Technical Report

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RD&D Programme 2007

Programme for research, development and demonstration of methods for the management and disposal of nuclear waste

September 2007

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Preface

SKB, Svensk Kärnbränslehantering AB (the Swedish Nuclear Fuel and Waste Management Co), is owned by the companies that operate the Swedish nuclear power plants. SKB has been assigned the task of managing and disposing of the radioactive waste and the spent nuclear fuel from the reactors. The Nuclear Activities Act requires a programme of comprehensive research and development and whatever other measures are needed to manage and dispose of the waste in a safe manner and to decommission and dismantle the nuclear power plants. SKB is now presenting RD&D Programme 2007 in fulfilment of this requirement. The programme describes in general terms the planned measures and the facilities that are needed for the task, with a focus on the plans for the period 2008–2013. The period of immediate concern is 2008–2010. The level of detail for the three subsequent years is naturally lower.

The programme provides a basis for designing systems to manage and dispose of the radioactive waste from the nuclear power plants. SKB intends to dispose of the spent nuclear fuel in accordance with the KBS-3 method. In the RD&D Programme we describe our activities and the planning for it. We also deal with societal research and other methods for disposal of spent nuclear fuel. The planning for low- and intermediate-level waste, as well as for the societal research, is presented in separate parts. The upcoming review of the programme can contribute valuable outside viewpoints. The regulatory authorities and the Government can clarify how they view different parts of the activity. Municipalities and other stakeholders can, after studying the programme, offer their viewpoints to SKB, the regulatory authorities or the Government.

The most important milestone during the coming three-year period is to submit applications under the Nuclear Activities Act for the final repository for spent nuclear fuel and under the Environmental Code for the final repository system. RD&D programme 2007 therefore focuses on the technology development that is needed to realize the final repository for spent nuclear fuel. The site investigations in Forsmark and Laxemar will be concluded in 2007. The work of compiling the applications for the final repository is under way. In contrast to the immediately preceding programmes, RD&D Programme 2007 therefore also contains a summary of the site investigation phase and a look ahead at the steps that remain before the final repository can be put into operation.

RD&D Programme 2007 consists of six parts:

Part I SKB's plan of action

Part II Final repository for spent nuclear fuel

Part III Technology development within the nuclear fuel programme

Part IV Safety assessment and natural science research

Part V Social science research

Part VI LILW programme and decommissioning

Part I and Part II look ahead to the time when the final repository for spent nuclear fuel is put into operation. On the way, SKB will pass a number of milestones. At each milestone, a given body of technical and scientific background material must be available. The scope of this background material and the technology development that is required are described in detail in Part III. Part IV focuses on the results of the research on long-term changes that must be available for the next safety assessment, SR-Site. Part V describes our social science research programme and Part VI provides an overview of the programme for low- and intermediate-level waste (LILW), including decommissioning. It is our hope that the above structure and approach will provide a clear picture of how far research and technology development have come in different areas and what factors are most important for safety in our facilities.

Stockholm in September 2007

Swedish Nuclear Fuel and Waste Management Co

Claes Thegerström

President

Tommy Hedman

Head of Technology Department

Summary

RD&D Programme 2007 presents SKB's plans for research, development and demonstration during the period 2008–2013. The plans for the first three-year period are for natural reasons more detailed than those for the next one. SKB's activities are divided into two main areas: the nuclear fuel programme and the programme for low- and intermediate-level waste (the LILW programme).

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Part V Social science research

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The preceding RD&D programme, RD&D-Programme 2004, was mainly focused on the fabrication and sealing of canisters for spent nuclear fuel. The reason for this was that SKB's immediate goal at that time was to submit an application under the Nuclear Activities Act for Clab and the encapsulation plant. This was done in the autumn of 2006. The next major goal for SKB is to submit an application under the Nuclear Activities Act for the final repository for spent nuclear fuel and an application under the Environmental Code for the final repository system at the end of 2009. Much of the work described in the RD&D programme is being done to obtain technical supporting documentation for these applications. This RD&D programme is therefore focused on the efforts planned within technology development, see further Part III.

A brief summary of the contents of each part follows below.

Part I SKB's plan of action

SKB's plan of action is divided into planning for the nuclear fuel programme and planning for the LILW programme. The timetable for building and commissioning the facilities needed for final disposal of the spent nuclear fuel and the low- and intermediate-level waste is controlled by the need for technical development work and by the statutory permit requirements. Based on this we have identified a number of important milestones.

The most important milestones for the nuclear fuel programme are:

- Application under the Environmental Code for the final repository system and application under the Nuclear Activities Act for the final repository.
- Interconnection of Clab and the encapsulation plant.
- Applications for trial operation of the final repository and of the integrated encapsulation plant and Clab.
- Applications for shipments of spent nuclear fuel.
- Applications for routine operation of the final repository and of the integrated encapsulation plant and Clab.

The most important milestones for the LILW programme are:

- Safety analysis report for SFR 1.
- Dry interim storage of long-lived waste from other nuclear power plants than Oskarshamn in BFA (rock cavern for waste) on the Simpevarp Peninsula.
- Application for licensing of transport cask.
- Application for extension of SFR.
- Application for routine operation of extended SFR.

Part II Final repository for spent nuclear fuel

The plans for those parts of the nuclear fuel programme that pertain to the final repository for spent nuclear fuel are presented in this part of the RD&D programme. The structure of the presentation is based on the stepwise implementation of the programme described in SKB's plan of action.

Current situation

The site investigations in Forsmark and Laxemar have largely been concluded. At present the work is being concluded with the final versions of the site descriptive models, which will in turn serve as a basis for the next design step and the safety assessment SR-Site.

Our preliminary judgement is that the picture we have of Forsmark will not be appreciably altered. Design of the facility in Forsmark is based on the assumption that the repository can be located within the priority area and that facilities and activities above ground can be accommodated within the existing industrial area. The depth of the repository should be increased from 400 metres as previously proposed to between 450 and 500 metres. The reason for this is that the rock stresses do not increase as rapidly with depth as we assumed they would. The location of the fracture zones also makes it simpler to position the deposition areas at the lower depth compared with closer to the surface.

The investigations in Laxemar will be concluded during the first quarter of 2008. After the initial site investigation, a preliminary layout was worked out for a repository at a depth of 500 metres. Inasmuch as the investigations have since been shifted to the southern and western parts of the area, the layout will probably undergo great changes. The data that have come in after the initial site investigation confirm the picture of Laxemar, but also show lower fracture frequency and lower water permeability compared with data from the parts on which SR-Can were based.

Licensing

Permits under both the Nuclear Activities Act and the Environmental Code are required in order to establish and operate the final repository – as is the case with the encapsulation plant and Clab. Furthermore, the activity must comply with the municipality's detailed development plan and area regulations, and must have been granted building and site improvement permits. Important milestones during this phase are:

- The municipal council decides to support the activity.
- The Government rules on permissibility under the Environmental Code and a permit under the Nuclear Activities Act.
- The municipality adopts a detailed development plan.
- The Environmental Court grants a permit and issues conditions under the Environmental Code.
- SKI issues conditions under the Nuclear Activities Act.
- SSI issues conditions under the Radiation Protection Act.
- SKB submits an application for a building permit.
- The municipality grants a building permit.

Construction

The construction phase begins when SKB has obtained all permits and will last for six to seven years. The activity is dominated by extensive rock excavation works. Important milestones during this phase are:

- Establishment and start of construction.
- Skip shaft finished.
- Start of rock works at repository level.
- Ramp finished.
- Central area finished.
- Production building finished.
- Updated safety analysis report.
- Facilities and installations for integrated testing finished.
- Surface facilities finished.

Commissioning

Commissioning of the final repository begins when the rock works and technical installations at repository level have come so far that this is possible. Machines, handling equipment and parts of the surface facilities must be in place. Important milestones during this phase are:

- Start of integrated testing.
- Updated safety analysis report.
- Application for trial operation submitted.

Operation

When the operating phase starts, SKB has received a permit for trial operation. Canisters with spent nuclear fuel then arrive at the final repository for the first time. An important milestone during this phase is the transition from trial operation to routine operation.

Part III Technology development within the nuclear fuel programme

The applications are based on a KBS-3 repository with vertical deposition. The different system parts in the final repository (canister, buffer, backfill etc) must meet special requirements, which are defined in SKB's requirements database. These properties are determined by the design premises and specifications that are formulated, but also by the production and inspection methods that are used. In order to illustrate this we use the concept "production lines". SKB has chosen to define six production lines:

- The rock line
- The buffer line
- The fuel line (included in the canister line in this RD&D programme)
- The canister line
- The backfilling line
- The closure line

Technology development is largely conducted in cooperation with Posiva (Finland), whose work is also based on the KBS-3 method.

Besides the production lines, RD&D Programme 2007 also deals with retrieval of the canisters and the alternative repository design KBS-3H (horizontal deposition). As far as retrieval is concerned, no special development efforts are planned for the coming RD&D period. The objective for a possible continued development of KBS-3H is to satisfy the requirements on long-term safety and be able to compare with the reference alternative. A decision to continue can be made when the evaluation of the current project is finished at the end of 2007. The work presented in Part III is based on the assumption that the decision will be positive.

The rock line

The rock line includes the construction of all chambers in the final repository's underground facility. Two issues in particular are in need of technology development: grouting and inspection of the excavation-disturbed zone. We must develop methods, grouts and equipment in order to be able to manage the inflows that may occur in the final repository. It is particularly important to learn to seal small fractures with very high water pressures. The material used may not give rise to leachate of too high a pH so that the buffer is adversely affected. When tunnels and rock caverns are built, fractures form in the rock nearest the tunnel wall. The area containing the fractures is called the excavation-disturbed zone (EDZ). The size of the EDZ will depend on what method is used, among other things. Today we know how to limit the extent of the EDZ. However, we do not know enough about how the hydraulic properties are altered if the degree of disturbance changes.

The buffer line

The buffer line contains steps such as manufacture, handling and installation of the bentonite buffer that surrounds the canisters in the deposition holes. SKB has tested two methods for compacting the blocks and rings: uniaxial pressing and isostatic pressing. We haven't chosen a reference method yet. Both technologies must be further developed before they can be used on an industrial scale. Installation of the buffer will be demonstrated in the Bentonite Laboratory. But first a lifting tool and a radiation shielding hatch that prevents direct radiation up into the deposition tunnel must be developed. Tests will also be conducted in the Bentonite Laboratory to determine the highest manageable water flow into the deposition holes.

The canister line

The canister line describes how the canisters in which the spent nuclear fuel will be encapsulated are fabricated, sealed, transported and deposited. In 2005 we chose friction stir welding as a reference method for sealing the canister. What now remains to be done is to further develop the fabrication methods for the different canister components. A number of trial fabrications are scheduled for the upcoming period. Both welds and canister components will be examined by means of nondestructive testing. There has been a great deal of progress when it comes to testing of welds. Method development is still under way for testing of canister components.

The backfilling line

The backfilling line includes manufacture, handling and installation of backfill in the uppermost part of the deposition holes. After the most recent the safety assessment, SR-Can, we were able to conclude that a backfill consisting of blocks of swelling clay worked best in the final repository. The steps that will require the greatest development efforts during the coming RD&D period are installation of backfill in the upper part of the deposition hole and backfilling with blocks and pellets or granules in the deposition tunnel. The backfilling method will be tested on a full scale in the Äspö HRL after initial tests in the Bentonite Laboratory. We also need to find out where the limit goes for the maximum permissible flow of water into the deposition tunnel. This is being done in the Bentonite Laboratory, where it is possible to vary the size of the water flow.

The closure line

The closure line contains the steps that are needed to backfill and plug all other openings than the deposition tunnels in the final repository. It also includes closure of investigation boreholes from the surface and from tunnels in the final repository. One question to be investigated during the coming RD&D period is how the properties of the backfill change when it freezes in the shallow parts of tunnels and shafts and then thaws again. The basic concept for closing investigation boreholes is to seal them with perforated copper tubes filled with highly compacted smectitic clay. Furthermore there are other methods for closure of boreholes, also based on sealing with smectitic clay. During the coming period, SKB will, together with Posiva, demonstrate closure of up to 1,000-metre deep boreholes.

Part IV Safety assessment and natural science research

Long-term safety in the final repository is examined and evaluated by means of safety assessments. The work with the safety assessments is focused on examining the safety of a KBS-3 repository with vertical deposition. In very simplified terms, a safety assessment involves describing the repository's initial state, after which the changes that could conceivably occur in the long term and their consequences for man and the environment are analyzed. The changes are driven by different process, which may be:

- Thermal – caused by heat output.
- Hydraulic – caused by flowing gas or liquid.
- Mechanical – caused by high pressures and sudden movements in the rock.
- Chemical – caused by chemical reactions.

The different processes are described in the safety assessment with models. Sometimes the processes affect each other so much that we have to regard them as interconnected systems, using integrated modelling. Input data to the model calculations come from the results delivered by the research activities and the site investigations.

Besides studying the processes that occur in a KBS-3 repository, SKB is also keeping track of the development of two other methods for disposing of spent nuclear fuel: partitioning and transmutation (P&T) and direct disposal in deep boreholes.

Safety assessment

SKB's most recent safety assessment is called SR-Can and was submitted to the regulatory authorities on 1 November 2006. The assessment was carried out according to a thoroughly tried and tested ten-step analysis methodology. The methodology is now considered to be mature for the most part and will also be used in the next safety assessment, SR-Site. SR-Site will comprise a portion of the supporting material for the application for the final repository. For most processes in the final repository, we have enough knowledge today to meet the needs of the safety assessment. But there are knowledge gaps in some areas that must be filled prior to SR-Site.

Climate change

SKB's climate programme serves as a basis for the research activities. The climate changes continuously and affects shoreline displacement as well as the development of permafrost and ice sheets in Sweden. This in turn affects the environment both on the ground surface and the rock. An important issue for the climate programme is to determine what climate domains are possible and describe how they can affect the safety of the final repository in the long term. One question we need to know more about is how a continental ice sheet affects the hydrology and hydrochemistry in the area around a final repository. We therefore intend to start a project on western Greenland near the ice sheet in cooperation with Posiva. The rocks there are very reminiscent of those in Oskarshamn and Forsmark. We will also study how a warmer climate affects the sea level, how permafrost spreads, and what happens if the backfill material freezes.

Fuel

The programme for fuel also contains some remaining questions. Fuel dissolution in particular is a priority area. Now that the nuclear power companies have announced that they want to increase the average burnup for both PWR and BWR fuel to 60 MWd/kgU, additional calculations are also required of, for example, radionuclide inventory, decay heat and criticality prior to SR-Site. New leaching tests also have to be done.

The canister as a barrier

The canister is the most important barrier for isolating the spent nuclear fuel. SKB's reference canister consists of an inner container of cast iron and an outer shell of copper. Here the research efforts are mainly being concentrated on investigating how the canister's insert and shell are deformed. There are both external forces due to, for example, earthquakes and internal forces due to the formation of corrosion products that cause pressure to build up inside the canister. Corrosion – above all stress corrosion cracking – is another area where questions remain. The high radiation dose to which the cast iron insert is exposed could cause the material to become more brittle. The consequences of this will be further investigated.

Buffer

The buffer is supposed to protect the canisters, but also to act as a filter and prevent radionuclides from a leaky canister from contaminating the environment. In order to evaluate safety it is important to be able to predict what state the buffer reaches after deposition. The water saturation process is controlled by hydraulic, thermal and mechanical processes and is studied both in the field and by modelling. When the buffer is saturated with water it is easier to describe, but there are still a number of processes that must be studied, for example gas transport, colloid formation and above all erosion.

Backfill

The backfill is supposed to stabilize the tunnels, keep the buffer in place and prevent water flow through the tunnels. Swelling is an important process for the backfill, just as it is for the buffer. Processes that can affect swelling are therefore also important. During the upcoming RD&D period we will therefore study the impact of freezing and erosion in particular.

Geosphere

Development of models for rock movements will continue during the next RD&D period. One question in particular that is being studied is the effects of earthquakes.

Microbes can affect conditions in the final repository both positively and negatively. Studies of the role of microbes will continue.

Modelling of radionuclide transport will continue to be developed. Among other things, the new program code Marfa will be tested.

Biosphere

The biosphere is the part of the Earth where most life is found. It is also where a release from the final repository could have consequences in the form of radiation dose to man and organisms. The biosphere programme has taken a great step forward in that we can now devise ecosystem-based models of the sites and in this way follow the path of the radionuclides. We are also calculating the radiation dose to man in a completely new way, based on mass flows of water and organic carbon in the ecosystems.

Other methods

SKB is following the development of other methods for managing, treating and disposing of nuclear waste. The main methods being studied are partitioning and transmutation and disposal in deep boreholes. As far as deep boreholes is concerned, a project is being conducted entailing a general systematic comparison between this method and the KBS-3 method. Our previous basic conclusion regarding deep boreholes remains valid. The method does not satisfy the requirements of controlled deposition in all steps and is associated with such fundamental uncertainties that further efforts to develop the method are not warranted.

Part V Social science research

SKB also conducts and funds research in the social sciences. The purpose is to be able to give decision-makers at different levels a broader body of data that also sheds light on the nuclear waste issue from a societal perspective. Four areas of social science have been deemed to be particularly relevant:

- Socioeconomic impact – Macroeconomic effects
- Decision processes
- Public opinion and attitudes – psychosocial effects
- Global changes

Socioeconomic impact – Macroeconomic effects

Socioeconomic impact includes both narrowly economic aspects such as employment and industrial establishment and macroeconomic effects. The research supported by SKB is aimed at gaining better knowledge of how the economy and demographics of individual communities are affected by the establishment of a new, large facility in the community. This knowledge can contribute to both SKB's and the concerned municipalities' and other stakeholders' assessments of how the establishment of the final repository may affect the community's economy and demographics.

Decision processes

Siting of a final repository for spent nuclear fuel has repercussions for community planning, national energy policy and international policies. By addressing political questions of this special character, the research is attempting to lay the foundation for a general knowledge concerning decision processes in complex issues. This knowledge can in turn make contributions to consultations, surveys, planning and decision-making.

Public opinion and attitudes – psychosocial effects

The purpose of this research is to study how opinions and attitudes are formed and change. This knowledge contributes to a better understanding of different actors' decision-making. Opinions and attitudes are not just a reflection of decision-making, actual events and communicated messages. Individual characteristics and perceptions of reality also play a role. Deep-seated values and norms, group identification, perceived fears, anxiety about risks, and self-interest are some examples of factors that also influence public opinion and attitudes. It is therefore also important to shed light on the "symbolism" surrounding the final repository and its activities.

Global changes

The establishment of the final repository is a question that is clearly related to changes in the world around us. Research in the field can lead to a greater knowledge of relevant global factors and global changes. This knowledge can make a very valuable contribution to planning, studies, consultations and decision-making before and after the permit/licence applications. The knowledge may also be important for the future operation of the deep repository. The economic situation and trend in the local community is dependent on a variety of circumstances in the surrounding world. What kind of future Swedish state will assume responsibility for the final repository? Legislation, regulation and financing, as well as the country's economic situation, are factors of importance. Another important global change is Sweden's participation in the development of the European political and economic cooperation.

Part VI LILW programme and decommissioning

The LILW programme embraces all low- and intermediate-level waste that will be disposed of in SKB's facilities. The facilities covered by SKB's RD&D programme are SKB's own existing and future facilities for final disposal of waste from the Swedish nuclear power plants. Interim storage of long-lived low- and intermediate-level waste from the nuclear power plants in BFA (rock cavern for waste) is also included in the LILW programme. The Nuclear Waste Fund finances the final disposal of decommissioning waste and the final repository for long-lived low- and intermediate-level waste. SKB may also dispose of radioactive waste from Studsvik, the Ågesta reactor, the fuel factory in Västerås and Ranstad. Disposal of the waste from these facilities will then be financed separately. Final disposal of the operating waste from the nuclear power plants is financed directly by the licensees.

The area "decommissioning and dismantling" includes conducting decommissioning studies for the purpose of estimating waste quantities, both radioactive and inactive as well as free-release material, and estimating the costs of decommissioning. The studies are based on strategies and technologies that are developed in cooperation with the power plant owners. Although SKB disposes only of the radioactive waste, SKB calculates the volumes and the costs of all decommissioning waste in its studies.

The most important milestones during the coming three-year period are:

- Completion of a new safety analysis report (SAR) for the final repository for radioactive operational waste (SFR 1), which will be submitted to the regulatory authorities at the end of 2007.
- Design and modification of the existing BFA on the Simpevarp Peninsula for interim storage of core components.
- Licensing and manufacture of the ATB-1T waste transport container for intermediate-level long-lived waste. The supporting material for licensing will be ready in 2009. Manufacture will start one year later.
- Planning for an extension of SFR begins in 2007. The extension should be ready for operation by 2020. Investigations of the bedrock will start during 2008.

The next six-year period also includes the following milestones:

- Start of operation of dry interim storage of long-lived waste from other power plants than Oskarshamn in BFA (rock cavern for waste), no earlier than the end of 2011. OKG is already using BFA today for dry interim storage.
- Application for a permit to extend SFR. Preparation of a preliminary safety analysis report (PSAR) and an environmental impact statement (EIS). According to the plans, the application will be submitted to the regulatory authorities in 2013.

The planning for the final repository for long-lived low- and intermediate-level waste (SFL) will begin after the application for a permit to extend SFR has been submitted. SFL is not expected to start operation before 2045. The waste quantities to SFL are relatively small, and the facility will be the last one to be closed, since it will receive waste from other facilities until they are decommissioned and dismantled. In view of the small volumes in question, SKB judges that it is reasonable to wait with the operation of SFL until most of the waste is available for deposition.

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Part I

SKB's plan of action

1 Management of radioactive waste

The Swedish power industry has been generating electricity by means of nuclear power for more than 30 years. A large part of the management system that is needed to manage and dispose of the waste from operation of the reactors has been built up during that time. The system consists of the interim storage facility for spent nuclear fuel (Clab), the final repository for radioactive operational waste (SFR) and a system for transportation.

What remains to be done for the spent nuclear fuel is to build and commission the system of facilities needed for final disposal. This system includes an encapsulation plant for encapsulating the fuel in copper canisters and a final repository where the filled canisters will be deposited. An extension of SFR and a repository for long-lived low- and intermediate-level waste (SFL) will also be needed. Furthermore, existing systems and facilities (Clab, SFR, transportation system) must be constantly maintained and modernized, particularly in view of planned extended operating times for the Swedish reactors and thereby for the nuclear waste system. This plan of action gives an account of SKB's plans to realize these remaining parts of the management system in such a manner that man and the environment are not harmed – today or in the future.

1.1 SKB's plan of action

Chapter 1 of the plan of action deals with our mission and goals. Then a picture is given of how far we have come so far, what resources are available for implementation and the strategy we have chosen to achieve the goals. The chapter also contains a timetable, which can be realized under certain given conditions. Planning to implement the programme for disposal of the spent nuclear fuel and the programme for disposal of the low- and intermediate-level waste then follows in Chapters 2 and 3. The plan of action does not, however, deal with the content of the applications that will be submitted for the different facilities.

The regulatory authorities have issued statements of comment on SKB's planning on a number of occasions. In the statement of comment on RD&D Programme 2001, SKI called for a clearer account of the planning for the remainder of the nuclear waste programme. The main reason given by SKI for this request was that the regulatory authorities need to know what reviews they will be called upon to perform during the next ten years so that they can better plan their own work. This demand was also expressed in the Government's decision on RD&D Programme 2001.

SKB presented a plan of action in RD&D-Programme 2004 /1-1/. In March 2005, SKB announced certain changes in and additions to the plan of action. According to SKI, SSI and Kasam, the revised plan of action offered a good systematic description of SKB's timetables and how different parts of SKB's programme are dependent on each other. However, the regulatory authorities concluded that the plan of action can and should be further developed.

To further clarify the planning for the nuclear fuel programme during the years to come, SKB presented "Application plan for the encapsulation plant and the final repository for spent nuclear fuel" (in Swedish only) /1-2/. This plan shows what milestones will occur in the nuclear fuel programme up until the final repository has been taken into operation and what reporting to the regulatory authorities is planned on each occasion.

The plan of action in RD&D-Programme 2004 contained only a brief description of the planning of the LILW programme. The Government's statement of comment on RD&D-Programme 2004 stated that "*SKB should determine the shortest time that is required for a licensing process for final disposal of decommissioning waste to begin*". In response to this comment, as well as others by the Government and the regulatory authorities on RD&D-Programme 2004, we present in this plan of action the timetables and milestones for the LILW programme in the same way as for the nuclear fuel programme.

1.2 SKB's mission

The holder of a license to operate a nuclear power plant is also responsible for disposing of the radioactive waste in a safe manner. This includes decommissioning and dismantling the facilities at the end of their service life, conducting comprehensive research and development on final disposal, and studying alternative options. Svensk Kärnbränslehantering AB, SKB (the Swedish Nuclear Fuel and Waste Management Co), has been commissioned by the nuclear power plant owners to manage and dispose of the nuclear waste in such a manner that human health and the environment are protected in both the short and long term, as well as to conduct the necessary research and development. The Swedish Nuclear Power Inspectorate (SKI) and the Swedish Radiation Protection Authority (SSI) oversee SKB's work. Other important actors are Kasam (the Swedish National Council for Nuclear Waste) and the county administrative boards and municipalities that are affected by the different nuclear facilities.

