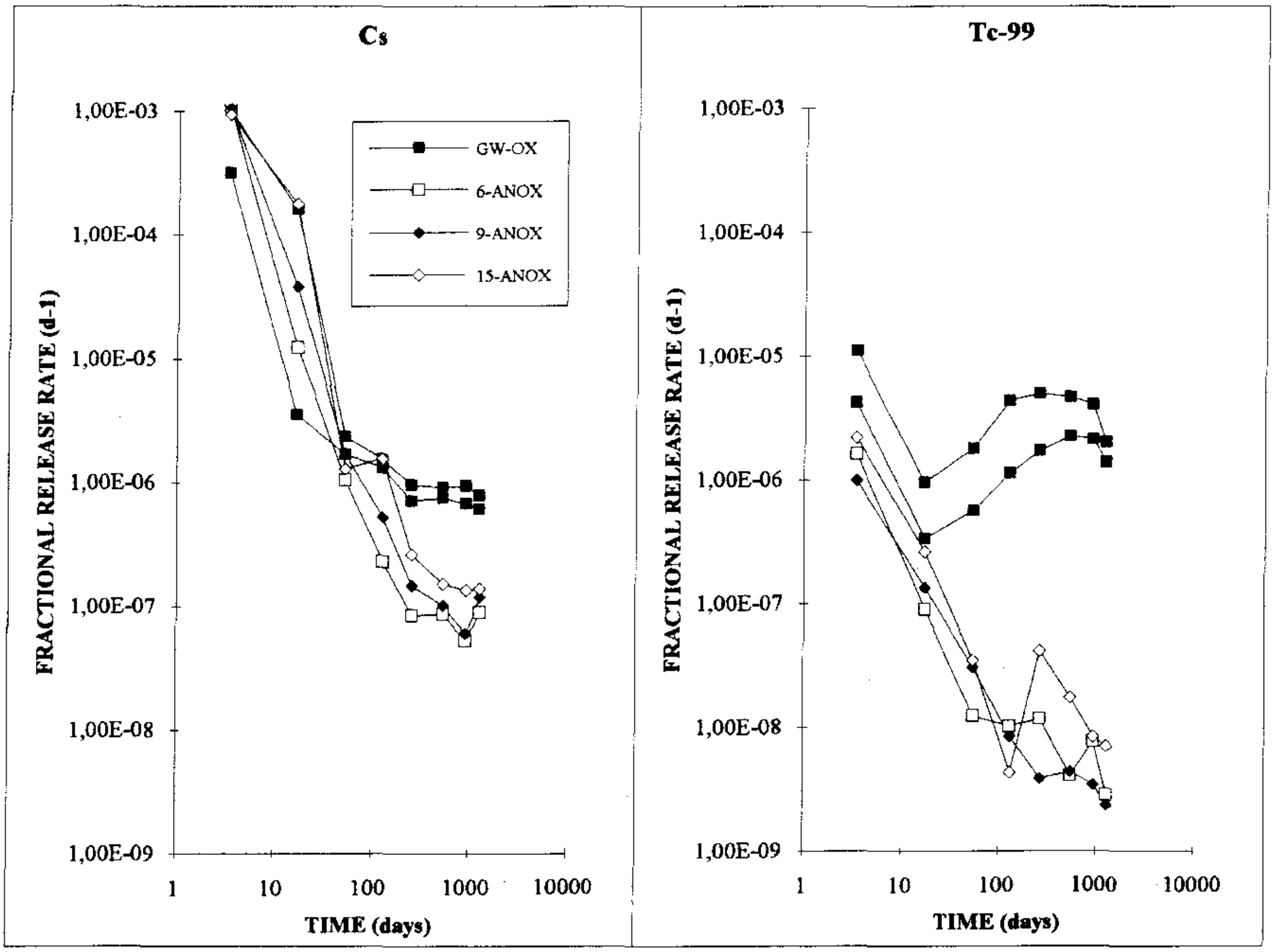


Figure 5.3-1. Fractional release rate per day for caesium (Cs) and technetium (Tc-99) under oxic (GW-OX) and anoxic (6, 9, 15 – ANOX) conditions.

Table 5.3-1: Cumulatively released fraction of the inventory after four contact periods. GS: gamma spectrometry. RC: radiochemical analysis. The > sign means that the nuclide was not detected in the first contact.

		Reference samples		"Power bump"-samples	
Nuclide	**Measurement-method**	**13-1**	**13-2**	**13-3 33,0 kW/m**	**13-4 42,6 kW/m**
Cs-133	ICP	$5{,}20 \cdot 10^{-3}$	$5{,}82 \cdot 10^{-3}$	$2{,}18 \cdot 10^{-2}$	$1{,}16 \cdot 10^{-1}$
Cs-137	GS	$5{,}02 \cdot 10^{-3}$	$5{,}57 \cdot 10^{-3}$	$2{,}08 \cdot 10^{-2}$	$1{,}12 \cdot 10^{-1}$
I-131	GS	NM	NM	$7{,}05 \cdot 10^{-3}$	$7{,}77 \cdot 10^{-2}$
Rb-85	ICP	$4{,}61 \cdot 10^{-3}$	$4{,}82 \cdot 10^{-3}$	$5{,}74 \cdot 10^{-3}$	$3{,}39 \cdot 10^{-2}$
Rb-87	ICP	$1{,}25 \cdot 10^{-3}$	$1{,}29 \cdot 10^{-3}$	$5{,}62 \cdot 10^{-3}$	$3{,}58 \cdot 10^{-2}$
Sr-89	RC	NM	NM	$1{,}70 \cdot 10^{-4}$	$1{,}79 \cdot 10^{-4}$
Sr-90	RC	$2{,}82 \cdot 10^{-4}$	$2{,}93 \cdot 10^{-4}$	$1{,}75 \cdot 10^{-4}$	$1{,}86 \cdot 10^{-4}$
Sr-90	ICP	$2{,}81 \cdot 10^{-4}$	$4{,}06 \cdot 10^{-4}$	$1{,}73 \cdot 10^{-4}$	$1{,}79 \cdot 10^{-4}$
Sr-88	ICP	$2{,}76 \cdot 10^{-4}$	$3{,}51 \cdot 10^{-4}$	$1{,}49 \cdot 10^{-4}$	$1{,}53 \cdot 10^{-4}$
Ba-138	ICP	$3{,}51 \cdot 10^{-4}$	$3{,}67 \cdot 10^{-4}$	$2{,}38 \cdot 10^{-4}$	$5{,}30 \cdot 10^{-4}$
Ba-140	GS	NM	NM	$>2{,}1 \cdot 10^{-4}$	$6{,}14 \cdot 10^{-4}$
Mo-98	ICP	$1{,}24 \cdot 10^{-4}$	$1{,}17 \cdot 10^{-4}$	$3{,}04 \cdot 10^{-4}$	$5{,}88 \cdot 10^{-3}$
Mo-99	GS	NM	NM	$>2{,}8 \cdot 10^{-4}$	$>7{,}5 \cdot 10^{-3}$
Tc-99	ICP	$6{,}50 \cdot 10^{-5}$	$6{,}27 \cdot 10^{-5}$	$7{,}44 \cdot 10^{-5}$	$1{,}60 \cdot 10^{-4}$
U	ICP	$2{,}01 \cdot 10^{-5}$	$2{,}36 \cdot 10^{-5}$	$5{,}64 \cdot 10^{-6}$	$1{,}20 \cdot 10^{-5}$

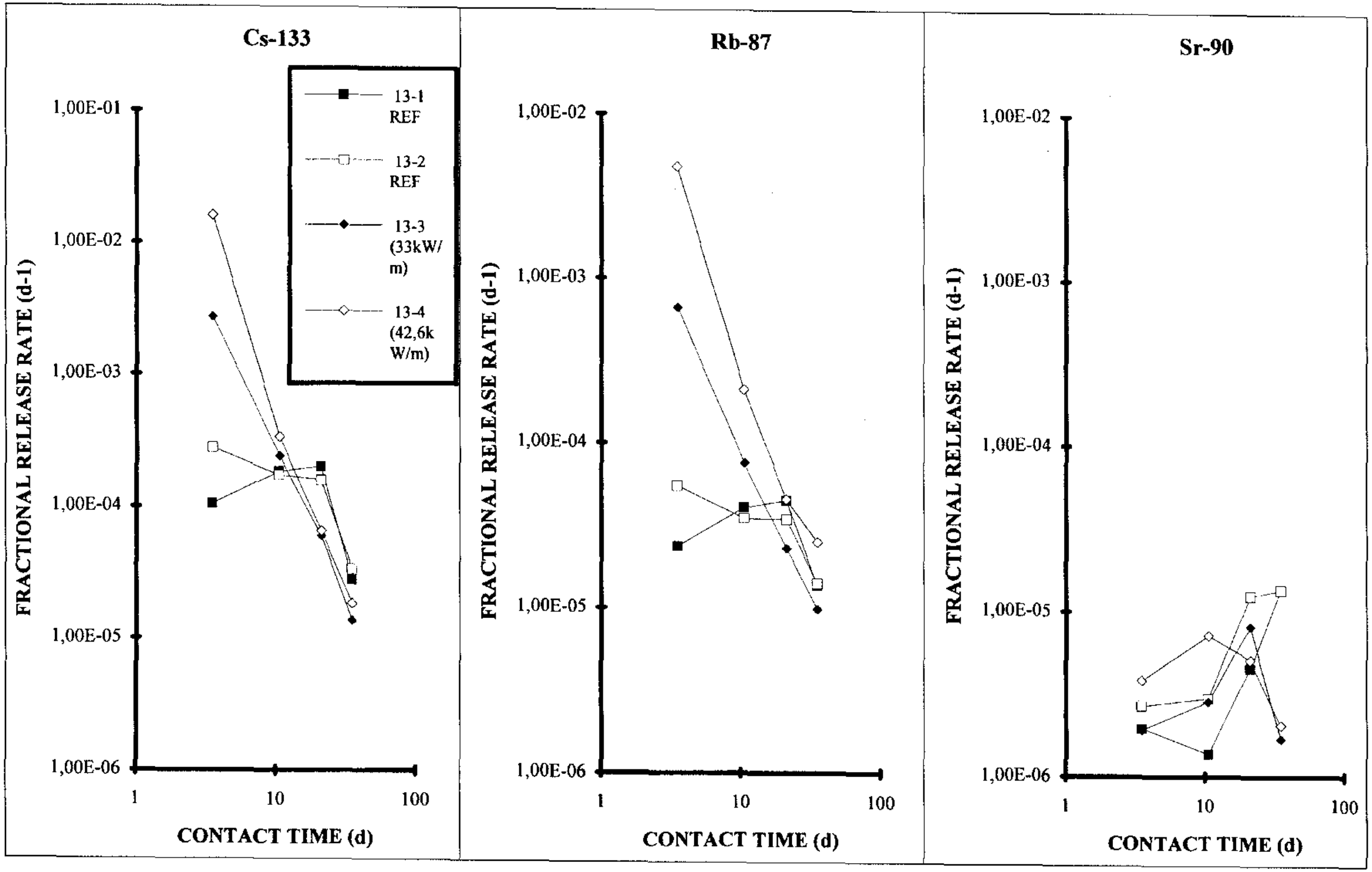


Figure 5.3-2. Fractional release rate per day for reference samples (13-1 and 2) and "power bump" samples (13-3 and 4).

/5.3-21/, as well as in leaching studies of uraninite, SIMFUEL /5.3-22/ and fuel /5.3-23/. In this type of reactor, the system will evolve to a steady state if the flow, the composition of the incoming solution, the composition of the solid phase and its surface area remain constant. No precipitation of secondary phases will take place, since the reaction products are flushed out of the reactor before any saturation occurs. An important distinguishing characteristic of this system is that the solid phase that is under observation does not require any manipulation. When the outer layer has been dissolved, new surface will continuously be exposed to the leaching solution. Diffusion of solution species to the surface of the solid phase is also minimized by using thin layers of solid phases in the reactor. The same fuel can be studied under different conditions by changing the leaching solution outside the reactor. Planning to utilize the aforementioned technique in SKB's fuel studies is under way.

5.3.2 Other components in the near field

Investigations of the influence of bentonite on fuel corrosion have been going on since the second half of the 1980s. Preliminary evaluations of experiments with contact times of up to one year have been reported previously /5.3-12, 13/. The evaluation of the release of ^{90}Sr from fuel in contact with compacted bentonite for six years has also been concluded /5.3-14/. Figure 5.3-3 shows the release of strontium as a function of time. After six years the fraction of released Sr is five to ten times lower than in similar experiments in the absence of bentonite. In experiments performed with bentonite containing metallic iron or the Fe(II) mineral vivianite, the fraction of released Sr is lower than in bentonite with metallic copper or without any additives whatsoever.

The leaching behaviour of caesium is different from that of strontium and exhibits an initial pulse of a rapidly released fraction /5.3-13/. The evaluation of the caesium leaching in bentonite does not exhibit any significant increase in released fraction over a six-year period. The small but steady increase in released caesium that was observed in the leaching experiments without bentonite /5.3-1/ is probably concealed by the quantity of initially released caesium, which in the experiments with bentonite remains throughout the experimental period /5.3-14/.

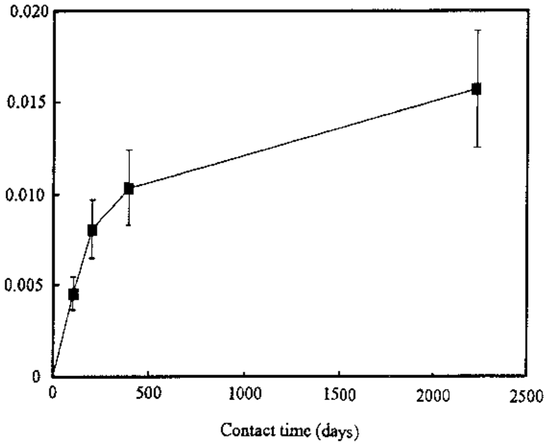


Figure 5.3-3. Released fraction of ^{90}Sr after different contact times with bentonite clay without additives.

5.3.3 Models

Experimental data from dissolution of spent fuel and uranium dioxide under oxidizing conditions suggests a kinetic rather than thermodynamic control of the process. The total dissolution rate in carbonate-containing groundwater can be related to the following processes:

- Initial rapid dissolution of already oxidized UO_{2+x} surface layer. This initial dissolution rate has been determined experimentally /5.3-15/.
- Oxidative dissolution of the matrix in bicarbonate solution. The rate of the process is dependent on the concentrations of oxidants and bicarbonate.
- Precipitation of secondary phases. The rate of this process is dependent on the U(VI) concentration, the fuel area to solution volume ratio, and the composition of the groundwater.

Preliminary calculations indicate that it is possible to develop a quantitative model that takes the above-mentioned processes into account. Approximate calculations show that it is possible to reproduce experimental observations. Additional experiments and modelling work are necessary to strengthen the grounds for the model.

5.3.4 Natural analogues

Safety and performance assessments of a deep repository are based on, among other things, descriptions of the fuel's behaviour over long periods of time. Fuel leaching experiments aimed at kinetic and thermodynamic modelling of fuel dissolution under the conditions prevailing in the deep repository cannot be directly extrapolated to very long times. These time scales can be bridged by studies of alteration processes in natural uraninites under mildly oxidizing and reducing conditions.

The fuel's long-term stability is linked to the reaction paths for the oxidative transformation of the fuel matrix. The oxidation of natural uraninite in air /5.3-16/ shows that at temperatures of up to 300°C, only U_4O_9 type oxides are formed. Experimental and literature data cannot confirm that α-U_3O_7 is formed. With a further increase in temperature, or in the partial pressure of oxygen, a saturation of excess oxygen in the isometric UO_{2+x} structure is probably reached and it is transformed in air to U_3O_8. In the presence of water, uranium oxide hydrates such as schoepite are formed.

Studies of air oxidation of irradiated light-water reactor fuel indicate a similar oxidation mechanism /5.3-17/. First cubic U_4O_9 is formed, which is stabilized by the fission products and reaches an oxygen/uranium ratio of up to 2.4 while maintaining the same fluorite structure. The influence of the fission products is confirmed by a similar behaviour for Gd-doped irradiated UO_2. Further oxidation does not appear to proceed via U_3O_7. This makes it necessary to revise the importance of this phase in the modelling of the long-term corrosion of the UO_2 matrix in spent fuel.

Dissolution experiments have been conducted with natural uranium phases under various redox conditions, combined with detailed characterization of the solid phases before and after the experiments /5.3-18/, in order to obtain supporting data for a thermodynamic and kinetic model for the long-term oxidation of uraninite. These results can be applied to the long-term behaviour of spent fuel. As a part of this work, the solubilities of soddyite, uranophane and becquerelite have also been determined.

5.3.5 Activities in relation to goals in RD&D-Programme 92

- Progressively refine the models for the safety assessment in 1996. – Work is under way on determining the importance of the α-radiolysis for the oxidation/dissolution of the fuel and interim results will be published /5.3-19, 20/.
- Develop a realistic model for radionuclide release from the fuel by the end of the 1990s in time for the application for an environmental licence for the deep repository for demonstration deposition. – The work is related to the work on α-radiolysis.

5.4 BUFFER AND BACKFILL

5.4.1 Functional requirements

Buffer

The choice of buffer material and the design of the buffer around the canister are based on the fundamental functional requirements in section 4.3. In addition there are economic requirements on good availability of the material type to be used and low occurrence of accessory minerals in the form of sulphur minerals and organic substances. Swelling clay with a high smectite content comes closest to meeting these requirements.

If the fundamental requirements are met, a number of other favourable properties are also obtained, such as:

- limitation of transport of corrodants up to the canister surface (diffusive transport),
- sorption of radionuclides,
- only diffusive transport of radionuclides from a defect canister to the rock in the near field,
- drying-out and filtering of micro-organisms,
- stabilization of the walls of the deposition hole,
- stabilization of the chemical environment (Eh, pH).

The different functions are controlled by the following measurable properties of the buffer:

- water content,
- hydraulic conductivity,
- swelling pressure,
- swelling capacity,
- shear strength,
- rheological properties,
- pore volume,
- diffusion and sorption properties,
- thermal conductivity,
- chemical composition.

Approximate values for satisfying the various functional requirements determine the suitable composition of the buffer, acceptable accessory minerals and impurities, and the limits within which the material's bulk density after deposition and water saturation should lie. Such considerations have governed the choice of buffer material in the BMT tests in the Stripa Project /5.4-1/.

Interaction with near-field rock

The importance of the rock for the bentonite buffer has been analyzed in different studies /5.4-2, 3/. The following requirements on the rock have hereby been specified in order that the buffer should achieve and retain the desired function:

- The rock supplies the buffer with groundwater so that water saturation and swelling occur.
- The near rock has such a composition that the buffer is not affected in a way that leads to serious cementation or mineral alteration.
- The rock does not contain discontinuities of such a nature that openings are formed in which bentonite can penetrate, causing a considerable decrease in buffer density in the deposition hole.

It is judged that these requirements can be satisfied in commonly occurring Swedish crystalline rock at the depths in question for the deep repository. Practical experience has been obtained through the Stripa Project /5.4-4/. Furthermore, water saturation and swelling can be facilitated by compaction of the bentonite blocks with a high water content and by filling the gaps between block and canister and between block and rock with water in conjunction with deposition.

Backfill materials

Different mixtures of bentonite and aggregate are planned to be used for backfilling of tunnels, rock caverns and shafts. The required function of these materials is to:

- counteract swelling of the bentonite out of the deposition hole,
- prevent or limit the flow of water in the tunnel and around canister positions,
- resist chemical transformation during a long period of time,
- not lead to significant chemical transformation of the buffer around the canister.

In those cases where the water transport around the canisters is not affected by the hydraulic conductivity in certain sections of the tunnel, the requirement on mechanical stability will be the most important. Unmixed aggregate can then be considered. Such tunnel sections may have to be sealed at either end.

The properties that determine the performance of the material and that can be measured are the same for bentonite/aggregate mixtures as for pure bentonite. An additional property of importance for backfill materials is compressibility, which determines how swelling-out from the deposition holes can be limited.

5.4.2 Step-by-step development stages and compilation of present-day knowledge

Knowledge of the properties of bentonite clay as a buffer around the canister has been built up over a long period of time through extensive studies in laboratories and in the field. The activities have been pursued iteratively with the following thrust:

- Fundamental knowledge about the buffer:
  - Build-up of broad knowledge
  - Development of calculation models
  - Inventory of materials

- Analysis of individual processes:
  - Interaction with rock
  - Interaction with canister
  - Longevity

- Analysis of coupled processes:
  - Function in deep repository

At present a compilation of knowledge and experience gained so far from the research conducted is in progress. It will comprise three parts, of which Part I, which deals with basic definitions and method descriptions, is finished /5.4-5/. Part II is concentrated on material descriptions and Part III on compilation of models. The purpose of the compilation is to present uniform definitions of physical and chemical concepts and phenomena relating to buffers and backfills, standardized and recommended laboratory and field test methods, and mathematical models for description and prediction of practically significant processes and functions.

5.4.3 Properties of different bentonite materials

The material structure of bentonite buffers has been described qualitatively in a general microstructural model (GMM) /5.4-6/. This model is based on the fact that the buffer material consists of ground, dried bentonite which, on being compacted, forms a mass with a random distribution of bentonite grains and with a random size and shape of interstitial pores. On water saturation and subsequent homogenization, the pores are first filled with water and then with bentonite gel, whereby the end product is a buffer with bentonite grains of high density interspersed with pore spaces filled with a bentonite gel of lower density. Different grades of end products are obtained for Na- versus Ca-based bentonites. The gel-filled pore spaces are assumed to constitute the dominant passages for transport in the buffer, and GMM serves today as a tool for judging the reasonableness of laboratory-determined transport parameters for water and gas.

Mass transport in a water-saturated bentonite buffer is limited to diffusion. This applies to both transport of solutes from e.g. the groundwater in towards the canister and transport of radionuclides out from a defective canister. Diffusion is a very slow process and is therefore an important barrier property of the bentonite clay. It protects the canister against the influence of harmful substances from the outside and is an extra barrier against the escape of radioactive materials if the canister should fail.

In order to predict the degradation of buffer and backfill materials, a model has been developed founded on the mathematical model for conversion from smectite to illite that is based on Pytte's theorem /5.4-7/. The model shows that degradation takes place either in the form of a transformation from smectite to illite via mixed-layer minerals or by new formation of illite. In both cases, the change is assumed to be of the Arrhenius type, i.e. controlled by the activation energy and the temperature, but also dependent on the supply of potassium. Applications to geological examples (Kinnekulle, Hamra and Burgsvik) and laboratory experiments /5.4-8/ support the validity of the model and thereby the conclusion that the illite alteration in the buffer and backfill with crushed rock as aggregate does not constitute a problem on a 100,000-year time scale if a suitable type of bentonite has been chosen. The primary alteration that is foreseen to occur will take place during the period with elevated temperature immediately after deposition.

A chemical influence that has been brought to attention in the ongoing work of modelling of bentonite degradation is that salt enrichment can take place in the buffer nearest the canister in conjunction with wetting when the groundwater has a high electrolyte content. Laboratory tests conducted with samples with a low water content from the start indicate, however, that the phenomenon can be avoided if the density of the water-saturated buffer amounts to about 2.0 g/cm^3 and blocks with a high original degree of water saturation are used in combination with a supply of water with a low electrolyte content /5.4-9/.

The result of an inventory of different buffer materials is presented in /5.4-10/. This study shows that with application of the model for degradation by conversion of smectite to illite /5.4-11, 12/, the lowest initial smectite content should be 50%. The study shows that only the smectite types montmorillonite and saponite with sodium as the main adsorbed ion should be considered. However, a high initial smectite content is very valuable to ensure effective self-healing and homogenization of the buffer. Such bentonites, with a montmorillonite content of 70-90% and with sodium as the dominant adsorbed cation, are commercially available in the USA, Greece and Italy. No commercially interesting bentonite deposit has been found in Sweden. However, the State Mining Property Commission (NSG) has investigated the prospects for exploitation of deposits in the southernmost province of Sweden and found indications of deposits in wellholes. The few clay analyses that have been performed show that smectitic clay minerals exist in a basalt-tuff parent rock. However, very little is known about the extent and thickness of the tuffs.

The preliminary choice of backfill material is mixtures of 10-20% bentonite and the remainder aggregate that has been laid out and compacted in place. For environmental and economic reasons, use of the rock that is excavated in the deep repository, which is crushed to a suitable grain size, is recommended. The properties of such material have been investigated and found to be comparable with the properties of quartz sand /5.4-13/.

A technique for determination of the thermal conductivity of buffer material has been developed and determinations have been performed at different densities and degrees of water saturation. The results have been compared with theoretical predictions and with data from field tests at Stripa /5.4-14/. The results exhibit good agreement when the buffer is near water saturation, but not so good under unsaturated conditions.

5.4.4 Calculation models for various functions

A general model for Thermo-Hydro-Mechanical (THM) processes in water-saturated buffer has been developed /5.4-15/. It can be applied to, among other things, swelling of buffer against backfilled tunnels, settlement of the canister and impact of rock movements on the canister's integrity. The model has been verified on laboratory scale, with the exception of volume shrinkage under pressure and plastic, volumetric strain. These phenomena can be evaluated when ongoing long-term tests are interrupted during the first half of the six-year period.

A preliminary model has been developed for THM processes in unsaturated buffer which for some cases shows acceptable agreement with experimental data but still has serious shortcomings /5.4.16/. It has been applied in the international DECOVALEX project, where it has been used for calculation of PNC's "Big Ben" experiment. The model calculations indicated that the buffer material nearest the heater would dry and shrink in volume. The test shows good agreement with regard to temperatures and the decrease in water content. Since the pore volume was not measured in the tests, the shrinkage could not be evaluated. The measured total buffer pressure was higher than the calculated value /5.4-17/.

For the homogenization process, a numerical model has been sketched and applied to both pure bentonite and a mixture of bentonite and sand with the aid of the model for water-saturated buffer /5.4-18/. The model can now be applied in two-dimensional geometries.

5.4.5 Gas transport

If water enters the canister, hydrogen gas will be formed by anaerobic corrosion of iron. The potential pressurization of the canister and the gas's effect on the water movements around the canister have been studied /5.4-19/ for the purpose of clarifying which mechanisms control the transport of hydrogen gas from the canister and what the consequences of this transport are. The following conclusions were drawn:

- The long-term effect of gas generation is primarily dependent on the gas generation rate and the capacity of the bentonite to permit gas to escape.
- The quantity of gas that can be dissolved in water and is transported away by diffusion is small compared to the expected generation rate, which means that gas phase flow through the bentonite is expected to be the dominant transport mechanism.
- Once the gas has passed through the bentonite, there are enough transport pathways to enable the gas to

continue on through the rock towards the ground surface.

The most important questions to be answered are therefore what the bentonite's gas transport capacity is and whether any permanent weakening of the buffer occurs with time as a consequence of gas transport. Experiments have been conducted /5.4-20/ to determine at what pressure the bentonite opens to allow gas to escape. It was hereby found that:

- the gas passes through the clay in a few pore passages, so that there is very little drying-out caused by gas,
- the clay opens at a pressure corresponding to the hydrostatic head plus 50–90% of the swelling pressure at the densities being considered for the deep repository,
- when the pressure drops the clay closes and self-heals,
- the effect of repeated gas passage cycles is being studied in ongoing experiments.

5.4.6 Bacteria

Oxygen and sulphide are in practice the only substances that could conceivably corrode copper. Deep groundwater is reducing and thereby completely oxygen-free. Furthermore, it can be shown that the oxygen that is trapped in the repository at closure is soon consumed by the reducing substances present both in the backfill material (e.g. pyrites in bentonite) and in the rock (ferrominerals and sulphides). Sulphide occurs at low concentrations in deep groundwaters. Groundwater can contain relatively much sulphate and the bentonite contains quite a bit of soluble sulphate. Sulphate does not react spontaneously with copper, nor is sulphate reduced by the reductants that may be present in a final repository, unless this is mediated by bacteria. Sulphate-reducing bacteria occur at repository depth, and it is urgent to identify what might limit their action. One important limitation is the living conditions in the bentonite buffer.

These questions are being studied both in the laboratory (own experiments) and in-situ (cooperation with AECL in their URL). The results so far indicate that the bacteria do not survive. If this proves true, then the bentonite constitutes a barrier to microbes. A review of the importance of microbes to the long-term safety of the deep repository is provided in /5.4-21/.

5.4.7 Concrete

Concrete is a very useful material for construction and reinforcement. Possible uses in a deep repository are grouting, paving, shotcreting of walls and roof, underground constructions, plugging of tunnels and shafts etc. The use of concrete gives advantages during construction and operation of the repository, but it is necessary to evaluate its long-term properties and the importance of concrete on long-term safety. Modern cements have not been around very long, but knowledge about the minerals that are formed in cured cement and the composition of the pore water has increased considerably /5.4-22/.

5.4.8 Clarified and remaining questions

The aim of the ongoing compilation of accumulated knowledge and experience is to serve as a preliminary basis for design and selection of materials. Subsequent development steps include:

- deepening of knowledge,
- field tests,
- optimization.

The purpose of these activities is to gather detailed background data for design and selection of materials in conjunction with assessment of performance in the deep repository on candidate sites.

Properties of different bentonite materials

Theoretical explanations of the buffer's performance can be provided by a preliminary version of GMM. What remains is to describe in greater detail the bentonite's homogenization after water saturation for redistribution of water and bentonite between bentonite grains with high bentonite density and interstitial pore volumes with low bentonite density, as well as for bentonite-aggregate mixtures where the corresponding homogenization takes place in the pore volume between the ballast grains.

Temperature-induced conversion of montmorillonite to non-expanding illite can be predicted with a developed model. Since the process is slow and difficult to reproduce exactly in the laboratory environment, natural analogues also constitute suitable verification examples. Several Swedish natural analogues have been studied and others, Swedish as well as foreign, are deemed to be able to furnish supplementary evidence of the accuracy of the model for Swedish deep repository contexts.

Knowledge of the quality of different commercial bentonites has primarily been acquired via information from suppliers and own analyses of the product. In conjunction with the future choice of quality for the deep repository, it must be established which quality the supplier can be counted on to be able to deliver in the long term.

Calculation models for various functions

The function of buffer materials, with particular emphasis on rheology and transport of water and ions in deposition holes under water-saturated conditions, can be described and calculated today using developed models. These models have been verified by laboratory tests, with the sole exception of the two plastic alteration processes mentioned previously. Tests are under way for these processes.

For unsaturated conditions, i.e. with regard to processes associated with wetting of buffer and backfill, several processes and boundary conditions relating to water exchange between near-field rock and buffer and water distribution in the buffer remain to be clarified, so that the time for water saturation can be calculated with sufficient accuracy, primarily for use in evaluating buffer tests in the Äspö HRL, and secondarily for performance assessment of final disposal. Thermal, hydraulic, mechanical and chemical processes interact, and the couplings between them are crucial for the results. Calculation models for thermo-hydro-mechanical processes are studied today as coupled models, while chemical processes are regarded separately.

Gas transport

The transport mechanism for gas through a water-saturated and swollen buffer is known, while the effect of repeated gas pressure increases and gas passages requires additional laboratory testing.

5.5 THE BEDROCK

5.5.1 The role of the rock in the deep repository

The barrier functions in the KBS-3 version of a deep repository for spent nuclear fuel and other long-lived radioactive waste are described in chapter 4.

Some central properties of the bedrock, see Figure 5.5-1, are essential to guarantee the performance and long-term radiological safety of the deep repository, and there are certain obvious couplings between these properties:

- long-lasting mechanical stability
- a chemically stable environment with a groundwater which does not contribute to corrosion of the canister material or alteration of the buffer material, and which ensures low solubility and high retardation of the radioactive constituents in the waste,
- a slow and preferably constant groundwater flux which limits the transport of substances having an adverse effect on the waste and the backfill material, or on radionuclide transport.

Besides the above geoscientific properties, it is essential to minimize the risks of future intrusion by:

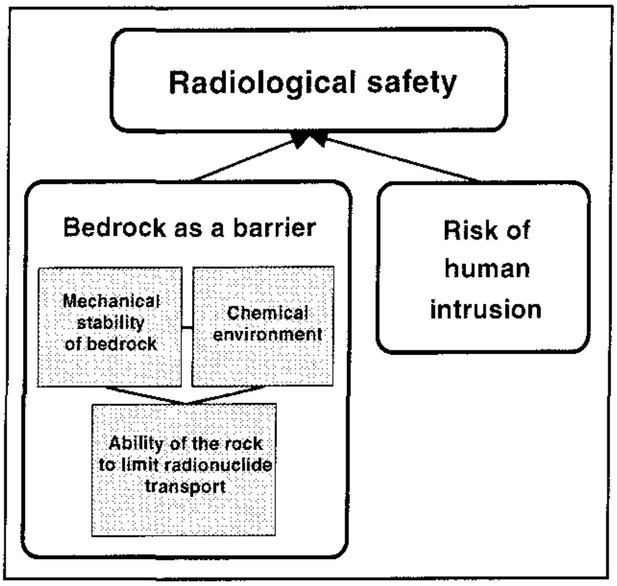


Figure 5.5-1. Properties and conditions in the bedrock that are of importance for the long-term radiological safety of a deep repository.

- avoiding rock volumes or proximity to rock volumes with a potential for exploitable metals and minerals, energy storage and energy extraction.
- locate the repository on such a site and at such a depth that the risk of intrusion by drilling (wells, prospecting, exploitation) is very small.

The Swedish crystalline basement forms a part of the Baltic Shield that stretches from the Kola Peninsula and Karelia over Finland and Sweden to Southern Norway. Most of the Swedish crystalline basement has an age of about 1,700 million years. The Baltic Shield offers a generally suitable environment for safe deep repositories, with respect to the aforementioned desirable properties of the bedrock.

5.5.2 Geoscientific data and uncertainty

Geoscience has, in a historical perspective, been a descriptive science where most interest has been devoted to the genesis and general characteristics of geological formations. The applied direction of geoscience within the field of nuclear waste management makes greater demands on quantification of geological processes and predictions of the future. The great heterogeneity of the rock means that generalizations cannot be made without describing the variability of different rock properties. Furthermore, the properties and their variation can depend on the scale on which a given problem is regarded.

The bedrock with its component parts is deterministic, i.e. it exists and has apparently measurable, predictable properties and structures on all scales. The complex structure and great variability of the bedrock mean, however, that it is impossible to rely solely on observations in a detailed quantitative description. For example, when it comes to hydraulic conductivity in different rock types, the difference in mean values between different rock types is less than the range of variation within a given rock type. For this reason, both deterministic and stochastic calculation models are utilized in geoscientific contexts.

The geological aspects are mainly associated with the performance and safety of the repository. However, geological conditions are also of importance for the actual construction of the repository. There is a connection between the design of the repository, its safety and its placement in the rock. This connection does not have to be such that construction-related difficulties always entail long-term safety risks. For example, clay-filled zones may pose an engineering problem, but not an obvious problem for future radiological safety.

The long-term safety of a deep repository is judged in a more or less site-specific safety assessment, which is based on, among other things, a general geoscientific understanding of the area in question on a scale that is relevant for the repository. The repository site, a square kilometre or so in size, must be considered in its regional-geological context. Site characterization can be both quantifying and qualitatively descriptive.

Regardless of the scale on which the safety-related conditions at the repository site are considered, the studies should be rooted in the safety assessment's need for relevant information. On general scales, judgements are largely of a qualitative character. The borderline between a qualitative judgement on a general scale and a quantitative judgement on a detailed scale is not always obvious.

Uncertainties in geoscientific data and information are associated with:

- measurement accuracy,
- the heterogeneity and anisotropy of the particular property,
- the degree of confidence for mean values and variance,
- the directional dependence and dimensionality of the investigation methods,
- the volume representativity of the investigation methods (scale),
- subjectivity in interpretation.

It is, in other words, important that investigations in rock be conducted step-by-step on different scales and iteratively, i.e. with progressive knowledge accumulation and increasingly detailed information.

5.5.3 General goals of the activities

The geoscientific programme at SKB entails broad knowledge accumulation within geology, geophysics, rock mechanics, geohydrology, geochemistry and groundwater chemistry. The programme also includes further refinement of numerical computer models, and there is a strong coupling to development of instruments and measurement methods.

The work is integrated with efforts within:

- The study site investigations.
- The Stripa Project.
- The Äspö Hard Rock Laboratory.
- Safety assessments.
- Natural analogues.
- The siting programme's general studies, feasibility studies and site investigations.
- Repository design.
- Alternative studies of waste disposal, particularly very deep holes.

The general goals of the geoscientific R&D activities at SKB are:

- to further refine knowledge of rock mechanics, geochemical and hydrogeological conditions in order to permit better quantification of uncertainties and margins in the rock's capability to isolate the waste, in preparation for the siting process.

Important interim goals are thereby:

- to deepen understanding of the georelated processes which can affect the long-term safety of a deep repository, and to further refine the capability to predict such changes,

- to further refine models for calculation of groundwater flow in fractured rock, for water flows in conjunction with glaciation and deglaciation, for coupled phenomena such as temperature, rock stresses and hydraulic conductivity and for rock mechanics at a pace that corresponds to the need in assessments of the performance and long-term safety of the candidate sites.

- to ensure that suitable measurement technology is available for high-quality collection of such data as are required to characterize rock volumes for the construction of a deep repository.

The following sections present the state of knowledge and results obtained (1993–1995) for mechanical stability, groundwater chemistry conditions and the rock's capability to limit nuclide transport. The presentation largely follows the subdivision into siting factors in the supplement to RD&D-Programme 92 /5.5-87/. An account is also given of the state of knowledge concerning various model tools that are used in SKB's activities when it comes to hydrogeology, transport of solutes in groundwater and rock mechanics.

Certain results from Äspö are spotlighted and discussed in the following subject-by-subject account of geoscientific knowledge. A coherent status report on experience from the R&D work that has been done at the Äspö HRL up to and including the construction phase will be published in separate reports during 1995 and 1996. However, a brief summary of results is presented in the programme for the Äspö HRL (see chapter 12). Experience from site investigations and detailed characterization at Äspö is presented in section 8.2.2.

5.5.4 Structural geology and mechanical stability

A KBS-3-like repository presupposes a crystalline basement host-rock. This section deals with geological and bedrock-structural conditions as well as **the mechanical properties of the crystalline rock (movement proneness).** Figure 5.5-2 shows a schematic division into a number of **processes** that might occur, whose consequences are dependent on structural and mechanical conditions. Stability questions may be associated with natural movements or induced movements, depending on the layout of the repository. Consequences of natural movements may be dependent and/or independent of the repository.

The overall purpose of the R&D work devoted to rock stability is to:

- meet the rock-mechanics functional requirements so that the deep repository can be constructed and function stably during the deposition phase. Working conditions must be safe for both personnel and the waste to be handled.
- meet the requirement that shearing movements in the rock in the 100 000-year perspective will not damage the integrity of the canisters so that unacceptable doses occur.

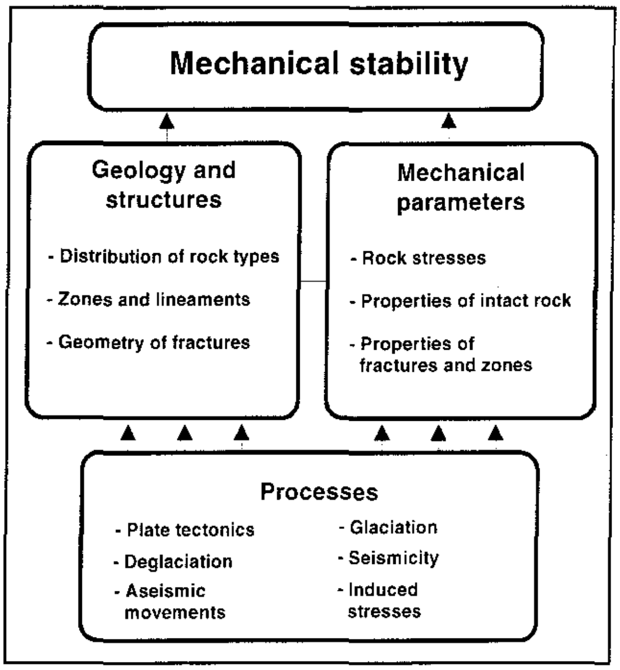


Figure 5.5-2. Processes and factors within bedrock geology, structural geology and movement proneness that may be of importance to safety.

A brief resumé of studies performed at SKB during the years 1993–1995 is given below. The reader is otherwise referred to SKB's Annual Reports /5.6-8 et al./ and reports in SKB's TR series.

Geological and bedrock-structural conditions

The bedrock in Sweden can be divided into three major units: The crystalline basement, the Caledonides and the sedimentary bedrock regions outside the Caledonian mountain chain. Most of Sweden's crystalline basement was formed by means of foldings, alterations and magma intrusions between 500 million and 2 500 million years ago. What we see today of the exposed surface of the crystalline basement lay at great depths when it was formed. Erosion has reduced the thickness of the crystalline basement by 10–30 km.

The Swedish waste management programme has focused on magmatic and highly metamorphic rock types as host rock for a repository. The rock types are often gneissic with a granitic composition. These rock types were studied during the "study site investigations" /5.5-1, 2, 3, 4, 5, 6/.

Basic rock types, particularly gabbro, have been proposed as an alternative, since they are able to offer better sorption properties and conditions for self-healing of fractures. However, the occurrence of large and homogeneous rock volumes with bodies of basic rock types is strictly limited. From a rock engineering point of view, experience from basic rock types does not differ essentially from experience from more acid bedrock types. In terms of hydraulic properties, available results show that basic rock types are generally slightly less hydraulically conductive than granites and gneisses. The range of variation within a rock volume is considerable, however. It is known from investigations in Taavinunnanen, for example, that granitic dykes can occur in gabbro bodies and that the dykes have a much higher hydraulic conductivity, relatively speaking. The relatively low thermal conductivity of basic rock types necessitates utilizing large repository volumes in order to keep temperatures from becoming too high in the near field. Another negative factor is that gabbro is often of interest for extraction of metals (e.g. nickel).

In summary, manifest difficulties are encountered in trying to find large homogeneous rock volumes with basic rock types for a deep repository. A comparison that takes into account hydrogeology, geochemistry and rock engineering does not reveal any obvious advantages for gabbro in relation to granitic rock types /5.5-7, 8, 9, 10, 11/.

The Swedish crystalline basement is intersected by certain very old super-regional zones of deformation /5.5-14/. The Southwest Scandinavian Gneiss Province is bounded on the east by a zone that extends from Skåne to Värmland, known as the Protogine Zone /5.5-12/. Within the Southwest Scandinavian Gneiss Province, the Mylonite Zone stretches from the Norwegian border in Värmland southward via Värmlandsnäs to Varberg. The Mylonite Zone is a sign of severe deformations in the bedrock about 1 000 million years ago. East of the zone the rock types are mainly gneisses of magmatic origin, while west of the zone surface rock types are most common. The Tornquist Zone is a very elongated zone within the Eurasian plate. The zone constitutes a boundary between the Baltic Shield and an expansive depressed area in the western part of continental Europe. In Skåne, the Tornquist Zone takes the form of crystalline basement horsts and intervening deep depressions with sedimentary rock. The Tornquist Zone exhibits recent movements from the Quaternary period /5.5-13/.

When it comes to structural-geological elements in a regional perspective (aside from the above), different conceptual models exist. The morphology of the bedrock surface can be compiled and serve as a basis for a structural and tectonic interpretation /5.5-15/. Several structural models have also been devised working from lineament interpretations based on, for example, the Swedish height data base and satellite images /5.5-14, 60, 61, 105, 106/. Some models suggest, for example, that Sweden should be divided into a few super-regional blocks separated by elongated shear zones /5.5-16, 107/.

Rock-mechanics experience from underground facilities says that siting of the deep repository in a super-regional deformation structure within the Baltic Shield does not have to be ruled out. A deformation zone may contain rock volumes with suitable conditions. This is clarified by site investigations /5.5-80/.

Observations from shield areas around the world provide evidence of the fact that fractures and fracture zones, from a detailed scale to the regional perspective, occur with discrete directional concentrations. The displacements as well as the length and width of the deformation structures, often indicate fractal dimensionality. Intensive development work is under way to increase our knowledge of the bedrock's fracturing /5.5-62, 63, 64/.