The management of radioactive substances is regulated by legislation. The focus of the work has furthermore been determined by a long series of political decisions and statements, which can be summarized in the following points:

- The waste from the Swedish nuclear power plants will be disposed of within the country's borders.
- Sweden will not dispose of waste from other countries.
- The spent nuclear fuel will not be reprocessed.

The fundamental guidelines and division of roles for the management of nuclear waste from nuclear power production were laid down long ago. Nuclear waste that is produced in Sweden must also be disposed of there. It is SKB's responsibility to plan and execute the various steps in the management of the waste and to calculate the costs. These calculations also include the costs of decommissioning and dismantling the nuclear power plants. The reactor owners then carry out decommissioning and dismantling.

SKB is responsible for the facilities until they have been closed. However, there has previously been some doubt as to who is responsible for the final repository for spent nuclear fuel from the time the repository has been closed. In its statement on RD&D-Programme 2004, the Government commented on the concern expressed over this by the municipalities in question, Oskarshamn and Östhammar. SKI was therefore instructed by the Government to issue recommendations, in consultation with SSI, on how the Nuclear Activities Act can be clarified in this respect. In a report /1-3/, SKI and SSI propose amendments to the law that note the state's ultimate responsibility for final disposal of spent nuclear fuel.

1.3 SKB's current situation

The Swedish system is the result of more than 30 years of continuous work. Regular payments to the Nuclear Waste Fund have ensured stable financing, without parallel in other industrial sectors, see section 1.3.5. Administratively, the work has gradually found appropriate forms and now rests on a stable foundation of rules and regulations with a clear division of roles both at the national level and in the concerned municipalities.

1.3.1 SKB's programme for research, development and demonstration

SKB is required to submit a programme for research, development and demonstration – an RD&D programme – to the regulatory authorities every third year. The Act on Nuclear Activities regulates the periodicity and scope of this programme. The RD&D programme is reviewed by the regulatory authorities after extensive circulation for comment. The Government then decides whether or not to approve the programme. The focus of the RD&D programme has varied through the years, depending on where the emphasis has been in SKB's activities. Much of the RD&D is conducted in our laboratories in Oskarshamn: the Äspö HRL, the Bentonite Laboratory and Canister Laboratory, see section 1.3.3.

The KBS-3 method and the associated systems for manufacture and inspection of the barriers have been under development since the end of the 1970s. The method was first described in a report /1-4/ as a basis for the decision to commission the most recently built nuclear power reactors. It has since served as a basis for SKB's programmes for research, development and demonstration.

A brief summary of the RD&D programmes presented by SKB is given below. All the programmes described below have been circulated for comment and subsequently approved by the Government.

RD&D-Programme 84

As an appendix to the applications for fuelling permits for the Forsmark 3 and Oskarshamn 3 reactors, SKB submitted a research programme that focused on the KBS-3 method. The detailed repository layout and site selection required more research and development. The regulatory authorities commented on the programme and accepted it with a few minor criticisms.

RD&D-Programme 86

We submitted the first complete research programme under the new Nuclear Activities Act in 1986 /1-5/. In accordance with the requirements of the Nuclear Activities Act, SKB pointed out the importance of alternative studies and went through other methods that could be regarded as alternatives to the KBS-3 method in a background report to RD&D-Programme 86 /1-6/.

In 1977, SKB started a research programme at the Stripa mine in Västmanland. Due to the fact that the water conditions were influenced by the fact that the mine had been in operation since the Middle Ages, research was planned to be concluded there. Instead SKB proposed that a new underground laboratory should be built in undisturbed rock in order to make it possible to continue to study the geological and hydrogeological properties of the rock and nuclide transport on a real scale.

RD&D-Programme 89

The KBS-3 method has been accepted by the regulatory authorities and the government as acceptable in terms of safety and radiation protection. It is therefore a reference alternative for further studies of other interesting alternatives. In the programme /1-7/, SKB provided information on its plans for a safety assessment, SKB 91. The reason was the need to evaluate what variations in geological conditions mean for the performance and safety of the final repository. Preliminary investigations to locate a hard rock laboratory in the Simpevarp area were conducted and showed that good prospects existed for locating such a facility on Äspö, north of Simpevarp. In its decision regarding RD&D-programme 89, the Government found that the research work ought to include an account and a follow-up of alternative disposal methods. A binding commitment should not be made to a method until a complete picture was obtained of safety and radiation protection aspects. A point of departure for the continued RD&D activities should be that a final repository for nuclear waste and spent nuclear fuel could be put into operation stepwise.

RD&D-Programme 92

The programme /1-8/ was the start of the siting of a final repository. In accordance with the Government's wishes, the National Board for Spent Nuclear Fuel's proposal that the repository should be built stepwise was taken up and incorporated in the programme. In an initial step, demonstration deposition of about 400 canisters was planned, which is about ten percent of the total number. Only after this step has been completed and evaluated will a decision be made concerning a continuation. It will then be possible to either continue along the chosen path or retrieve the fuel. The plan to build an encapsulation plant adjacent to Clab was presented for the first time in the programme. Important background reports to the programme were the safety assessment SKB 91 /1-9/ and the Pass report /1-10/, which compares different encapsulation methods and final disposal methods (KBS-3, very deep holes, very long holes, medium-long holes). The Pass report recommends keeping the KBS-3 reference system with a copper canister with a steel insert. The Government's decision called for a supplementary account to SKI. SKB was supposed to supplement RD&D-Programme 92 by describing:

- the criteria and methods that can form a basis for the selection of sites suitable for a final repository,
- a programme for description of design premises for an encapsulation plant and a final repository,
- a programme for the safety assessments which SKB intends to prepare,
- an analysis of how different measures and decisions influence later decisions in the final repository programme.

Supplement to RD&D-Programme 92

SKB submitted the requested supplement in August 1994 /1-11/. In its subsequent decision, the Government made it clear that a licence application for a final repository should contain comparative assessments based on site-specific feasibility studies on between five and ten sites in the country and that site investigations should be conducted on at least two sites. The reasons for the selection of these sites should be given. The siting factors and criteria stipulated by SKB should, in the Government's opinion, serve as a point of departure for the continued siting work.

RD&D-Programme 95

The emphasis in RD&D-programme 95 /1-12/ was on how SKB plans to carry out the development projects (encapsulation, final repository) that are required to initiate deposition of encapsulated fuel. The programme also included the supportive research and development work needed for the projects as well as a follow-up of and research on alternative methods. The following comprised important background documents for the programme:

- The reports on the feasibility studies in Storuman and Malå.
- A nationwide survey of conditions and background for the siting work – General Siting Study 95.
- A template for safety reports, SR 95.

In its review of RD&D-Programme 95, SKI said that considerable progress had been made since RD&D-Programme 92. Newly developed methodology now needed to be applied and evaluated. Previous assessments of important safety factors must be reconciled with new knowledge and modifications of the repository system. Furthermore, SKI stressed that, as a basis for future decisions on the final choice of system solution, the zero alternative in particular should be reported as a reference for the disposal alternative.

RD&D-Programme 98

SKB presented detailed information on the points which the Government had highlighted in reference to RD&D 95, i.e. alternative solutions to KBS-3, system analysis of the entire final repository system, siting data and site selection criteria /1-13/. Besides alternative solutions, the report contains a broad account of both alternative methods and variants of the KBS-3 method. The long-term safety of the final repository was dealt with and a coming report on a safety assessment (SR 97) was announced. SKB also described the work that was planned prior to coming site investigations up to a decision in 2001. The reference canister with a five centimetre thick copper shell and a cast iron insert was also specified in the programme. In its decision on RD&D-Programme 98, the Government requested that SKB submit a supplementary account regarding alternative methods, background material for site selection, and a programme for the site investigations.

Supplement to RD&D-Programme 98

In November 1999, SKB presented the announced safety assessment, SR 97 /1-14/, which was received very positively when circulated for comment by both regulatory authorities and scientific experts. The regulatory authorities found that the KBS-3 method was a good basis for SKB's upcoming site investigations and the continued development of the engineered barriers. In December 2000, SKB submitted the supplementary accounts which the Government requested in its decision on RD&D-Programme 98 /1-15/. SKB proposed that the site investigations should be conducted in Oskarshamn and in Northern Uppland and that they should be commenced during 2002.

RD&D-Programme 2001

RD&D-Programme 2001 concentrated on questions related to the safety assessment and its research and technology development needs /1-16/. Questions relating to siting of the facilities were not taken up, since SKB was at this time waiting for the Government's decision regarding the supplement to RD&D-Programme 98. The programme took as its point of departure the regulatory requirements on long-term safety and linked this to the development of methodology for the safety assessment and to the research on the long-term processes in the repository. The programmes for safety assessment and research were then linked together with the programmes for development of methods and instruments for the site investigations and the design of the deep repository, the encapsulation plant and the canister. An overall goal for SKB was to start the initial operation of a final repository for spent fuel in 2015. The timetable calls for regular operation (now called routine operation) to commence in the early 2020s before the storage chambers in Clab are full, thus avoiding the necessity of a further extension of Clab. According to the plans, the encapsulation plant will be ready for operation one year before the final repository. The timetable also included conducting safety assessments of the final repository, based on data from the site investigation phase. These assessments will provide a basis for site selection. In their comments on RD&D-Programme 2001, SKI and SSI called for an clearer account of the planning for the remainder of the nuclear waste programme /1-17/. The Government then requested a plan of action in connection with the approval of the research programme.

RD&D-Programme 2004

This RD&D programme was mainly concerned with the development of fabrication and sealing of canisters for final disposal of spent fuel /1-1/. The reason was that SKB was supposed to submit an application for a licence under the Nuclear Activities Act for an encapsulation plant during the coming programme period.

In RD&D-Programme 2004 we presented the plan of action that was called for in the review of RD&D-Programme 2001. The plan was divided into two parts: the nuclear fuel system and the waste system for low- and intermediate-level waste (LILW). The emphasis in the work during the programme period 2004–2009 was on the nuclear fuel programme. The plan entailed that SKB should gather the material that was needed to submit the applications for the encapsulation plant and the final repository. In its review statement on RD&D-Programme 2004 /1-18/, SKI stated that they thought that SKB's plan of action was incomplete and needed to be structured better. SKI called for a more detailed account of the content of the background material which SKB intended to submit on the different reporting occasions.

1.3.2 Existing facilities

SKB has for some years been operating a final repository for low- and intermediate-level waste (SFR), an interim storage facility for spent nuclear fuel (Clab) and a system for transporting the nuclear waste between the different facilities, see Figure 1-1. SFR, which is situated near the Forsmark nuclear power plant, was put into operation in 1988. Clab, which is situated at the Oskarshamn nuclear power plant, was put into operation in 1985.

Final repository for radioactive operational waste (SFR 1)

A final repository for radioactive operational waste receives the short-lived low- and intermediate-level operational waste from the nuclear power plants. This part is now called SFR 1, see Figure 1-2. The facility is located at a depth of 50 metres beneath the seabed.

The storage chambers in the existing part – SFR 1 – consist today of four 160-metre-long rock caverns of various configurations and a 70-metre-high rock cavern in which a concrete silo has been built. One of the four rock caverns contains low-level waste enclosed in ordinary ISO containers.

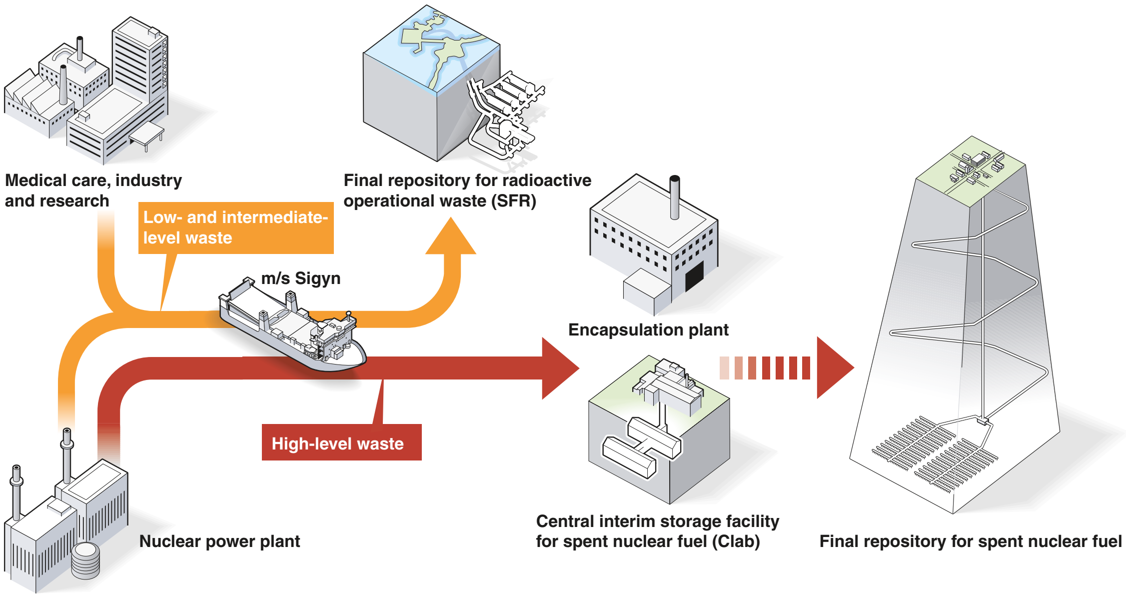

Figure 1-1. *System for management and disposal of radioactive operational waste and spent nuclear fuel.*

Figure 1-2. *Interior from the final repository for low- and intermediate-level operational waste.*

This rock cavern is called BLA (rock cavern for low-level waste). The waste in this part of the facility can be handled without any kind of radiation shielding. Three of the caverns receive waste that requires radiation shielding. They are called BMA (rock cavern for intermediate-level waste) and BTF 1 and 2 (concrete tank repositories). The concrete silo is also intended for intermediate-level waste, mainly filters and ion exchange resins used for purification of reactor water. At the end of 2006, 31,000 m^3 of waste had been deposited in SFR 1. The total deposition capacity in SFR 1 is 63,000 m^3. The single largest factor that determines the quantities of operational waste is how long the nuclear power plants are in operation. Forsmark and Ringhals plan to operate their reactors for 50 years, and OKG has decided on an operating time of 60 years. The estimated operating time was originally shorter – 25 years – since all nuclear power plants were supposed to be shut down by 2010. Prolonging the service life of the reactors theoretically leads to greater volumes of operational waste to be disposed of. At the same time, however, waste management is being developed. The waste now being produced is smaller in volume but has a higher concentration of radionuclides than the forecasts originally assumed. Even with operating times of up around 60 years, the total waste volume from operation will not be greater than was originally estimated for 25 years of operation.

The volumes of short-lived low- and intermediate-level waste will increase in connection with major rebuilds and when the nuclear power plants are finally decommissioned. SKB judges that an extension of SFR is the best solution to deal with these increased quantities of short-lived low- and intermediate-level waste. The extension is described in section 1.4.2, where the designation of the different parts of the repository is also described.

Central interim storage facility for spent nuclear fuel (Clab)

The spent nuclear fuel is interim-stored in water pools in a central interim storage facility (Clab) at the nuclear power plant in Oskarshamn, see Figure 1-3. Clab consists of a receiving section at ground level where transport casks with the spent fuel are received and the fuel is unloaded under water.

The actual storage chamber consists of two rock caverns whose roofs are 25–30 metres below the ground surface. Each rock cavern is approximately 120 metres long and contains four pools and one reserve pool. The water in the pools serves both as a radiation shield and a cooling medium. The top end of the fuel is eight metres below the water surface. The radiation level at the edge of the pool is so low that the personnel can stand there for an unlimited time.

At the end of 2006 there were 4,775 tonnes of fuel (counted as the original quantity of uranium) in the facility. The total storage capacity is 8,000 tonnes of fuel: 5,000 tonnes in the original pools and 3,000 in the new ones.

Figure 1-3. *The central interim storage facility for spent nuclear fuel.*

Transportation system

In Sweden, nuclear waste shipments go by sea, since all nuclear power plants and nuclear waste facilities are situated on the coast. The transportation system consists of the specially built ship m/s Sigyn, a number of transport containers/casks and special vehicles for loading and unloading. The system has been gradually extended and augmented since the start of operation in 1982. Normally Sigyn makes between 30 and 40 trips per year between the nuclear power plants and Clab or SFR. The ship is also chartered out for other heavy shipments.

Low-level waste does not need any radiation shielding. It can therefore be transported in ordinary freight containers. Intermediate-level waste, on the other hand, requires radiation shielding and is embedded in concrete or bitumen at the nuclear power plants. The waste is then shipped in transport containers with 7–20 centimetre thick walls of steel, depending on how radioactive it is, see Figure 1-4. The spent fuel is shipped in transport casks with approximately 30 centimetre thick steel walls, see Figure 1-5. These casks are also equipped with cooling fins to dissipate the decay heat.

Figure 1-4. *The lid on an ATB transport container for radioactive waste is lifted off.*

Figure 1-5. Transport cask for spent nuclear fuel.

The function of the transportation system in conjunction with encapsulation and deposition is to move the sealed canisters from the encapsulation plant to the final repository. This is done in a safe and environmentally friendly manner to prevent damage to the canisters or the environment. For this purpose we will develop a new type of transport cask.

1.3.3 Resources for research, development and demonstration

Much of the research and development for encapsulation and final disposal of spent nuclear fuel needs to be done in a realistic setting. SKB now has three laboratories where we can carry out research and development projects on a full scale for all three barriers in the final repository. In addition to the Äspö HRL and the Canister Laboratory, which have been in operation for a long time, the Bentonite Laboratory was inaugurated in March 2007. Organizationally, the Bentonite Laboratory is a part of the Äspö HRL. The results of the experiments and projects in the three laboratories serve as a basis for designing the final repository and the encapsulation plant and for the safety assessments that will be conducted. We can also make use of the results from similar types of laboratories in other countries in various ways.

Canister Laboratory

The Canister Laboratory, situated in the harbour area at Oskarshamn, was built during the period 1996–1998. One of the old welding halls, which had been used for shipbuilding, has been converted for the development of sealing technology for the copper canisters. It is mainly equipment for welding of copper lids and bottoms and for nondestructive testing of the welds and the different parts of the canister that is developed there. Equipment and systems for handling of fuel and canisters in the future encapsulation plant are also tested and developed in the Canister Laboratory. Another purpose of the activities is to train personnel in preparation for commissioning of the encapsulation plant. The Canister Laboratory is therefore planned to remain in use until the encapsulation plant is put into operation.

There are stations in the Canister Laboratory for testing different welding techniques and different methods for nondestructive testing. The goal is to develop methods that meet the stipulated quality requirements and have sufficiently high reliability to be used in the encapsulation plant. The most important items of equipment in the laboratory are a friction welder, an electron beam welder, and equipment for radiographic and ultrasonic testing. An interior picture from the Canister Laboratory is shown in Figure 1-6.

Äspö HRL

The Äspö Hard Rock Laboratory, which was built during the period 1990–1995, is situated on Äspö north of the Oskarshamn nuclear power plant. The purpose of the HRL is to investigate how the final repository's barriers and parts (canister, buffer, backfill, closure and rock) prevent the radionuclides in the fuel from reaching the ground surface. The laboratory is continuing the work previously conducted in the Stripa mine. The role of the Äspö HRL has changed in recent years from investigating the function of the barriers to developing and demonstrating methods for construction and operation of the deep repository. In the future, the facility will also be used to train the personnel who will work in the final repository. We therefore expect the laboratory to be in operation for a long time to come.

The underground laboratory consists of a tunnel from the Simpevarp Peninsula, where the Oskarshamn nuclear power plant is located, to the southern part of Äspö. On Äspö the main tunnel descends in two spiral turns to a depth of 460 metres. The various tests are being performed in branches and niches in the tunnel. Figure 1-7 shows examples of concluded and ongoing experiments. The laboratory's surface facility is located on the island of Äspö.

Figure 1-6. *Interior from Canister Laboratory.*

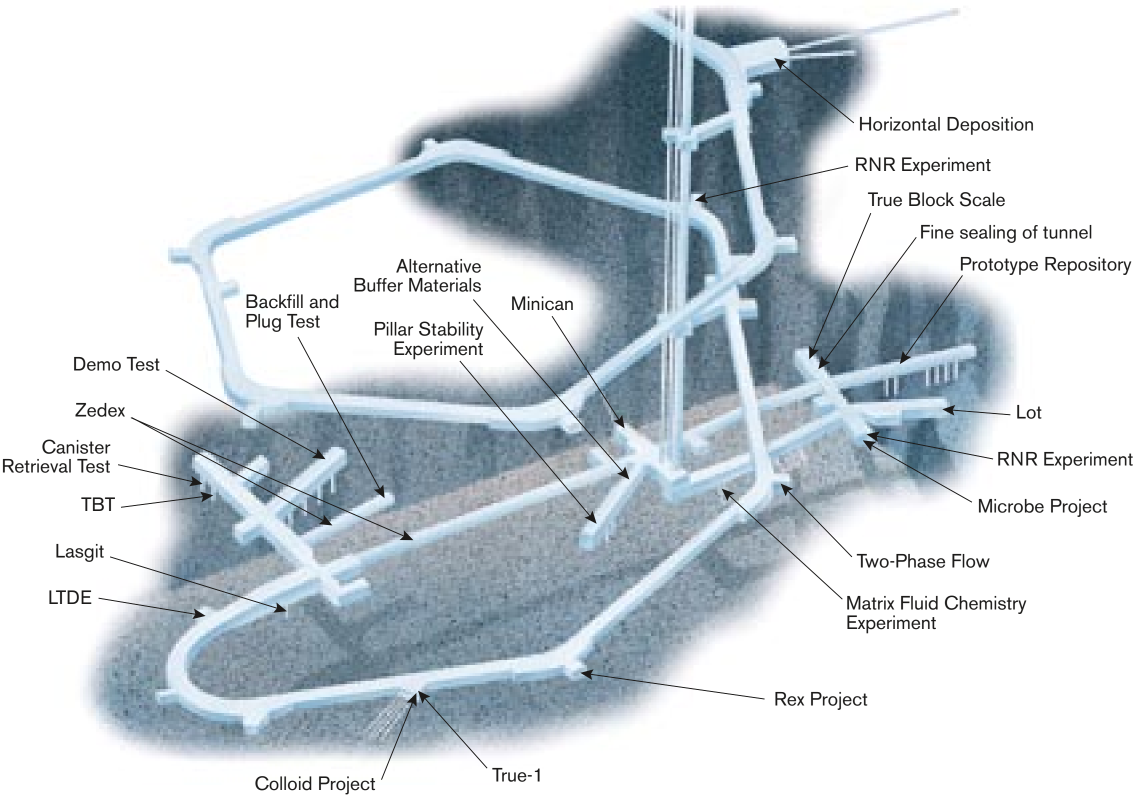

Figure 1-7. *Examples of concluded and ongoing experiments in the Äspö HRL.*

Many different countries are participating in the experiments being conducted at the Äspö HRL. SKB is collaborating with a number of countries and organizations that work with nuclear waste issues. In different forms and project groups we are working with sister organizations, research institutes and universities in Canada, the Czech Republic, Finland, France, Germany, Japan, Switzerland and Spain. The international contacts are important for being able to compare different methods for calculations and analyses, as well as for a thorough discussion and evaluation of the results. Cooperation also means our resources can be better utilized. They also give us an opportunity to engage the foremost experts in different fields.

Bentonite Laboratory

Going from small-scale experiments in the laboratory and different prototype tests to industrial-scale production requires stepwise development of production and inspection methods that can be repeated with sufficiently high quality.

Now SKB has taken the same step for the buffer as for the canister, and another laboratory – the Bentonite Laboratory – was inaugurated in Oskarshamn in March 2007, see Figure 1-8. The laboratory is situated adjacent to the Äspö HRL and will complement the experiments that are already being performed there. We also want to develop methods for backfilling the repository's tunnels and building plugs to seal the deposition tunnels.

The advantage of the Bentonite Laboratory is that it offers opportunities to simulate different water conditions in a controlled manner.

Figure 1-8. The Bentonite Laboratory was inaugurated in March 2007 and activities there have just begun.

1.3.4 Resources in the form of competence and organization

SKB has a management system today that is certified to the quality and environmental management standards ISO 9001 and ISO 14001. SKB took over the operation of Clab on in January 2007. At that time a new management system was introduced with procedures that are required to operate nuclear activities. This new management system lives up to all relevant requirements in SSI's and SKI's regulations and will constitute an important base for the organization that SKB needs to build the planned facilities.