Conventional geological and geophysical investigation methods mainly map steeply dipping structures and their appearance on the ground surface. It is, however, desirable to further develop methods for mapping subhorizontal structures in the bedrock. Further development of seismic reflection investigation and interpretation methods is being pursued within SKB /5.5-67/.

Mechanical properties of the crystalline basement rock

Due to the low temperatures and pressures that prevail in the upper part of the lithosphere, stresses both during the construction phase and on a geological time scale can result in brittle fracturing. Brittle mechanical behaviour may include formation of fractures and zones or propagation and reactivation of already existing fracture zones. Brittle-mechanics deformation can occur on all scales.

The mechanical theories for the behaviour of intact crystalline bedrock are relatively well-developed and tested on a laboratory scale /5.5-16, 17, 18, 19/. Once a fracture or a zone has formed, future movements are controlled more by friction than the properties of the intact rock. Various empirically founded parameters are used to describe the mechanical properties of fractures /5.5-20/. Important properties of the individual fracture are, for example, proportion of contact surface, roughness of the fracture plane, grinding caused by the movement, fracture-filling material, distribution and size of the normal stress with respect to liquid pressure, etc.

Mechanical properties of major discontinuities such as fracture zones are relatively unknown. A compilation of existing information has been done /5.5-21/ based on observations from limited sections of zones or from large-scale load changes, mainly in the mining industry. The knowledge is essential from both a rock-engineering and safety-assessment point of view. The study finds, among other things, that the assumption of flat zone structures with uniform function in calculation models is dubious, and that the geometry and morphology of zones ought to be represented more realistically.

It is essential to be aware of couplings between mechanical, thermal and hydraulic properties in a deep repository. The thermo-mechanical coupling has been examined relatively thoroughly, while the constitutive relationship between mechanical and hydraulic properties in fractures is under development /5.5-22, 23, 24/.

Geodynamic and mechanical processes

Stability in a deep repository is affected by both geological processes and induced movements due to the geological configuration of the repository /5.5-30/.

Tectonics is a collective term for the deformation of the earth's crust and the structural forms arising as a result. The term covers deformation and structural forms from a millimetre to a kilometre scale.

A review has been made of the various tectonic regimes in the Baltic Shield during the last 1 200 million years /5.5-25/, with a focus on different dominant stress fields associated with them. The surface of the present-day crystalline basement exhibits fracture patterns and heterogeneities that have been shaped and developed over many hundreds of millions of years. It is worth pointing out in this context that sedimentary rock strata covered large parts of Sweden with a thickness of up to 3 km during the Devonian-Triassic periods. Fracture patterns with four to five dominant fracture directions usually occur on the basement surface. These are the result of shear and/or tension fractures. Since then the stress field has varied in direction and size through the ages. Analyses show that super-regional stresses have caused the fractured bedrock to be deformed along already existing fractures and zones. Any active loads during the coming 100 000-year period will thus probably reactivate old zones and fractures. The present-day tectonic regime with a relatively passive response to the Mid-Atlantic ocean floor spreading is a calm period (anorogenic) for the Baltic Shield.

Figure 5.5-3 shows the largest principal stress from undisturbed measurements at levels of 400–1000 m /5.5-31/. The stress picture, with a principal compression in the northwesterly direction, verifies the effect of the Mid-Atlantic ocean floor spreading on the rock stresses in Sweden. Similar conclusions are also obtained from focal plane analyses of seismic events in the Baltic Shield /5.5-48, 49, 50/.

This present-day super-regional tectonic state, which was initiated about 50 million years ago when the Atlantic began to form, is expected to persist during the next 100 000 years /5.5-26/. However, as far as the stress situation is concerned, it is necessary to take into account expected changes caused by glaciations and deglaciations /5.5-27, 28, 29/.

Dating techniques have been developed in recent years to determine when the most recent significant movement has occurred in individual fractures or zones. Examples of dating methods are paleomagnetism, radiometric dating, electron spin resonance (ESR) and petrographic evolutionary history. A comparative study of different methods has been performed on fracture-filling material from the Äspö HRL /5.5-30/. The study has yielded valuable experience of sampling technique, measuring accuracies and representative time resolution. In the project in question, the K-Ar analyses were considered to be the most reliable, and the interpretations suggest that the most recent significant fault movements took place more than 300 million years ago. In the near future, different dating methods for the activity of fractures can be expected to become valuable tools for shedding light on the stability of the rock.

Glaciations can affect the safety of a deep repository. In cooperation with Teollisuuden Voima OY (TVO), SKB has surveyed the international state of knowledge concerning future ice ages and when they can be expected, and what changes in the geosphere may then occur /5.5-27/. Interesting questions in this respect are mechanical aspects, groundwater hydraulics and groundwater chemistry.

SKB has had a numerical glaciation model of Scandinavia developed. The three-dimensional model is time-dependent and includes thermomechanical coupling /5.5-32/, see Figure 5.5-4. The glaciation model is driven by changes in the air temperature and predicts the state of the ice mass on a predetermined topography and how the bedrock is affected mechanically. A simple groundwater flow model has also been coupled to the model /5.5-33/ which makes it possible to perform general and regional groundwater simulations during both the glaciation and deglaciation phase, see further section 5.5.9.

Previous stability calculations with an ice load and where changes in water pressure have been taken into consideration show that any movements are absorbed in already existing zones. In a calculation example based on data from the Finnsjön study site, the movement amounts to about 0.05 m in a normal case. In extreme situations with low in-situ stresses, displacements of about 0.5 m could be obtained in zones. It is assumed that canisters will not be emplaced in such zones /5.5-34, 35/.

The aforementioned glaciation model will make it possible to shed further light on the prospects of reactivation in zones and possible hydraulic fracturing of the rock due to high water pressures during a glaciation.

Land uplift following the most recent glaciation is a conspicuous geological process in Sweden, especially along the coast of Västerbotten in northern Sweden where the land is rising relative to the Bothnian Sea at a rate of about 9 mm per year.

At the beginning of the melting phase of the Weichsel Glacial Stage (about 18 000 years ago), the surface of the world ocean was about 120 m lower than today and the surface of the ocean started to rise (eustatic rise). The warmer climate brought large flows of meltwater to the oceans. As the continental ice sheets gradually melted, the pressure of the ice on the earth's crust decreased and a process of land uplift began (postglacial isostatic rebound). The previous highest coastline and the evolutionary stages of the Baltic Sea are shown in Figure 5.5-5.

Viewed in an overall perspective, land uplift has been and is a relatively continuous process in space and time. Within the area covered by a deep repository, differences in the rate of land uplift are completely negligible for the mechanical stability of the repository. Based on detailed Quaternary geological studies, however, it is possible to analyze shoreline displacements that could be a sign of local postglacial movements in existing fractures or zones. SKB is funding some such studies, the results of which are expected to be published within the coming year /5.5-37, 38/.

Our knowledge of the process of land uplift can be expected to be deepened by data from the recently established GPS (Global Positioning System) network. Approximately 20 fixed measurement stations were recently commissioned in Sweden. Fine adjustment, calibration and analysis of measurement accuracy are currently under way /5.5-39/.

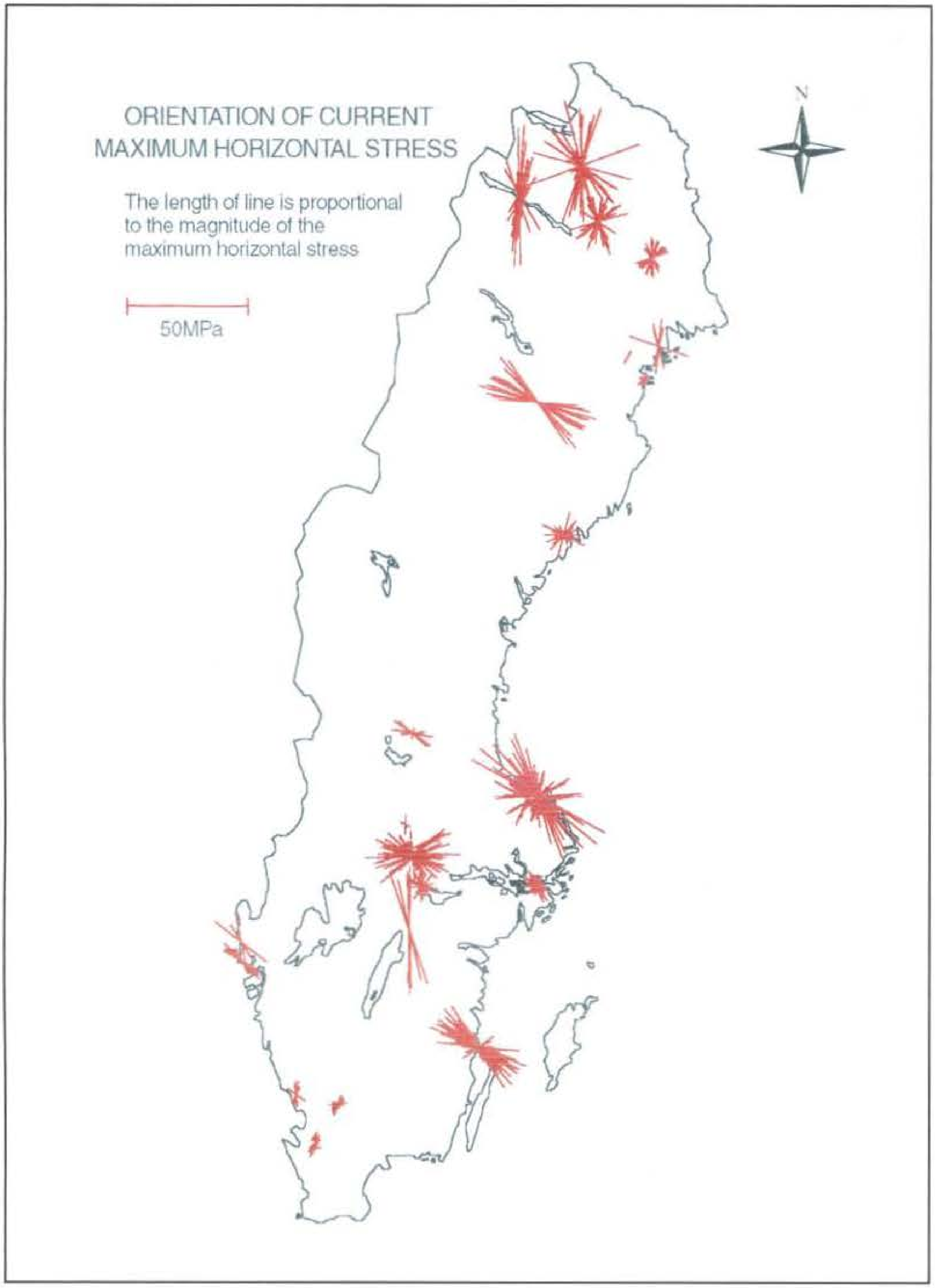


***Figure 5.5-3.** Rock stress measurements at levels of 400–1000 m below the surface in Sweden (from /5.5-31/).*

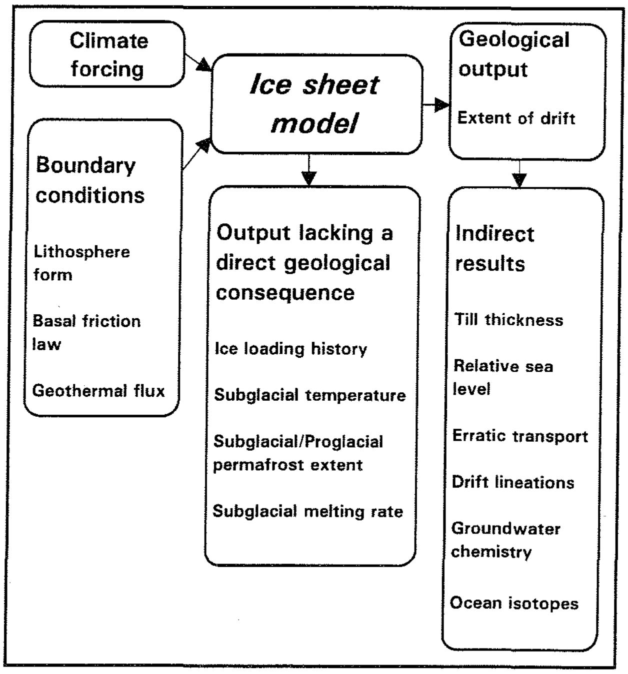


Figure 5.5-4. *Input data and results from SKB's glaciation model (after /5.5-32/).*

Neotectonic and postglacial movements are objects of thorough studies. By "neotectonic movements" is usually meant displacements that have taken or are taking place during the current tectonic regime, i.e. during the time when the Atlantic Ocean has existed. Movements after the most recent deglaciation are called postglacial. It is essential to ascertain whether such movements can lead to new fracturing or seriously alter the hydrogeological or chemical conditions for a deep repository.

Postglacial faults in the northern part of the Baltic Shield have been known and have been the subject of investigations for about 20 years /5.5-40, 41/. During the period 1986–1992, SKB carried out a comprehensive programme of geoscientific research in the Lansjärv area, about 150 km north of Luleå. The field studies were concentrated to certain sections of the faults and also included test pit investigations /5.5-42/. An excursion was arranged to the area with international experts in June 1991. Summarizing reports /5.5-43, 44/, including expert comments, conclude the following:

- The postglacial faults are primarily reactivations of older dominant zones, but the occurrence of some few new fractures cannot be ruled out.

- The causes of the postglacial movements are probably a combination of relatively rapid changes of the vertical loads (associated with deglaciation) and horizontal compression from the Mid-Atlantic Ridge related to continental drift. Landslides and violently disturbed soil strata (seismites) are clear indications of brief instability.

- No clear evidence is available today to suggest that the postglacial faults are still active. Thus, these fault movements were probably caused by specific stresses in conjunction with glaciation and deglaciation and have little or no connection with the present-day stress situation in northern Sweden.

Some researchers claim that postglacial structural elements not only occur in northern Sweden but are common all over the country /5.5-45/. Rock movements are said to have taken place in conjunction with the most recent deglaciation. It is asserted that indications of this can be found in redistributions of boulder accumulations at the surface of the crystalline basement. There is uncertainty as to the depth of the structures, however.

The previously mentioned projects intended to map displacements of old shorelines, as well as various dating projects and use of GPS technology, will shed further light on neotectonic and postglacial phenomena.

Seismicity can be said to be a sign of active tectonics in a geological time perspective. More than 95% of all earthquakes take place at the boundaries of the continental plates. Approximately a million earthquakes with a magnitude of more than 2 on the Richter scale take place annually in the world. Of these, about 10 quakes occur in Sweden. In other words, our country is a seismically inactive area. The biggest earthquakes in Sweden reach a maximum magnitude of about 5.

The Swedish earthquakes are mainly concentrated in two areas. One area extends from Lake Vänern down to the west coast. The other area follows the coast along the Gulf of Bothnia towards Tornedalen and northern Lapland. The majority of the Swedish quakes take place deep down in the bedrock, so that the epicentre of the quake lies about 10–20 km below the ground surface and the movements there are small. Calculations indicate displacement sums of about 10 mm at magnitudes of 5 /5.5-46/. The movements take place as a reactivation in an existing fault structure and within a radius of about 900 m down at the epicentre of the earthquake.

The mechanisms that control the quakes within the continental plates, for instance within the Baltic Shield, are relatively poorly understood /5.5-47/. In Sweden, the discussion concerns whether the earthquakes are controlled by the processes of plate tectonics, the ongoing process of land uplift, or a combination of the two mechanisms /5.5-47/. Seismic measurements /5.5-48, 49, 50/ show that most of the stress that triggers an earthquake has a compression direction of N60W, which is roughly perpendicular to the continental movement from the Mid-Atlantic Ridge. The worldwide database from the World Stress Map Project also exhibits good agreement between crustal plate tectonics and the largest horizontal principal stresses, i.e. compressions. Certain deviations in the stress field occur in the Baltic Shield, especially

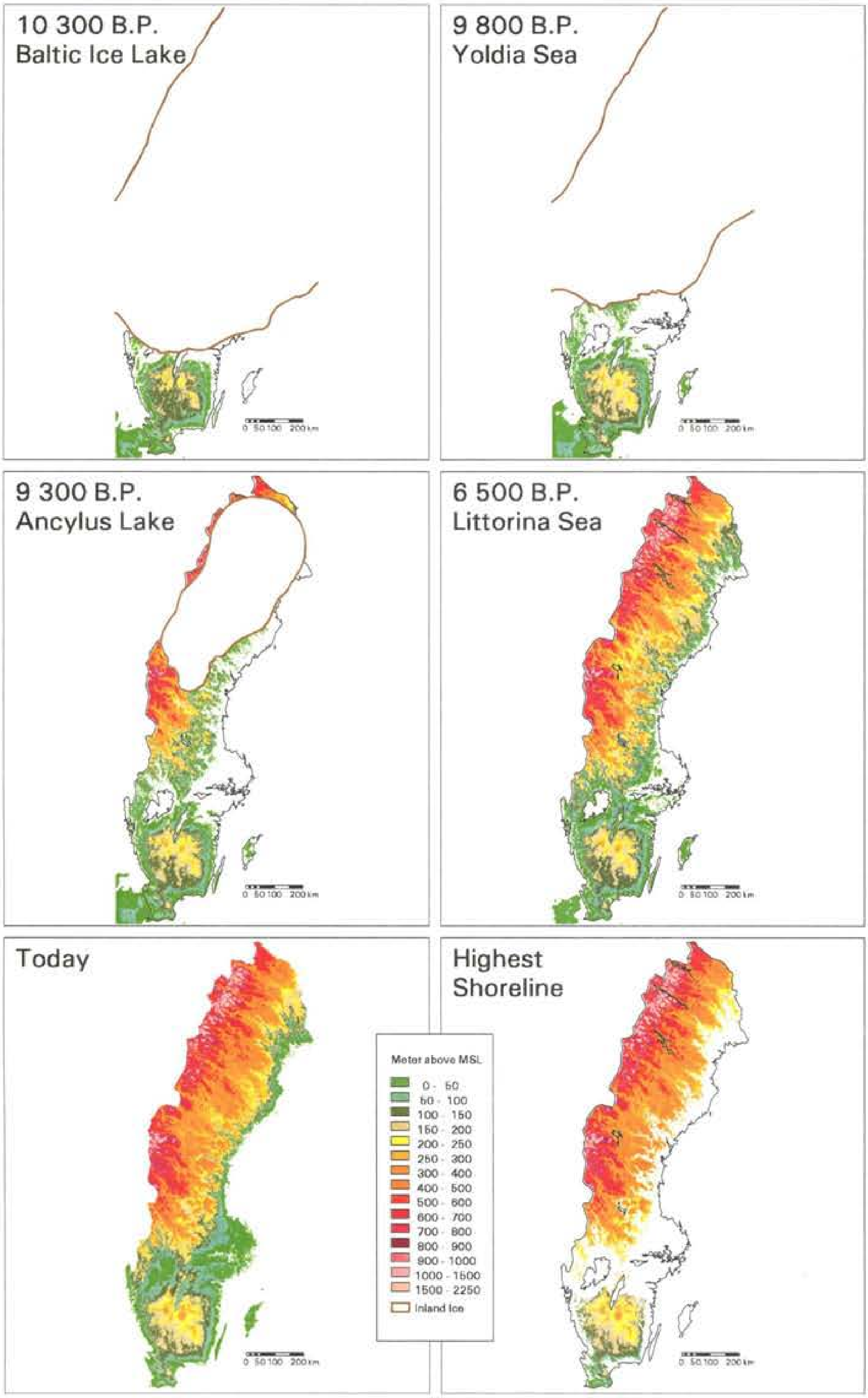


Figure 5.5-5. *The different evolutionary stages of the Baltic Sea after the most recent glaciation and a picture of the previous highest coastline. The pictures were produced from SKB's Geographic Information System.*

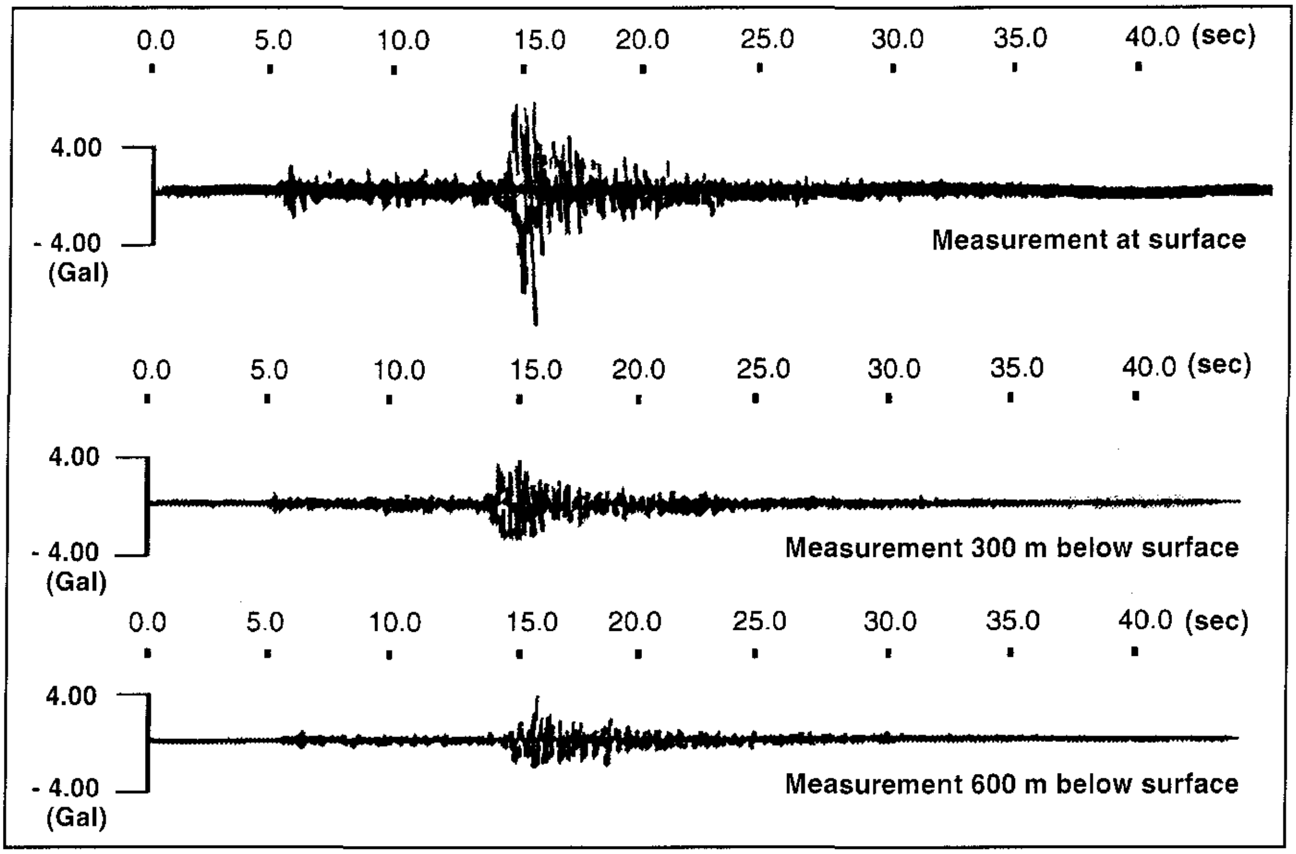


Figure 5.5-6. An example of the decline of the vibrations with depth. The earthquake took place on 27 January 1991 with a magnitude of 4.6, near the Kamaishi Research Mine in Japan. The seismograms show registrations of the quake made at different depths.

near the ground surface, which can be explained as effects of the processes of glaciation and postglacial land uplift. A separate seismo-tectonic compilation carried out on behalf of SKB particularly emphasizes the influence of land uplift /5.5-51/.