A new Department of Nuclear Safety was formed in conjunction with the takeover of Clab. The department plays an independent role within SKB with responsibility for reviewing SKB's activities (independent review in accordance with nuclear activities legislation) and for development in the field of safety and radiation protection

SKIFS 2004:1 and the Environmental Code require that the activity operator acquire the knowledge needed to maintain safety and to prevent the activity from causing harmful effects to human health and the environment, as well as knowledge of how to prevent or mitigate such harmful effects.

During 2005–2006, SKB conducted a study on what the future organization should look like during the years after an application for the final repository is submitted. This study sheds light on a number of scenarios having to do with the siting of the final repository, time aspects surrounding the licensing process, etc. The study also proposes alternative organizations and identifies what competence SKB will need in the different phases of the activity. The conclusion was that SKB should pursue its activities within the framework of two different programmes: The Nuclear Fuel Programme and the Programme for Low- and Intermediate-Level Waste (the LILW programme). Operation of the existing facilities (Clab, SFR and the transportation system) takes place within the framework of the operating process. Coordination of the programmes is important from several aspects. Besides legal requirements, long-term planning must also consider resources in the form of competence and access to contractors. A well-coordinated planning of the programmes is necessary to ensure an efficient utilization of resources.

A second phase of the organization study began in early 2007. The purpose is to arrive at detailed proposals for how SKB's activities can be structured and managed during the time up until the final repository and the encapsulation plant will be put into operation.

1.3.5 Financial resources

The companies that own nuclear power plants in Sweden are responsible for the management and disposal of spent nuclear fuel and radioactive waste from the Swedish nuclear power plans and for their subsequent decommissioning. On behalf of the nuclear power companies, SKB prepares a cost estimate and then makes proposals for fees and guarantees on the basis of this. The size of the fees and the guarantees is decided by the Government. The money goes into a fund which is deposited in an interest-bearing account at the National Debt Office or invested in treasury bills. The fund is managed by a separate authority, the Nuclear Waste Fund. The average fee is currently around 1.3 öre (about 0.14 euro cent) per kWh. At the end of 2006, the market value of the fund was about SEK 38 billion.

The total cost for the system is calculated based on an assumed operating time of the reactors in Forsmark and Ringhals of 50 years and in Oskarshamn of 60 years (the reactors Barsebäck 1 and 2 were taken out of service in on 30 Nov. 1999 and 31 May 2005, respectively).

The cost in 2007 prices[1] for managing and disposing of all radioactive waste from 50 or 60 years of operation of the reactors and decommissioning them is calculated to be about SEK 94 billion. Of this amount, around SEK 27 billion has already been used to build and operate the existing facilities and for research and development. The future costs from 2008 onward are about SEK 67 billion.

The Riksdag (Swedish parliament) passed a new Financing Act in May 2006, and one year later, in May 2007, the Government issued an ordinance based on the new act. The new legislation entails certain changes in the data underlying the Plan Calculation and its presentation. Among other things, the so-called "earning time" has been lengthened from 25 years to 40 years. The fee or charge, as is prescribed in the Financing Act with associated ordinance, is based on the waste quantity that exists after an operating period of 40 years, but with at least six years' remaining operating time for plants in operation (the earning time). This means that the funding need has grown due to the increasing quantity of waste products to be disposed of, but at the same time the electricity production over which the fee is spread has also increased. Another important change compared with the former system is that the obligation to pay fees persists after a reactor has been permanently shut down. This currently applies to the reactors in Barsebäck.

In the new system the fee is levied on the electricity that is produced in the nuclear power plants for the reactors that are in operation. In the case of reactors that have been permanently shut down, an annual fee is charged. As a basis for determining the fee, SKB periodically calculates the costs for the necessary measures. This year's calculation is presented in a report, Plan 2007, which was handed over to the Swedish Nuclear Power Inspectorate, SKI, on 29 June 2007. This report will serve as a basis for fees and guarantees for 2008 and 2009.

[1] The most recent cost calculation was prepared at the January 2007 price level and pertains solely to future costs from 2008. The total cost is obtained by adjusting incurred costs to the same price level and adding them to the Plan Calculation's total cost.

1.4 SKB's strategy

This section deals with the strategic choices regarding methods and procedures which SKB must make in order to build and commission the remaining facilities.

SKB considers it to be the responsibility of those generations who have benefited from the electricity produced by the nuclear power plants to ensure that a solution is found to the waste problem. The technology, financing and political will to find such a solution exist today. The different repositories should therefore be built as soon as they are needed. The selection of suitable sites for the repositories should be made in steps through an open democratic process in consensus with regulatory authorities and the concerned municipalities.

The development of the KBS-3 method, see Figure 1-9, is in a phase dominated by pilot- and full-scale tests and demonstrations of the different system parts. The Canister Laboratory, the Bentonite Laboratory and the Äspö HRL are the central resources for this. After several years of development of welding methods, we were able to choose friction stir welding as the reference method for sealing canisters in the encapsulation plant. At the same time we have acquired knowledge of Swedish bedrock, what properties the rock must have and how the engineered barriers in the final repository for spent nuclear fuel should be designed to satisfy the existing requirements. All methods and technology for building the final repository for spent nuclear fuel, depositing copper canisters and bentonite and backfilling the tunnels have been tested on a full scale. The methodology for assessing long-term safety is also well developed and tested. We therefore judge that the KBS-3 method satisfies both legal requirements and technical requirements on safety.

1.4.1 Strategic choice of method for disposal of spent nuclear fuel

Internationally there are two main strategies for managing the spent nuclear fuel: reprocessing and direct disposal. The choice between these alternatives is determined by whether a country chooses to regard the fuel as waste or as a resource. In several states, reprocessing is viewed as a necessity in order to conserve existing uranium resources. Other countries have, for political or economic reasons, chosen to regard the fuel as waste. Regardless of whether the waste consists of spent fuel or has been partitioned in a reprocessing plant, it must be deposited in some type of geological formation. The radionuclides are then prevented from reaching the biosphere by a system of barriers.

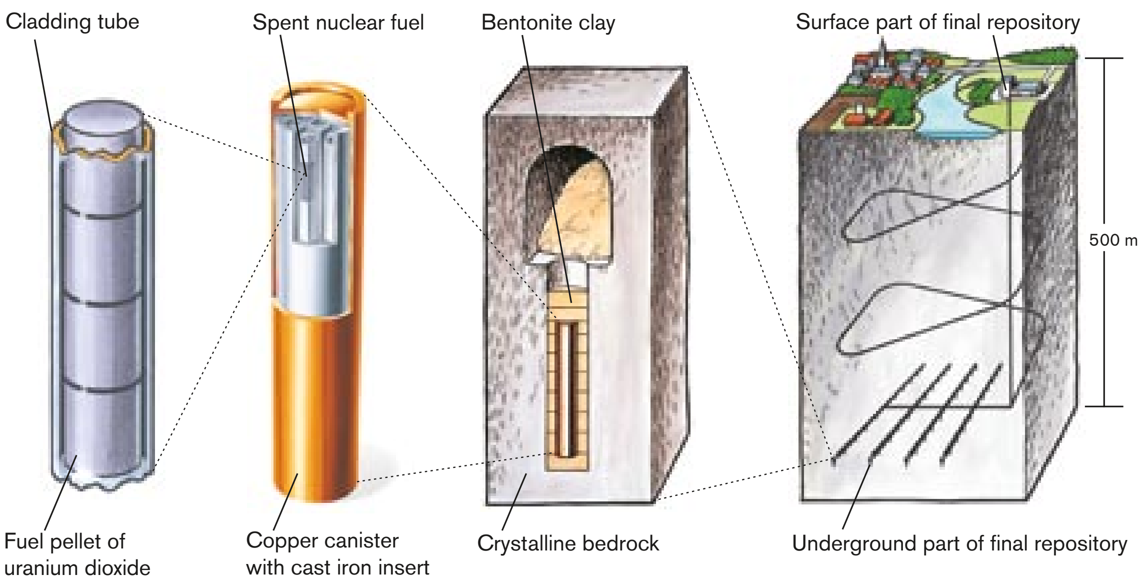

Figure 1-9. *In the KBS-3 method the spent nuclear fuel is encapsulated in copper and deposited at a depth of about 500 metres in the crystalline bedrock. The canisters are surrounded by a buffer of bentonite clay intended to protect against corrosion and movements in the rock.*

The idea of geological disposal existed back in the 1950s. Other more or less realistic strategies have also been studied, such as launching the fuel into space, disposing of it beneath the seabed or burying it in the continental ice sheet. A large number of countries are agreed today that geological disposal is the only solution that satisfies all requirements on safe final disposal and that this can be achieved by adapting available technology.

The principles behind SKB's safety philosophy for geological disposal are as follows:

- The repository shall be situated in a long-term stable environment that is protected from both societal changes and long-term climatic changes.
- The repository shall be situated in bedrock that can be assumed to be of no economic interest to future generations.
- The spent fuel shall be surrounded in the repository by multiple barriers. The barriers shall primarily isolate the fuel.
- If the isolation should be breached, the barriers shall retard any escaping radionuclides.
- Engineered barriers shall consist of naturally occurring materials that are long-term stable in the repository environment.
- The repository shall be designed so that high temperatures are avoided.
- The barriers shall work passively, i.e. without human intervention and without input of energy or materials.

Together with a number of other considerations, for example that the repository shall be technologically feasible to build, these principles have led to the KBS-3 system for spent nuclear fuel.

The choice of the KBS-3 method as the reference design in the Swedish nuclear fuel programme has taken place stepwise within the framework of the presentation and review of the RD&D programmes, see section 1.3.1, and studies related to them /1-19, 1-20, 1-21, 1-22, 1-23 and 1-24/.

SKB carried out a comparative system analysis in 2000 /1-25/. The analysis evaluates different strategies for disposing of spent nuclear fuel. The previous studies are used as background material. The different strategies and methods studied over the years are compared with the stipulated requirements. The analysis takes into account general and societal requirements as well as environmental, safety and radiation protection requirements. Methods that have been studied and compared with KBS-3 for repositories in crystalline rock are Very Long Holes (VLH), WP-Cave and deep boreholes (also known as VDH = Very Deep Holes).

In an integrated evaluation against the requirements, KBS-3 was judged to be the most advantageous method. The most recent safety assessment we have conducted based on data from the site investigations /1-26/ shows that a KBS-3 repository has good prospects for satisfying the regulatory requirements. One argument in particular in favour of the KBS-3 method is that the operating phase provides individual control over both canisters and buffer. The repository is also easier than other methods to adapt to conditions on a specific site.

1.4.2 Strategies for low- and intermediate-level waste

The current final repository for radioactive operational waste (SFR 1) is only licensed to receive waste from the operation of the nuclear power reactors. Power increases, rebuilds and extended operating times for the reactors will influence the space requirement. Since the quantity of waste will increase in conjunction with the decommissioning and dismantling of the nuclear power reactors, SKB had originally planned to extend the repository and call the new part the final repository for decommissioning waste (SFR 3). This part would then be licensed to receive decommissioning waste as well.

SKB's current main strategy and planning to dispose of radioactive decommissioning waste entails that we will be able to start receiving decommissioning waste from Barsebäck in 2020. A prerequisite for this to be possible is that the present-day final repository is extended. The main strategy is for SFR to be extended in two stages. In conjunction with the extension, the whole SFR will be relicensed to be able to receive both operational and decommissioning waste. After the extension, the terms SFR 1 and SFR 3 will be abolished and the facility will only be designated SFR. The first stage will accommodate the radioactive decommissioning waste from Barsebäck 1 and 2, the increased quantity of operational waste that arises due to the extended operating time of present-day reactors, and odd large components from the power increase projects. A second stage will be built to accommodate the decommissioning waste from those reactors that are in operation today. It has not yet been decided when the construction of stage two is to be finished.

The long-lived low- and intermediate-level waste is interim-stored today in storage canisters in the pools in Clab, or in pools at the nuclear power plants. SKB and the Swedish nuclear power companies have decided that a chamber for dry interim storage of core components is needed as a complement or substitute for wet interim storage in Clab. Interim storage in Clab is expensive and space-taking and can in the long term lead to a shortage of space in Clab for spent nuclear fuel. The core components are in need of radiation shielding, but not cooling. Preparations are under way for dry storage of long-lived low- and intermediate-level waste from all nuclear power plants in BFA (rock cavern for waste) in Simpevarp. OKG is already using BFA today for dry interim storage. A new waste container, ATB-1T, is being designed that conforms to the size of the steel cases in which the core components will be transported and interim-stored. Delivery of ATB-1T is scheduled for 2011, whereby dry interim storage of waste from other power plants than Oskarshamn can begin. At present, dry storage does not include control rods and equipment containing fissile material; this waste will continue to be stored in Clab. Interim storage will continue until the final repository for long-lived low- and intermediate-level waste is commissioned.

The last facility that will be built in the LILW programme is the final repository for long-lived low- and intermediate-level waste. The final repository for long-lived low- and intermediate-level waste does not have to be finished until the majority of the Swedish nuclear power plants have been decommissioned, which will be 2045 at the earliest.

1.4.3 Siting

Siting of the remaining facilities in the system is based on a stepwise process with well-underpinned and firmly anchored decisions. At the end of 2006, SKB submitted an application under the Nuclear Activities Act for Clab and the encapsulation plant to the regulatory authorities. The evaluation of the site investigations performed in Forsmark and Laxemar for a final repository for spent nuclear fuel is currently under way. On the basis of these and other investigations, we intend to select one of these sites by mid-2009. At the end of 2009 we plan to submit an application under the Nuclear Activities Act for a permit to build the final repository and an application under the Environmental Code for the final repository system.

1.4.4 Additional facilities

In order to manage and dispose of the spent nuclear fuel, new facilities are needed – primarily an encapsulation plant for encapsulating the spent fuel in copper canisters and a final repository where the canisters are deposited. According to the plans, the encapsulation plant will be integrated with Clab and operated together with it. A transportation system that is tailored to the encapsulation plant and the final repository is also required. Furthermore, a final repository is needed for the short-lived low- and intermediate-level decommissioning waste, and a final repository for the long-lived low- and intermediate-level waste.

Encapsulation plant

The work of designing the encapsulation plant started in 1993. Since then the facility has been further developed and modified. Building the plant in Oskarshamn adjacent to Clab has always been SKB's main alternative. We have, however, also studied the possibility of building the encapsulation plant in Forsmark. A prerequisite for this is that the final repository is also located there.

The encapsulation plant contains a number of stations for different work operations, see Figure 1-10. All handling of the spent fuel takes place by remote control. The encapsulation process begins with the transfer of the fuel from the pools in Clab to the pools in the encapsulation plant via the existing fuel elevator in Clab. The fuel is dried in the radiation-shielded handling cell. The fuel is lifted over to the canister and combined in such a manner that the total heat output in each canister is not excessive. The air in the canister is replaced with argon. The canister is then sealed by means of friction stir welding, after which the quality of the weld is inspected. If the weld is approved, the canister is further transferred to the machining station, where the excess material is machined off. Then a new quality inspection is performed. After cleaning – if necessary – the sealed canister is placed in a special transport cask and transported to the final repository to be deposited.

1 = Handling pool. The fuel is moved over from a storage canister to a transfer canister.

2 = Handling cell. The fuel is dried and lifted over to the canister.

3 = Atmosphere change. The air in the canister is replaced with argon.

4 = Sealing. Welding by means of friction stir welding.

5 = Nondestructive testing. The welds are inspected by means of ultrasonic and radiographic testing.

6 = Machining.

Figure 1-10. *The encapsulation plant contains stations for the different work operations that are needed to encapsulate the spent fuel and inspect the seal.*

Final repository for spent nuclear fuel

In its basic design, the final repository consists of a ramp, shafts, central area and a number of deposition areas with deposition tunnels, see Figure 1-11. There are a number of deposition holes in each deposition tunnel. The placement of the deposition tunnels, as well as the spacing between the deposition holes, is determined by local conditions of the rock on the site.

The shipment of canisters arrives at the final repository where it is transloaded to a specially built transport vehicle, which takes the canisters down to the deposition level. This can be done in different ways, depending on where the final repository is sited. The canisters are then transloaded to the deposition machine to be deposited. After the canisters have been emplaced in the deposition holes, surrounded by bentonite clay, the tunnel is backfilled with swelling clay. Other chambers are also backfilled when all fuel has been deposited.

The KBS-3 method entails that the canisters can be emplaced either vertically (KBS-3V) or horizontally (KBS-3H). The reference design of the KBS-3 method is based on vertical deposition, while horizontal deposition can be regarded as another possible configuration of the final repository.

The work of finding a suitable site for a final repository for spent nuclear fuel has been under way for several decades. Complete site investigations in Forsmark in Östhammar Municipality and in Laxemar in Oskarshamn Municipality will be concluded during 2007. SKB wants to build the final repository on the most suitable of these sites. We have also conducted an initial site investigation in Simpevarp in the municipality of Oskarshamn.

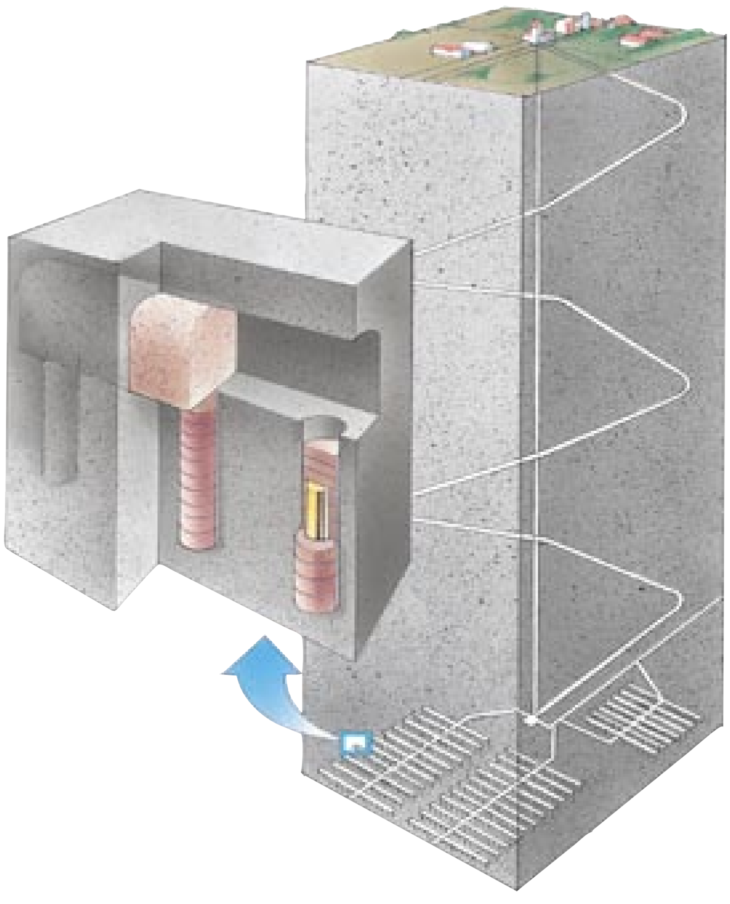

Figure 1-11. *Final repository for spent nuclear fuel.*

Final repository for long-lived low- and intermediate-level waste (SFL)

SKB plans to dispose of heavily neutron-irradiated long-lived waste, such as core components and reactor internals, in a facility similar to SFR but located at greater depth. The waste consists in part of components from the reactor core that have been replaced during the reactor's operating time (such as control rods and detector probes), and in part of structural parts from the reactors (such as core grids and core barrels). The goal is to be able to provide a more detailed account of how SKB plans to design the final repository for long-lived low- and intermediate-level waste in RD&D Programme 2010. The report may include a strategy for choice of site and repository depth as well as studies of the dimensions of the repository. A waste inventory and evaluation of the long-term safety of an envisioned repository will be performed when the application for extension of SFR has been completed.

1.5 Premises for planning

The planning is guided by different premises. In part it is a question of determining the layout of the different facilities. The radioactivity of the waste is the main determining factor here. Another premise is the waste quantities to be disposed of. This is directly dependent on the operating time of the different reactors. The properties of the waste are also a factor. The trend right now is towards higher average burnups. High burnups can, for example, entail that more research is needed in preparation for the safety assessments for the spent nuclear fuel. This is dealt with in Chapter 22 in Part IV.

Different types of radioactive waste

The nuclear waste is divided into different categories according to the level of radioactivity (low-, intermediate- or high-level waste) as well as according to the longevity of the activity (short- or long-lived waste).

Most of the waste from the nuclear power plants, about 85 percent in terms of volume, is short-lived and low- and intermediate-level. It arises both during operation of the facilities and when they are decommissioned. Operational waste consists, for example, of spent filters, replaced components and used protective clothing, while decommissioning waste consists of such items as scrap metal and building materials.

Long-lived low- and intermediate-level waste also arises during the operation and decommissioning of the nuclear power plants. Spent components from the reactor core or its immediate vicinity belong to this category. The components contain long-lived radionuclides that are formed when stable elements in, for example, steel are exposed to strong neutron irradiation from the reactor core.

Spent nuclear fuel comprises a small fraction of the total waste volume, but contains by far most of the total radioactivity, both short- and long-lived. The decay of the radionuclides causes them to emit radiation and generate heat, so-called decay heat. Eventually, as the short-lived substances decay, the radioactivity in the spent fuel will be dominated by the long-lived substances. Spent nuclear fuel requires radiation shielding in conjunction with all handling, storage and final disposal. The decay heat that is generated requires cooling to prevent the fuel from overheating. The content of long-lived radionuclides determines the layout of a final repository. The presence of fissionable material requires measures to prevent criticality and keep the fuel from falling into the wrong hands.

Waste quantities

The total quantities of nuclear waste to be disposed of depend on the number of nuclear reactors and their operating time. At present there are ten reactors in operation. The waste quantities affect the required capacity and operating time of the different waste facilities. The quantities do not, however, influence the fundamental steps or the types of facilities needed to dispose of the waste.

The quantity of spent nuclear fuel is usually given as the quantity of uranium that was originally present in the fuel. The fuel quantity[2] that has been consumed in the Swedish power reactors up to and including 2006 is 5,000 tonnes of uranium from boiling water reactors (BWRs) and 1,500 tonnes of uranium from pressurized water reactors (PWRs).

The nuclear fuel programme is supposed to manage all spent fuel stemming from the operation of the Swedish nuclear power plants. It must therefore be adapted to different outcomes in terms of remaining nuclear energy production. Recently the owners of the nuclear power plants changed the estimated operating time. Previously all forecasts were based on an operating time of 40 years, which gave rise to 9,600 tonnes of fuel (counted as uranium), equivalent to 4,500 canisters. The long-term planning for the nuclear fuel programme is now based on a new reference scenario where the reactors in Ringhals and Forsmark are assumed to have an operating time of 50 years and OKG's reactors 60 years. The quantity to be disposed of amounts to about 12,000 tonnes of uranium, equivalent to around 6,000 canisters.

The LILW programme is aimed at disposing of all the low- and intermediate-level decommissioning waste from the Swedish nuclear power programme. The only exception is the very low-level operational waste which the power companies choose to deposit on their own near-surface repositories. The LILW programme is also affected by the extended operating times for the reactors. The new reference scenario gives rise to a total of about 212,000 m^3 of short-lived waste and about 8,700 m^3 of long-lived waste from the nuclear power plants.

The increased operating time of the reactors means that the operating times for both SFR and the final repository are changed, as well as the volumes of waste and fuel. The operation of Clab and the encapsulation plant is extended at the same time as the start of operation of the final repository for long-lived low- and intermediate-level waste, SFL, is postponed.

Burnup

Burnup is a measure of the energy that has been extracted from the fuel assembly and is specified in megawatt-days per kilogram of uranium (MWd/kgU). When burnup has reached a certain level the fuel assembly is replaced. As a result of technical advances, both fuel burnup and fuel enrichment have increased steadily since the reactors were originally put into operation. The reason is to optimize the operating economy of the reactors.

The design values for burnup and enrichment stipulated in the application for Clab and the encapsulation plant are:

BWR 55 MWd/kgU; 3.6 percent uranium-235

PWR 60 MWd/kgU; 4.3 percent uranium-235

BWR Mox 50 MWd/kgU; 4.5 percent Pu-fiss

Today the nuclear power companies have plans to use fuel with higher enrichment and burnup: 60 MWd/kgU and 5 percent uranium-235 for both PWR and BWR fuel. In this planning it is important to clarify what consequences these changes can have for the final repository system. An important factor is that the premises are the same for all parts of the system (transport cask for spent fuel, Clab, encapsulation plant, transport cask for filled copper canister and final repository). We believe that we have enough data today for the coming safety assessment, SR-Site, for the fuel on which the application for Clab and the encapsulation plant is based. However, an adjustment must be made for OKG's Mox fuel. The question of criticality also needs to be further discussed on account of the higher degree of enrichment.

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[2] Includes discharged fuel and current reactor cores.

1.6 SKB's main timetable

The timetable for building and commissioning the facilities needed for final disposal of the spent nuclear fuel and the low- and intermediate-level waste is controlled by the need for technical work and by the statutory permit/licence requirements. Based on this we have identified a number of important milestones up until the time the final repository is put into routine operation. The milestones for the two programmes are specified and described in Chapters 2 and 3. Figure 1-12 shows an overview of SKB's planning for the entire nuclear waste programme.

Other important premises that must be fulfilled in order for the timetable to be realized are:

- The encapsulation plant must be joined to Clab so the two form an integrated facility. If the Clab siting is rejected as the main alternative, the timetable must be revised.
- Development of the technology for encapsulation and deep disposal continues at the planned pace and with the anticipated progress. Unexpected problems at some critical juncture may lead to delays and revisions.
- SKB obtains permissibility and licence decisions from the Government within two years from submission of an application under the Nuclear Activities Act for the final repository and an application under the Environmental Code for the final repository system. Moreover, these decisions must not be appealed to a higher instance.

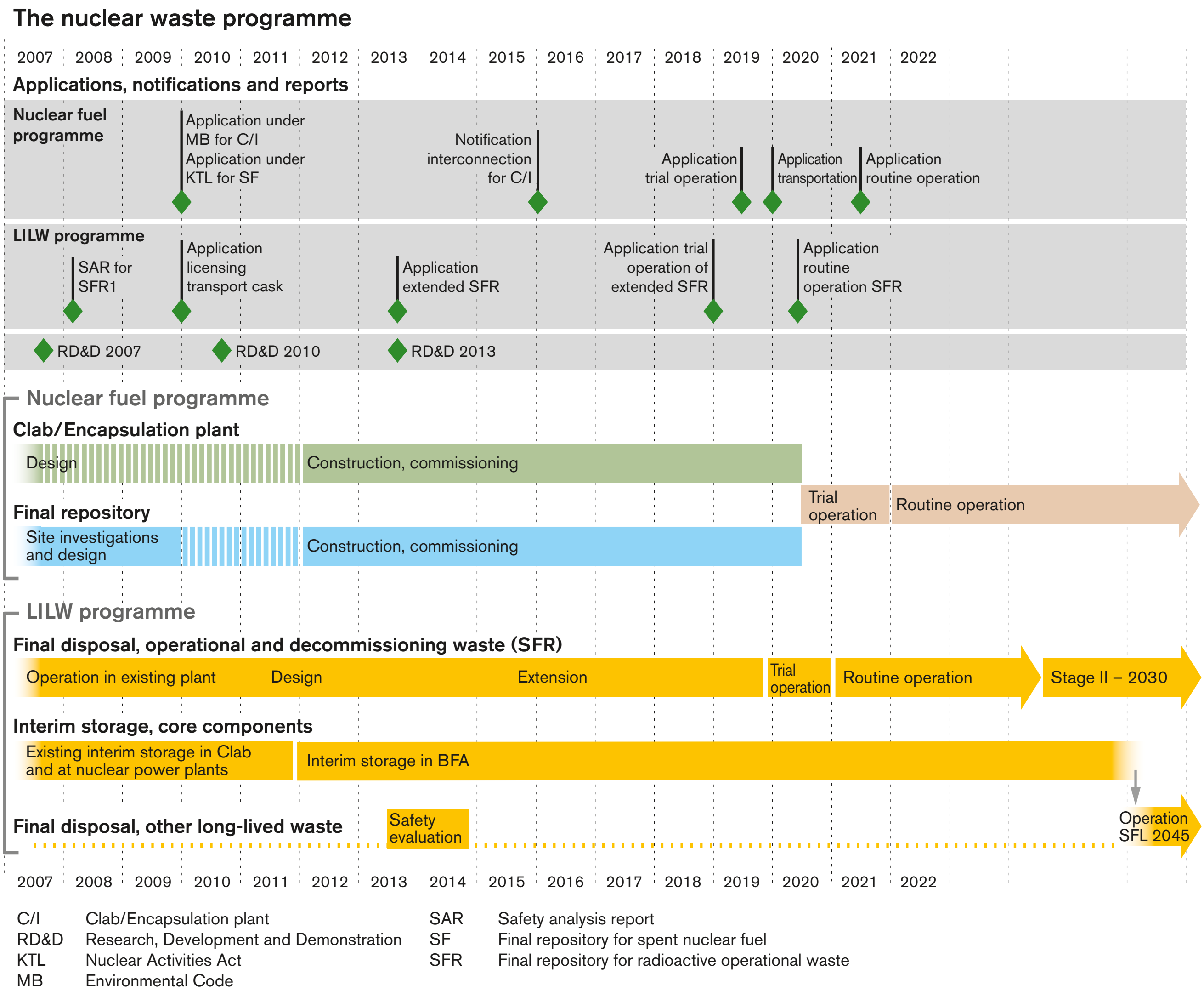


Figure 1-12. SKB's main timetable with applications, notifications and reports.

2 Nuclear fuel programme

The timetable for building and commissioning the facilities needed for final disposal of the spent nuclear fuel – encapsulation plant, final repository and transportation system – is controlled by the need for technical work and by the statutory permit/licence requirements. Based on this we have identified a number of important milestones up until the time the final repository is put into routine operation. The planning describes all the measures needed to implement the nuclear fuel programme. The more detailed planning extends over a period of about 15 years.

Figure 2-1 shows the overall plan and the important milestones. The more detailed planning prior to each milestone is presented in Parts II–IV of the RD&D programme. With regard to the content and scope of the application under the Nuclear Activities Act for the final repository for spent nuclear fuel and the application under the Environmental Code for the final repository system, see the report "Application plan for the encapsulation plant and the final repository for spent nuclear fuel" (in Swedish only) /2-1/. SKB's work with the structure and content of the applications and compilation of supporting material will continue until the applications are submitted. Regular cross-checks will be made with the regulatory authorities within the framework of the consultations that are held in accordance with previous Government decisions on RD&D. SKB also intends to provide information on the planned content of the applications in other forums.

The important milestones are divided into two categories. The first group consists of applications, notifications and statutory reports. The second group contains other important milestones that we need to pass in order to build the facilities and put them into operation. These include, for example, site selection, start of construction and commissioning.

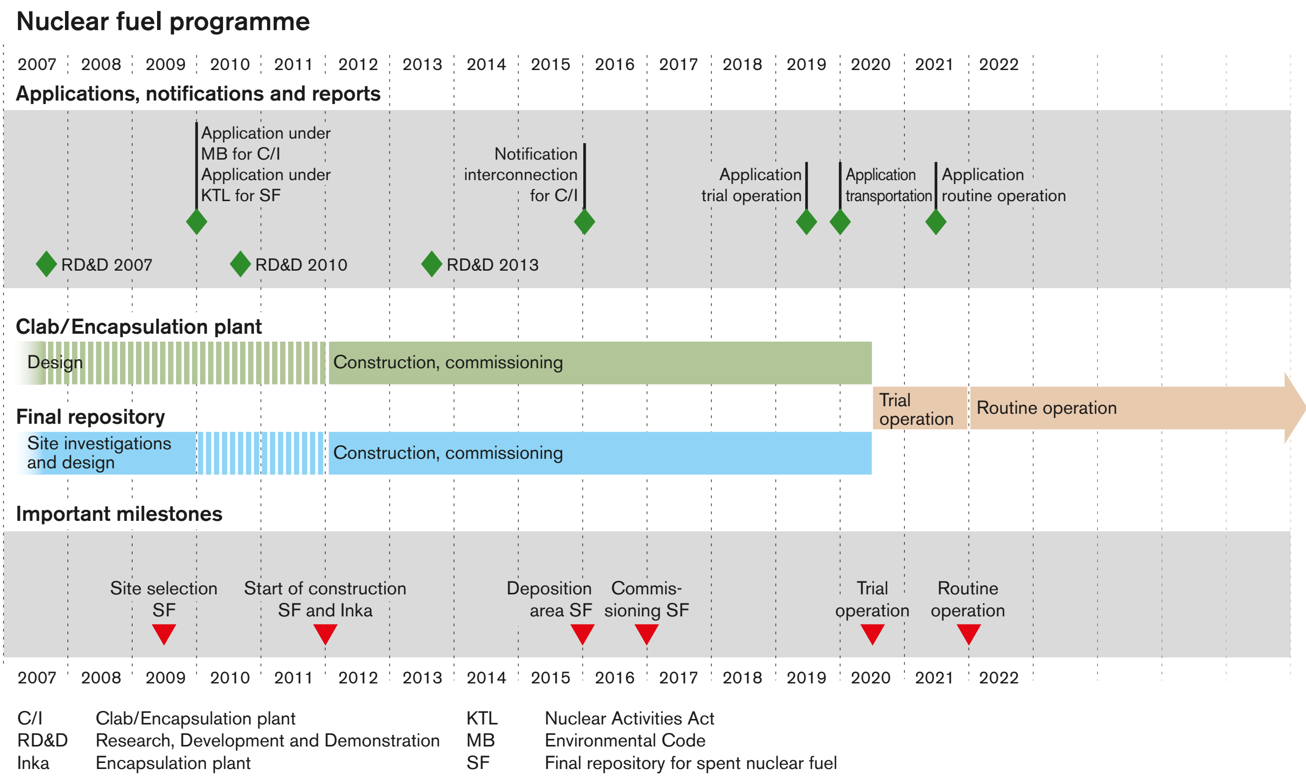


Figure 2-1. Timetable for nuclear fuel programme.

The link between the progress of the programme in relation to its milestones and the need for results from technology development is described in Part II, where the plans for the construction of the final repository are presented. The following account provides a general description and references to relevant sections in Part II. The planned technology development work is then described in Part III and the link to the milestones is obtained via the references in Part II. The work on the safety assessment and the prioritized research areas is presented in Part IV.

2.1 Planning

The Swedish nuclear fuel programme will probably be the first project of its kind in the world to undergo licensing. Work on the programme has been under way for several decades and has proceeded throughout this time in the form of stepwise development. As more knowledge has emerged on the KBS-3 system and its subsystems and components, the premises have been adjusted, and the timetable has been updated as a consequence of such adjustments.

The period up to the application for the final repository contains the last cycle in the site investigations of data collection, data analysis, design and safety assessment. During this period the application under the Nuclear Activities Act for the final repository, the application under the Environmental Code for the final repository system and the supplement of the application under the Nuclear Activities Act for Clab and the encapsulation plant will also be compiled. Judging from experience, SKB now estimates that the application under the Nuclear Activities Act for the final repository can be submitted at the end of 2009.

The review viewpoints provided by SKI and SSI on the application under the Nuclear Activities Act for Clab and the encapsulation plant and on the safety assessment SR-Can may influence the timetable for preparing the applications planned for 2009. The timetable may have to be further adjusted due to the scope of the measures that may be entailed by the viewpoints.

During the period from when an application has been submitted until a licence has been issued, the various licensing matters will be dealt with by SKI, the Environmental Court and the Government. In addition, the municipality will issue a statement in the Environmental Code matter and the planning and building permit matter will be dealt with. SKB has limited means to influence the time it takes from when an application under the Environmental Code has been submitted until the final permit has been granted, but estimates the length of the period to be at least two years.

SKB has estimated the time needed to build the encapsulation plant, the accesses to the repository level, and the final repository's central area. There are uncertainties dependent on the characteristics of the site, which method is used to excavate rock and technology development for the different subsystems. Besides pure construction activities, the work includes everything associated with the updated safety analysis report prior to trial operation. During this period the machines and systems needed to manufacture canisters, buffer and backfill and deposit the canisters are also finished. Before trial operation can begin, the regulatory authorities review the application and its supporting material. We estimate that the time from start of construction until application for trial operation will be seven years.

Trial operation and routine operation are based on the terminology and the point of view expressed in SKI's regulations.

The time of transition from trial operation to routine operation occurs is also dependent on regulatory decisions. Estimating when routine operation can begin is naturally associated with great uncertainties, since it is so far ahead in time. However, we estimate that it can be commenced within two years of the start of trial operation.

An obvious prerequisite for being able to build and operate the final repository is that the technology that is needed in different phases is developed and ready to be put into industrial use as the need arises. Part II (Chapter 6) describes the current situation for the work methodology that is being developed for design and implementation of technology during construction and operation. SKB's programme for technology development is presented in Part III, where the development needs for different subsystems are also described.

2.2 Milestones

2.2.1 Applications, notifications and reports

Application under the Nuclear Activities Act for the final repository

In the application under the Nuclear Activities Act for the final repository, SKB will present the technical supporting material that is needed to determine whether the final repository satisfies the requirements that are imposed on the facility by the Nuclear Activities Act and the Radiation Protection Act with associated regulations and ordinances. A safety analysis report (PSAR) of operational and long-term safety will be one of the supporting documents for the application. The application also includes an environmental impact statement and an account of how SKB satisfies the Environmental Code's general rules of consideration. The environmental impact statement will be common for the facilities in the licensing processes under the Nuclear Activities Act and the Environmental Code. A general description of the contents of these applications can be found in "Application plan for the encapsulation plant and the final repository for spent nuclear fuel" (in Swedish only) /2-1/.

In the application we will describe the technology which we want to use to build and commission the final repository as well as how the work is intended to be carried out. Part II (Chapter 6) describes the current situation for the work methodology that is being developed for design and implementation of technology during construction and operation of the final repository. In Part II (Chapter 5) we also describe how far we plan to have come with regard to technology development when the application is submitted, see Tables 2-1 to 2-4. SKB's programme for technology development is presented in Part III.

Application under the Environmental Code for the final repository system

SKB will submit an application to the Environmental Court for the activities within the KBS-3 system that require a permit under the Environmental Code.

A prerequisite for granting a permit under the Environmental Code is that the activity in question does not conflict with the relevant detailed development plan or area regulations under the Planning and Building Act. Matters under the Planning and Building Act will be dealt with in parallel with the processing and licensing described above by regulatory authorities, the Environmental Court and the Government.

RD&D Programme 2010

The next RD&D programme, RD&D Programme 2010, will be focused on the LILW programme and the progress with regard to state of knowledge and technology development that has been made on the final disposal of spent nuclear fuel.

Notification of interconnection of Clab and the encapsulation plant

When the encapsulation plant has been erected it will be interconnected with Clab. This means that the walls of the buildings will be opened to each other, whereby rooms and corridors will be joined together. The different systems will then also be joined together, after which the installations will be tested system by system. Notification must be made to SKI before this interconnection takes place.

Application for transportation permit

SKB already has permits from SKI and SSI for the transportation of nuclear material. These permits are renewed at roughly three-year intervals. Aside from the permits, each shipment must be notified to the regulatory authorities in advance. Before the canister shipments begin, SKB will apply for a permit from the regulatory authorities to transport canisters with spent fuel in manner a similar to the way fuel shipments take place today. SKB also intends to license the canister transport casks in Sweden. The licensing process will commence before the transport permit is updated.

Applications for trial operation

Integrated testing of the different facility systems can take place once the facilities have been built. When systems and processes function as intended, SKB submits an application for the facility in question for a permit to commence trial operation. Trial operation entails that nuclear material is brought into the facility and handled there. SKB's request to be allowed to commence trial operation contains updated assessments of long-term safety, updated safety analysis reports and safety-related technical specifications.

Applications for routine operation

The purpose of trial operation is to gather experience. The safety analysis reports and the safety-related technical specifications are supplemented and included as supporting material in SKB's application for a permit to start routine operation of the facilities.

2.2.2 Other important milestones

Besides the accounts we have to submit to the regulatory authorities to obtain various permits or consents along the way to a commissioned facility, there are additional important milestones that occur at other times. The group "other important milestones" includes, for example, various decisions that must be made by SKB.

Site selection

Selecting one of the two candidate sites for the final repository is a prerequisite for being able to begin concrete preparations for establishing the repository. Background material that will be available as support in selecting a site includes site descriptions based on completed investigations and analyses and site-adapted final repositories, as well as analyses and assessments of environmental consequences, safety and radiation protection during operation and post-closure. Integrated evaluation and site selection are described in Part II, section 4.3.

In connection with site selection, SKB plans to start a project with task of building the final repository. Planning of this project is under way.

Construction

When all the necessary permits and conditions under the Nuclear Activities Act, the Radiation Protection Act, the Environmental Code and the Planning and Building Act have been obtained, the facilities can begin to be built, both above and below ground. SKB must consider the consequences of the conditions in the permits before the start of construction and adapt the planning accordingly.

Planning of the construction phase includes preparing a programme for investigations during construction and operation and defining planning premises that will control the construction of the final repository and the encapsulation plant. The planning includes describing how we will conduct further technology development and how it will be coordinated with the actual construction of the final repository system.

Accesses to repository depth

The technology for building the accesses to the repository – shaft and ramp – must have been chosen and thoroughly prepared by the start of construction. These facility parts are time-critical during the construction phase, and their excavation will therefore be started as soon as possible. We must also have demonstrated that we can manufacture and install the canisters and buffer, and that we can backfill all openings in a manner such that requirements and specifications can be fulfilled. In Part II (Chapter 7) we also describe how far we plan to have come with regard to technology development by the start of construction, see Tables 7-1 to 7-4.

Start construction of deposition areas

The exact location and layout of the deposition area will not be determined at the time when a permit is applied for under the Nuclear Activities Act for the final repository. Investigations will be carried out during the construction of the hard rock facilities to support the safety assessment and to determine the detailed layout of the repository. During the excavation of accesses and the central area, the investigations will mainly be guided by design and construction needs. Prior to and during construction of the deposition area, the need for information with a bearing on long-term safety will have a more direct influence on the investigations that are conducted. Before construction of the deposition areas begins, SKB must have decided which rock excavation method is to be used and what dimensions the deposition tunnels should have. The access to the repository level is an important checkpoint for development and implementation of the technology that will be used in the final repository. At that time, all technology for deposition of canisters and buffer should be thoroughly tried and tested and under running-in, see also Tables 8-1 to 8-4 in Part II. The same applies to backfilling of the deposition tunnel.

Commissioning

Before SKB applies for permission to commence trial operation of Clab and the encapsulation plant or the final repository, the systems have to be commissioned. The function of the entire system must also be tested as a whole, without nuclear material in place. Commissioning includes integrated testing of all component systems and system parts in both Clab and the encapsulation plant as well as in the final repository. Continued construction of the deposition areas in the final repository proceeds throughout the commissioning process. Commissioning of the encapsulation plant and the final repository does not have to start simultaneously.

Commissioning entails that all technical systems are put into operation. At that time they must be tested, verified etc. Qualifications of fabrication, sealing and nondestructive testing of the canister must also be completed prior to commissioning.

Trial operation

Trial operation includes handling of spent fuel in both facilities: the encapsulation plant and the final repository. Trial operation commences when SKB has received consent to begin trial operation of the facility in question and continues until SKI gives its consent for routine operation to begin.

Routine operation

Routine operation starts and continues until closure can begin.

Closure

An important principle in the development of the KBS-3 method is that when the repository has been closed it should not be dependent for its safety on systems for monitoring or surveillance. Sweden has no formal requirements on retrieval of deposited canisters. How a canister is retrieved depends on when the decision is made. The more time that has passed after the deposition of a canister, the greater the input of labour that is required. If the decision is made immediately after deposition and the deposition tunnel has not been backfilled, the canister can be retrieved with the same machine used for deposition. If the deposition tunnel is backfilled and sealed, however, a greater labour input is required. If canisters are to be retrieved several years after deposition and the bentonite has reached full swelling pressure, an even greater input of labour is required due to the fact that deformations can create a risk of falling rock when the backfill is removed. Furthermore, the canister must be freed from the buffer before it can be lifted up out of the deposition hole. In the Canister Retrieval Test in the Äspö HRL, SKB has shown that it is possible in practice to free a canister from saturated bentonite and retrieve it.

Upon closure of the repository, SKB has complied with the legal requirements on safe final disposal of the spent fuel. Ultimate responsibility for the final repository is described in /2-2/. By then we will have furnished the world with the information which we consider to be sufficient in order for future generations to be able to take whatever action they deem necessary.

2.3 Alternative repository design – KBS-3H

SKB initiated studies of horizontal deposition of canisters, KBS-3H, in 2002. Horizontal deposition can offer advantages from an environmental and cost viewpoint. Since the deposition tunnels in horizontal deposition also constitute the actual deposition holes, the rock volume that needs to be excavated is reduced, as well as the volume of openings that need to be backfilled. It is therefore possible that KBS-3H will be of interest from an optimization perspective.

Research on KBS-3H is being conducted in close cooperation Posiva in Finland. The development situation is described in Part III of the RD&D report. Posiva makes a similar statement in its research programme /2-3/. At the same time RD&D Programme 2007 is being written, we are conducting an initial evaluation of horizontal deposition. According to preliminary conclusions, we believe there is reason to continue the development work on KBS-3H. Before we make a decision on whether to continue, this evaluation needs to be finished, which will happen at the end of 2007.

The objective of a possible continuation is to develop KBS-3H so that the requirements on long-term safety are met and we have enough knowledge to be able to compare it with the reference alternative.

A large part of the knowledge needed for the evaluation of KBS-3H already exists due to the development work we have done. Surface facilities, descents and the central area in the repository will be affected only marginally by how deposition is done. Encapsulation technology and canister dimensions will not be affected either. Since the safety philosophy for the two alternatives is the same, the focus in the safety assessment will be on the differences. The results of studies of buffer and backfill material conducted for vertical deposition will be equally important for both alternatives. However, some processes are specific for KBS-3H, such as saturation of the buffer along the deposition tunnel and the presence of steel components in the tunnel. Studies of these aspects are already under way. Since we assume that a KBS-3H repository will be able to make use of the same rock volumes as a KBS-3V repository, no work is planned on repository layout in this phase.

An important strategic question on which we have to make a decision is when a switch to KBS-3H has to be done and what reasons are considered to warrant it. Important conditions for a switch are:

- To satisfy the safety requirements.
- Applicable technology is not as reliable as for KBS-3V.
- Better use of resources.
- Less impact on the environment.

The planning for a continuation of the development work on KBS-3H must also take into consideration the planning for the reference alternative. For example, the time for changes in production buildings and the economic consequences must be taken into account. We have therefore identified some important milestones. In planning these milestones, we have also taken resources into consideration:

- Decision on start of next development phase (2007/2008).
- Decision on full-scale test of entire KBS-3H system (no earlier than autumn 2009).
- Report on long-term safety, operational safety and EIS (no earlier than 2011/2012).
- A decision to switch to horizontal deposition can be made when enough background data exists for comparison with KBS-3V (2012/2013).

SKB can terminate the development of KBS-3H at any time during the period up to 2012 if reasons for this emerge in the development work.

2.4 Requirements management and qualification

One of the prerequisites in order for SKB to obtain an operating licence for its facilities is that they must satisfy all requirements made by SKB, the regulatory authorities and other stakeholders. When it comes to the final repository, SKB is developing methodology and procedures for this. Stipulated requirements and other design premises are documented in a database.

As far as fabrication of canisters is concerned, another step has been taken to ensure that the requirements are satisfied. Suppliers and fabrication and inspection processes will be qualified. SKB has presented a programme for how this will be done.

Requirements management

The emphasis early in the development of the KBS-3 method was on analyzing and evaluating long-term safety. Operational safety, environmental impact, quality assurance and efficiency have become increasingly important components in more recent evaluations. In order to get an overall picture of the requirements and restrictions that comprise the design premises for the final repository, we have developed a methodology for systematic management of requirements and other design premises. An overall purpose of systematic requirements management is to clarify goals and facilitate system understanding. In this way, details in the work of engineering and design are put into context and can be derived from stipulated requirements. Background data and reasons for the layout of the final repository thereby become traceable.

Results from the preceding development phase, which constitute the basis for the subsequent phase, are documented as restrictions in a requirements database. The background data on which layout and restrictions are based are also documented. This ensures that the development of the entire system will be traceable. Systematic requirements management also provides a basis for designing inspection programmes so that they focus on satisfying stipulated requirements.

The design premises have been divided into *requirements* and *restrictions*. The requirements are expressions or statements made by different interest groups for accepting the final repository or any of its parts. Restrictions are conditions, properties, events or processes that influence the layout and that can limit freedom of choice. The restrictions may be natural, such as the properties of the site. They may also be man-made, such as the properties of the spent fuel.

The requirements are grouped into levels related to the final repository, its subsystems and components – from overall goals and principles to detailed specifications. At the uppermost level are the *stakeholder requirements*. They are based on the requirements and preferences of the stakeholders. Examples of stakeholders are the surrounding society and SKB's owners. Society's requirements are generally expressed in the form of laws, ordinances and regulations with which SKB must comply.

At the next two requirement levels are *system*- and *subsystem requirements*. They are based on the stakeholder requirements and the chosen system solution. The system and stakeholder requirements express how the KBS-3 repository and its subsystems are supposed to function and what features they should have in order to satisfy the superordinate requirements.

At the level below subsystem requirements are *design requirements*, which serve as a basis for the design work. The design requirements are based on the subsystem requirements and on the restrictions, which describe the conditions under which the subsystem requirements must be satisfied. Finally there are specifications, which describe how the subsystems' different components should be designed, manufactured and inspected. Figure 2-2 shows the different types of design premises and how they are related to one another.