As far as the effects of earthquakes on underground facilities are concerned, the mechanical stresses on such facilities are in general less than for facilities on the surface of the ground. Many observations, above all from mines, exist to support this contention /5.5-52, 53/. SKB has recently become involved in a Japanese project in the Kamaishi research mine in order to study the seismic and construction-related effects of earthquakes. Kamaishi is situated in a seismically active area with frequent quakes with magnitudes of 5-7. Figure 5.5-6 shows results from seismographs in Kamaishi at different levels below the ground surface. The free energy (the amplitude of the acceleration) is greatest at the ground surface and declines with depth.

In addition to the mechanical effects of seismicity, the geohydraulic and hydrochemical effects are also being studied both at the Kamaishi Mine /5.5-81/ and in other international projects /5.5-54, 55/.

In summary, Sweden is located in a seismically inactive region. There are no signs today that this will change on a 100 000-year time scale, except for the changes in stress conditions that might be caused by a future ice age.

Induced loads implies rock stresses that arise as a consequence of the disturbance caused by the very existence of a deep repository or its construction. Induced stresses cannot be avoided, as they occur necessarily as a consequence of the construction of the deep repository. The questions are where, when and how displacements and stresses will occur. The induced loads, and movements associated therewith, tend to be local and to be initiated in the immediate vicinity of the deep repository.

The creation of cavities in the rock mass causes stress redistribution and stress concentrations. The short-term stress picture around the repository depends on, besides the properties of the rock mass (initial stresses, fracturing and strength), the extraction method (careful or conventional drilling and blasting) and the geometric shape ("rectangular" or "circular" tunnel cross-section). The rock excavation works (drilling, blasting) causes some fracturing of the rock near the tunnels. A high-strength and fracture-poor rock promotes the risk of rock burst.

Heat generation in the stored waste will give rise to an elevated temperature in the vicinity of the deep repository up to about 80°C locally, which then slowly declines. Locally around the deposition tunnels, the thermal load causes increased tangential stresses. On cooling, sections with low stresses can arise with a risk of local instability (rock outfall). Local temperature differences during the heating phase (gradient problems) can lead to increased fracture formation. The time perspective is crucial for the importance of thermo-induced stresses.

In the long run, the rock will strive by means of creep to even out stress concentrations. An ongoing very slow fracturing of the rock near the tunnels can be expected.

The induced stresses are known by experience from similar underground excavations, such as mines and hydropower plants. There are good opportunities to calculate the mean occurrence of such stresses in the facility with the aid of well-documented models. The greatest difficulty lies in quantifying different types of long-term effects. The local variations that occur can be handled, provided quality control is effective during the building phase /5.5-57/.

For further comments and description of the state of knowledge when it comes to the repository's design, layout and construction methods, see chapter 8.

Activities in relation to goals in RD&D-Programme 92

A number of goals were set up in RD&D-Programme 92 for the R&D work on bedrock stability during the period 1993–1998. Here is a brief account of the situation in relation to the goals:

- Carry out a seismotectonic compilation for the Baltic Shield. – A separate report has been written and presented at an expert seminar /5.5-51/.

- Carry out a pedagogical compilation that shows the brittle-tectonic history of the Baltic Shield with the load situations that have taken place. – A separate report has been compiled, and it was also presented at an expert seminar /5.5-25/.

- Make a detailed study of and map the land uplift in different regions of Sweden. – Compilation work is under way following field work. The intention is to initiate the activities based on the results of GPS measurements.

- Carry out detailed studies of former shorelines in some regions of Sweden to clarify postglacial tectonics. – Compilation work is under way following completed field work.

- Increase knowledge of the brittle-tectonic fragmentation of the crystalline bedrock. – Certain studies have been conducted within the framework of the Äspö Project /5.5-19, 59/. Literature studies are under way and rough data simulations have been carried out.

- Further refine methods for dating fracture zone movements. – A separate report on results has been compiled /5.5-30/. The work has been presented at several international conferences. Scientific papers have been published /5.5-58/. Additional measures are planned in Laxemar, borehole KLX 02 and in the Äspö HRL.

- Increase understanding of the representativity of rock stress measurements. – A database of reliable stress measurement results has been compiled within the framework of the siting programme's general studies. Programme work is under way to initiate a separate study.

5.5.5 Groundwater chemistry

The importance of groundwater chemistry and its coupling to the mineralogical composition of the rock and to hydrological conditions are examined in this section.

The goal of the efforts within SKB's hydrochemical and geochemical research activities is to be able to ensure a favourable chemical environment in the repository by

- clarifying geohydrochemical conditions of importance for the repository's long-term performance,
- clarifying the processes that can affect the geohydrochemical conditions over long periods of time,
- supporting the geohydrological groundwater flow models via hydrochemical observations in the bedrock.

A description of the state of knowledge within the area is given in RD&D-Programme 92. For a full account, see this presentation and SKB's Annual Reports. New knowledge beyond this has been obtained within the following areas:

Groundwater types with different origins

Both fresh and saline waters in the rock's fracture systems are mixtures of several water types with different origins /5.5-145/. Multivariate analysis has been used to identify and group the water samples and to identify end members. Groundwater from Äspö and the deep borehole KLX 02 at Laxemar (see section 5.5.7) can be described as a mixture of modern infiltrated fresh water, modern Baltic Sea water and very old saline water, see Figure 5.5-7. The figure shows that water samples taken in various contexts are tightly grouped. For example, the waters sampled during the pre-investigation phase are a mixture between "saline water" and "glacial water". The water sampled in the tunnel has a larger content of "Baltic Sea water".

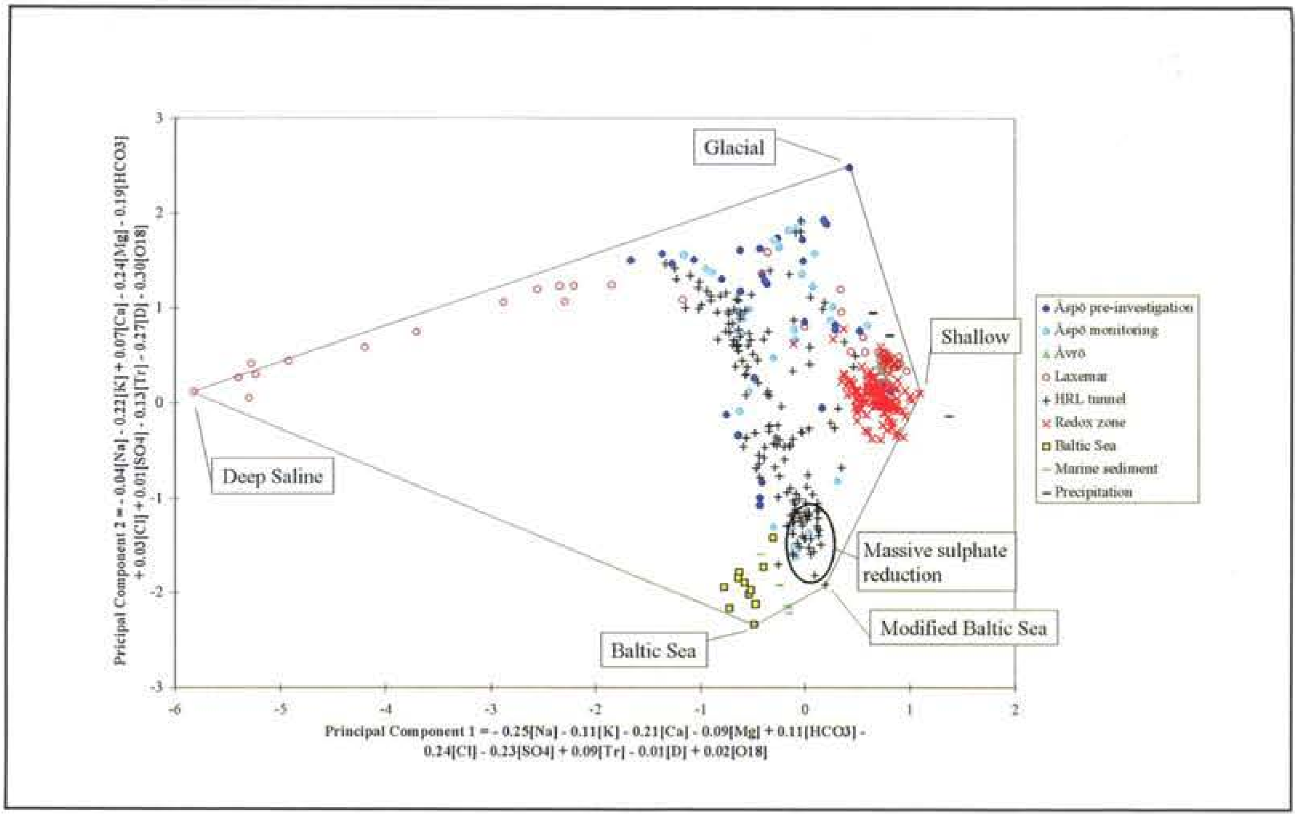


Figure 5.5-7. *Results of principal component analysis of Äspö data. The different selected end members are indicated. The area with massive sulphate reduction is marked. The importance of the different elements is shown in the equations for the axes.*

By making use of the special character of the different water types (i.e. content of certain substances and isotope ratios), it is possible with multivariate technique to determine the proportions of constituent original waters in a water sample with an estimated uncertainty of about ±10% /5.5-146/. This multivariate-based evaluation technique will be further refined in preparation for future site investigations. The goal is to be able to identify favourable and unfavourable geochemical conditions with respect to the function of the different barriers at an early stage of a site characterization.

Groundwater residence time

RD&D-Programme 92 describes how the water's chemical composition, in combination with different stable and radiogenic isotopes, can be used to determine the groundwater's residence time. The origin of the various water types can also be used to determine the water's turnover time. Lately, the combination of the strontium-87, carbon-13 and oxygen-18 conditions in groundwater and fracture-filling minerals has been very useful.

An aggregate interpretation of the data that describe groundwater turnover on Äspö provides the following picture: Down to a depth of about 500 m, the groundwater on Äspö has been affected by conditions prevailing since the most recent ice age. It is possible to trace the earlier stages in the evolution of the Baltic sea in the water composition.

At even deeper levels, the water is insignificantly affected by postglacial events and therefore to be regarded as stagnant in a 10 000-year perspective /5.5-147/.

The very saline water that has been found at a depth of about 1000 m in KLX 02 can be regarded as very old and stagnant /5.5-145/. To further clarify this relationship, more dating methods will be applied, including Cl-36 analysis and noble gas analyses. The results from both Äspö and Laxemar show that the chemical conditions at great depth, 1000 m, have presumably been stable on a time scale of 100 000 years or longer.

To be able to evaluate the groundwater flux in the environs of Äspö in detail, the evolution of the Baltic Sea has been charted /5.5-148/. The changes that can be used to trace previously prevailing groundwater conditions are mainly changes in the isotope ratios of oxygen-18 and deuterium and carbon dioxide pressure. The values of these parameters and others have been listed for the conditions that prevailed before, during and after the glaciation.

This investigation work is an important link to the paleogeohydrological studies and modellings that are expected to go on for many years. The work is aimed at providing a global picture of the variations in groundwater flow and composition that could conceivably occur in conjunction with glaciations, see section 5.5.8.

Redox conditions

In order that the copper canister should not corrode, oxygen-free (anoxic) conditions are required. Changing from an oxygen-rich (oxidizing) to an oxygen-free (reducing) environment requires reactions and processes that consume the oxygen (redox buffer). This usually takes place in the most superficial rock at a depth of a few tens of metres. It has been assumed that the redox buffer capacity, as well as the redox buffer level (Eh value), is dominated by reducing (iron-containing) minerals in the bedrock. (See RD&D-Programme 92 for a more thorough description.)

However, *bacterial oxygen reduction* has been found to be most important when it comes to consuming dissolved oxygen in infiltrated surface water /5.5-149/. The water's content of organic matter has been transformed to hydrogen carbonate and the oxygen has been reduced via bacterial action. If the quantity of organic matter exceeds about 10 mg/l in the infiltrating water, all dissolved oxygen will be consumed near the ground surface. At a large surplus of organic matter, the carbon oxidation proceeds via bacterial reduction of iron(III) minerals and sulphate even under oxygen-free conditions.

Under forced water flux as well, which can be caused by inflow to various parts of the repository, dissolved oxygen will be reduced near the ground surface and will thus not affect the reducing conditions that prevail in the bedrock prior to repository construction.

The occurrence of *bacterial sulphate reduction* has been detected in the tunnel section between Hålö and Äspö. An integrated interpretation of hydrological, chemical and biological data shows that it is probably due to the presence of about 40% or more sediment water (see Figure 5.5-7) that this process has occurred on a large scale /5.5-150/. Chloride concentrations in the range 4000–6000 mg/l and TOC concentrations >10 mg/l correlate positively with high hydrogen carbonate concentrations, low sulphate concentrations and the presence of sulphate-reducing bacteria. The product of this process is sulphide, which can in this way be generated in large quantities, about 100 mg/l, locally. Sea sediment with high organic content can therefore constitute a condition for the occurrence of sulphate reduction, cf. 5.4.6 and 5.6.2.

Water-mineral reactions

The composition of the groundwater is mainly determined by five different processes:

- Equilibrium with minerals on fractures and in the rock matrix.
- Surface reactions: ion exchange and sorption.
- Dissolution and precipitation of minerals.
- Bacterial activity e.g. of sulphate- and iron-reducing bacteria.
- Mixing of waters with different origins.

In order to be able to ascertain the effects of water-mineral reactions, the mix of different types of water must first be determined. With multivariate technique it is possible, as described previously, to quantitatively derive the proportion of different original waters in a water sample. The mix calculations are primarily based on the content of so-called conservative constituents, mainly chloride and stable isotopes. Non-conservative constituents then exhibit a deviation in concentration compared with the mix calculation. The deviation is the result of water-mineral reactions.

The interaction between water and minerals has, over a shorter or longer period of time, led to the composition of the particular original water. In the deep saline water from KLX 02, oxygen and hydrogen isotope data deviate from the linear relationship of the Meteoric Water Line, which applies to all meteoric waters. This is a strong indication of a water-mineral interaction that has gone on for a very long time, perhaps up to millions of years. The extremely high salinity may also derive from a very long residence time.

At prevailing groundwater temperatures, the *new formation of stable secondary minerals* is very slow and equilibrium is only achieved between water and reactive minerals such as calcite. Traditional geochemical equilibrium modelling can therefore not be expected to give a correct prediction of the groundwater's chemistry /5.5-154/, since the water's chemical composition is not in equilibrium with the different mineral phases. This is verified by the pilot test that was performed at Äspö of sampling water from low-conductivity blocks and analyzing main and trace elements /5.5-151/. Table 5.5-1 shows a comparison between samples taken in low- and high-conductivity boreholes in different rock types /5.5-152/.

The fact that there are no great differences between the composition of samples in low- versus high-conductivity blocks and in diorite versus greenstone indicates that the mineral-water reactions on a micro-scale are of subordinate importance compared with mixing and other process that take place on a macro-scale.

Ion exchange equilibria with clay minerals in fractures and fracture zones have a notable effect on water chemistry, above all on the concentrations and proportions between Na, Ca, Sr, Rb and Cs /5.5-147, 153, 154, 155/. The kinetics of the ion exchange reactions are such that the reactions can be studied in the lab and in the field and are affected by changes in groundwater conditions during tunnel construction.

Table 5.5-1. Chemical composition of groundwaters in Äspö diorite and greenstone. The concentrations are give in mg/l, * in μg/l.

	ÄSPÖ DIORITE		GREENSTONE
Substance	High conductivity	Low conductivity	Low conductivity
flow ml/min	600	30	2.5
Na	2030	1990	2080
Ca	1700	1680	1720
Mg	77	72	68
HCO_3	40	34	24
Cl	6400	6200	6600
Br	34	38	45
SO_4	435	444	450
Sr	26	27	30
Fe	0.44	0.32	0.05
Mo*	50	71	79
U*	0.6	0.07	0.53
La*	0.7	0.56	0.76

The *dissolution* of easily weathered minerals such as calcite, Ca-plagioclase and biotite can also be expected to contribute to changes in the water's composition in a shorter time perspective. These reactions preferably take place near the ground surface where the water's pH value is low and the weathering takes place at a rate that can be studied in the lab /5.5-156/.

Bacterial processes can, as mentioned previously, influence the composition of the water. This, however, requires a good supply of organic matter or another substrate. Bacterial processes that have influenced the water chemistry on Äspö are:

- Reduction of dissolved oxygen that has led to an increase in the hydrogen carbonate concentration and a decrease in the concentration of organic matter /5.5-155/.
- Reduction of iron(III) minerals and accompanying increase in carbonate and iron concentration /5.5-155/.
- Reduction of sulphate and increase in carbonate and sulphide concentrations /5.5-150/.

These rapid processes can lead to new formation of minerals such as calcite, magnetite and pyrite. Calcite and magnetite have been observed in fresh rust (iron hydroxide) precipitates /5.5-153/.

The *fracture-filling mineral composition* bears traces of former hydrochemical conditions. This can be utilized in two different ways: 1. to trace previous groundwater flow patterns 2. to evaluate the transport of radionuclide-like substances. Research aimed at clarifying former flow situations is being conducted within the hydrogeological programme, see section 5.5.8.

The distribution of uranium, thorium and rare earth metals (radionuclide analogues) in fracture-filling minerals and water is described in RD&D-Programme 92, Detailed R&D-programme 1993–1998. Since then the binding to the three most common minerals has been studied by sequential leaching of clay minerals, iron hydroxides and calcite /5.5-153/. These three mineral types constitute the largest contact surface with water in fractures and fracture zones on Äspö.

Ion exchange with clay minerals is the most important retention factor for Cs and Rb, and probably also for Sr (which is also incorporated in calcite). Th and rare earth metals are enriched in clay minerals, but also in iron oxides and calcite. Ba and Ra are found in iron oxide and calcite precipitates.

Incorporation in calcite mineral can, in a long time perspective, be regarded as a completely reversible process, since calcite precipitation and dissolution are fast reactions that are influenced by carbon dioxide pressure, pH and temperature conditions in the rock.

Cs uptake on clay minerals consists of a fast and a slow sorption, previously called reversible and non-reversible, respectively. In a long time perspective, however, it is probable that the slow sorption is also reversible, e.g. the Cs concentrations in water of very high salinity in the borehole KLX 02 are correlated with the Na concentrations, which are controlled via reversible ion exchange /5.5-154/. Rb and Ba are also sorbed reversibly on clay minerals.

Continued work will be focused on better clarifying reversible/non-reversible sorption and its importance on the time scale of the repository.

Activities in relation to goals in RD&D-Programme 92

A systematic processing and sorting of all chemistry data in SKB's database – GEOTAB – into quality classes and type classes has been carried out /5.5-157/. Waters that are representative of the environment where they have been sampled are considered to be of high quality. The quality classification has been done in cooperation with TVO and has thereby been able to utilize a larger database. The type classification is an interpretation of existing data that has been systematically applied to the evaluation of conditions at both Äspö and Laxemar /5.5-145, 146/.

Multivariate analysis is used in connection with the type classification. This increases the reliability of the interpretations in that all evaluations are done in the same way. The quality classification cannot be performed in the same strict manner, however. A certain measure of expert judgement is necessary /5.5-157/.

The distribution of trace elements (radionuclide analogues) in fracture-filling minerals has been determined for the most commonly occurring minerals /5.5-153/. A traditional K_d determination with the same mineral samples is planned.

Different isotope methods have been tested in analysis of fracture-filling minerals, drill cores and water for determination of the groundwater's residence time and history /5.5-147, 153, 154, 155/. Their usefulness is strongly dependent on the complexity and variations in the investigated material. An example of this is the carbon-14 determinations that have been done in the redox zone in the Äspö HRL. Carbon-14 activity is highest in water from the deepest borehole and lowest in the shallowest. Counted in age, the analyses give 3,365 years for a depth of 15 m and 250 years for a depth of 70 m. Even though the C-14 analyses are misleading as a dating method in this case, they have been useful for quantitatively establishing the effects of bacterial oxygen reduction.

The presence of much saline and presumably stagnant water at great depth both on Äspö and at Laxemar is significant for paleohydrogeological and regional groundwater conditions. The hydrochemical conditions are the subject of extensive analyses in this respect /5.5-145, 146, 147, 154/. The work will continue within the framework of the paleohydrogeological programme /5.5-158/.

The effects of acidification on the rock /5.5-159/ and on the water /5.5-110/ have been investigated. In summary it can be concluded that acidification caused by the combustion of fossil fuels does not have any appreciable effect on a deep repository.

Water in low-conductivity blocks in the rock has, contrary to expectation, been found to have a composition similar to that of water in more conductive blocks. Variations in rock type are also of very little importance for chemical composition /5.5-151, 152/.

The size of the wet surface in the flow paths from the ground surface down to the redox zone was expected to be of importance for the rate of oxygen reduction. The redox experiment showed, however, that it is bacterial activity that consumes the dissolved oxygen. Since the reduction rate is then dependent on the supply of oxidizable organic matter, the wet surface is irrelevant in this context /5.5-149/.