The database, with its requirements and restrictions, is updated as new knowledge is obtained and new conditions are stipulated by the regulatory authorities. Major reviews and updates are expected to take place on the following occasions:

- When the application for the final repository is submitted and the detailed design process commences. At this time the results of the SR-Site safety assessment are taken into account.
- When a permit has been obtained to build the final repository and conditions for construction and operation have been established.
- When updated or augmented safety assessments have been carried out or when the design process enters a new phase, for example in connection with application for a permit for trial operation.

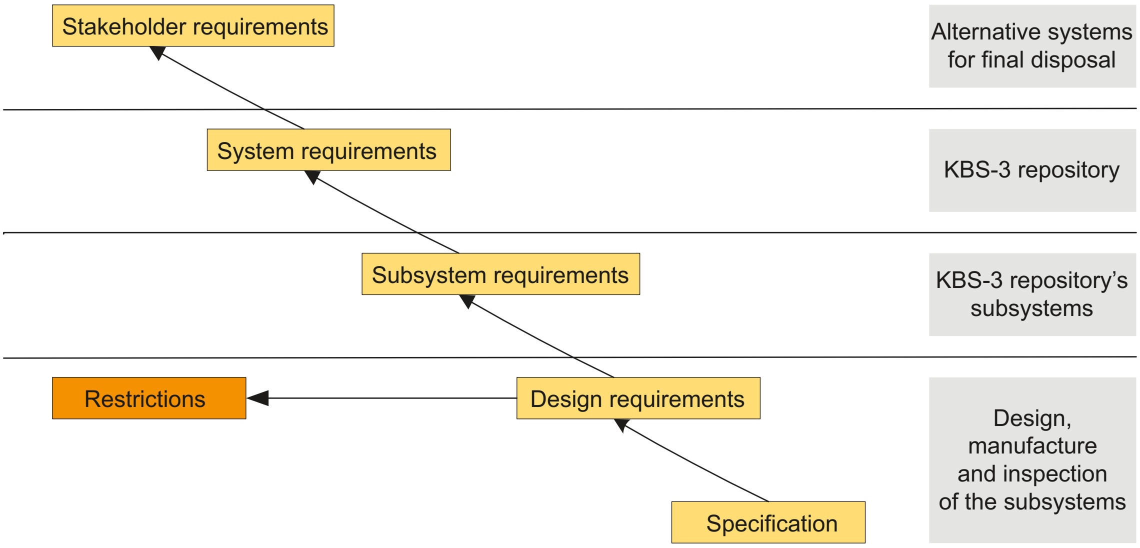


***Figure 2-2.** The hierarchy of requirements and other design premises, their relationships to one another and their relationship to the level of detail in the final repository.*

Qualification of fabrication and welding of canisters

In RD&D-Programme 2004, SKB described the overall work of qualification of fabrication and welding methods for the canister and of methods for nondestructive testing, NDT. In its review, SKI pointed out the necessity of formulating design premises, load data and strength analyses as a basis for the qualification requirements. SKI also emphasized the importance of defining in detail the processes and products to be qualified.

The canister qualification work has been carried out in accordance with RD&D 2004. We have presented a programme that describes how we intend to continue the work of qualification /2-4/. Furthermore, we have carried out a systematic requirements analysis for processes and systems and have developed preliminary design premises for the canister /2-5/.

The reliability of the nondestructive testing of the seal weld has been analyzed /2-6/, as has the reliability of the welding process /2-7/. The probability of defective welds has also been studied. These studies comprise the first steps towards compiling qualification documentation for welding and NDT of the weld.

Damage tolerance analyses of the canister's components, taking into account different load cases and possible types of damage, are being carried out for the purpose of establishing detection goals for NDT.

An initial informal qualification (prequalification) of a manufacturing process according to the quality and environmental management system for canister fabrication "Qualification of Manufacturing Process (KT0602)" has been carried out. The purpose of the prequalifications is to obtain experience of how qualification in different industries should be carried out in accordance with SKB's procedures. The qualification constitutes the first of a series of prequalifications as described by the qualification programme /2-8/ and includes both fabrication and welding processes.

SKI has in a study report /2-9/ clarified its standpoints regarding how SKI's regulatory framework is to be applied in an inspection regime for the canister.

We find it expedient to coordinate the questions surrounding an inspection regime for the entire final repository. A common strategy will be derived where adjustments are made for the different production lines.

3 LILW programme

A series of reports are required at various times in order to put the LILW programme's facilities into operation. During the next 40 years, SKB will pass a number of important milestones. This chapter has to do with the importance of the milestones and how they relate to each other. Figure 3-1 shows the timetable for the LILW programme.

The milestones are described in greater detail in section 3.2. We have chosen to divide them into two categories:

- Applications, notifications and reports.
- Other important milestones.

An important milestone for the whole LILW programme is RD&D Programme 2010, which will be focused on low- and intermediate-level waste. The LILW programme is described in greater detail in Part IV of this RD&D programme.

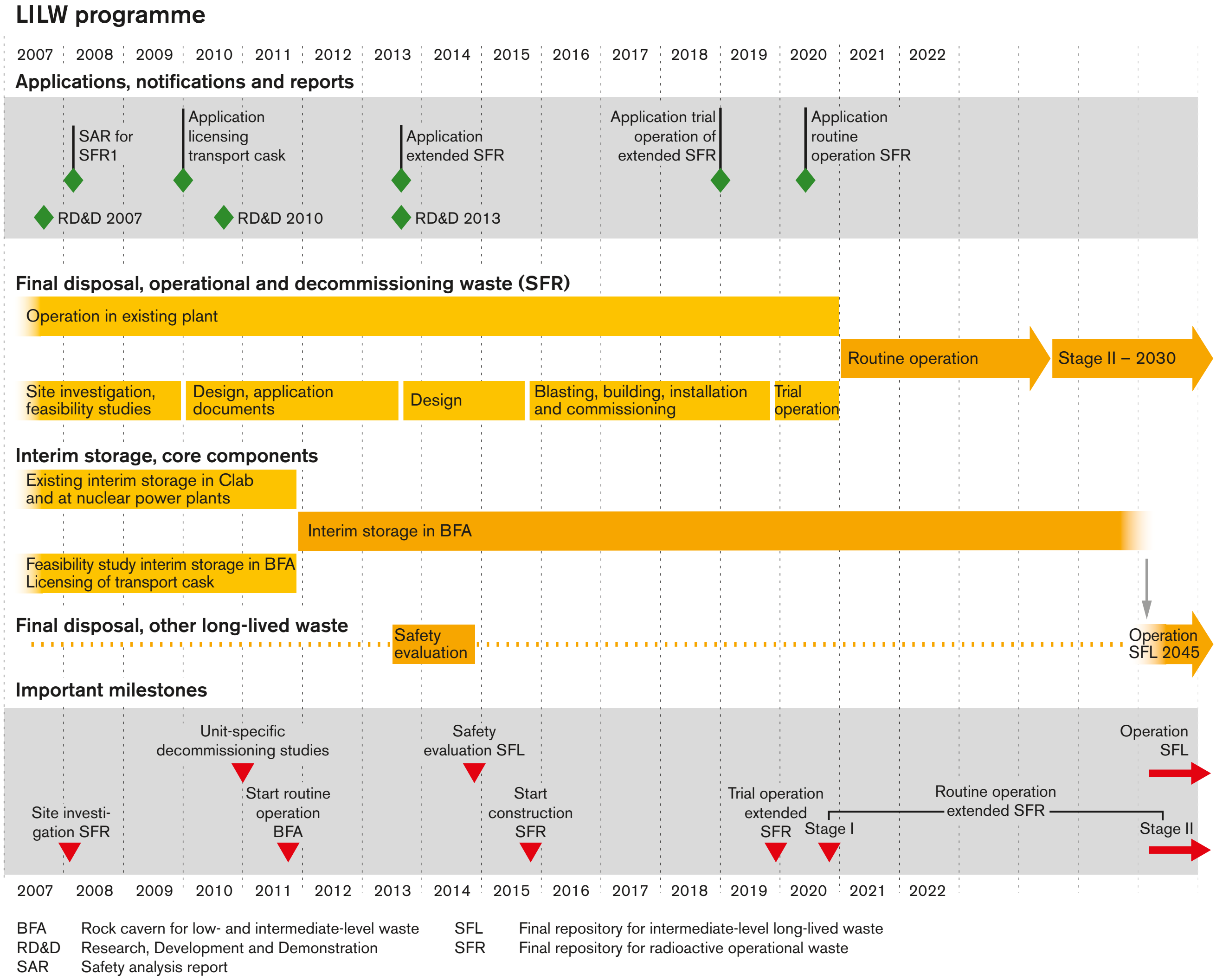


***Figure 3-1.** Timetable for LILW programme.*

3.1 Planning

3.1.1 Planning for SFR

The operating licence for the final repository for radioactive operational waste (SFR 1) only covers operational waste today. In order to be able to accept the quantities of decommissioning waste that are calculated to arise in the future, the facility must be extended. The extension was originally named the final repository for decommissioning waste (SFR 3). In conjunction with the extension, all of SFR 1 and SFR 3 will be relicensed so that both decommissioning and operational waste can be disposed of. This will enable the disposal volumes to be utilized in a more optimal manner. The final repository will subsequently only be called SFR.

We plan to extend SFR in two stages. In connection with the first extension, the entire SFR will be licensed for deposition of operational and decommissioning waste. The stage 1 extension is estimated to be ready to be put into operation in 2020. The extended volume will be based primarily on the following:

- The quantity of decommissioning waste that arises in connection with the decommissioning of the Studsvik R2 reactor, Barsebäck 1 and Barsebäck 2, and a possible decommissioning of the Ågesta reactor.
- Increased quantity of operational waste due to extended operating time.
- The need of disposal space for large odd components (above all from power upgrade projects).

A rock vault of the BMA type (rock cavern for intermediate-level waste) will be built in stage 1. Other rock vaults will be of the BLA type (rock cavern for low-level waste).

The planning for the extension of SFR commenced in 2007. Site investigations will be commenced in 2008. The results of the investigations will serve as a basis for a decision on where the extension will be located.

The stage 2 extension must be ready to receive the decommissioning waste from the Ringhals, Forsmark and Oskarshamn nuclear power plants at the proper time. The location of the stage 2 extension has not yet been determined.

3.1.2 Planning for BFA

The long-lived waste resulting from operation, modernizations and decommissioning of the nuclear power plants is planned to be interim-stored under dry conditions in the existing BFA (rock cavern for waste) on the Simpevarp Peninsula. OKG is already using BFA today for dry interim storage. The operating licence for BFA is held by OKG. SKB has a right of use in BFA by agreement. A relicensing of BFA is required to permit its future use for interim storage of core components from other power plants than OKG. Since BFA is OKG's facility, OKG takes care of the updating of the safety analysis report and the relicensing, which is described in section 3.3. A new waste container called ATB-1T is being developed for transporting the long-lived low- and intermediate-level waste from other power plants than Oskarshamn to BFA. BFA will also need to be rebuilt to some extent, with a new transloading station among other things. The project to develop the ATB-1T transport container is under way, and is the time-critical factor for when BFA can be taken into operation. It is estimated that interim storage of core components in BFA will be able to start no earlier than the end of 2011, when delivery of ATB-1T is planned.

3.1.3 Planning for SFL

The last facility that will be built in the LILW programme is the final repository for long-lived low- and intermediate-level waste. The goal is to be able to give a more detailed account of how SKB plans to design the facility in RD&D 2010. The report will include a strategy for site selection and repository depth as well as studies of the repository's dimensions.

A decision on the siting of the final repository for long-lived low- and intermediate-level waste will be made in a couple of decades at the earliest, which means this is still an open question.

3.1.4 Planning for decommissioning

A working group consisting of representatives from SKB and the power companies has worked to develop strategies for decommissioning and dismantling of the nuclear power plants since the beginning of this century. The main strategy is to start dismantling a plant as soon as it has been taken out of service. In this way a long period of shutdown operation is avoided. In order for this to be possible we plan to extend SFR to be able to receive short-lived low- and intermediate-level waste from the decommissioning of the units. The extension of SFR will be finished in 2020. The main strategy can thus not be applied to the Barsebäck plant. The power companies' common goal for decommissioning of the nuclear power plants is that the site should be used for future energy production after decommissioning, since there is extensive and valuable infrastructure there including power lines, roads, harbours, cooling water channels etc. Certain buildings will also be able to be used after being released for unrestricted use. Dismantling of a unit is not begun until adjacent units with common buildings and/or systems have been taken out of service. Alternatively, the common units' operating time will be adjusted so that they are taken out of service at the same time in order to avoid a long period of shutdown operation. The dismantling process is begun about two years after the unit has been shut down. System dismantling is done first and takes at least three years. Then buildings and contaminated building parts are dismantled, after which the site is released for other use. With a decommissioning period of about five years, a unit can be expected to be released for other use about seven years after shutdown, see Part VI, section 40.2.2.

3.2 Milestones for SFR

3.2.1 Applications, notifications and reports

Updated safety analysis report for SFR 1

A safety analysis report (SAR) for a nuclear facility must be updated every tenth year /3-1/. An updated SAR for SFR 1 was submitted in 2001. The regulatory review of this report called for a supplement. SKB is currently updating this report, and the updated safety analysis report will be sent to the regulatory authorities at the end of 2007.

Application under the Nuclear Activities Act

An extension of SFR and a relicensing of SFR 1 will require the Government's permission, according to the Nuclear Activities Act. In the application SKB will present the technical background material that is needed to determine whether SFR 1 satisfies the requirements imposed on the facility under the Nuclear Activities Act and the Radiation Protection Act with associated regulations and ordinances. The application will also contain a preliminary safety analysis report (PSAR) and an environmental impact statement.

Application under the Environmental Code

Prior to the extension, SKB will apply for a permit from the Environmental Court in accordance with Chapter 9 of the Environmental Code (environmentally hazardous activities) for the entire SFR facility. According to the current design, it would not appear possible to limit the licensing process solely to the extension (called an "add-on permit"); the whole SFR will probably have to be relicensed. The licensing process also includes an assessment of how spoil from blasting or excavation should be dealt with, for example whether it will be dumped on a landfill or sold as fill for roadbuilding. The extension of SFR will also require a permit under Chapter 11 of the Environmental Code (water operations).

A prerequisite for granting a permit under the Environmental Code is that the activity in question does not conflict with the relevant detailed development plan or area regulations under the Planning and Building Act. Matters under the Planning and Building Act will be dealt with in parallel with the processing and licensing described above by regulatory authorities, the Environmental Court and the Government.

Application for permit for trial operation of extended SFR

When the facilities have been built and systems and processes function as intended, SKB will submit an application for a permit to commence trial operation. The application will contain an updated assessment of long-term safety, an updated safety analysis report (SAR) and safety-related technical specifications. The purpose of trial operation is to gather experience. The safety analysis reports and the safety-related technical specifications will then be supplemented and included as supporting material in SKB's application for permission to begin routine operation for the facilities.

Extension of the final repository for reactor waste will take place in two stages. An application for a permit for trial operation of the stage 1 extension to SFR will be submitted in 2018 at the earliest, with the objective of putting the facilities into operation in 2020.

3.2.2 Other important milestones

Site investigations for extension of SFR

Site investigations with test drilling and other investigations of the bedrock will commence in 2008.

Site selection for extension of SFR

The exact location of the extension of SFR has not yet been decided. However, the facility will be situated adjacent to the existing repository. The exact location will depend on the results of the site investigations.

Start of construction for extension of SFR

When all the necessary permits and conditions under the Nuclear Activities Act, the Environmental Code and the Planning and Building Act have been obtained, construction of the extension of SFR can begin. We will then consider the consequences of the conditions in the permits before the start of construction and adapt the planning accordingly.

3.3 Milestones for BFA

3.3.1 Applications and notifications

Licensing of BFA is handled by OKG. OKG obtained a new permit for its environmentally hazardous activities in 2006 and then obtained a permit to use BFA as a common storage site for core components. This means that it is permitted from an environmental viewpoint to store core components in BFA. OKG also sent in an updated safety analysis report (SAR), including safety-related technical specifications (STF), for BFA to SKI in 2007. When this report has been approved by the Inspectorate, SKB will have a permit to store core components from other nuclear power plants.

3.3.2 Other important milestones

Start of operation of BFA

In order for us to be able to use parts of OKG's rock cavern for waste (BFA) in an efficient manner, we have to develop new waste containers and a new vehicle and install new handling equipment in BFA. The goal is that BFA in Oskarshamn will be able to receive core components placed in so-called BFA tanks starting in 2011, and that it will be possible at the same time to transport the core components to BFA.

3.4 Milestones for SFL

The final repository for long-lived low- and intermediate-level waste is expected to be ready to be put into operation in 2045 at the earliest. The decision on where the repository should be located will be made in a couple of decades. RD&D Programme 2010 will focus on the LILW programme and SFL.

A waste inventory and an assessment of the long-term safety of an envisioned repository will be carried out when an application of SFR has been submitted.

3.5 Milestones for decommissioning

3.5.1 Applications, notifications and reports

Both units in Barsebäck have been taken out of service. Barsebäck 2 was shut down in May 2005 and went into service operation on 1 December 2006. At this time the last spent nuclear fuel had been shipped to Clab. A new SAR (safety analysis report) and a new STF (safety-related technical specifications) for shutdown operation have been submitted to the regulatory authorities and are now being applied. The environmental permit that has been obtained is valid until 2012. A renewed licence for shutdown operation requires a new environmental licensing process.

Permission from the regulatory authorities is required in order to obtain a new permit for decommissioning. The Environmental Court must also review the application. According to current plans, dismantling will be commenced in 2020.

Forsmark and Ringhals plan to operate their reactors for 50 years and OKG for 60 years. Milestones for the decommissioning of these power plants will be presented in later RD&D programmes.

With regard to management of the decommissioning waste, the reader is referred to the milestones for the extension of SFR, the utilization of BFA for interim storage, and the construction of the final repository for long-lived low- and intermediate-level waste.

3.5.2 Other important milestones

Unit-specific decommissioning studies

SKB is conducting decommissioning studies together with the power companies with the objective of providing an increasingly reliable and detailed body of data for determining waste volumes, activity quantities and decommissioning costs for the different nuclear power plants. Future studies will be based on the detailed study that has been conducted for the reference plant Oskarshamn 3 and on the experience gained from Barsebäck. The studies will be adapted to the specific conditions prevailing at other power plants with regard to the physical design of the power plants and the licensees' plans for decommissioning their own plants. An update of the existing study for Ringhals 2 will serve as a basis for the PWR plants. The results of the studies will serve as a basis for determining the capacity of the future final repository for decommissioning waste as well as for the safety assessments for the final repository that are required in the licensing process. The decommissioning studies are also intended to provide a better estimate of the decommissioning costs for the nuclear power plants.

Part II

Final repository for spent nuclear fuel

4 Current situation

5 Points of departure for construction and operation

6 Work methodology during construction and operation

7 Main phase: Licensing

8 Main phase: Construction

9 Main phase: Commissioning

10 Main phase: Operation

4 Current situation

This part of the RD&D programme presents the plans for those parts of the Nuclear Fuel Programme that relate to the final repository for spent nuclear fuel. The account is structured with reference to the stepwise execution of the programme in accordance with SKB's plan of action and comprises the main phases up to and including routine operation of the facility. The purpose is to provide a complete picture of the current situation in the planning of the final repository to permit a better overview of the applications of the results from research, development and demonstration in different phases.

At the turn of the year 2006/2007, the planning work for the final repository and the encapsulation plant was integrated into a single project. In keeping with the provisions of the Environmental Code, consultations with concerned municipalities, regulatory authorities and other stakeholders are being held as a part of this project. Consultations with the regulatory authorities are also being held in accordance with special Government decisions /4-1, 4-2/. Results, status and plans are presented in detail as they become available within the framework of these consultations. In this way SKB continuously obtains valuable viewpoints, which can be taken into consideration in the continued work. More general, but comprehensive, accounts of the site investigations are provided in the site investigation reports that are published annually, the most recent ones for 2006 /4-3, 4-4/.

Thus, accounts of ongoing activities are mainly presented in other forms than through the RD&D programmes. For this reason the status report provided in this chapter is brief. The emphasis lies instead on coming phases, when the final repository will be built, put into operation and operated until all spent fuel from the Swedish nuclear power plants has been deposited.

4.1 Siting alternatives

After more than five years of work, the site investigations in Forsmark and Oskarshamn have largely been concluded. Before the investigations began, SKB made extensive preparations:

- Investigation and analysis methods were developed and improved.
- Finishing touches were put on the methodology used to gather, manage and process data.
- Investigation and evaluation programmes were prepared and reviewed by the regulatory authorities.
- Working groups were organized for modelling, analysis and evaluation of data, as well as for facility design and safety assessments.
- Site organizations were established.

After an initial phase with some fine adjustments, stable routines were established and the activities have since proceeded smoothly. Now work is under way to evaluate data, revise site descriptions, arrive at site-adapted solutions for the repository, study environmental consequences and prepare the safety assessment SR-Site. Both of the siting alternatives will be studied to the point that they can be evaluated in all relevant respects, both independently and in relation to each other. On this basis, the intention is then to select one of the sites.

Figure 4-1 provides an overview of completed, ongoing and remaining main activities, as well as links between them, leading up to application. Investigations and analyses are iterative processes and are divided into two main stages: initial site investigation (ISI) and complete site investigation (CSI). A similar breakdown applies to the process of designing the final repository's facilities, where two versions, D1 and D2, are produced. Data from ISI has served as a basis for the D1 version and for the preliminary safety assessment SR-Can. In a similar manner, data from CSI will serve as a basis for the final design results (D2) and the safety assessment SR-Site. On-site data collection has been done with more frequent checkpoints, so-called data freezes. The same applies to the different versions of the site descriptions that have been produced.

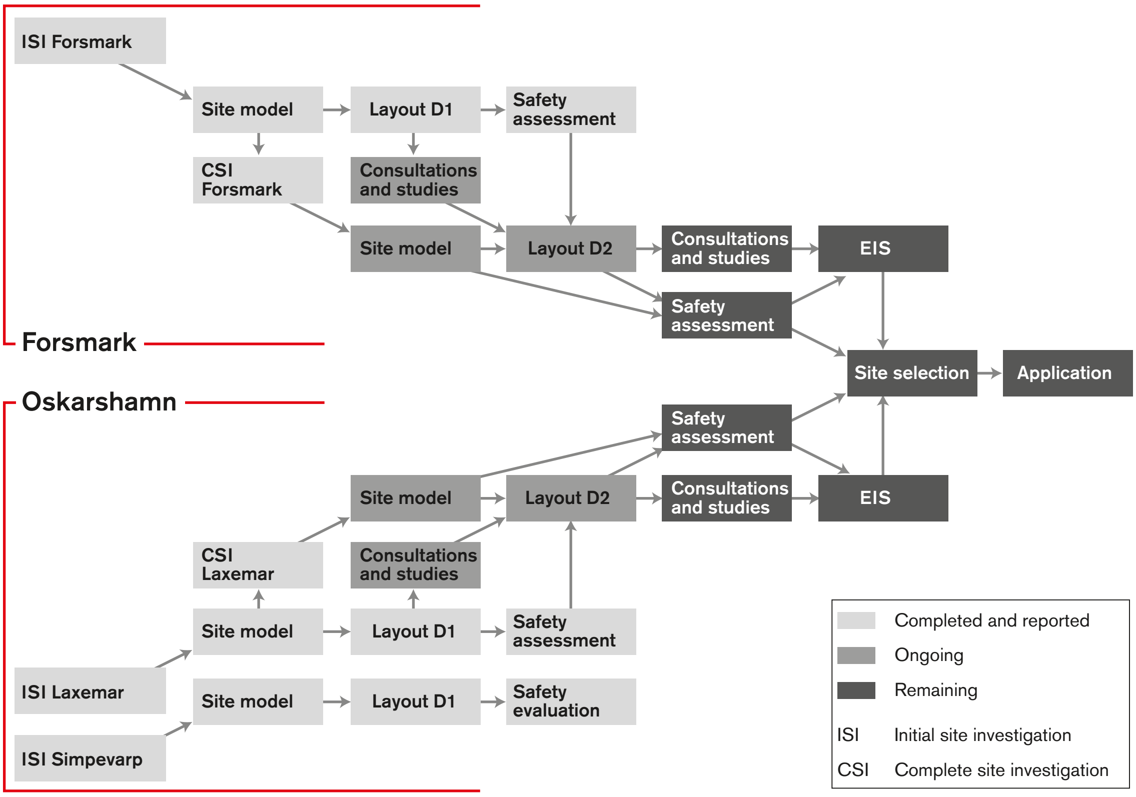


Figure 4-1. *Completed, ongoing and remaining main activities during the site investigation phase.*

Together with the design results, data from the investigations provide a basis for studying environmental questions. This work is pursued continuously and includes both present-day conditions and assessments of the consequences which the establishment of a final repository may have in different phases. Completed studies describe the consequences of construction, operation and transportation for the natural and cultural environment, the landscape, recreation and outdoor activities. Consequences for the residential environment and health will be assessed and reported when sufficient material has been gathered. The environmental assessments are updated as the planning of the final repository progresses. Conversely, the results of the environmental studies can be fed back to design as a basis for adapting facilities, infrastructure and activities so that the consequences for the environment are mitigated. Preventive and compensatory measures will be devised to minimize the impact.