5.5.6 Ability of the rock to limit nuclide transport

The rock's ability to limit the transport of various substances is a composite property, related to groundwater flows and flow paths. These are in turn determined by the rock's hydraulic conductivity, the degree of inhomogeneity, the topography of the area, water balance, etc. If water transport takes place without the influence of retentive mechanisms, it is regarded as non-reactive. The non-reactive transport process includes advection (convection), kinematic dispersion and molecular diffusion.

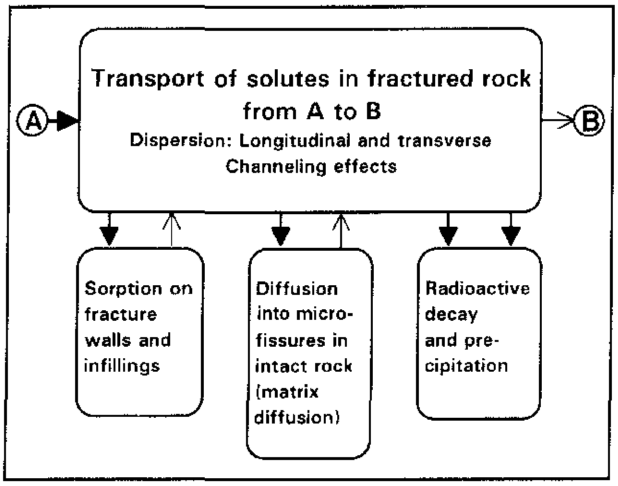


Figure 5.5-8. Schematic illustration showing the retention processes on nuclide transport in the bedrock (after /5.5-82/).

The aggregate retardant effect on nuclide transport is determined by the diffusion into intact rock (matrix diffusion) and by the bedrock's sorption properties. These are in turn determined by the groundwater chemistry, the mineralogical composition of the rock, microfissures in the rock, the character of the fracture pattern and the availability of sorption surfaces, see Figure 5.5-8.

The overall purpose of the RD&D work devoted to the ability of the rock to limit groundwater flow and pollutant transport is to:

- meet the hydrogeological functional requirements so that the deep repository can be constructed and function stably during the deposition phase.
- be able to describe and quantify how the groundwater flows are distributed in the bedrock,
- quantify processes of importance for solute transport,
- describe the rock's retention properties,
- be able to identify bedrock with good retention properties.

A brief resumé of the general state of knowledge with references to studies conducted at SKB during the period 1993–1995 is given below. The reader is otherwise referred to SKB's Annual Reports and reports in the TR series.

Groundwater flow and advection

Many studies have shown that Darcy's law is applicable within a wide range of hydraulic gradients. Darcy's proportionality constant, which is normally called hydraulic conductivity, is related to the density and viscosity of the liquid, and a form factor that is dependent on the geometry of the liquid passage. The most common model for calculating and describing flow in fractured rock, which can be presumed to be laminar, is based on Darcy's law.

During the past decade, theoretical and experimental studies have contributed towards a gradual improvement in our understanding of the flow process in fractured bedrock. Use of geostatistical methods for processing of hydraulic properties and fractal characterization of fracture lengths, fracture apertures, etc., as well as knowledge of two-phase flow and multi-porosity systems, has increased. Geophysical methods have been developed into valuable complements to hydraulic tests, thereby creating a better conceptualization for the modelling work. Greater interest is being devoted to processes coupled to the groundwater flow, i.e. thermo-hydro-mechanical relationships and hydrochemical dependencies.

Hydraulic gradients that control the groundwater flows in the bedrock have been found by experience to exhibit relatively little variation. Ordinary values are 0.1–1%, and the gradient can increase slightly where large topographical differences exist.

Credible boundary conditions are essential in groundwater modelling. The three-dimensional models are becoming more common, which means that increasingly complex flow geometries are being analyzed. The greatest interest in groundwater modelling for a repository is being devoted to levels about 500 m below the ground surface. Based on classical theory for groundwater flow, the flow at a deep repository can be expected to be influenced by regional groundwater systems. The local topography at a repository area with small height differences probably has very little to do with the flow conditions at the repository level. The flow at the deep repository is then determined by regional gradients.

Using the Swedish height database, wavelengths and amplitudes in the Swedish topography are currently being analyzed (a signal analysis approach). The goal of the study is to increase understanding of the depth dependence of the hydraulic gradient and the influence of the topography /5.5-65/.

One of the driving forces for groundwater flow is differences in the density of the liquid. The groundwater in the bedrock exhibits a salinity variation that influences the density and the prevailing pressure conditions in detail. If it were possible to measure vertical pressure variations at model boundaries with greater accuracy to a depth of 1 km, more realistic regional flow descriptions would probably be obtained than flows calculated from boundary conditions based on topographical data.

Another aspect that has a bearing on the salinity and density of the groundwater is any convection flows that might arise due to heating from deposited canisters. Results show that a salinity gradient with depth has an opposing and counterbalancing function on any convection flows /5.5-66/.

Hydraulic conductivity is a central parameter for being able to describe the flow of the groundwater in any geological media. As mentioned above, it is related to the properties of both the flow medium and the liquid. (If conductivity is integrated over the thickness of the water-conducting stratum, the parameter is termed transmissivity.)

In-situ methods for determination of hydraulic conductivity and storage characteristics in fractured rock are constantly being refined. Great efforts are being made in particular within the field of gas and oil prospecting. The analysis methodology has been improved through the Stripa and Äspö projects, particularly when it comes to cross-hole tests (interference tests). There is nevertheless a need for a greater understanding of the dependence of the in-situ methods on scale, rock heterogeneity, dimension of measurements, rock volume covered by measurement, etc. This work will also be pursued in conjunction with the Äspö Project and the tests that have been begun in the deep borehole Laxemar KLX 02. A separate state-of-knowledge compilation with suggestions for development was recently performed by an expert group at the initiative of SKB /5.5-69/.

In RD&D-Programme 92, it was stated that the results of several tunnel investigations have shown that hydraulic conductivities appear to decrease nearest the tunnel walls. Explanations have been sought for this phenomenon in stress redistributions and chemical precipitations. Another explanation is that the decrease in conductivity may be a phase boundary mechanism between air or other gas and water. The process is then regulated by a two-phase flow. Preliminary theoretical calculations support the latter theory /5.5-70/ and SKB has, together with the US DOE (U.S. Department of Energy), initiated experimental activities focusing on two-phase flow at the Äspö HRL /5.5-71/. Furthermore overall understanding of two-phase flow is important for interpretation and conceptualization of groundwater flows based on tunnel mapping.

Knowledge of two-phase flow in fractured rock is also essential for understanding the water homogenization of the bentonite buffer during the deposition phase and when it comes to the conditions for gas migration.

Flow porosity (kinematic) is a central parameter when the advection process or the groundwater's mean flow velocity is to be determined. Relatively few guideline values are given for crystalline rock types in the international literature. Generally speaking, flow porosity is low and on the order of 10^{-5} to 10^{-2} /5.5-72, 77, 78/.

Values of kinematic porosity can be obtained indirectly from hydraulic tests or via tracer tests. In the case of hydraulic tests, permeability is interpreted and fracture apertures are generalized using a relationship saying that the hydraulic conductivity is proportional to the fracture aperture cubed ("cubic law relationship"). In tracer tests, the available flow porosity is interpreted on the basis of a mean velocity and with reference to a kinematic dispersivity.

Within the framework of the Äspö Project, certain in-situ studies have been initiated which will provide a better database on available porosity and its variation in connection with transport modelling of groundwater /5.5-73/. On assignment for SKB, a method has also been developed for fracture porosity determination where fluorescent epoxy is injected into drill cores and mapped/analyzed by means of an image processing system, see also below and Figure 5.5-8.

Kinematic dispersion is a "mixing phenomenon" that is dependent on velocity differences for the flow in a fracture and between different fractures. The flow is mixed through fractures which intersect each other, and changes in the concentrations of solutes in time and space are obtained. It has been found that the classic dispersion equation only seems to be valid after long flow times and for large distances from the point of release. The dispersion for instantaneous releases is, for example, probably controlled by time-dependent dispersion coefficients and not by any scale effect in space /5.5-76, 79/.

Molecular diffusion entails that substances dissolved in the water (solutes) move from areas with high concentrations to areas with low concentrations (Fick's law). Molecular diffusion is generally considered to be subordinate to the effect of kinematic dispersion in non-reactive transport and is not dealt with for the fractures and zones in the bedrock /5.5-79/. The process is, on the other hand, essential for diffusion into the microfissures in the rock, so-called matrix diffusion.

The **storage coefficient** in the bedrock is of importance when the transient flow situation of the groundwater is to be described. The specific storage coefficient is defined as the volume of water removed per unit decline of the hydraulic head and is dependent on the porosity and the compressibility of the water and the rock. It has been found in theoretical studies that the storage coefficient is proportional to the cube root of the transmissivity. For more channelled flows, the corresponding relationship is a simple root expression. Field measurements of hydraulic diffusivity support these theories /5.5-74, 75, 76/.

Databases of storage coefficients for crystalline basement rock are relatively limited. As transient cross-hole tests become more common in fractured bedrock, experience of variability and possible scale effects is expected to improve. Ordinary values of the storage coefficient for Swedish crystalline basement rock lie in the range $5 \times 10^{-4} - 5 \times 10^{-6}$.

Retention

The state of knowledge concerning the bedrock's hydrochemical environment is described more thoroughly in section 5.5.5. The state of knowledge concerning radionuclides and the geochemical environment for the repository's various barriers in its entirety is described in section 5.6. This section provides a brief commentary solely on the retention properties of the radionuclides' transport pathways with respect to sorption mechanisms and diffusion into the rock's microfissures, known as matrix diffusion. Brief comments are also made on conditions for transport with naturally dissolved gases in the groundwater.

Sorption is strongly dependent on the ions' charge, hydrolysis and possible complexes with strong complexing agents. It is therefore essential to know the groundwater's pH, redox conditions and content of complexing agents such as humic and fulvic acids. Ion exchange is an important sorption mechanism for e.g. Cs^+ and Sr^{2+}. The salinity of the water is therefore also of importance, see section 5.5.5.

The minerals that constitute the substrate for sorption have different capacities to absorb radionuclides. Certain minerals are, for example, good ion exchangers, while others are not, and so on. The K_d values that are used in the safety assessment are chosen so that the retention of radionuclide transport is not overestimated. Complexing with humic and fulvic acids can reduce the sorption of some of the radionuclides. The chosen K_d values can be adjusted with this in mind /5.5-89/.

Sorbing radionuclides could in principle be transported with the water if they adhered to colloidal particles in the groundwater. The concentration of colloids in the groundwater is lower than 0.4 mg/l. They consist of inorganic particles, e.g. calcite, iron hydroxide, clay etc. and can of course sorb radionuclides. If the uptake of radionuclides on colloidal particles is reversible, it is of no consequence for radionuclide transport. Somewhere along the streamline the nuclide is then turned over to the rock. If, on the other hand, the nuclide should become sorbed irreversibly, the nuclide will be transported with the particle and, at worst, not be retarded at all by sorption in the rock. Laboratory tests verify that the sorption is largely reversible. The strength of the sorption is roughly equivalent to measured K_d values for corresponding minerals and solutes /5.5-90/.

Thorough analyses of the groundwater show that bacteria also exist at great depth. All species have not been identified, but methane bacteria and sulphate-reducing bacteria have been found. The environment is poor in nutrients. Substances that could conceivably be included in the metabolism of the micro-organisms are, for example, methane, hydrogen, organic matter, carbonate, sulphate, etc. Laboratory tests show that bacteria can take up radionuclides. In principle, radionuclides should be able to accompany bacteria in the same way as they accompany other colloidal particles in the groundwater. However, the concentrations of microbes are very low (less than 50 mg/m^3). The importance of bacteria transport for safety has been analyzed in the same way as for inorganic colloids and the conclusions are that it has a negligible effect /5.5-90/.

Development of more detailed models for sorption and matrix diffusion that will better describe the physical and chemical processes involved is being pursued both in Sweden and in several other countries /5.5-88/.

Matrix diffusion of dissolved radionuclides could take place to the micropores in the rock that surround the larger fractures and zones. At later stages, radionuclides could diffuse back to the flowing water in the fractures. These processes have noticeable effects on the transport of both non-sorbing and sorbing radionuclides. The relatively large surfaces in the micropores are of essential importance for the sorbing nuclides. The most important parameters that determine matrix diffusion are specific area, the diffusion coefficient and the diffusion porosity /5.5-77, 92/.

Gas transport of nuclides is a possible transport mechanism. Transport with naturally occurring gases (geogas) and transport with hydrogen gas generated by canister corrosion are conceivable.

Regarding geogas transport, it has been claimed that trace quantities of metals can be transported with gas bubbles in the rock /5.5-96/. The conclusion is based on analyses of geogas above relatively deeply-lying ore bodies. The gas has contained traces of metal from the ore. But the concentration of metal in the gas compared with the quantity of metal in the ore shows that only very small quantities could be released and transported to the biosphere in this manner. In order for gas bubbles to be formed, the water must be saturated with gas at the pressures that prevail at repository depth. Experience from the Äspö Project shows that the groundwater at the depth in question is greatly undersaturated with respect to dissolved gases, more than 90% of which consist of nitrogen. The depth at which the measured dissolved quantity of gas passes over into a separate gas phase is no deeper than about 50 m /5.5-89/.

Hydrogen gas can be formed by anaerobic corrosion of iron if water should enter a copper-steel canister, see chapter 6. The hydrogen gas can be a carrier of radionuclides that exist in the gas phase, for example ^{14}C, ^{85}Kr. If the hydrogen gas passes the bentonite buffer and backfill, model calculations show that the conditions exist for direct gas transport to the ground surface from the deep repository /5.5-97/. In order not to underestimate the effects of nuclide transport in a pure gas phase in SKB's safety assessments, a direct short-circuit is assumed between the near field and the biosphere. A general knowledge buildup on gas migration and two-phase flow has begun at the Äspö HRL.

Characterization of fractures with regard to nuclide transport and retention

Due to the heterogeneity of the bedrock, flow calculations and retention assessments must be based on certain assumptions. For example, channel flow with constant water chemistry, hydraulic gradient, fracture mineralogy and porosity along the entire flow path can be assumed in a transport modelling.

A transport model can be more or less grounded in geological reality. The characteristics of a fracture, such as porosity, fracture mineralizations, etc., are naturally a result of the mode of formation and development of the bedrock on a geological time scale. In recent years, SKB has started and completed several projects with the overall goal of improving the classification of individual fractures and fracture systems with a focus on radionuclide transport and retention. Fractures are thereby characterized with respect to rock type, tectonic evolution, mineralizations and alterations in the vicinity of the fractures. A fracture characterization with this focus is being applied and tested at the Äspö HRL /5.5-19/.

Both quantitative and qualitative understanding of fracture characteristics will increase as results from underground laboratories become available. This subject area has high priority when experimental activities begin in the Äspö Project.

Figure 5.5-9 provides a summary of geological, hydrogeological and hydrochemical data with a focus on the processes in a transport model that are commented on briefly in the previous sections in this chapter.

Several important results have been presented with regard to hydrothermally altered rock matrix around fractures. For the red-coloured rock near fractures in the Äspö tunnel, for example, higher porosity, lower density and greatly reduced magnetic susceptibility have been found. Furthermore, it was found in the study that calcium had been replaced by potassium and sodium in the altered portions of the rock (albitization). The red coloration in Äspö is due to an oxidation of magnetite minerals to hematite and iron hydroxides. These observations indicate properties in the fracture surfaces that contribute to strong retention of solutes /5.5-83/.

One goal is to improve our understanding of fracture flows with respect to the detailed geometric conditions that prevail in an individual fracture. SKB has had a special laboratory apparatus manufactured, a biaxial cell, where relationships between rock stresses over individual fractures and groundwater flows are studied. Half-metre long drill cores with a diameter of 200 mm can be placed in the cell. The cell is set up at the Chalmers University of Technology, Gothenburg, and image processing analysis of fractures is done at the Royal Institute of Technology, Stockholm, see Figure 5.5-10. One of the findings is that the ratio between mechanical and hydraulic mean fracture aperture is about 1.4 /5.5-84, 119, 120/.

Activities in relation to goals in RD&D-Programme 92

A number of goals were set up in RD&D-Programme 92 for the R&D work for the period 1993–1998 concerning the ability of the rock to limit transport. Following is a brief status report in relation to these goals:

- Further refine methods for description of the geometry and hydraulic properties of fractures. – This is a central field of research in SKB's activities. Compilations are being made continuously, including material from the Äspö Project.

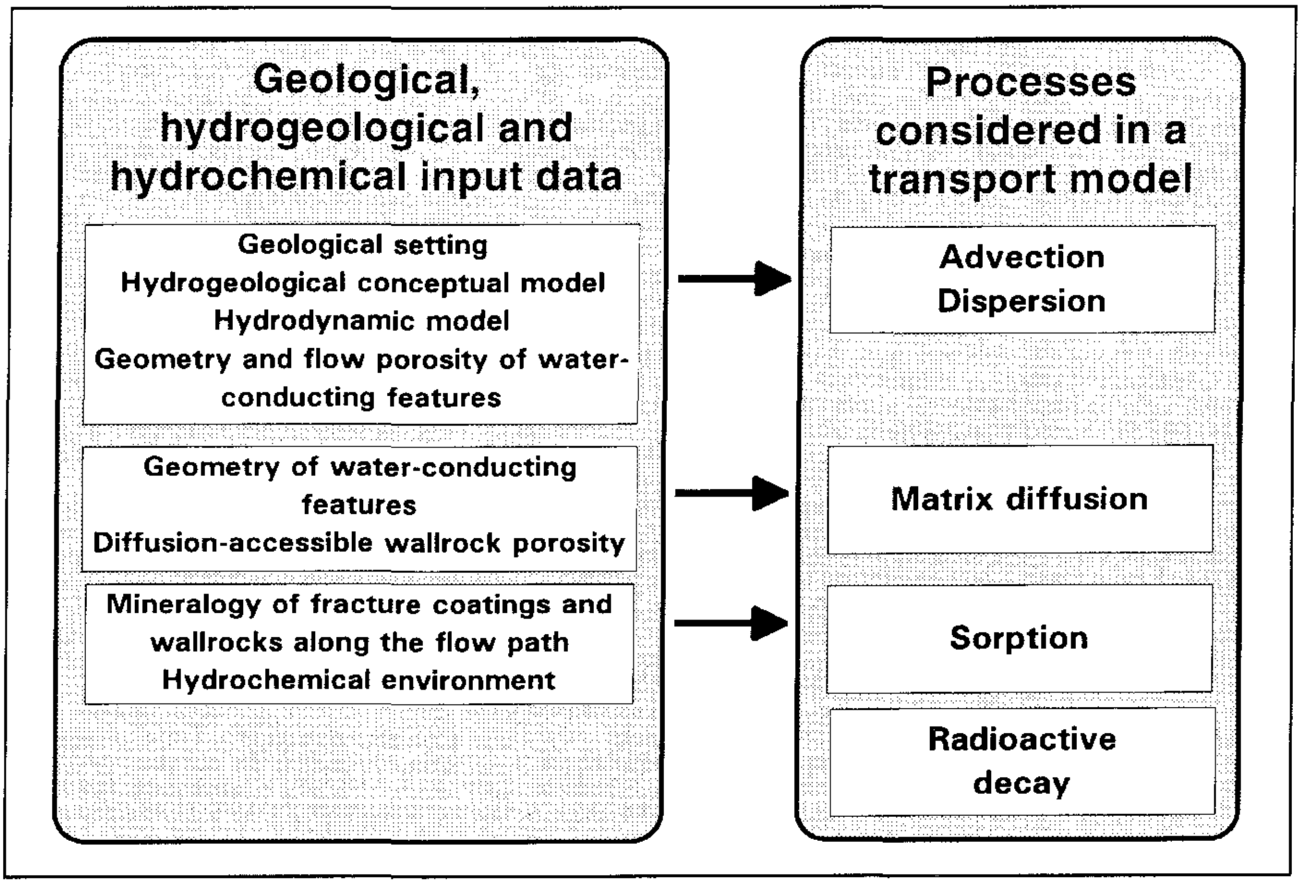


Figure 5.5-9. *Use of geological, hydrogeological and hydrochemical information in modelling of radionuclide transport – an overview of parameters and processes (after /5.5-19/).*

- Further refine in-situ methods for determination and analysis of hydraulic properties in fractured rock. – Method development has taken place in the Äspö Project and in the Laxemar deep borehole. A separate working group recently compiled a state-of-the-art report /5.5-69/.

- Investigate the large-scale dependence of the hydraulic properties on fracture mineralizations, rock stresses and former permafrost depths. – Work is being pursued with a primary focus on the correlation between permeability and rock stresses. The main sources being used for this are SGU's well archive, study site results and the nationwide rock stress database compiled by SKB.

- Investigate and compile indirect signs of the groundwater's flow pattern in fractured rock for both model structuring and verification of models. – A project for characterization and classification of fractures is being pursued in cooperation with NAGRA of Switzerland. The methods are being tested in the Äspö HRL.

- Investigate risks of short-duration pressure changes in the groundwater reservoir at repository level due to earthquakes. – Cooperation has been initiated with PNC, Japan, and SKB is participating in a project for this purpose in the Kamaishi research mine.

- Further refine theories of non-reactive flow transport in fractures and systems of fractures. – Separate laboratory studies have been conducted in cooperation with the Chalmers University of Technology in Gothenburg and the Royal Institute of Technology in Stockholm.

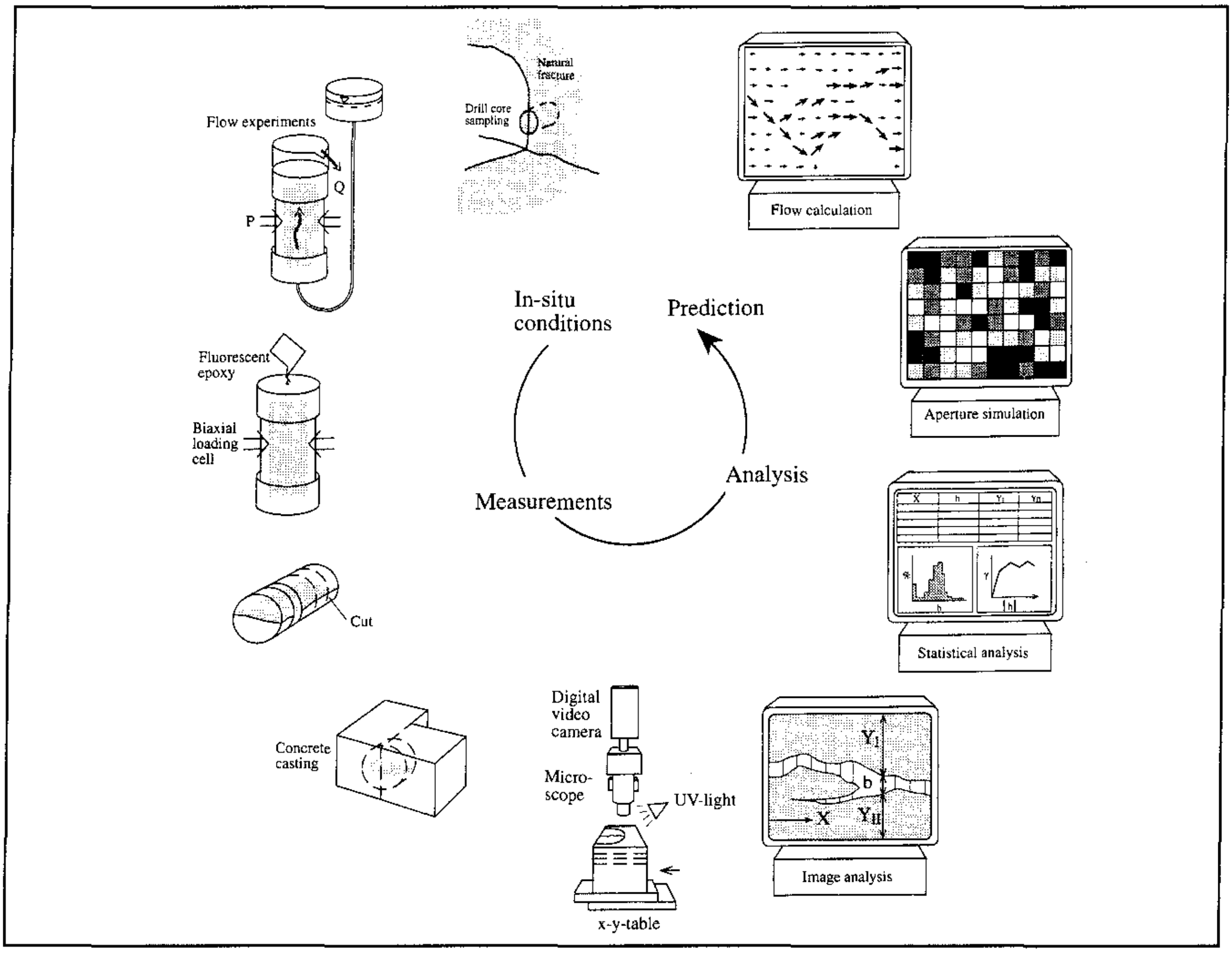


Figure 5.5-10. Survey of fracture geometries and fracture flow – project structure.

5.5.7 Project "Deep drilling KLX 02 – Laxemar"

Sections 5.5.4–5.5.6 deal with, in order of mention, the state of knowledge regarding the rock's mechanical stability, hydrochemical environment and ability to retain radionuclides. Mechanical, hydraulic, thermal and chemical aspects are all being studied in the field in a small integrated project, "Deep drilling KLX 02 – Laxemar". The project, which is being undertaken alongside of the Äspö HRL, was initiated in the autumn of 1992 with the following goals:

- to broaden knowledge of the composition and properties of the rock at great depth and to obtain new information regarding the flow pattern and chemical composition of the groundwater.

The project has further had the following interim goals:

- to identify different possible drilling techniques for exploratory drilling to great depth and to demonstrate such drilling to a depth of about 1500 m below the surface,
- to demonstrate methods for investigations in boreholes within the depth range 1000–1500 m.

The drilling of KLX 02 was carried out during the period October–November 1992 to a depth of 1700 m using the wire-line technique. An intact drill core exists for the 200–1700 m interval. After drilling, the investigative activities have included geological mapping, mineralogy, geophysical measurements, groundwater chemistry and groundwater hydraulics. Equipment has been modified to measure rock stresses at levels deeper than 1000 m /5.5-121–130, 147/. The deep borehole KLX 02 at Laxemar furnishes essential input data to SKB's paleohydrogeological programme, see section 5.5.8.

As the hole has been drilled to 1700 m, it also furnishes important information to the programme within SKB that deals with the alternative repository concept "Very Deep Holes", see section 13.2.

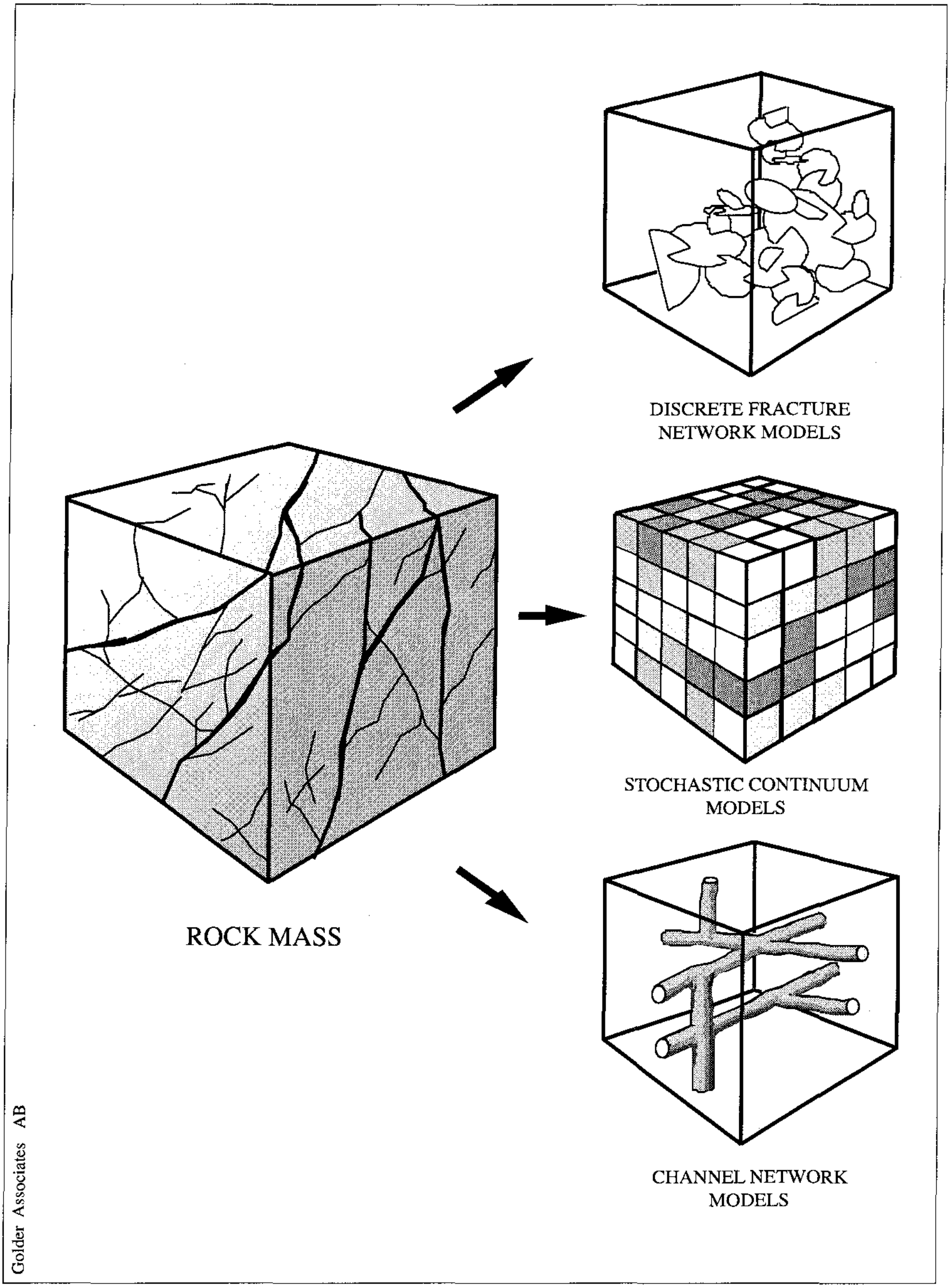


Figure 5.5-11. *Three common approaches to modelling groundwater flow and groundwater transport in fractured bedrock (from /5.5-98/).*

5.5.8 Model tools and model development

Mathematical models for groundwater flow, nuclide transport and rock mechanics comprise important tools in the work of waste disposal. As the computation capacity of computers increases, numerical model codes are being developed alongside of purely analytical equation solutions and empirical relationships. The options available for solving calculation problems with various coupled physical and chemical processes have thus increased in recent years.

SKB's overall view on model concepts and how models are used in its activities is described in section 5.1. The mathematical tool for calculating and describing a chemical or physical process can be a numerical model or an analytical equation solution. Assumptions, simplifications and relationships that are utilized for the calculation are shown by a conceptual model. The conceptual model is thus a description of how the geometric assumptions (the structure) and the component processes are organized and represented /5.5-85/.

SKB's efforts in model development have been concentrated on necessary calculation tools for performance and safety assessments, at the Äspö Hard Rock Laboratory and in the Stripa Project.

Groundwater modelling

Modelling of groundwater flow and groundwater transport of dissolved substances in fractured, low-permeability rock is relatively complex compared with in geologically porous media. Connections between fractures form flow paths which can be very irregular. To describe the groundwater flow in the bedrock, it is necessary to represent the heterogeneous structure of the rock in models and to take into account the scale on which the calculation problem is being regarded. Different types of approaches, conceptual models, are used, and they can be said to represent different idealizations of how the groundwater flows. The conceptual model is the basis of the mathematical model, which contains equations that are solved analytically or numerically. Three different approaches are illustrated in Figure 5.5-11.

Discrete Fracture Network (DFN) modelling is intuitively appealing because the primary flow paths are assumed to be represented by a network of interconnected fracture planes. The model is built up on the basis of a statistical description of the geometric and hydraulic properties of the individual fractures. This requires data that give distributions of the position, length, orientation and transmissivity of existing fractures. Different fracture populations can thereafter be simulated based on these statistics.

Stochastic Continuum (SC) modelling is based on the assumption that properties in the rock (hydraulic conductivity, storage coefficient, etc.) can be described as variations with spatial distribution functions. The stochastic approach contains several geostatistical steps. Stochastic continuum modelling is used to advantage for analyses aimed at studying regional scales (km scale) and for conditional simulation with the aid of e.g. kriging. Classical or deterministic continuum modelling can be said to constitute a special case of stochastic continuum modelling.

Channel Network (CN) modelling represents the flow in fractured rock as limited, discrete and for the most part one-dimensional flow paths, channels, which intersect each other at certain intervals. The approach is based on observations in the field, mainly from tunnels, where groundwater often occurs as flows along channels in fractures in the rock. The properties of the channels are derived from field data. Measurements of channel widths are necessary. Field measurements in tunnel fractures are, however, associated with uncertainties due to the disturbances in the rock caused by the tunnelling work.

A more detailed description of these basic concepts is provided in SKB reports, e.g. /5.5-98/ and /5.5-99/. Further details on the three concepts with a special emphasis on the data requirement are provided in separate reports /5.5-100, 101, 102/.

The choice of model for an analysis is entirely dependent on the purpose of the analysis in question, which geometric scale is intended to be studied and available data. Regardless of model concept, there are a number of common central questions to be taken into consideration in groundwater modelling.

The boundary conditions influence the calculation results. Uncertainties can include the degree to which groundwater movements at repository depth, alongside the regional groundwater system, are influenced by local topography in combination with steeply dipping water-conducting structures /5.5-103/. When density differences in the groundwater, caused by salinity variations, are taken into account in the modelling, this must also be dealt with in the choice of boundary conditions.

Dominant water-conducting structures are handled differently in modelling depending on the model concept. The heterogeneity of the bedrock, with large differences in material properties, gives rise to both conceptual uncertainties and numerical difficulties in the modelling.

Input data to the modellings are obtained from different field investigations in boreholes. These are conducted on a given geometric scale. It may be uncertain which rock volume the actual tests represent, see section 5.5.6. In the modelling it is necessary to scale the information interpreted from field data down or up to fit the numerical calculation. This scale adaptation requires extra care in the modelling /5.5-104/.

Modelling of radionuclide transport

Modelling of groundwater flow and groundwater transport of solutes should preferably take place in a single context. In a safety assessment, however, flow/advection is often dealt with by means of a groundwater model (including dispersion, for certain model concepts), while diffusion, dispersion and retention are dealt with by means of a separate nuclide transport model. Consequently, the flow model is used to evaluate boundary conditions for the transport model in the form of length of transport pathways or alternative water travel times.

The transport processes that were discussed at the beginning of section 5.5.6 are dealt with summarily in the following way in the numerical models:

- **Advection** with the groundwater: The mean velocity of the groundwater is often modelled as the Darcy velocity divided by the flow porosity. The flow porosity is the proportion of the rock that is occupied by the flowing groundwater, and it is less than the total porosity..

- Molecular **diffusion** is described by Fick's law.

- Hydrodynamic **dispersion** is usually modelled with a diffusion term proportional to the velocity of the groundwater; transversal dispersion is often much lower than longitudinal dispersion. With this procedure, the mass flow of a substance along with the flow in the rock is given by the product of the concentration gradient, the groundwater velocity and a coefficient called the longitudinal dispersion length. The latter can be very uncertain to estimate, due to the difficulty of conducting tracer tests in fractured rock over suitable length scales. The scale dependence for the dispersion coefficient determined in the field is sometimes simulated by the use of a constant, called Peclet's number. Peclet's number represents the ratio between a characteristic time for dispersive transport and a characteristic time for advective transport. The parameter is included in the advection-dispersion formulation for particle transport in rock that is often used in safety assessment contexts. For a detailed discussion of this subject, see /5.5-77 or 82/.

- Chemical and physical **retention**: The sorption models are often based on the assumption that actual kinematic behaviour can be simplified and modelled with a linear equilibrium model. For this purpose, distribution coefficients, K_d values, are posited for each nuclide. The K_d values are determined in laboratory tests and give the ratio between the concentrations in the solid phase and in the solute phase. The equilibrium model applies if the concentrations are small and if the time scale for sorption is much smaller than the time scale for transport with advection and dispersion. Physical retention through matrix diffusion in the rock is usually handled in modelling by a double-porosity description of the fractured medium. An exchange system between the fractures and the intact rock (the rock matrix) is included in the analysis. Transport in the fractures is dominated by advection, while transport between the fractures and the intact rock is dominated by diffusion /5.5-77/.

- **Radioactive decay**, including chain decay, is also dealt with in connection with modelling of nuclide transport.

Rock-mechanics modelling

The calculation models for the mechanical properties of the rock, i.e. strength and deformation, can in principle be divided into two main groups:

- Continuum models.
- Discontinuum models.

The continuum models describe the rock as a uniform rock mass where the effects of discontinuities in the rock are included without being able to define them specially. Movements in the rock are described in these models by means of continuum mechanics, which means that only limited effects of movements along discontinuities can be taken into account. The continuum models can be of the differential or integrated type. Finite Element Methods (FEM) and Finite Difference Methods (FDM) are examples of differential methods, while Boundary Element Methods (BEM) are examples of integral methods.

In discontinuum models, the rock mass is described using a coupled model between the intact rock and occurring discontinuities in the form of fractures and zones. These models can describe movements in the rock with deformation mechanisms for sliding along fracture planes, separation of fracture planes and rotation of rock blocks. Distinct Element Methods (DEM) simulate the rock mass as a discontinuum and can be used, for example, to calculate non-linear material behaviours and large deformations which can lead to collapse /5.5-93/.

Coupled models

The deep repository's influence on the rock mass is a coupled phenomenon which, besides chemical reactions, includes thermal, hydrological and mechanical processes. These processes affect each other mutually to a greater or lesser extent. In recent years, interest has increased in developing coupled models in order to be able to describe the conditions in the near field of a repository in particular with greater realism /5.5-94, 95/. Analytical calculation methods can very seldom be employed for the complex relationships to be described in the coupled processes. Development is being pursued with numerical equation solvers, which require extensive verification.

Coupled thermo-hydro-mechanical models have been developed and verified in the DECOVALEX Project (international cooperative project for the DEvelopment of COupled models and their VAlidation against EXperiments in nuclear waste isolation) /5.5-22, 23, 24/. One of the conclusions from the first stage of the project is that the temperature field around a repository can very well be described in pure thermal conductivity terms without reference to hydro-mechanical coupling. Stress and displacement conditions are often consistent between different modelling concepts, while the hydraulic results have shown appreciable differences. The general validity of the results is also very sensitive to the choice of boundary conditions, according to whether the calculation cases are two- or three-dimensional /5.5-112/.

Äspö HRL's international Task Force on Modelling

One of the goals of the Äspö Project is to "test models for description of groundwater flow and nuclide transport". During the pre-investigation phase and the design phase, the modelling work has primarily dealt with groundwater flow. Some work has been devoted to transport of solutes, particularly saline groundwater, and evaluation of a tracer test. Modellings have also facilitated the Äspö HRL's experiment planning with design calculations.

An international Task Force on Modelling of Groundwater Flow and Transport of Solutes has been tied to the

Table 5.5-2. Organizations and model groups with their computer codes in the Äspö HRL's international Task Force on Modelling. The table also shows the calculation tasks performed during the period 1992–1995. (*) T=Task.

ORGANIZATION	MODEL GROUP	CONCEPTUAL MODEL	COMPUTER CODE	CALCULATION TASK (*)
ANDRA France	BRGM(I)	continuum	MARTHE/SESAME	T1
	BRGM(II)	continuum	ROCKFLOW	T1
	ITASCA	channel network	CHANNET/TRIPAR	T1, T3
CRIEPI Japan	CRIEPI	continuum	FEGM/FERM	T1, T3
PNC Japan	PNC/Golder	discrete fracture network	FracMan/MAFIC	T1, T3
	Hazama	stochastic continuum	SETRA/ARRANG	T1
SKB	CFE	stochastic continuum	PHOENICS/PARTRAK	T1, T2, T3
SKB	KTH, Chemical Engineering	channel network	CHAN3D	
		continuum	–	T2
SKB	KTH, Water Resources Engineering	stochastic continuum	TUBA, etc.	T2
SKB	Geosigma	continuum	SUTRA	T2
TVO Finland	VTT (flow)	continuum	FEFLOW	
	VTT (transport)	–	–	T1
UK NIREX United Kingdom	AEA Technology fracture network	continuum/discrete	NAMMU/NAPSAC	T1, T3
US DOE USA	LBL	equivalent discontinuum with inverse modelling	–	T2

Äspö HRL. The Task Force was initiated by SKB at the end of 1992. The active groups and the modellings carried out to date are shown in Table 5.5-2. The tasks have so far included: A large-scale long-term pumping test (Task 1), design calculations for forthcoming tracer tests (Task 2) and hydraulic impact on the Äspö tunnel (Task 3). The model concepts that have been utilized are also presented in the table, where relevant. The model results are presented in the Äspö HRL's international report series /5.5-73, 108–111, 113–116/.

The Task Force is a forum for the organizations that are participating in international cooperation within the Äspö HRL. The Task Force also includes representatives of NAGRA (Switzerland), AECL (Canada) and BMBF (Germany). The emphasis is on gaining confidence in and experience of the methods that are used in performance and safety assessments. The Task Force has also produced a table of the key issues in safety assessments (Issue Evaluation Table), which are related to the ongoing or forthcoming experiments at the Äspö HRL. The table of key issues should also serve as a basis for choosing future modelling tasks.

Paleohydrogeological programme and regional modelling

The safety assessment's reference scenario deals with a climate situation similar to that existing today, whose geoscientific parameters and boundary conditions do not change with time. Effects of possible future periods with permafrost and glaciation are associated with extreme and necessarily speculative scenarios. The questions relate to the performance of a deep repository and the radiological risks to humans, animals and vegetation after the next ice age.

Based on knowledge of the extent of the Weichsel Glacial at different times and indirect climate data from pollen and isotope analyses, SKB has had a time-dependent glaciation model developed /5.5-32, 33, 118/. The model, which exists in a two- and three-dimensional version, is able to handle coupled processes with:

- temperature changes in ice and bedrock,
- growth and flow of the continental ice sheet in the landscape with actual topography,
- generalized mechanical impact on the lithosphere,
- meltwater flows at different stages during a glaciation cycle.

A simple model code for groundwater flow has also been attached to the model for the purpose of being able to handle and describe hydrogeological changes in connection with permafrost, glaciation and deglaciation. Of special interest are, for example, pressure and gradient changes under the ice and in the bedrock. The groundwater model also allows the flow of infiltrated meltwater to be followed in a simplified manner.

The development work with the glaciation model has had two purposes, namely to:

- increase the reliability of the predictive calculation models covering long periods of time that are used by improving understanding of thermo-hydro-mechanically and chemically coupled processes and their development (paleohydrogeological programme),
- create a better platform for handling extreme future scenarios that include permafrost, glaciation and deglaciation.

The glaciation model developed by SKB thus makes it possible to discuss and justify scenarios for the future performance and safety of a deep repository with a good underpinning. Site-specific data should be included in the assessment to as great an extent as possible. The hydraulic aspects are of central interest, but thermal, mechanical and certain hydrochemical aspects can also be dealt with.

A development project with groundwater modelling in a regional perspective is currently under way. The region includes the Simpevarp Peninsula, Äspö and the Laxemar area north of Oskarshamn. The project has a paleohydrogeological orientation, i.e. modelling results concerning groundwater flow and transport of dissolved salts are compared with hydrochemical analyses from the Äspö HRL and the 1700 m deep borehole KLX 02 in Laxemar, see also section 5.5.7. A separate programme for the activities with all their integrated parts has been compiled /5.5-158/.

Data management

A calculation problem within applied geology consists of both quantitative and qualitative data. When evaluating large quantities of data and how they can be used, it is necessary to take into account measurement and interpretation methods, representative dimension and from which geological unit samples have been taken, etc. See also section 5.5.2.