Aside from the investigations, local information and public relations activities have been an important task for the site organizations. A large number of visitors of all categories have come to see the activities. Great importance has been attached to contacts with landowners and nearby residents who are directly affected by the investigations in an attempt to reconcile the activities with other interests, settle compensation matters etc.

Contacts with the local municipality and county administrative board have also been vital tasks. Ever since the feasibility studies and the start of the site investigations, the municipalities of Oskarshamn and Östhammar have actively followed our activities through their own organizations and working groups and are furthermore conducting their own competence building and information activities. We also collaborate with the municipalities in matters relating to community development and how a final repository will impact this development.

The current status of the development plans for land use would not allow a final repository to be built on either of the sites being considered. Planning matters are regulated by the Planning and Building Act, and are the responsibility of the concerned municipality. In both cases the municipalities have initiated decision processes to carry out the planning adjustments that are required.

SKB's site organizations have consisted of about 35 persons on each site. With the conclusion of the investigations the workforce will be reduced radically. However, we will retain sufficient resources to handle information and public relations on the site, as well as monitoring, general maintenance and preparedness for supplementary investigations.

4.1.1 Forsmark

Investigations

The investigations in Forsmark commenced in 2002 and were largely concluded in the summer of 2007. Prior to the start, an investigation programme was prepared that mainly covered the initial part of the site investigation (ISI) /4-5/. The programme targeted the roughly ten square kilometre area southeast of the Forsmark nuclear power plant that had previously been recommended for a site investigation, known as the candidate area, see Figure 4-2. The focus of the investigations was on answering general and site-specific questions that were regarded as crucial for assessing the suitability of the site.

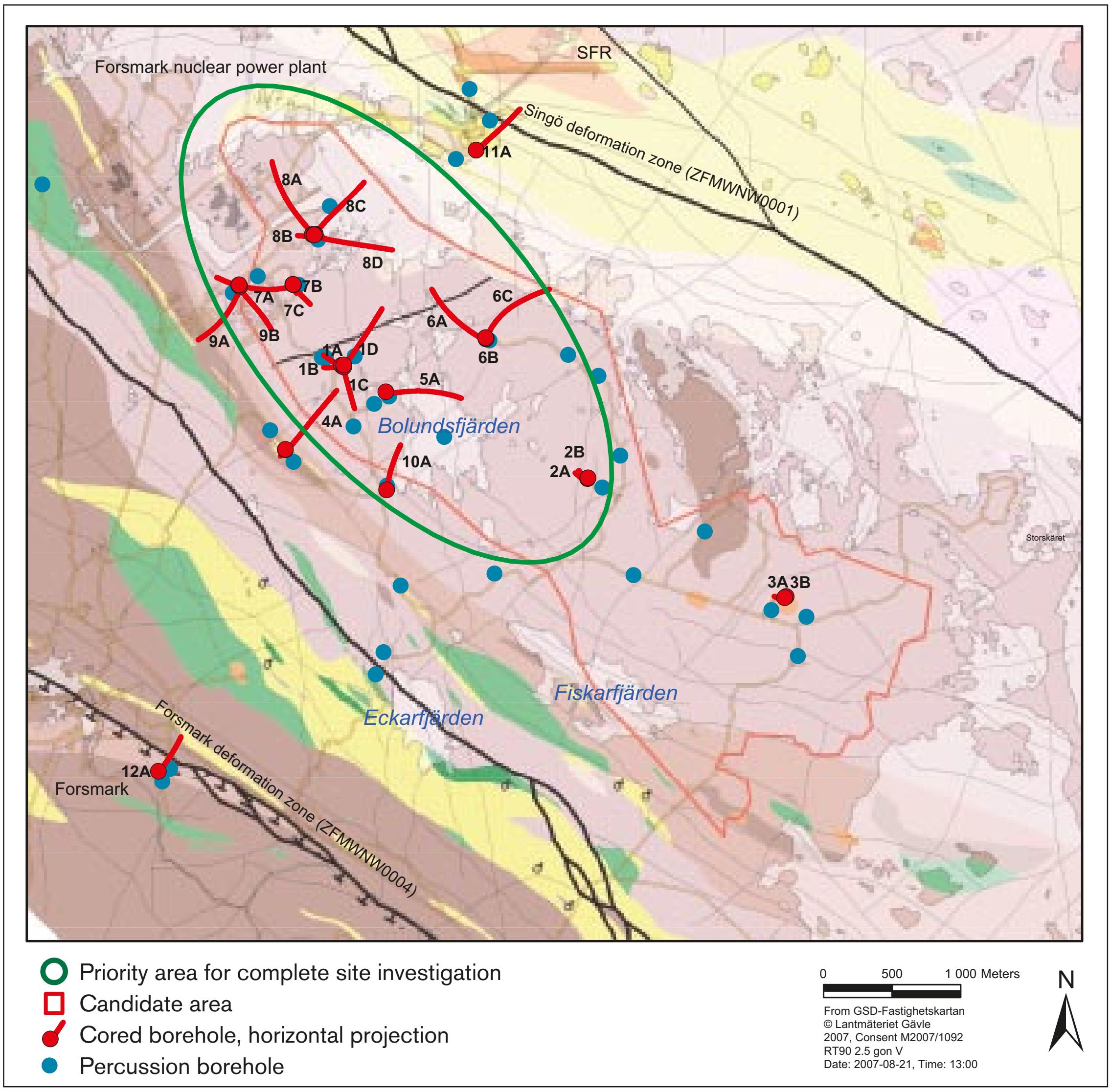


Figure 4-2. Candidate area, priority area for complete site investigation and borehole locations in Forsmark.

When the initial investigation phase had been completed and a preliminary site descriptive model had been constructed, the state of knowledge was cross-checked against the fundamental requirements that had been established before the site investigations and that must be shown to be satisfied in order for a site to be of interest for the final repository /4-6/. The conclusion was that the site satisfied the requirements and that further investigations were therefore warranted – something which was subsequently verified by the preliminary safety assessment SR-Can /4-7/. The cross-check also permitted remaining data needs to be identified, along with a strategy and programme for further investigations.

With this as a basis, a programme was drawn up for the concluding part of the site investigation (CSI) /4-8/. The strategy that was chosen gave priority to the northwestern part of the candidate area, see Figure 4-2. The investigations had already indicated at an early stage that both the northwestern and the southeastern parts of the candidate area had bedrock that warranted further investigations. The difference that could nevertheless be noted was a higher frequency of gently-dipping, permeable fracture zones in the southeastern part. The main reasons for prioritizing the northwestern part at that time were that:

- Preliminary studies of space requirements and possible locations showed that a repository could in all probability be accommodated within the northwestern part.
- The location partly beneath the industrial area permitted a repository layout with surface facilities that could be accommodated on existing industrial land. This was deemed to offer a number of technical and environmental advantages.

The aims of the investigations included in the programme were to:

- Determine the geological boundaries of the available rock volume at repository depth.
- Characterize the available rock volume to the required extent and level of detail.
- Characterize the priority site's hydraulic boundary areas.

It has for the most part been possible to adhere to the strategy, scope and focus of the investigations presented in the investigation programmes. The changes that have been made have mainly been adjustments of borehole locations, investigation sequences or timetables in response to obtained results or practical circumstances. Additional major work includes more extensive rock stress measurements than were foreseen from the beginning and a late-stage cored borehole. The rock stresses in the area have proved to be relatively high, leading to a greater need for measurement data in order to be able to design the repository's rock openings so that good stability is obtained. This, together with limitations in the applicability of the measurement methods, warranted extra efforts to determine the rock stresses and their variation. The additional cored borehole was aimed at clarifying the importance of results from ground geophysical surveys.

Site descriptions

Site descriptive models for Forsmark have been published as planned /4-9, 4-10, 4-11/. The preliminary site descriptive model (version 1.2) corresponds to the results from the ISI and served as a basis for design step D1, preliminary safety evaluations /4-12/ and the safety assessment SR-Can /4-7/. During the concluding part of the site investigation (CSI), three modelling steps are being carried out, of which the first has been reported. The main purpose of this first step (version 2.1) was to provide feedback to the investigations in order to ensure effective information gathering during the remainder of the site investigation. In addition, the geological model for lithology and deformation zones was updated, but no complete integrated site descriptive model was constructed. At present the work in modelling step 2.2 is being concluded with updated models for site geology, rock mechanical and thermal properties as well as hydrogeology and transport properties. These models will be the point of departure for design step D2 and for modelling step 2.3, whose product is a final integrated site descriptive model designated SDM-Site Forsmark. The integrated model is planned to be finished in early 2008. Together with the results of design step D2 it will serve as a basis for the safety assessment SR-Site. The body of data is now considerably larger than for version 1.2, especially with respect to conditions at repository depth. The preliminary evaluation is that this will not appreciably alter the picture of the site.

Facility design

The design of a final repository in Forsmark is based on the assumption that the actual repository can be placed within the priority area as shown in Figure 4-2, while surface facilities and activities can mainly be accommodated within the existing industrial area. With this as a point of departure, different proposed layouts have been presented and evaluated. The design in stage D1 resulted in a preliminary layout for a repository at a depth of 400 metres and with an extent as shown in Figure 4-3 /4-13/. Two alternative proposals were produced for the system design, i.e. the locations of the surface facilities and solutions for communication between them and the repository. In one alternative, most of the facilities were located adjacent to SFR. In the other alternative, the facilities were gathered in an operations area east of the entrance to Forsmark on the south part of the industrial area (where today there is a barracks for temporary accommodation). After a comparative evaluation /4-14/, the location at the entrance was prioritized. An important argument was that this area is located above the repository's central area so that rock haulage can take place via a vertical skip shaft. This provides substantial operational advantages in comparison with a layout where all heavy goods have to be transported via a ramp. Other arguments in favour of this choice were better availability of areas for handling of rock spoil and smaller total transport needs. Figure 4-4 shows a photomontage of planned surface facilities.

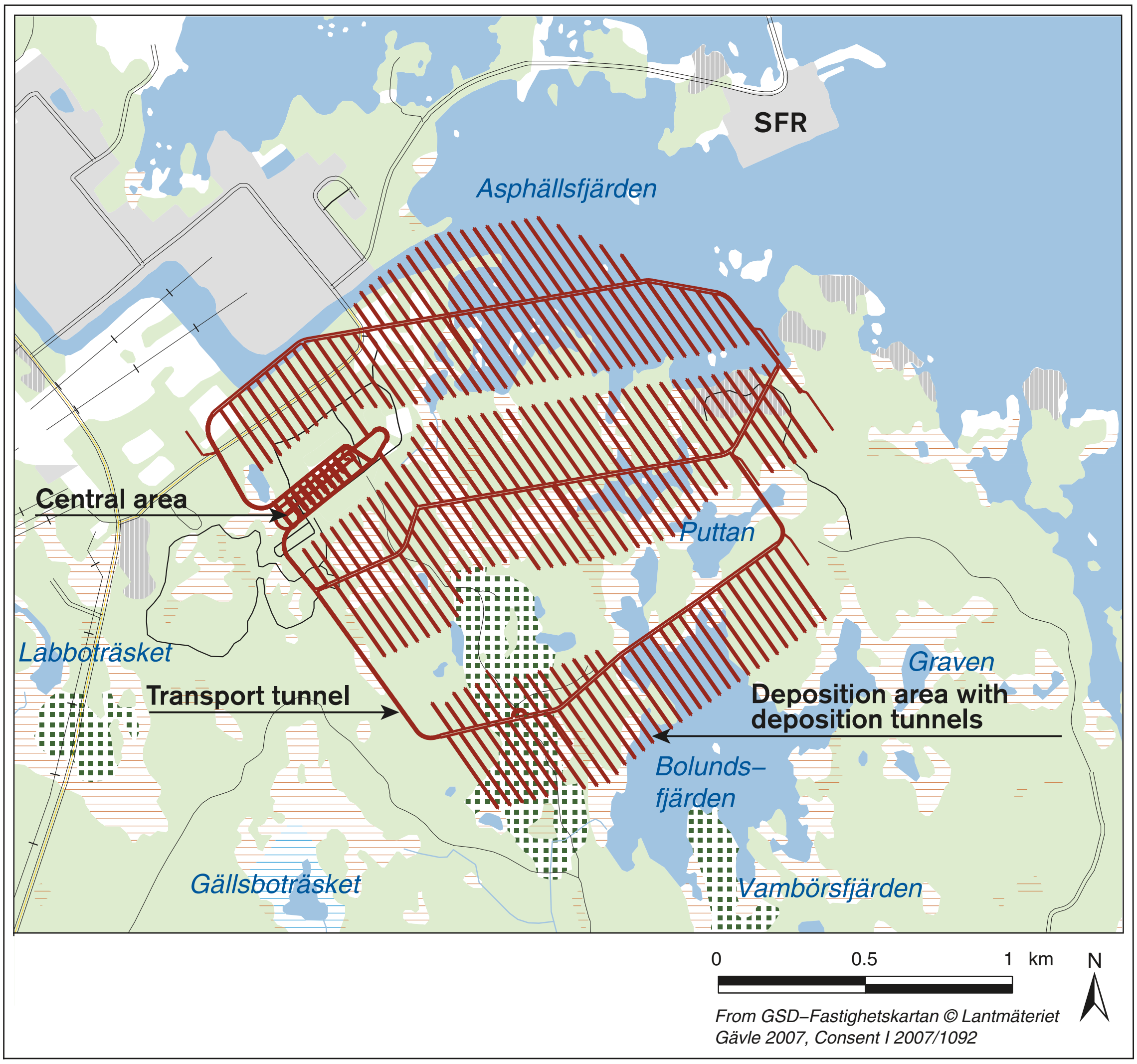


Figure 4-3. Preliminary layout for a final repository in Forsmark (Layout D1).

***Figure 4-4.** Photomontage showing the final repository's surface facilities located on the southern part of the industrial area in Forsmark (Layout D1).*

Design step D2 is currently under way, which entails that the layout of all parts of the repository is being revised and refined taking into account the new data. One proposed change is that the depth of the repository be increased from 400 metres to 450–500 metres. The reasons for this are that the rock stresses exhibit a lower rate of increase with depth than was initially assumed and that the pattern of fracture zones on the site provides more favourable conditions for locating the repository's deposition areas within the proposed depth interval.

Preliminary safety assessment

The preliminary safety assessment SR-Can /4-7/, which is based on the results of the initial site investigation and the corresponding site model /4-10/, states that "*a KBS-3 repository at Forsmark will comply with SSI's risk criterion. Uncertainties in the hydrogeological interpretation and understanding of the Forsmark site are, however, considerable and, when propagated to various parts of the analysis, lead to a wide range of conclusions regarding e.g. buffer colloid release and water flow properties. A reduction of these uncertainties would allow more definite conclusions in future assessments. Even the most pessimistic interpretation of the Forsmark site is, however, assessed to comply with the regulatory risk criterion.*"

The investigations that have been conducted since then have been evaluated as a part of the ongoing site modelling process /4-11/. The conclusion is that the uncertainties have been considerably reduced. The additional boreholes that have been drilled in the planned repository area, as well as the results of detailed surface-based geophysical surveys, largely confirm the picture of the site that emerged after the initial site investigation. The location and character of the layout-determining deformation zones have only been modified in detail. All boreholes show that the frequency of water-conducting fractures at levels below around 350 metres is very low.

Great efforts have been made to further assess the rock stresses by means of direct and indirect methods. This has improved the reliability of the assessments of the stress state. It is difficult to come farther in this important question, given the limitations inherent in surface-based investigations.

4.1.2 Laxemar

Investigations

The investigations in the Laxemar area will be concluded during the first half of 2008. In their final phase, the investigations have been concentrated on an approximately six square kilometre area, see Figure 4-5, which has been prioritized for a possible final repository. This prioritization is the result of a gradual narrowing-down that took place prior to and during the site investigation.

A programme for initial site investigation of the Simpevarp area was presented in the autumn of 2002 /4-15/ and covered the approximately 60 square kilometre area that was recommended as a result of the feasibility study. Drilling was started immediately on the Simpevarp Peninsula, which had been singled out in the feasibility study. The results indicated rock conditions that could satisfy the requirements for a final repository. Due to the limited space on the peninsula, the area was enlarged to include Ävrö, Hålö and nearby water areas ("Simpevarp subarea" as shown in Figure 4-5), after which an initial site investigation was completed on this area.

West of Simpevarp the investigations started with helicopter-borne geophysical surveys, field checks etc over a considerably larger area than that shown in Figure 4-5. Based on these surveys, several areas were identified with rock conditions judged to warrant further investigations and large enough to accommodate a final repository with ample margin /4-16/. The area shown in Figure 4-5 – about nine square kilometres in size and called the "Laxemar subarea" – was prioritized. Several other areas were judged to be equivalent from a geological viewpoint, and nearness to the Simpevarp Peninsula was the main argument for then choosing the Laxemar subarea. Starting in early 2004, an initial site investigation was conducted on the Laxemar subarea, after an agreement had been reached with the concerned landowners.

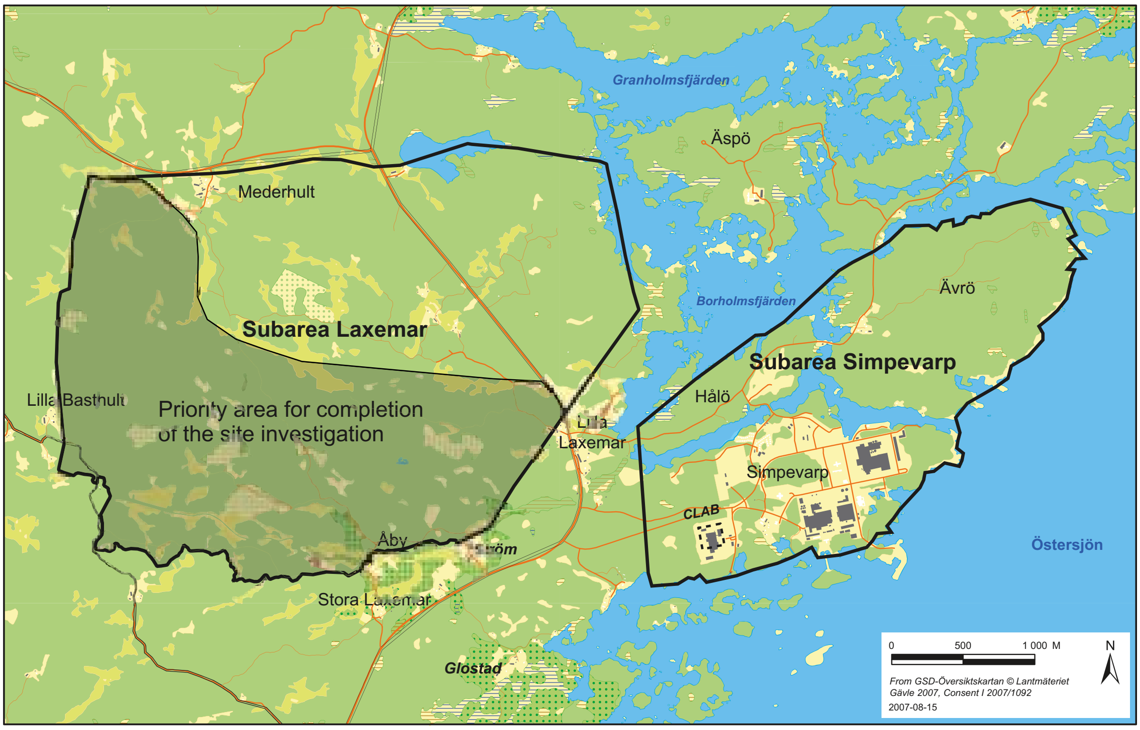


Figure 4-5. *Subareas for initial site investigation and priority area for completion of the site investigation in Laxemar.*

The next milestone was to prioritize one of the subareas Simpevarp or Laxemar for a complete site investigation. When the initial site investigations were completed, the Laxemar area was given preliminary priority. The comparison material that was later obtained in the form of site descriptions, design results (stage D1) and safety evaluations for both areas did not change the preliminary judgement, and a final decision was made to proceed with Laxemar. The main arguments for choosing the Laxemar area can be summarized in the following points /4-17/:

- Both areas can probably accommodate a repository, but in the case of Simpevarp the margins are small. In the case of Laxemar there is plenty of space and thereby good margins. This provides flexibility for future modifications of the repository layout and for handling any geological surprises, even at late stages.
- The safety evaluations that have been presented indicate that both areas satisfy the requirements. The more homogeneous bedrock in parts of the Laxemar area can, however, offer advantages in the form of a relatively low fracture frequency and water flow rate. The great flexibility offered by Laxemar also makes it easier to adapt a repository so that all safety requirements can be shown to be satisfied.
- A repository in Laxemar entails building new surface facilities and infrastructure on forest land, resulting in an impact on the environment. Simpevarp, however, is planned industrial land and the environment is already affected by the existing industrial activities. On the other hand, the availability of suitable land within the industrial area is limited, and in other parts of the Simpevarp area the potential for land development is limited by nature conservation interests. The advantages and disadvantages of the areas are difficult to compare, but both alternatives are deemed to be fully acceptable.

Prior to the complete site investigation the size of the investigation area within the Laxemar subarea had to be reduced, but the information on the properties of the bedrock was not sufficient to permit a well-founded focusing. An investigation step was therefore first carried out in order to obtain the required information /4-18/. Then a programme was drawn up for the complete investigation stage /4-19/. The investigations have gradually been focused on the southern and western parts of the area, see Figure 4-5. The reason is variations in the bedrock conditions in the area. The southern and western parts are dominated by quartz monzodiorite, which has proved to be more homogeneous and fracture-poor than the bedrock that dominates the northern and eastern parts of the area. Figure 4-6 shows the locations of the investigation holes that have been drilled in the Laxemar area.

The investigation activities stipulated in the programme /4-19/ have been carried out. A decision has been made to drill a supplementary cored borehole for the purpose of investigating the importance of a presumed deformation zone in the southern part of the area, and the bedrock at repository depth north of this zone. This hole will be drilled in the autumn of 2007, after which the site investigation will be concluded with a verifying pumping test.

Site descriptions

Site descriptive models based on the initial site investigations have been presented for subareas /4-20, 4-21/. These models (version 1.2) served as a basis for preliminary site-adapted repository layouts (version D1) and preliminary safety evaluations /4-22, 4-23/. Two modelling steps were carried out during the concluding part of the site investigation. The main purpose of the first step (version 2.1 /4-24/) was, in the same way as in the Forsmark case, to provide feedback to the investigations to ensure effective information gathering during the remainder of the site investigation. In addition, the hydrogeochemical and thermal models were updated, but no complete integrated site descriptive model was constructed. At present the final modelling work is being done with updated models for the site's geology, rock mechanical and thermal properties as well as hydrogeology and transport properties. These models serve as a basis for design step D2 and for the end product of the modelling project, which is a final integrated site descriptive model designated SDM-Site Laxemar. The integrated model is planned to be finished at the end of 2008. Together with the results of design step D2 it will serve as a basis for the safety assessment SR-Site. The body of data from the southwestern parts of Laxemar is now considerably larger than for version 1.2, especially with regard to the properties of the dominant quartz monzodiorite.