In the international perspective a large development is under way regarding geostatic analysis methods and their practical application, see e.g. /5.5-131–137/. Activities at SKB have mainly been focused on:

- developing and applying methods for statistical inference, i.e. limiting the uncertainties regarding properties in the rock outside the actual measurement points and being able to posit a value for how reliably these properties are described. This is done e.g. by means of variogram analysis and/or by the use of methods for non-parametric geostatistics,
- developing methods for analyzing whether data are statistically stationary or not (a parameter is stationary if both its mean value and variance are independent of "sampling scale" and geological unit),

- developing and applying regression methods, above all multivariate analysis, for hydrochemical data,
- refining and applying methods for hydrogeological classification in a siting process with continuous updating of available information according to the Markov-Bayes geostatistical model.

Studies with the above orientation have been presented in different articles and SKB publications, see e.g. /5.5-117, 138–144/.

Activities in relation to goals in RD&D-Programme 92

A number of goals were set up in RD&D-Programme 92 for modelling tools and model development for the period 1993–1998. Following is a brief status report in relation to these goals:

- Describe conditions for groundwater flow and transport at a deep repository in a regional perspective in the present-day climate situation. – A separate development programme is under way that is exemplified with data from the Äspö-Laxemar region.
- Describe the conditions for groundwater flow and transport at a deep repository in a regional perspective during glaciation and deglaciation. – a time-dependent glaciation model has been developed for Scandinavia /5.5-32/. A finite element code able to handle meltwater and groundwater flows during a glaciation cycle has been coupled to the model. In coordination with the above programme, the models are being tested with a paleohydrogeological orientation.
- Compile and structure geostatistical data that are used in conjunction with safety assessment and constructability assessment. – A separate compilation of factors is included in SKB's supplement to RD&D-Programme 92.
- Further develop how results from the volume representativity and dimensionality of hydraulic tests are to be integrated in a model structure. – A working group, HYDRIS, has compiled different aspects of execution, interpretation and use of test pumping results /5.5-69/. Development work is under way on volume representativity in the model structuring.
- Integrate and take into account general geological and geophysical information in the conductivity distribution for a site-specific stochastic groundwater modelling (indicator simulation). – Exemplifying calculations have been carried out and reported on /5.5-138/.
- Refine models for convection modelling in fractured rock. – Development work is under way.
- Refine rock-mechanics stochastic models and refine the scale dependence within rock-mechanics model structures. – Some model development has taken place within the framework of the international DECOVALEX programme /5.5-24/.
- Refine coupled hydro-thermo-mechanical models. – SKB is involved in several modelling tasks in the DECOVALEX programme.

5.6 CHEMISTRY

The results of the last three years' investigations within the chemistry programme are reported in a number of reports, publications and theses. Summaries and references to this material are found in SKB's Annual Reports (see e.g. /5.6-5/). A review of the rock's ability to influence nuclide transport through various bedrock-related factors is provided in section 5.5.6.

The following review is deliberately concise for the sake of anyone who wants to obtain a quick overview of what has happened since the last RD&D programme. SKB's Annual Reports provide more details and contain references to all background reports.

The chemistry programme with a focus on deep disposal of spent fuel has made substantial progress. Its scope has therefore been narrowed slightly and some investigations have progressed from a general orientation within the chemistry programme to applied studies. Certain general studies such as solubility, sorption, diffusion etc. are now concentrated within the project for other waste (long-lived low- and intermediate-level waste), see section 5.9.

5.6.1 Radionuclide chemistry

Solubility and complexation

Several of the radionuclides that are present in the waste and are important for long-term safety have a low solubility both in the groundwater and in the bentonite clay's pore water. Formation of complexes affects solubility, for example complexes with an actinide as the central atom and hydroxide or carbonate ions as ligands. This must be taken into consideration. Thermodynamic data and models are used to calculate solubility and speciation, and experiments are performed to improve the body of data. SKB has contributed to a large number of measurements of constants for formation of hydroxide and carbonate complexes with, for example, tetravalent thorium, technetium and neptunium, see Table 5.6-1 /5.6-1, 2, 3, 4/. It has been argued that complexation between tetravalent actinides and phosphates is of importance, despite the low concentration of phosphate in groundwater and bentonite. The conclusion is based on

Table 5.6-1. Equilibrium constants for thorium and neptunium(IV) in carbonate containing solution.

Equilibrium reaction	Equilibrium constant log K
Thorium[a]	
$\mathrm{ThO_2(s) + 4H^+ = Th^{4+} + 2H_2O}$	9.47±0.13
$\mathrm{ThO_2(s) + H^+ + H_2O + CO_3^{2-} = Th(OH)_3CO_3^-}$	6.11±0.19
$\mathrm{ThO2(s) + 4H^+ + 5CO_3^{2-} = TH(CO_3)_5^{6-} + 2H_2O}$	42.12±0.32
Neptunium[b]	
$\mathrm{Np(OH)_4(s) = Np(OH)_4(aq)}$	-8.28±0.23
$\mathrm{Np(OH)_4(aq) + CO_3^{2-} = Np(OH)_4CO_3^{2-}}$	3.00±0.12
$\mathrm{Np(OH)_4(aq) + HCO_3^- = Np(OH)_3CO_3^- + H_2O}$	3.23±0.12
$\mathrm{Np^{4+} + 4OH^- = Np(OH)_4(aq)}$	46.2±0.3
$\mathrm{Np^{4+} + 4OH^- + CO_3^{2-} = Np(OH)_4CO_3^{2-}}$	49.2±0.3
$\mathrm{Np^{4+} + 3OH^- + CO_3^{2-} = Np(OH)_3CO_3^-}$	45.2±0.3

a Reference /5.6-3/
b Reference /5.6-4/

Table 5.6-2. Experimentally determined stability constants β for thorium complexes with phosphate /5.6-6/.

Complex	Exp. pH 8.0	Exp. pH 9.0	Literature value$^{(1)}$
$\mathrm{ThHPO_4^{2+}}$	$(5 \cdot 10^8)$	$(5 \cdot 10^9)$	$2 \cdot 10^{13}$
$\mathrm{Th(HPO4)_{2.aq}}$	$1 \cdot 10^{15}$	$2 \cdot 10^{17}$	$3 \cdot 10^{26}$
$\mathrm{Th(HPO4)_3^{2-}}$	$1 \cdot 10^{21}$	$1 \cdot 10^{23}$	$8 \cdot 10^{34}$

(1) Moskvin et al. /5.6-7/.

databases that contain older and incorrect constants for complexation with phosphate. New and more exact measurements which SKB has had carried out (see Table 5.6-2, /5.6-5/), show that the phosphate complexes in these contexts are in fact less important.

Regarding the chemistry of plutonium, SKB has prepared new investigations and this is now a prioritized area. The task is not an easy one, since plutonium has a complicated chemistry (several different possible redox states), in addition to the fact that high standards of radiological safety are necessary at the laboratory. As an example, it can be mentioned that the technique that has been developed with SKB's support to study Np(IV) and Tc(IV) can probably not be used for plutonium /5.6-4/.

To be able to use equilibrium calculations, it is first necessary to know that the reactions take place. For this reason, reaction kinetics have also been investigated, for example to show how "high-mobility" pertechnetate, i.e. technetium(VII), and neptunyl, i.e. neptunium(V), are reduced to tetravalent technetium and neptunium with low solubility and high sorption /5.6-8/. It has now been established that such a reduction actually takes place under the geochemical conditions that prevail in a deep repository.

Co-precipitation is still difficult to utilize fully in transport calculations. SKB will continue to follow international developments in the field.

Sorption and diffusion

Sorption and diffusion are processes that influence the migration of the radionuclides. Ion exchange and surface complexation are used as models to describe the uptake of dissolved radionuclides on mineral surfaces in the rock and the bentonite clay. SKB is funding a number of such studies. The results of the experiments have not been used to replace the sorption coefficients (K_d values), but rather to increase understanding of the sorption mechanisms and determine what they are dependent on, i.e. how reliable the sorption can be considered to be /5.6-9/.

There is still no good method for determining the flow-wetted surface area, but studies are being conducted for example in the Äspö programme.

Supplementary measurements of diffusion in concrete and bentonite have been and are still being carried out. Regarding bentonite, the aim is to determine data that describe diffusion and sorption in bentonite.

A literature survey has been conducted of matrix diffusion by radionuclides in rock /5.6-10/.

5.6.2 Organic substances, colloids and microbes

Colloids

The column experiments with colloids and radionuclides have been concluded. The experiments show that colloids can take up and transport radionuclides, at least under special conditions /5.6-11/. However, deep groundwaters have such low contents of colloidal particles, that they cannot contribute to radionuclide transport to any appreciable extent /5.6-12/. In other words, it has been possible to show that the groundwater's natural content of colloidal particles is not of any safety-related consequence. There is, however, reason to look at the substances that come from the repository itself, e.g. clay particles from the bentonite buffer. A special case is transport with gas bubbles, to which more attention will be devoted.

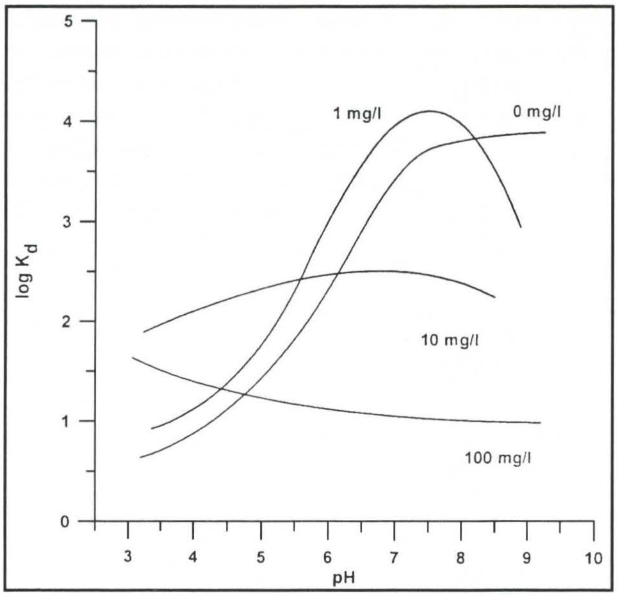


Figure 5.6-1. *Influence of fulvic acids on the sorption of Eu on alumina at different pH-values and concentrations of fulvic acid.*

Organic substances in the groundwater

A series of laboratory experiments with natural humic and fulvic acids has been carried out which verifies that the sorption of certain radionuclides, e.g. Am^{3+}, on minerals is hindered by complexation /5.6-13/. However, the same experiments show that, owing to the low concentrations of natural humic and fulvic acids in deep groundwaters, the size of the reduction of radionuclide sorption is limited or even negligible, see Figure 5.6-1. Similar conclusions have been arrived at in the majority of the countries that are considering emplacing their HLW in a deep repository in granitic rock /5.6-15/.

All organic matter in the groundwater is not humic and fulvic acids, however, and it still remains to determine what other organic substances in the groundwater consist of and what their chemical properties vis-à-vis radionuclides are.

Microbes

It is essential to investigate the importance of microbes. The area has been prioritized since 1992. In principle, microbes can influence a number of conditions of importance for the isolation of radioactive waste, e.g. migration, solubility and gas generation. Of the greatest importance is, however, the capacity of microbes to influence the chemical environment with which the canister and the waste can come into contact. The analyses and studies that have been performed at Äspö HRL support this view. Microbes can be helpful by contributing to the chemical reduction of oxygen and radionuclides, or harmful by reducing sulphate to sulphide. This can affect the waste canister, and for this reason special attention has been devoted to the occurrence of microbes in the chemistry programme.

Studies of microbes have been intensified and sampling has been carried out at Äspö and at most of the places where analogue investigations have been conducted, see Figure 5.6-2. A collaborative effort with AECL and ANDRA in microbial studies of the buffer (sand/bentonite) used in a Canadian "Buffer Mass Test" in the underground research laboratory, URL, in Manitoba

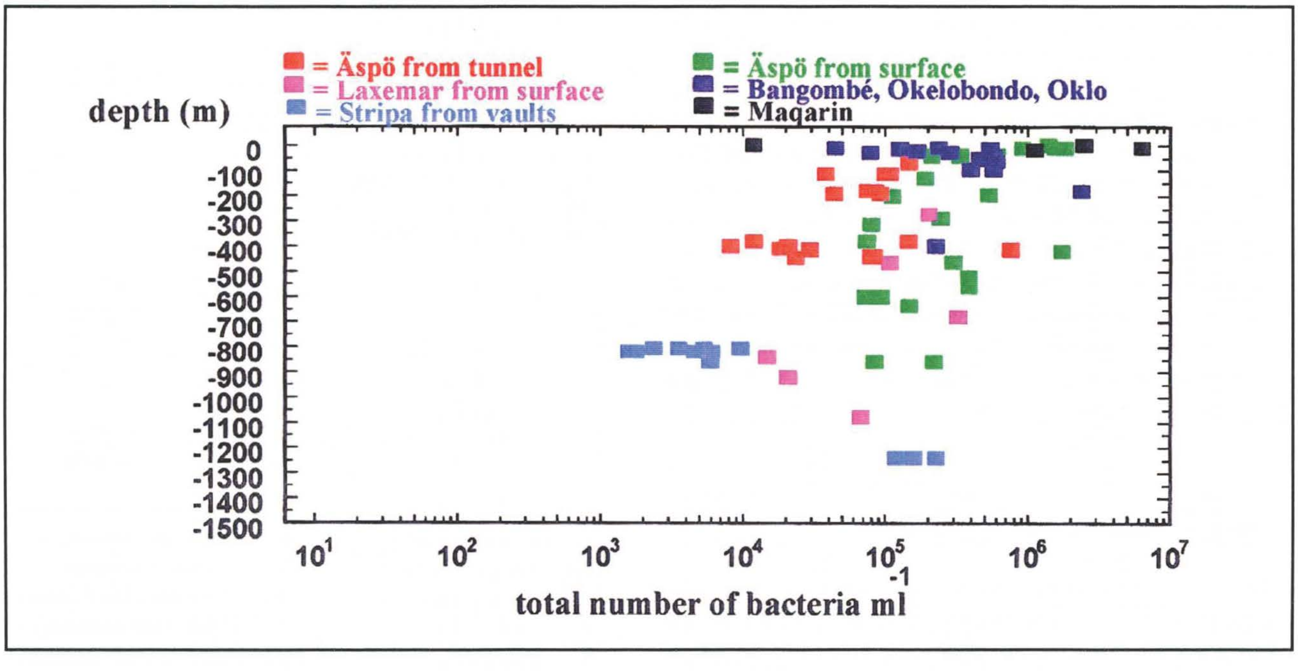


Figure 5.6-2. *The total number of bacteria in groundwater down to 1,240 m, determined with the acridine orange counting technique. Data has been collected over a period of 9 years from 30 boreholes at 49 different sections.*

have yielded essential information on bacteria in a bentonite buffer.

A summary of the present-day state of knowledge regarding microbes and their importance for long-term safety is presented in a technical report /5.6-16/. The following safety-related areas are dealt with in this report:

- Radionuclide transport and bacteria.
- Complexing agents from bacteria.
- Microbial processes in a repository.
- Steel corrosion and bacteria.
- Sulphate-reducing bacteria and copper corrosion.
- Bacterial sulphate reduction by hydrogen gas.
- Consumption of oxygen by bacteria.
- Reducing conditions and bacteria.
- The living conditions of bacteria in bentonite.

5.6.3 Validation experiments

The work of validating models and assumptions in performance and safety assessments is focused today on the in-situ experiments that will be conducted with the CHEMLAB probe in Äspö, see chapter 12. The objective of the CHEMLAB experiments is to test the models that are used to describe dissolution and migration of radionuclides. These experiments are being prepared in the laboratory. The tests which we will later perform in-situ in the CHEMLAB probe are first being tried on a bench scale.

Concrete is frequently used in underground construction, e.g. for paving of floors, shotcreting of walls and roofs, grouting of fractures, structures of various kinds, etc.

Ordinary Portland cement contains alkali hydroxides (NaOH and KOH) and portlandite ($Ca(OH)_2$), which give the pore water a high pH. To ascertain the long-term geochemical influence of concrete, experiments have been conducted where simulated cement pore water has been allowed to run through columns filled with granitic minerals. Calcium-silica-hydrate phases are formed by reactions with silicate minerals. The reaction proceeds very slowly and the new solid phases that are formed tend to clog the columns. The experiments are being performed by BGS (the British Geological Survey) in the UK with the support of NAGRA, NIREX and SKB. The objective is to validate the models that are used. The results of the first phase of the experiments in England have been reported /5.6-19/.

5.6.4 Hazardous substances

The important research work has to do with the radiological toxicity of the waste. A small portion of the substances included in the waste can, however, be classified as chemically toxic hazardous waste. This is particularly true of some metals such as lead, cadmium and beryllium. This has been investigated in conjunction with both the high-level waste (spent fuel) and the low- and intermediate-level waste. Hazardous substances have been inventoried and methods for assessing the safety of a repository with regard to these substances have been tested. SKB has found that the deep repository also provides very good protection against these substances /5.6-20/.

5.7 NATURAL ANALOGUES

5.7.1 Natural analogues and safety assessment

There is now a considerable body of results from analogue studies that can be used to assess the long-term safety of the repository. Such information has previously been used more sporadically for safety assessments such as KBS-3, SKB 91 and SSR-SFR, and most of the applications relate to conditions in the near field, see Table 5.7-1 /5.7-1/.

Table 5.7-1. Processes and analogues studied within SKB's programme /5.7-1/.

Processes in the near field	**Natural analogues**	**Safety assessment**
Canister corrosion	7	KBS-3
Bentonite stability	8 (3,4,6)	KBS-3
Concrete influence	6,11,12	
Fuel corrosion	3,4,5,9	KBS-2, SKB-91
Radiolysis	3,4	KBS-3, SKB-91
Formation of redox front	1	
Radionuclide solubility	1,3,6	
Radionuclide migration		
– colloids	1,3,6 (4)	
– organic matter	1,3,6 (4)	SFR
– microbes	1,3,6 (4)	
Processes in the far field		
Radionuclide solubility	1,3	
Radionuclide migration		
– colloids	1,3,5,6 (4)	SKB-91
– organic matter	3 (4,5,6)	
– microbes	3 (4)	
Radionuclide retention		
– absorption	1,2,13 (4,5)	
– co-precipitation	1,2,3,6 (4,5)	
– matrix diffusion	3,5 (4,6)	SKB-91

1. Poços de Caldas
2. Alligator Rivers
3. Cigar Lake
4. Oklo
5. Palmottu
6. Maqarin
7. Copper objects
8. Bentonite deposits
9. Uraninite samples
10. N Sweden (drill cores)
11. Porjus (old concrete)
12. Uppsala (old concrete)
13. Äspö (fracture filling)

These and similar examples are described in a book on which SKB has collaborated together with NAGRA and NIREX /5.7-2/. A more detailed account of some selected applications of analogues within the safety assessment has been prepared in collaboration between TVO and SKB /5.7-3/.

SKB is participating and has participated in a number of international analogue projects and is also represented in the international National Analogue Working Group, NAWG, which has been organized by the EU in cooperation with the US DOE. Its purpose is to discuss and evaluate the results of completed analogue studies.

5.7.2 Cigar Lake

The Cigar Lake project has studied a very concentrated, deep-lying and 1.3-billion-year-old uranium deposit in northern Saskatchewan in Canada. It has been studied by AECL as an analogue to a deep repository for spent fuel since 1984. SKB joined the project in 1989. This collaboration has now been concluded and the results reported /5.7-4/. Cigar Lake provides strong support for the deep repository concept in three areas in particular. The redox conditions in the deep groundwater have kept down the solubility for uranium and prevented it from escaping; the low hydraulic conductivity of the clay in and around the ore has slowed down the release of mobile nuclides; and radiolysis has had a moderate influence despite the long exposure to groundwater. The redox conditions can be described with the usual geochemical models and the release of mobile substances from the near field has been able to be described with mass transport models used in the safety assessment. The model developed to deal with the radiolysis of groundwater in contact with ore should also be able to be applied to the scenario of spent fuel in a damaged canister, see Figure 5.7-1.

5.7.3 Jordan

The Jordan Project is investigating the conditions in and around active hyperalkaline springs in Maqarin, see Figure 5.7-2, and similar fossil springs in central Jordan. Spontaneously formed combustion zones have generated portlandite and calcium silicates, which give the groundwater a pH of 12–13. A whole series of typical cement minerals have been formed as a consequence of the water's reactions with minerals in the area. The project was started in 1990 with funding from NAGRA, NIREX and Ontario Hydro. SKB has been participating since 1991. The results of the first phase have been published. A large part of the second phase involves testing (validating) chemical models for calculating the solubility of radionuclides. There are plenty of minerals in Maqarin, and one can see how the elements Sn, Se, Ni, Pb, Ra, Th and U dissolve in water with a high pH /5.7-5/. The project is now in its third phase and is currently being funded by NAGRA, NIREX, HMIP (Her Majesty's Inspectorate of Pollution) and SKB. The third phase is being coordinated and administered by SKB.

5.7.4 Oklo

The Oklo Project is investigating the natural fossil reactors at Oklo, Okelobondo and Bangombé in Gabon, Africa. The first reactor zone was discovered in 1972. Oklo is quite unique among the natural analogues. During uranium mining and prospecting in Oklo and the surrounding areas, no fewer than 15 different spots have been found with traces of nuclear reactions, i.e. reactor zones. It is the same type of nuclear fission as in a reactor with uranium fuel, and it has produced a large quantity of fission and activation products. This occurred nearly 2 billion years ago. The radioactive isotopes have since decayed and been transformed into predominantly stable products, but traces of the reactions remain, as do many of the materials that were involved. By tracing the daughter products, it is possible to see whether migration has occurred; for example, an elevated concentration of U-235 outside a zone indicates that diffusion of plutonium has occurred in the near field, which consists of clay minerals.

The project "Oklo, Natural Analogue for a Radioactive Waste Repository" has been carried out by CEA with financial support from the EU. SKB and several other organizations from various countries have been able to participate. SKB's interest has mainly been focused on the reactor zone in Bangombé, see Figure 5.7-3. It is suitable to study because it lies relatively close to the ground surface and far from the others (about 20 km), which means that no mining has yet taken place in Bangombé. The results of the first phase of the Oklo Project were published in the summer of 1995.

5.7.5 Palmottu

There is a uranium mineralization at Palmottu Lake in Finland. It forms a 1–15 m thick steeply dipping zone that extends to a depth of about 300 m down into the rock. It was discovered late in the 1970s and was thoroughly investigated, 62 exploratory holes having been drilled. The Palmottu analogue project started in 1988 and has been run by GTK (Geological Survey of Finland), with funding from STUK (Finnish Centre for Radiation and Nuclear Safety). The uranium deposit has been studied as an analogy to a deep repository for spent fuel in granitic rock. An advantage is that the conditions at Palmottu are the same as those that can be expected to exist at the sites chosen for deep disposal in Finland and Sweden. SKB has participated in the project as an "active observer".

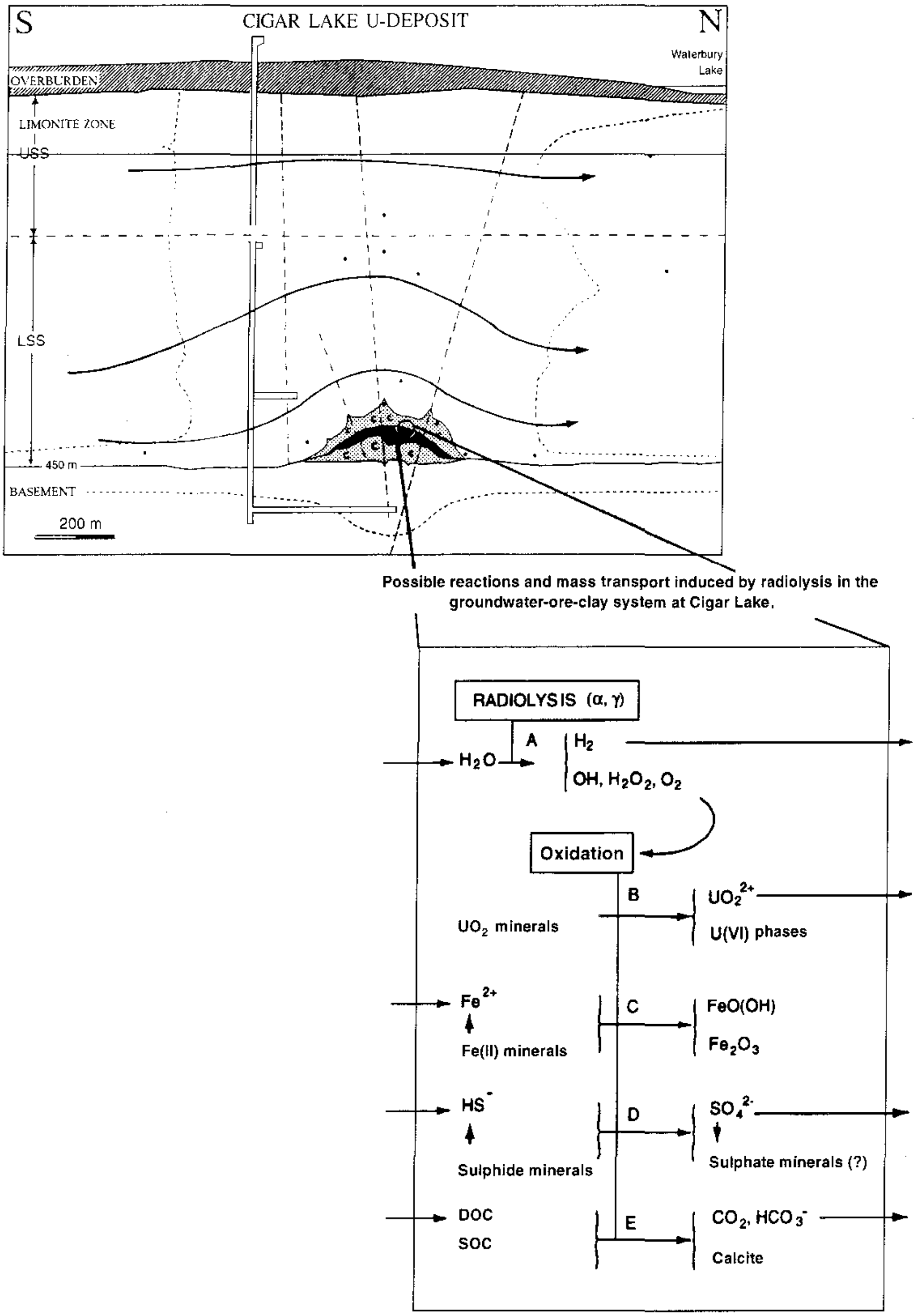


Figure 5.7-1. *Vertical profile through the uranium mineralization at Cigar Lake with the direction of the groundwater flow. The possible oxidation reactions that can be caused by radiolysis in the ore and the surrounding clay are shown schematically.*

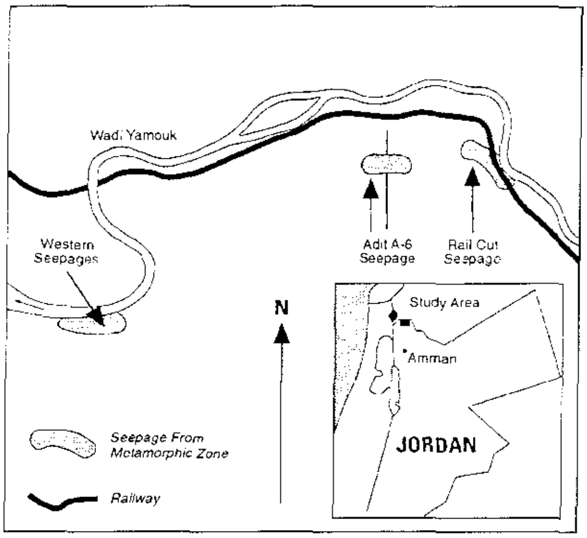


Figure 5.7-2. Location of the Maqarin analogue study site in northern Jordan. The sites of the hyperalkaline springs are shown.

5.7.6 Old concrete

Old concrete structures of Portland cement have been sampled to study how the cement paste changes with time. Wherever possible, an effort has been made to find samples that have been in a water-saturated environment. Where samples have been in air, carbonatization otherwise dominates, caused by the influence of the carbonic acid from the air. Portland cement was introduced at the start of this century. In other words it is not very old, but it is important to be able to discover trends towards changes in the samples, and some of the observations will hopefully be able to be verified by the results from the Jordan Project, which involves considerably longer periods of time. We now know more about which mineral phases are formed in cement and their properties. It should therefore be possible to shed light on what happens in the long term, provided that geochemical and hydrological conditions are given. The studies of old concrete have not been completed, but are expected to continue for some time yet.

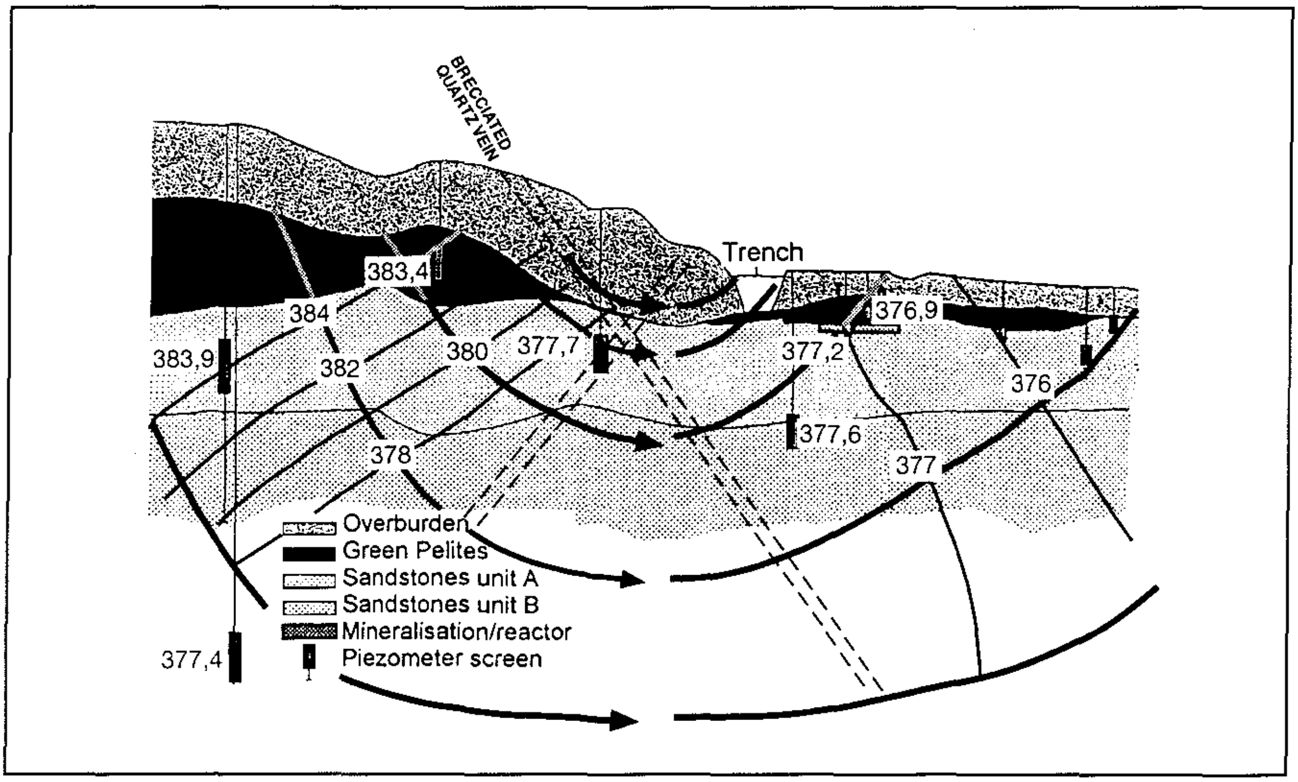


Figure 5.7-3. The Bangombé site. Piezometer measurements, hydraulic gradient (——) and groundwater flow (▬▬) directions are marked in the figure.

5.7.7 Results in relation to goals in RD&D-Programme 92

- The Cigar Lake Project has been concluded and an independent evaluation has been completed. The latter is finished, but the results have not yet been published.
- SKB has participated in Phase I of the Oklo Project. As planned, we have increased our involvement in the project and are now participating as co-applicants to Phase II of the EU project.
- The third phase of the Jordan Project has begun and SKB is in charge of the project management.
- SKB has participated in the investigations at Palmottu.

5.8 THE BIOSPHERE

5.8.1 General

In order to be able to assess the radiological consequences of possible releases of radioactive materials from a final repository, it is necessary to describe transport from the rock to man (or to other biota). The overriding goal of SKB's studies of the behaviour of radionuclides in the biosphere is to be able to carry out credible consequence calculations in the safety assessments.

The state of knowledge for modelling the transport of radionuclides in the biosphere is relatively good. The goals of a joint international project initiated by the Swedish National Radiation Protection Institute called BIOMOVS /5.8-1/ are to:

- examine how the conceptual models have been converted into calculation models,
- compare different transport models,
- document the methods for defining transport scenarios.

Fundamental questions in biosphere modelling that have been identified within BIOMOVS and are the subject of continued work concern the handling of different scenarios for biosphere evolution and of critical groups. These questions are closely linked to the formulation of the radiation protection requirements.

As far as scenario methodology is concerned, the possibility of applying the RES method to the biosphere has been tried by a working group within BIOMOVS /5.8-2/.

5.8.2 Data needs

The predominant uncertainty in today's biosphere calculations is rooted in the availability and quality of data. Previously, generic data have been used almost exclusively. The reason given for this has been the great changes that occur in the biosphere within relatively short spans of time. This is correct for times after the start of the next Scandinavian ice age. For the next 1000 years in particular, however, site-specific databases and specific assessments of the frames within which the biosphere on a given repository site may change are judged to provide a basis for a meaningful forecast.

Analysis of the uncertainties in generic calculations show a confidence interval of several orders of magnitude /5.8-3/. For modelling which aims at showing that dose limits will not be exceeded, this can be acceptable, even though reported consequences are highly overestimated. If, on the other hand, the modelling aims at an assessment of **expected** impact, such as for example in comparisons between repository sites or in optimization of radiation protection, such results are meaningless, as a rule.

Today's food production system is so complex that even if the levels of radionuclides in the constituent raw materials are known, it is not possible to calculate the intake to a given individual (with known dietary habits) with sufficient accuracy. The large dilution factor (several powers of ten) entailed by production and distribution is often overlooked in the safety assessment.

5.8.3 Model development

SKB's modellings of radionuclide transport in the biosphere have been carried out with BIOPATH, a calculation program developed by Studsvik EcoSafe and included in the BIOMOVS work. BIOPATH has been utilized for KBS-3, SFR and SKB 91 and has been progressively refined through the efforts of SKB, among others. For a detailed discussion of how biosphere modelling is performed and how it is utilized in safety assessments, the reader is referred to SR 95 chapter 8 and /5.1-3/.

At the same time as biosphere evolution and the choice of a critical group will increasingly be coupled to site-specific conditions, the structure of the BIOPATH model will be adapted to local conditions as well. The development work that is planned will be aimed at improving the data on which the transport models rest and trying to validate the models through studies of analogous transport processes.

5.8.4 Results in relation to goals in RD&D-Programme 92

Interim goals in RD&D-Programme 92 were:

- **Try to quantify the uncertainties that stem from changes in the biosphere**
  The results of this work have been reported in /5.8-2 and 3/. The large dissimilarities in dose conversion

factors associated with release in the Baltic Sea and in the interior of the country are worth noting. The ratio between them is more than two orders of magnitude, with better conditions in the Baltic Sea. This is partly due to favourable transport pathways and dilution conditions, partly to long residence times in the sea sediments.

- **Improve the database on which the transport models rest**
  Site-specific data have been gathered and utilized in modelling /5.8-3 and 4/. Models for how K_d values for soils and sediments can be calculated have been developed /5.8-5/.

- **Validate models through the study of analogous transport processes**
  The work within BIOMOVS II provides a good basis for judging the validity of the transport models /5.8-6/, as do studies of the interface between geosphere and biosphere /5.8-7/. Studies of natural analogues have begun with an inventory /5.8-8/.

5.9 OTHER WASTE

According to plans, long-lived LLW and ILW is supposed to be disposed of in a separate part of the deep repository called SFL 3, 4 and 5. Long-lived waste From Studsvik will be disposed of in SFL 3, along with such LLW and ILW that could otherwise go to SFR, but that arises after SFR has been closed and sealed. Decommissioning waste from CLAB and the encapsulation plant will be deposited in SFL 4, and reactor core components in SFL 5. The waste in SFL 3–5 is similar in nature to that which goes to SFR. It is mainly the higher content of long-lived nuclides, e.g. plutonium isotopes and nickel-59, which warrant deeper disposal in a separate repository.

The studies that have been carried out for safety assessments of SFR serve as a basis for the work with long-lived waste. Experience from the ongoing investigation work described below will also be applied to SFR.

5.9.1 Prestudy

A prestudy of the performance of the barriers in SFL 3–5 /5.9-1/ has been carried out. It was begun early in 1993 and concluded late in 1994. The goal was to make an initial preliminary assessment of the near-field barriers against the escape of radionuclides. The point of departure was the conceptual design of the repository presented in PLAN 93 /5.9-2/. Hydrogeological and other site-related premises were chosen with the aid of simplified assumptions and previous experience.

5.9.2 Inventory of the waste

The waste has been inventoried and characterized within the framework of the prestudy, see Figure 5.9-1 /5.9-3/. The quantity of radionuclides of various kinds has been estimated, along with some other components of importance for safety, such as metals, organic matter, concrete, etc. The most common metal in the waste is steel, primarily stainless steel, which will be found in all parts of the repository. Organic matter is concentrated to SFL 3.

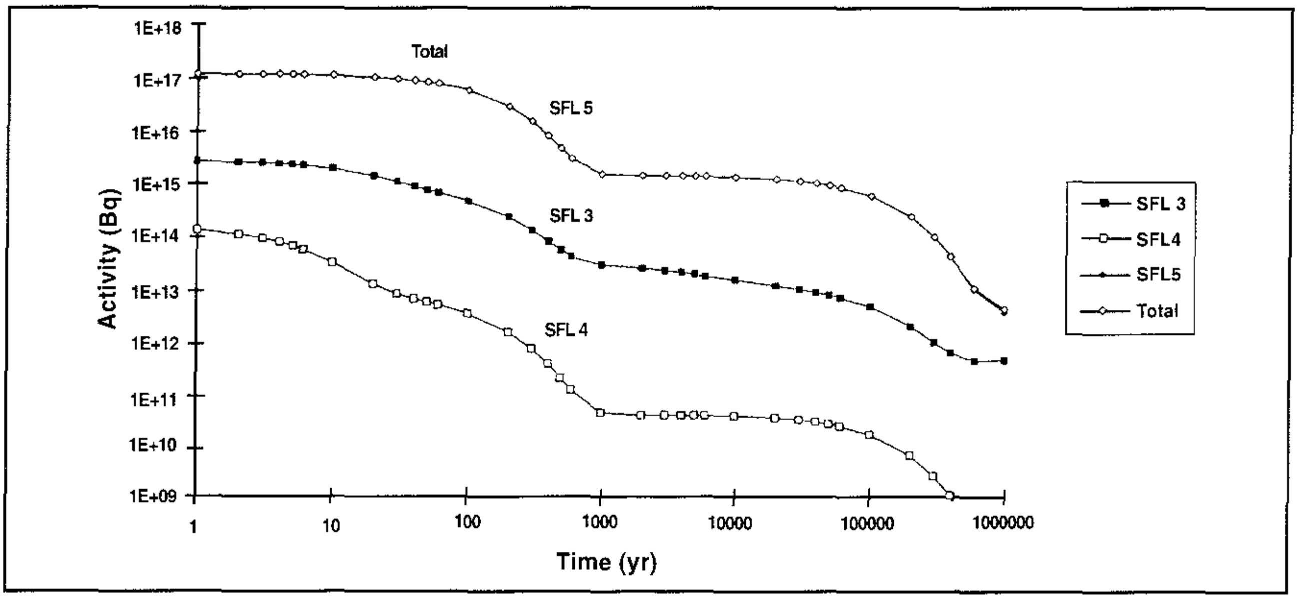


Figure 5.9-1. Content of activity (Bq) in the different parts of the repository as a function of time (from the year 2040).

5.9.3 Laboratory investigations

Laboratory investigations have begun with the goal of producing the necessary data and models to assess the performance of the barriers. The work is long-term and mainly focused on radionuclide chemistry in the repository (solubility, sorption, diffusion, etc.), the influence of organic substances and changes in the concrete. The following investigations are being conducted during 1995:

- Compilation of the state of knowledge in the area of concrete stability under repository conditions.
- Leaching of crushed cement paste with normal versus saline groundwater. The ions being analyzed are: Na^+, K^+, Ca^{2+}, Mg^{2+}, OH^-, SO_4^{2-}, Cl^-, Al_{tot} and Si_{tot}. The leached cement paste is examined after leaching to see which secondary minerals are formed.
- Solubility measurements of Ni, Pu, Eu and Th in cement environment.
- Measurements of radionuclide sorption on concrete (K_d values). The elements studied are: Th, Eu, Cm, Pm, Co, Ra and Ni (tetravalent, trivalent and bivalent elements).
- Measurements of radionuclide diffusion in cement paste and cement mortar. The elements studied are: Ni, Cs and tritium. Both diffusion profiles and diffusion are being studied.
- Measurements of radionuclide diffusion through a mixture of 15% bentonite (Wyoming MX-80) and 85% sand. The elements studied are: Cs, Tc and Ni. The influence of cement pore water on the diffusion is also being measured.
- Studies of how cellulose (crystalline cellulose, industrial products such as wood, paper, cotton, cement additives, etc.) are degraded at high pH values (10–13.5) under anoxic conditions; identification of degradation products, including strong complexing agents of the type polyhydroxycarboxyllic acid (especially isosaccharinic acid).
- Degradation of isosaccharinic acid at high pH values (10–13.5); long-term stability.
- Complexation capacity of isosaccharinic acid, especially with trivalent elements.
- Diffusion of isosaccharinic acid through cement.
- Influence of isosaccharinic acid and degradation products from cellulose on the absorption of radionuclides on cement. Experiments are being performed with trivalent and tetravalent elements and nickel (bivalent).
- Influence of organic complexing agents on diffusion of radionuclides through cement.

Similar work is being done in other countries and SKB has therefore started informal cooperation with ANDRA, NAGRA and NIREX. Results and experience have been applied in the prestudy /5.9-4/.

5.9.4 Performance assessment of near-field barriers

To test the ability of the barriers to retain and limit the release of radionuclides, transport calculations were carried out – simple calculations with a tank reactor model for all nuclides and calculations of advection-diffusion in concrete, bentonite and sand for specially selected nuclides. A couple of toxic metals were also included in the study. Calculations and results are described in connection with the prestudy /5.9-4/.

The prestudy has entailed an initial estimate and characterization of the waste that will go to SFL 3–5. Modern systematic scenario methodology has been tested /5.9-5/ and an initial assessment of the barriers has been carried out. The results show that the metallic waste from the reactors contains the most radionuclides. This waste will be collected in SFL 5. At the estimated time of closure, the activity in SFL 5 will be more than 10 times as high as in SFL 3, which will in turn be more than 10 times as high as in SFL 4. The calculated release of radionuclides is so low that the near field alone would suffice as a barrier. The results suggest that the proposed design of the repository is purpose-suited and provides large safety margins. Several scenarios remain to be analyzed, however, for example long-term evolution of the barriers, consequences of gas generation, ice age scenarios, etc. So far the prestudy has served its purposes: to estimate waste quantities and contents, to test the conceptual design, to focus the basic investigations on relevant issues, and to prepare for future safety assessments.

5.9.5 Results in relation to goals in RD&D-Programme 92

The goals in RD&D-Programme 92,

- to inventory and characterize existing and foreseen waste of this type,
- to modify the design of the deep repository for LLW and ILW, and
- to prepare for and gather data for necessary safety assessments,

have been pursued within the concluded prestudy and continue to be pursued in the ongoing second phase. The purpose of the latter is to gather data for a safety assessment that will form a part of the safety report in support of an application for a permit for detailed characterization for the deep repository. Laboratory experiments have been started as planned and active cooperation with NAGRA, NIREX and ANDRA has provided good guidance and a valuable exchange of information on chemical conditions etc.