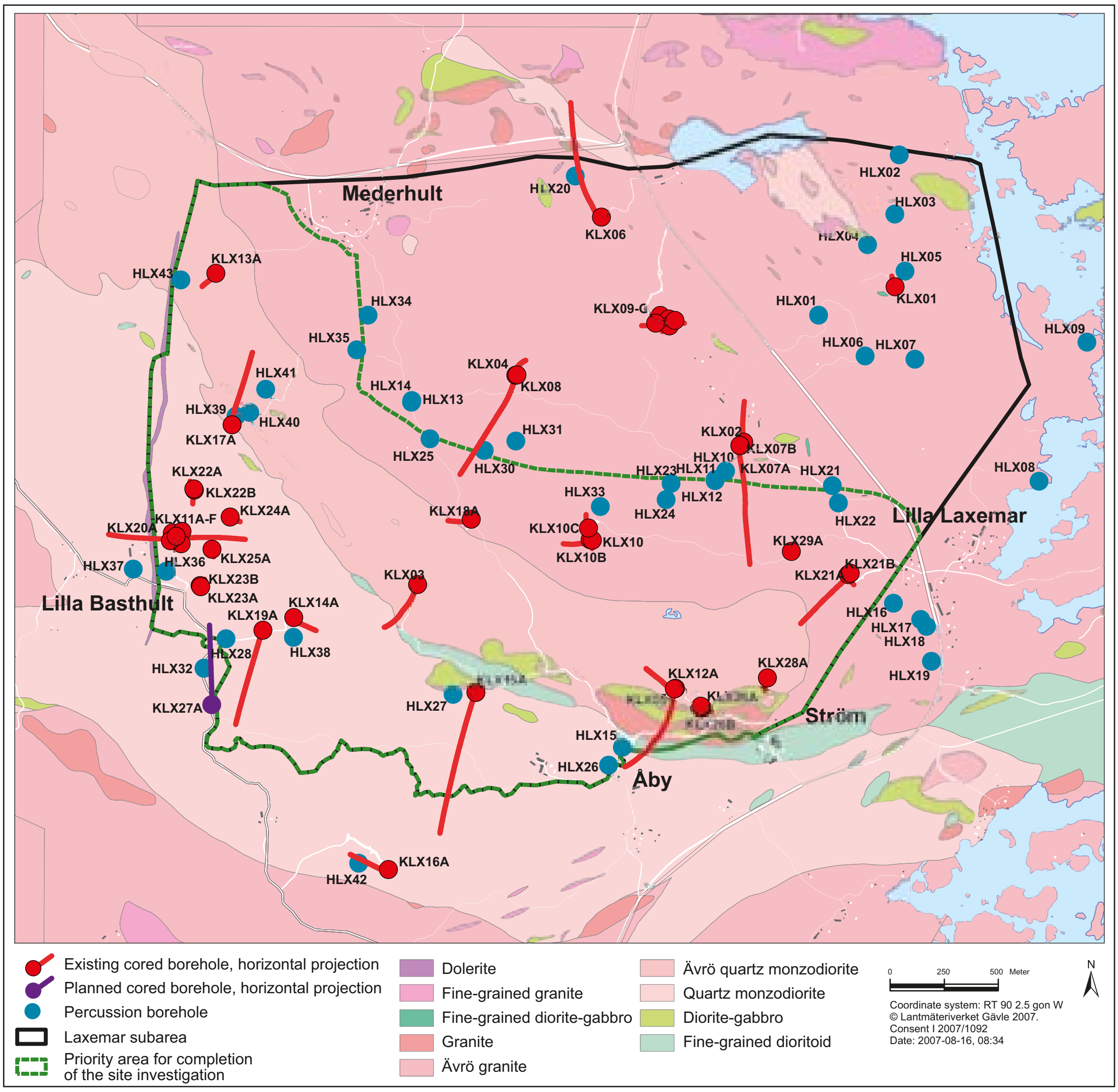


Figure 4-6. *The Laxemar subarea with priority area for completion of the site investigation plus the borehole locations.*

Facility design

As mentioned above, the preliminary repository layout that was devised for the Simpevarp subarea showed that a repository could probably be accommodated, but with small margins and remaining questions regarding space. This has a bearing on the decision to prioritize Laxemar. This decision eliminated the possible locations for the repository's surface facilities on the Simpevarp Peninsula, or Hålö, which had been studied in previous phases.

In the case of the Laxemar alternative, a preliminary layout was prepared for a repository at a depth of 500 metres after the initial site investigation /4-25/, see Figure 4-7. When the investigations were subsequently shifted more to the southern and western parts of the area, this altered the design premises and major changes in the layout can be expected as a result of the continued work.

The development of the system design for the final repository has led to a reference design where the above-ground facilities are gathered in an operations area located above the repository's central area /4-26/. This permits vertical shafts for rock haulage, among other things. This reference design is the point of departure in the work of selecting a site for an operations area in Laxemar and adapting the facilities to this site. This means that solutions where parts of the facilities are situated within the existing industrial area on the Simpevarp Peninsula, and the remainder at a final repository in Laxemar, have been ruled out.

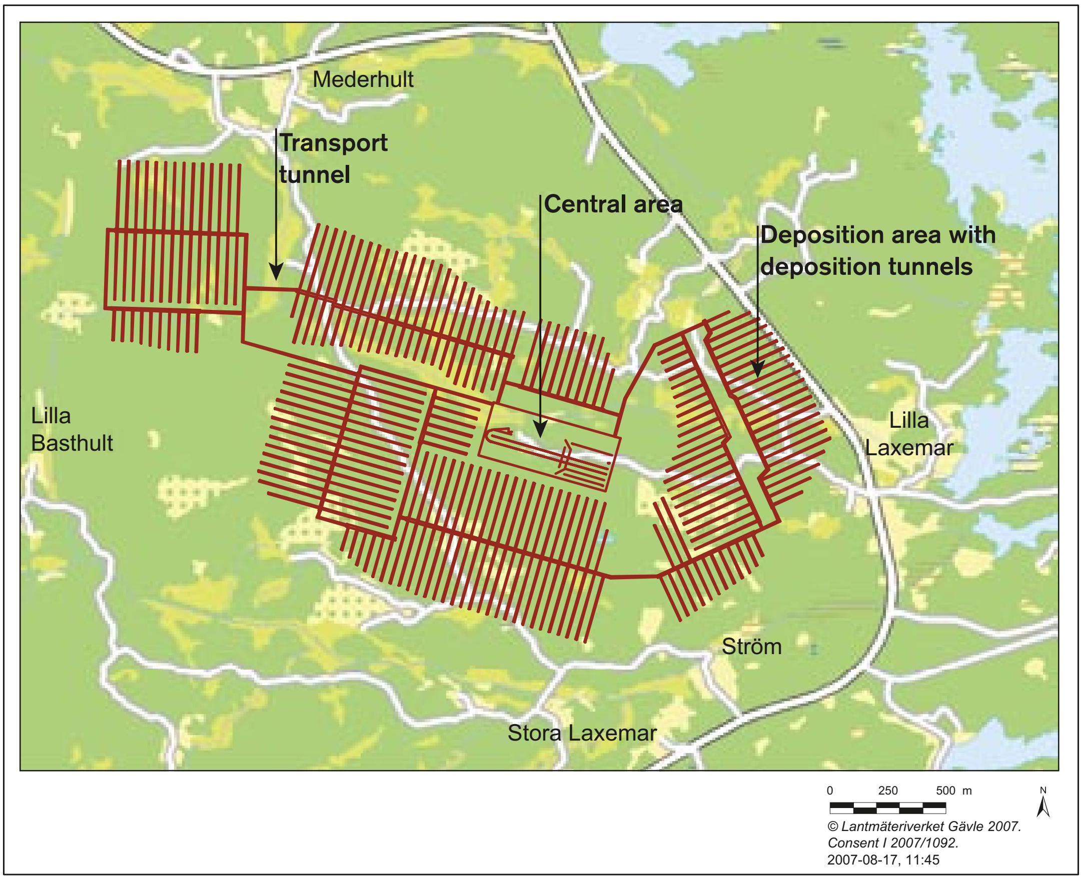


Figure 4-7. *Preliminary layout for a final repository in the Laxemar area (Layout D1).*

Based on these assumptions, different proposed locations for an operations area have been sketched and evaluated /4-17/. Rock conditions for accesses and central area are important to consider in these evaluations. Attempts to prioritize and pinpoint a location have therefore been dependent on initially scarce geological data. As data have become available from the ongoing complete site investigation, however, it has been possible to define a site more precisely. The site is called Oxhagen and is situated about two kilometres west of Simpevarp. Figure 4-8 shows how the final repository's facilities and rock heaps can be arranged on this site. At the same time as an operations area and facilities at Oxhagen are being designed, alternatives are being studied for road connections and other infrastructure that needs to be built. A special question is the transport of canisters from an encapsulation plant at Clab to the repository at Oxhagen. The distance is just over two kilometres, and the canisters are planned to be transported over a newly built private road that follows a power line corridor.

Preliminary safety assessment

The safety evaluation for the Simpevarp area has been commented on above. Regarding Laxemar, the preliminary safety assessment SR-Can /4-7/ states that "*The Laxemar site descriptive model version 1.2 is not sufficiently representative of the potential repository volume to allow definite conclusions regarding compliance*." This result is a consequence of the fact that the body of data for SR-Can was limited and that subsequent interest has been focused on the southern and western parts of the area. In order to ensure that Laxemar is a suitable site for a final repository, the uncertainties in the hydrogeological description need to be reduced. The investigations that have been done more recently have provided more representative data from those parts of the Laxemar area that are prioritized. The data that were obtained have for the most part confirmed the picture of Laxemar based on the initial part of the site investigation, but also reveal lower fracture frequency and lower permeability in the southern and western parts of the area compared with the data that served as a basis for SR-Can. There are also differences in the thermal properties of the rock, but this mainly affects the layout of the repository.

Figure 4-8. *View over parts of the Laxemar area with a photomontage of envisioned surface facilities and rock heaps for the final repository at Oxhagen and the Simpevarp Peninsula in the background.*

However, the remaining uncertainties in Laxemar are judged to be greater than the equivalent uncertainties in Forsmark. This is due to the greater heterogeneity of the bedrock in Laxemar. The uncertainties relate to, for example, the maximum extent of the quartz monzodiorite and the exact location and width of certain layout-determining deformation zones. The additional investigation holes that are planned are expected to provide valuable information about these questions. At some point, additional surface-based investigations may also be needed so that we can determine in detail which areas are most suitable for the later stages in the construction of the final repository. The existing data are, however, judged to provide a sufficient basis for planning the repository's accesses and initial deposition areas and to determine whether the available rock volumes are big enough for the later stages of the repository.

4.2 Feedback from the site investigations to the RD&D work

4.2.1 Investigations

The site investigations were able to build on a solid knowledge base obtained from geoscientific investigations. In response to the somewhat unique needs of this sector, strategies, methods and instruments for surface-based investigations have been developed and applied ever since the start of the nuclear waste programme. The foundation was laid during the study site programme. The subsequent establishment of the Äspö HRL (Hard Rock Laboratory) entailed an updating of the technology and a "dress rehearsal" for the site investigations. In preparation for the site investigations, investigation methodology that had not previously been used by SKB was also looked at and was added where necessary to the programmes that were established.

The discipline of surface ecosystems was not included in either the study site investigations or the investigations for construction of the Äspö HRL. Prior to the site investigations, extensive efforts were therefore made to identify what conditions and properties of the surface ecosystems needed to be determined, possible characterization methods and suitable models for the site modelling.

Based on our experience from the site investigations we can now conclude that the methodology and technology for both the geoscientific investigations and the investigations of surface ecosystems have in all essential respects performed as planned. The surprises have been few and of limited importance. The development work that has been pursued has with few exceptions had the character of updating and fine tuning of existing technology. The site investigations have also – once again – underscored the importance of adapting methodology and technology to site-specific conditions.

Two measurement methods should be mentioned for which significant quality defects have been detected and corrected during the course of the investigations. They relate to the measurement of borehole deviations and orientation of structures (fractures, rock contacts etc) using BIPS (Borehole Image Processing System). The methodology for deviation measurement has been refined by the introduction of two independent measurement methods and calculation of measurement uncertainties. The problems associated with BIPS had to do with deficiencies in the orientation of recorded structures. Since this was discovered, raw data have undergone extensive verification. In some cases, comparisons have been made with an independent measurement method. Procedures for calculating uncertainties have been developed and implemented for this method as well.

In some respects the site investigations have led to a marked increase in quality. Examples are controlling operational execution with programmes and procedures (activity plans and method descriptions) and the information flow from measurement to archive, in other words collection, processing, verification and reporting of data, transfer to databases, etc. The tools and procedures that have been developed and implemented to quality-assure the handling chains have changed the mode of working and considerably improved quality. This knowledge will be an important asset in future phases of the final repository project.

Overall competence for investigations is thus good and up-to-date. It is important to maintain this for future phases. Enhancements of methods and instruments are required prior to the investigations during construction and operation of the final repository. These needs are described in Part III, Chapter 12. A new feature will be that the investigations will then be carried out in an underground environment and integrated with design and rock works. Experience of such work is available from the Äspö HRL, but there are nevertheless reasons to emphasize the additional requirements that this entails, for example efficient feedback to the construction process.

4.2.2 Models for site description

In preparation for the site investigations, an overall strategy was presented for evaluating site-specific information and developing site descriptive models in an iterative process /4-27/. The strategy was then tested on available data from the Laxemar area /4-28/. The overall strategy proved to work well, while development needs were identified within the various disciplines as well as for overall integration. On this basis, the methodology for site modelling was further developed in a number of disciplines.

It was then decided that the further needs of method development that could be foreseen would best be handled as a part of the stepwise modelling process. It is during the practical work that new methods of analyzing data, the needs of the users and difficulties in communication between different disciplines are best identified.

Now that most of the site investigation phase's modelling work has been completed, we can conclude that the chosen strategy and the methods that were developed have been applicable for the most part. The additional development that has been required and conducted has mainly concerned the more detailed analysis methods. There has not been any great need to develop new numerical calculation codes. As a rule, proven calculation tools have been used. It has instead been in the choice of tools and how they are used that some development has taken place. The following examples can be mentioned:

- As expected the geological modelling has had to be adapted to some extent to site-specific conditions. For example, the relatively thick overburden in Forsmark means that topographic lineaments have a weak correlation to deformation zones, while the comparatively thin overburden in Laxemar means that topographic lineaments there are very important elements in the geological-structural interpretation. Reflection seismics has proved to be an even more important tool than foreseen in order to identify, together with borehole information, subhorizontal deformation zones.

- In preparation for the concluding modelling steps, the methodology for simulating fractures (DFN modelling) has been modified to better meet users' needs and quantify in a more defensible way the uncertainties in the resulting description.
- The methodology for thermal modelling has been updated for the purpose of better describing the spatial variation of the thermal properties and their correlation with rock types.
- The methodology for hydrogeological modelling and its integration with hydrogeochemical modelling has been developed. The revised methodology gives added weight to conceptual descriptions based on observations from various disciplines.
- In more recent model versions, more emphasis is placed on obtaining a concordant geological, rock mechanical and hydrogeological description of the fracture geometry, stress situation and hydraulic properties of the rock. But there has been little or no reason to use coupled model codes.

The methodology for modelling substance transport in the surface system was site-adapted and refined during the work with the first site descriptions. Based on site-specific data, ecosystem models have been developed for land, lake and sea. Furthermore, the methodology for describing flows and cycling of substances on the landscape level has been refined. Preliminary results from the site descriptions of the surface systems indicate possible transport pathways from the rock, up to the surface and further in the ecosystems. This is important information for the safety assessment's dose modelling and sets physical limits for cycling and accumulation of materials in the ecosystems.

The analysis methodology, which has been progressively developed during the site investigation phase, is expected to be applicable to a great extent in conjunction with construction and operation as well. Further development will still be needed as new experience is acquired. It is therefore warranted to review and revise current method descriptions in preparation for the construction phase. This revision should preferably be done after the permit/licence applications have been submitted.

There is also reason to review tools and methodology for rock visualization and geometric modelling (RVS) so that they are more widely used to quickly build up conceptual models. Furthermore, a practical methodology needs to be developed for effective evaluation of the new more detailed tests that can be performed under ground. An example is methodology for interpreting cross-hole tests and evaluating proposed acceptance criteria for deposition holes.

4.3 Integrated evaluation and site selection

4.3.1 State of knowledge after the site investigations

In the integrated account of method, site selection and programme prior to the site investigation phase /4-29/ that was presented in 2000 it is stated that the knowledge that is gathered in the site investigation phase "*will be utilized to evaluate the suitability of investigated sites for the deep repository and must be comprehensive enough to:*

- *Show whether the selected site satisfies requirements on safety and technical aspects.*
- *Serve as a basis for adaptation of the final repository to the characteristics of the site with an acceptable impact on society and the environment.*
- *Permit comparisons with other investigated sites."*

SKB makes the judgement that the investigations that are now being concluded provide the data needed to satisfy these requirements. This applies to both Forsmark and Laxemar. Even though considerable analysis work remains to be done before data from the concluding stages of the investigations have been translated into site-adapted repository solutions and safety assessments, it is not likely that this will change the preliminary assessment that the site investigations in both Forsmark and Oskarshamn have achieved established goals.

The regular updates of the site descriptive models provide an important basis for weighing the potential benefit of further investigations against the costs /4-30/. If the additional data do not appreciably change the models, this is a sign that the process of progressive knowledge accumulation through investigations has levelled off. Further investigations are then not warranted. This should not be interpreted as meaning that all possibilities for improving the body of data by means of further investigations from the surface have been exhausted. A new borehole could, for example, fill a local knowledge gap or reduce the uncertainties for a given parameter, but not to an extent that would justify the cost. In the case of Forsmark, it is clear that the models have now stabilized and that they correspond to a level of knowledge that is sufficient for the purposes outlined above. In the case of Laxemar as well, the models are judged to have stabilized for the most part when it comes to rock domains and major deformation zones. Supplementary investigations and analysis of data of importance for the final description of the extent of the quartz monzodiorite in the south and its properties at repository depth are still being conducted. These additional data are expected to contribute above all to the description of rock mechanical conditions, the distribution of groundwater flow and the hydrogeochemical situation, as well as the placement of the deposition areas.

The selection of a site for the final repository is a decision that entails considerable commitments in the nuclear fuel programme of a technical, political, temporal and financial nature. It is therefore important to minimize the risk of a decision that later turns out to be wrong. In view of this – and knowing that the decision must in the end be made on the basis of investigations from the surface – the site investigations have been conducted with a high level of ambition in terms of achieving a sufficiently good knowledge of the site. The fact that the crucial decision must be made before rock openings at repository depth become accessible nevertheless entails unavoidable limitations in the body of data and thereby also risks that must be taken into consideration. There are questions which, in order to be answered, require more detailed investigations than can be done from the surface and/or direct experience from rock construction on the site. An example is knowledge of rock mechanical conditions on a tunnel scale. Another is acceptance criteria for deposition positions. It is believed that detailed investigations under ground will provide data for criteria regarding placement of rock openings and deposition holes that are more exact, less restrictive and more effective than is possible based on the data from the site investigations. Owing to this remaining uncertainty, the repository layouts that serve as a basis for SR-Site will probably have to be based on restrictive assumptions and therefore be preliminary. Other uncertainties will have to be handled in a similar manner.

It is crucial for site selection that the fundamental assessments of the suitability of the sites are reasonably reliable and that the body of data permits the sites to be compared. In SKB's opinion, this is the case. What remains are risks that can be expressed in time and costs. These risks are linked to the incomplete knowledge of rock conditions, with accompanying uncertainties in resource requirements for building and operating a facility that satisfies the requirements. These are uncertainties for which SKB is prepared to accept responsibility.

4.3.2 Methodology and planning for site selection

SKB has in various contexts reported general factors that guide the work of siting the final repository /4-29/. Based on these siting factors and the requirements in the legislation, SKB intends to give an account of the choice of site with the support of underlying evaluations and arguments. The account must clarify how laws and regulations have been taken into account, as well as SKB's standpoints and values in relation to other criteria.

SKB's planning is aimed at being able to select, after comparisons, one of the two sites now being investigated. But first the sites must be evaluated separately for the purpose of clarifying their suitability for a siting. Of fundamental importance for suitability is that the purpose of the planned activity can be achieved, in other words final disposal of the spent nuclear fuel so that human health and the environment are protected. This is equivalent to saying that a repository on the site must satisfy the requirements on safety and radiation protection and that the measures required to achieve such a repository are feasible. If it turns out that both sites are found suitable, the next step is a comparative evaluation. The purpose of this evaluation is to be able to prioritize one site. The evaluation is done from a holistic perspective, where a variety of factors are taken into account. The guiding principle is that the site where the purpose of the final repository can be achieved with a minimum of damage or detriment to human health and the environment should be selected.

Aside from all data on the two siting alternatives from the site investigations, background and comparison material will play an important role in the evaluation of the merits of the sites. A large body of reference material is available from the many years of development and siting work /4-29, 4-31/, but also from other sources. Particularly valuable knowledge regarding rock conditions and safety aspects is available from investigations of study sites /4-31/, investigations within the framework of the Finnish siting programme /4-32/, more general studies of the advantages and disadvantages of sitings in different geological environments and geographic locations /4-31/, and experience from site-specific safety assessments. Background material on environmental and societal factors can be obtained to a great extent from studies conducted during the different phases of the siting process, above all the feasibility studies.

The background material for site selection is compiled as the supporting material for the application becomes ready. The planning is based on the fact that site selection takes place in a phase when both siting alternatives have been developed to the point that they can be evaluated in all relevant respects – individually and in relation to each other. The analysis results and reports that are required are expected to become available in preliminary form in good time before an application is submitted. Other scenarios are conceivable, however, depending on the outcome of remaining evaluations of the siting alternatives.

The choice of site must be justified in SKB's applications under the Nuclear Activities Act and the Environmental Code. SKB's reasons and arguments will be examined and reviewed by the competent authorities, the Environmental Court and other parties within the framework of the licensing processes. Material and arguments supporting the choice of site must be clearly presented in the applications. The requirements according to the siting principle in the Environmental Code (Chapter 2, section 6) define the framework.

Site-by-site evaluation

The sites are thus first evaluated individually, in relation to the requirements in the Nuclear Activities Act, the Radiation Protection Act and the Environmental Code as well as SKB's own requirements and preferences. The purpose is to determine whether the site in question is suitable in itself with respect to all relevant requirements.

In order to be suitable the site must, in addition to satisfying the fundamental safety and radiation protection requirements, also enable the facility to be built and operated with reasonable consideration for the environment and a reasonable input of resources. Provisions regarding for example conservation of land and water resources must be satisfied. In addition, the benefit of the facility must be weighed against the unavoidable damage and detriment it causes. Similarly, the benefit of measures that can be adopted to avoid or reduce detrimental impact must be weighed against the costs. The goal is to protect man and the environment.

In order for a site to be selected it must also be available, both purely physically and from a societal perspective. Physical availability entails that SKB must be able to obtain disposition over the requisite land and that relevant environmental protection and planning conditions to not seriously hinder an establishment. Prior to the site investigations, SKB found that no obvious obstacles in these respects could be foreseen for either of the sites. The same judgement is made today.

Availability from a societal perspective entails that the choice of site must have political support. In practice this means that the concerned municipality and the Government must accept the siting. For obvious reasons, nothing decisive can be expected on this central point until the Government has ruled on permissibility, whereby the municipality must also take a stand. As far as SKB can judge, attitudes to a possible establishment of the final repository are stable and positive at present in both Östhammar and Oskarshamn.

Comparative evaluation

Provided that both sites are found to be available and suitable for the final repository, a comparative evaluation is made. This must also be done from a holistic perspective. The comparative evaluation is based for the most part on the same body of material and the same criteria as the fundamental assessment of the suitability of the site. Examples of criteria that need to be taken into consideration are safety and radiation protection, the impact of the establishment on the natural, cultural and residential environment, transport needs, energy conservation and other resource aspects, and technical aspects such as efficiency and reliability in construction and operation. The intention is that the comparative evaluation should result in clear standpoints by SKB on important value issues, and finally in a selection of one of the two investigated sites on good grounds.

Provided that site selection can be carried out in the manner outlined above, the selected site will be the end result of a thorough and methodically executed siting process. The process has involved many years of knowledge accumulation concerning factors and conditions of importance for the siting of the final repository, geoscientific and other studies on a national and regional scale, and evaluations and comparisons of candidate sites arrived at during the feasibility study and site investigation phases. With the support of this process, SKB believes that the final choice of site can be justified in relation to every other site that can be considered suitable in the sense of being a potential siting alternative. This applies both to sites that have been in the selection pool in earlier phases of the siting process and to any other sites.

5 Basis for construction and operation

In conjunction with the selection of a site for the final repository, SKB intends to start a project aimed at building and commissioning the final repository. The planning for this project is under way. The following chapters should be regarded as a status report on the planning work. A more complete account will be included in the supporting material for the application.

Important points of departure for the project are:

- SKB's overall plan of action (presented in Part I).
- The site description for the selected site (SDM-Site).
- The site-adapted facility layout (Layout D2).
- The safety assessment SR-Site.
- Results from technology development.
- General knowledge and experience from construction of underground facilities.

5.1 Main phases and timetable

Figure 5-1 shows the division into main phases that serves as a basis for SKB's planning of the construction, commissioning and operation of the final repository, as well as important milestones and main activities. The timetable shown in the figure contains uncertainties. SKB has limited opportunities to influence the length of the licensing process, i.e. the time from when an application has been submitted until a permit/licence has been granted. SKB estimates that the process will take at least two years.

The time that is then required to build and commission the parts of the facility that are required for the start of trial operation can be estimated with greater certainty, but uncertainties exist here as well. Uncertainties remain, for example, regarding rock conditions on the site, what additional studies will have to be done by reason of SR-Site, and technological developments for the different subsystems. Additional requirements may also be imposed by the regulatory authorities in the form of conditions for construction and operation. Finally, commissioning of the final repository must be coordinated with the corresponding phase for other facilities in the system. Altogether, the time from start of construction to application for a permit for trial operation is estimated to be about seven years.

The main purpose of trial operation is to gain experience of operating the facilities and, on the basis of this experience, modify the safety analysis report as well as procedures and instructions for routine operation. When the transition from trial operation to routine operation takes place is dependent on when SKB is able to show that routine operation can be carried out as planned and with the desired capacity, as well as on the decision of the authorities. This – and the fact that this phase is far in the future – makes it difficult to pinpoint the time. It is estimated that routine operation can begin after at most two years of trial operation. How long routine operation will continue is not indicated in Figure 5-1, but is estimated on the basis of current planning premises to be about 50 years /5-1/.

5.1.1 Licensing

The main phase "Licensing" starts when permit/licence applications under the Nuclear Activities Act and the Environmental Code have been submitted. The applications will then be processed and reviewed by the regulatory authorities, the Environmental Court, the municipality and the Government. During this period the initiative in the project largely lies with these bodies, and the length of the process depends on how long they take for review and decision. SKB's main tasks are to participate in the licensing process in various ways and to make preparations for construction of the final repository. Responsibility for this rests with the project organization for construction and commissioning that is established in conjunction with site selection. The preparations include continued technology development and design, as well as preparing the procurement of suppliers.

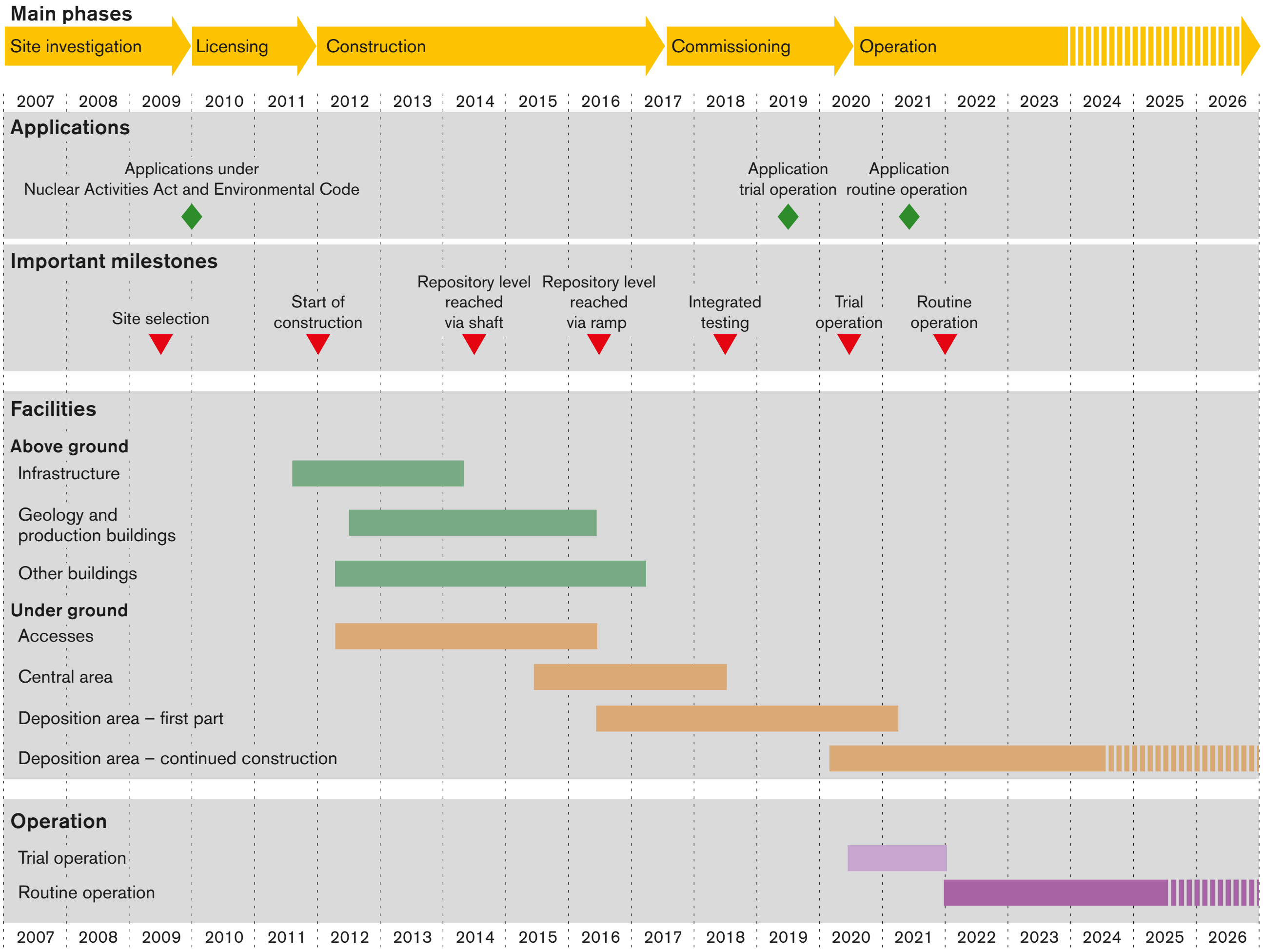


***Figure 5-1.** General timetable for final repository.*

5.1.2 Construction

After all permits, licences and conditions have been issued, the final repository will be constructed – both underground and above-ground (surface) facilities. Above ground, accesses are first built to repository level. When rock excavation operations can be established at repository level, the transport tunnels, the central area and the first tunnels with deposition positions are built. In parallel and integrated with the civil engineering works, investigations are conducted as a basis for the detailed design of the facility to stipulated requirements and restrictions. These investigations are also aimed at verifying the assumptions that have served as a basis for the safety assessment SR-Site. Above ground, the buildings and infrastructure needed to operate the facility are built.

5.1.3 Commissioning

Commissioning of the final repository's subsystems starts as the systems are put into place. The systems are tested, first one by one, then jointly in the facility, and finally the whole final repository system is tested, including encapsulation and transportation. The goal is that the entire system should function on an industrial scale, technically and organizationally. Running-in of technology and organization is concluded with integrated testing of the whole facility. As early as possible during commissioning, SKB updates the safety analysis reports (for both long-term safety and operation) and submits an application for a permit for trial operation. Commissioning is then concluded when the regulatory authorities issue a permit for trial operation. Responsibility for the facility then passes from the construction organization to the operating organization.

5.1.4 Operation

The operating phase begins with a period of trial operation. Deposition of canisters of spent nuclear fuel then starts, and the deposition capacity is built up gradually. Trial operation then transitions into routine operation. Besides the deposition sequence, operation also includes ongoing investigations and analyses, design, rock excavation and recurrent safety assessments. Operation of the final repository thus comprises a continuous cycle of design, construction and deposition. Operation continues until the last deposition tunnel has been closed and sealed.

5.2 Decision points and milestones

The final repository's life cycle contains a number of milestones. Figure 5-1 shows some of them. The milestones can be divided into two general categories: SKB's own decisions and interim goals, and regulatory decisions.

5.2.1 SKB's own decisions and interim goals

It is not possible to predict in detail SKB's decisions and interim goals for the final repository during construction and operation. However, starting after the submission of applications under the Nuclear Activities Act and the Environmental Code, the following important milestones can be discerned:

- Engage contractor for the initial construction works.
- Establish and commence the construction activities.
- Commence construction of rock facilities at repository level.
- Commence construction of the first deposition area.
- Commence integrated testing of the whole system.
- Apply for a permit for trial operation.
- Commence trial operation.
- Apply for a permit for routine operation.
- Commence routine operation.

5.2.2 Regulatory decisions

The following important regulatory decisions can be foreseen:

- Municipal council's decision to support the activities.
- Government's decisions on permissibility under the Environmental Code and a licence under the Nuclear Activities Act.
- Municipality's decision to adopt the detailed development plan for land use.
- Municipality's decision on a building permit.
- SKI's decision on conditions under the Nuclear Activities Act.
- SSI's decision on conditions under the Radiation Protection Act.
- The Environmental Court's decision on permits and conditions, e.g. under Chapter 9 and Chapter 11 of the Environmental Code.
- SKI's decision on a permit for trial operation.
- SKI's decision on a permit for routine operation.

To these may be added other decisions and checkpoints, for example under the conditions established when the licence for the final repository is granted and in conjunction with recurrent updates of the safety analysis reports.

5.3 Technology need

An obvious prerequisite for being able to build and operate the final repository is that the technology that is needed in different phases is developed and ready to be put into industrial use as the need arises. Chapter 6 describes the current situation for the work methodology that is being developed for design and implementation of technology during construction and operation. SKB's programme for technology development is presented in Part III, where the development needs for different subsystems are also described. A summary of the planned status of technology development prior to application is presented below. Equivalent summaries of the planned status for the main phases licensing, construction and commissioning are presented in Chapters 7, 8 and 9, respectively.

Prior to licence application under the Nuclear Activities Act for the final repository, a reference design is presented that provides a coherent picture of completed and remaining technology choices and how far the development of different subsystems has come at that point. Since several years still remain then until the start of construction, no component has to be immediately ready to be put into industrial use. The basic requirement is rather that technical solutions should be presented in a way that makes it clear whether they:

- satisfy stipulated requirements and design premises for the final repository,
- are feasible.

One consequence of this is that the solutions that are presented must have come so far in their development that they can be expected to be completed in time for their application in construction and operation.

Tables 5-1 through 5-4 summarize the planned status prior to application of technology components etc that will be used in construction and operation. The format for the tables conforms to Part III, where the technology needed to achieve the final repository's main subsystems is arranged in the following production lines:

- The rock line
- The buffer line
- The fuel line
- The canister line
- The backfill line
- The closure line

The production lines can be said to describe the production of the different subsystems from start to finish. For example, the buffer line describes the entire chain from mining of bentonite via transportation and various processing steps to the application of finished buffer blocks in the final repository's deposition holes. The development need for the technology required in different steps of the production lines varies within wide limits. In the case of the buffer line, for example, mining and transportation of bentonite involves proven technology that can be applied directly for the needs of the final repository. In contrast, the fabrication of blocks with the right quality is a unique operation that has required – and still requires – extensive development work before it can be implemented.

The left-hand columns in tables 5-1 through 5-4 correspond in simplified form to those parts of the production lines (excluding the fuel line and the closure line) that relate to the final repository. The right-hand columns give references to the sections in Part III that deal with the subsystem in question.

Table 5-1. Technology for rock engineering – planned status prior to application.

Technology	Planned status/interim goal prior to application	Reference to section in Part III
Investigations		
The goal of SKB's efforts in the area is to adapt and develop methods and instruments so that they satisfy the requirements on safety, speed and efficiency that will apply to investigations during construction and operation.		
Investigations in boreholes	Adaptation and development of instruments and methods within e.g. geophysics, hydrogeology, thermal properties and transport properties is under way. Special requirements must be met by instrumentation designed for high water pressures and flows.	12.3
Investigations in tunnels and deposition holes	Development of an efficient system for bedrock mapping etc is under way in cooperation with Posiva.	12.3.2
	Different methods for measuring water flows in ramps and tunnels have been developed and evaluated.	12.3.7
	Development of methodology and methods for measurement of inflow to deposition tunnels and deposition holes is under way.	12.3.8
Information systems and information technology	Programmes to develop, improve and adapt SKB's information systems (databases, visualization programs etc) have been established. Systems needed at the start of construction are prioritized.	12.3.11
Rock excavation		
The goal of SKB's efforts in the area is to show that the excavation methods for different parts of the facility that are described in the reference design satisfy the safety assessment's requirements. This means, for example, that technically critical steps have been tested in a realistic setting and that the excavation method for deposition tunnels has been demonstrated at the Äspö HRL.		
Technology for drill-and-blast	Technology for precision-controlled blast hole drilling tested.	11.1, 12.5
	Safe and effective use of emulsion explosive and electronic detonators tested.	11.1, 12.5
Excavation-disturbed zone	Characterization of zones with varying degrees of excavation disturbance has been carried out. The tests have examined the relationships between mechanical damage and hydraulic properties.	12.5
	Methods (controlled blasting, wire sawing) for limiting the excavation-damaged zone of the tunnel floor have been evaluated and compared.	12.5
Boring of deposition holes	Reference method for boring selected.	11.1, 12.7
	Preliminary design of prototype for machine for boring of deposition holes ready.	11.1, 12.7
Rock support		
The goal of SKB's efforts in the area is to adapt established methods for rock support by developing recipes for grout for rock bolts and shotcrete that satisfy the requirements on low pH.		
Materials for rock support	Reference materials for shotcrete, wire mesh and rock bolts that satisfy the requirements on low pH selected and tested.	11.1, 12.6
Shotcrete	Testing of equipment for grout with low pH is under way.	12.6
Sealing technology		
The goal of SKB's efforts in the area is to provide technology for handling all expected sealing needs, while taking into account the special requirements that apply for the final repository.		
Technology and material for sealing of water-conducting fractures and zones	The usefulness of silica sol for sealing of water-conducting structures at repository depth verified by field tests.	11.1, 12.4
	Reference material for low-pH grout selected and tested.	11.1, 12.4
Technology and material for sealing of large zones with heavy water flow	Strategy for sealing developed.	11.1, 12.4

Table 5-2. Technology for buffer – planned status prior to application.

Technology	Planned status/interim goal prior to application	Reference to section in Part III
Production and handling above ground		
Handling chain from mining to final repository	Preliminary design under way. Known and commercially available technology.	–
Treatment and interim storage – raw material	Preliminary design under way. Known and commercially available technology.	–
Compaction – blocks and rings	Reference method chosen with support of well underpinned arguments. Block properties of importance known.	11.2, 13.3.1
Production – pellets and granules	Production method chosen for each bentonite grade.	13.3.2
Interim storage – blocks and pellets	Requirements and premises clarified, reference methods chosen.	11.2, 13.4
Handling and application – deposition holes		
Fitting-out	Materials for reference design selected. Design and construction tested, buffer protection tested on full scale.	11.2, 13.5
Installation – blocks and rings	Reference method presented. Testing of installation method under way.	11.2, 13.6
Installation – pellets/granules	Method under development for materials in question. Reference method selected.	13.7

Table 5-3. Technology for canister handling and deposition at the final repository – planned status prior to application.

Technology	Planned status/interim goal prior to application	Reference to section in Part III
The goal of SKB's efforts in the area is a preliminary design of transport vehicle and other equipment. The deposition machine in the Äspö HRL should also be rebuilt so that it runs on wheels instead of rails.		
Handling of transport casks above ground and descent on ramp	Preliminary design of handling equipment for terminal building finished.	–
	Preliminary design of selected vehicle type for transport on ramp finished.	11.3, 14.8
	Risk analysis for ramp transport completed.	14.8
Transloading station and equipment for moving canisters from transport casks to deposition machine	Preliminary design of equipment for transloading station finished.	14.8
	Testing of technology for transfer of canister from cask to deposition machine and other handling under way (Äspö HRL)	14.8
Deposition machine and other equipment for installing buffer and depositing canisters	Existing rail-bound machine rebuilt to wheeled machine and equipped with navigation and positioning system for remote control. Rebuilt machine tested in different normal and abnormal situations.	11.3, 14.8
	Design and testing of equipment for emplacement of buffer blocks and rings with associated work operations under way; being done partly in cooperation with Posiva.	11.2, 13.6

Table 5-4. Technology for backfilling and closure – planned status prior to application.

Technology	Planned status/interim goal prior to application	Reference to section in Part III
Production and handling above ground		
Handling chain from mining to final repository	Preliminary design under way. Known and commercially available technology.	–
Treatment and interim storage – raw material	Preliminary design under way. Known and commercially available technology.	–
Compaction – block for upper part of deposition hole	Reference method chosen with support of well underpinned arguments. Block properties of importance known.	15.3
Compaction – blocks for deposition tunnel	Known and commercially available technology, trial fabrication of block of size in question completed.	15.3
Interim storage – blocks, pellets/granules	Requirements and premises clarified, reference methods chosen.	13.4, 15.4
Handling and application – deposition tunnel		
Removal of drainage and temporary buffer protection	Tested on full scale.	15.5
Backfilling – upper part of deposition hole	Reference method selected and verified at Bentonite Laboratory and Äspö HRL.	15.6
Backfilling – blocks in tunnel	Reference method presented. Prototype equipment for handling and emplacement built and tested.	11.4, 15.6
Backfilling – pellets/granulate in tunnel	Reference method presented. Prototype equipment for handling and application built and tested.	11.4, 15.7
Closure – temporary plug in tunnel	Different concepts evaluated. Reference alternative selected.	11.4, 15.8

6 Work methodology during construction and operation

The final repository consists of a number of facility parts. For each facility part, SKB will employ the work and design methodology that is best suited with respect to the type and function of the facility. A different methodology is required for the underground parts than for the surface parts. Ongoing planning of construction and operation includes devising a suitable methodology for designing and building all parts of the repository. This chapter provides a status report on the work and also comprises a preliminary programme declaration of how construction and operation of the repository will take place.

Section 6.6 briefly describes the current situation and points of departure for quality control, while section 6.7 presents an overview of ongoing and planned work with safeguards for the final repository.

6.1 Facility parts

On a general level, the final repository can be divided into underground openings, surface buildings and facilities, and technical installations, see Figures 6-1 and 6-2. The different parts will be constructed successively.

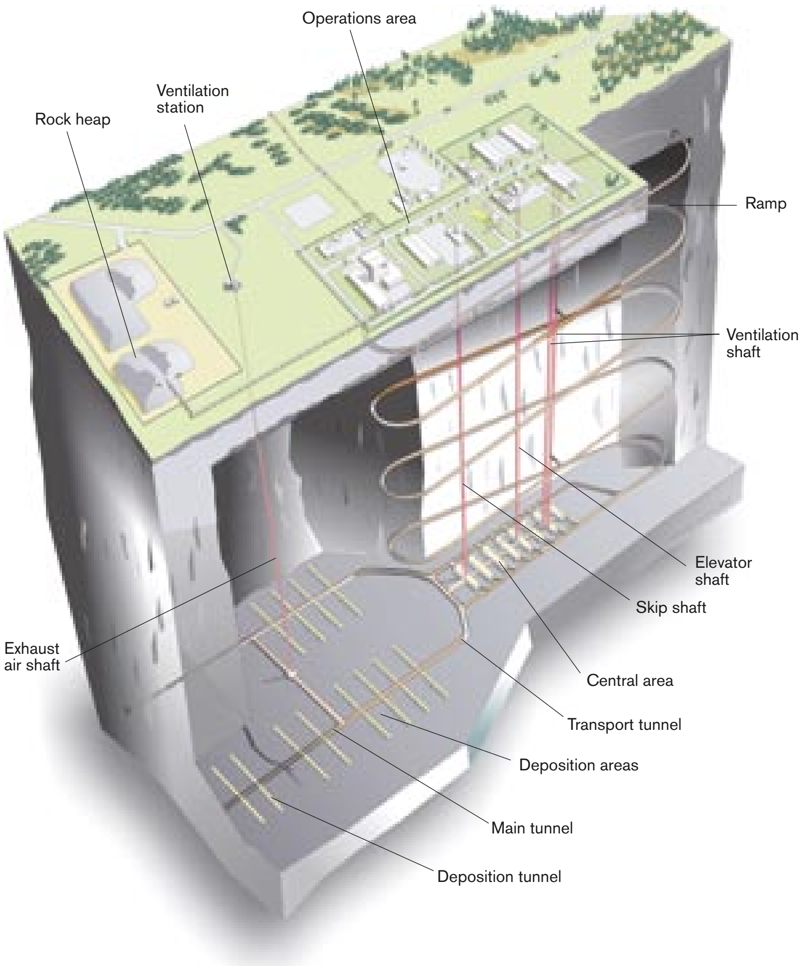


Figure 6-1. *The different parts of the final repository.*

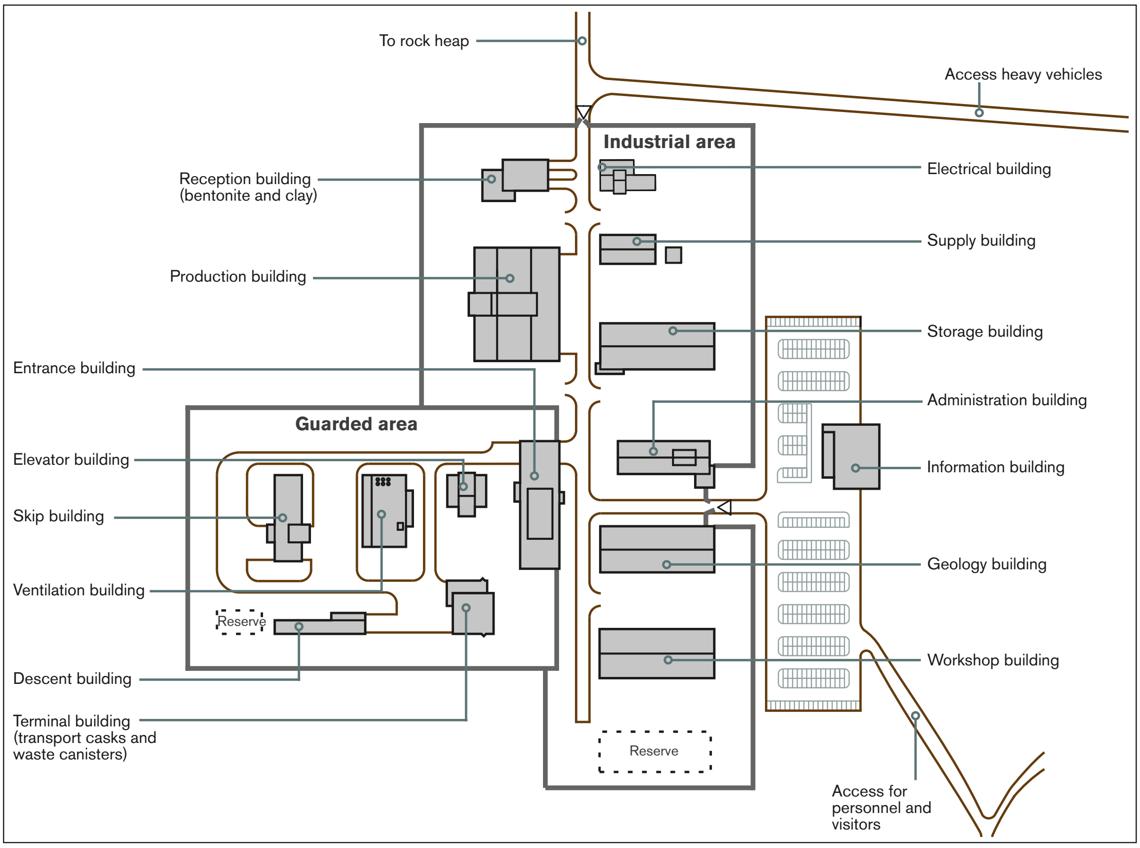


Figure 6-2. *Surface buildings and facilities.*

The openings under ground can be divided into the following facility parts:

- Ramp (descent tunnel)
- Skip shaft (shaft for hoisting of blast rubble)
- Other shafts (passenger transport, ventilation)
- Central area
- Transport tunnels
- Deposition areas (main tunnels, deposition tunnels)

Surface buildings and facilities are shown in Figure 6-2. Outside the actual operations area as shown in Figure 6-2 are access roads and other infrastructure, area for rock heaps and superstructures for ventilation shafts.

Technical installations include:

- Ventilation
- Water supply and sewerage, drainage
- Hoists and elevators, including rock haulage system
- Electric power
- Fire protection
- Communications, surveillance and monitoring

6.2 Important terms

Safety analysis report

Before a nuclear facility may be erected, a preliminary safety analysis report must be compiled. Trial operation of the facility may not commence until the safety analysis report has been updated. The facility may then be put into routine operation after the safety report has been augmented. The safety analysis report must then be updated regularly, normally every ten years /6-1, 6-2/.

The safety analysis report for the final repository shall cover both safety during operation and long-term post-closure safety /6-1/. Thus, to accompany the application for the final repository under the Nuclear Activities Act, SKB will prepare a preliminary operational safety analysis report (PSAR) showing how the facility satisfies the requirements on nuclear safety, and a preliminary safety analysis report on long-term safety (SR-Site).

During the construction of the repository, SKB will update and elaborate the site description and judge whether the conditions lie within the limits stipulated in SR-Site. An updated safety analysis report will be prepared prior to application for trial operation, and if it turns out at any point that the prerequisites in SR-Site or PSAR are not met.

Site description

The site description with associated site model comprises a description of a site and its regional environs. The site description includes current states and properties of the geosphere and the biosphere plus a description of the ongoing natural processes that can be expected to affect the long-term evolution of the site. The site description provides a basis for clarifying what new data need to be collected. It is used in design to position and configure the final repository and as a basis for assessment of the repository's long-term safety. A number of site descriptions with associated supportive models have been prepared during the site investigations. The site descriptions that are prepared when the site investigations are concluded, SDM-Site, will serve as a basis for SR-Site.

Reference design

In the stepwise design of the KBS-3 system, SKB uses the term "reference design". A reference design is valid from a defined point in time until something else is decided on. The established reference design will be used as a premise for technology development, design and assessments of safety, radiation protection and environmental impact. A decision on the reference design will be made within the framework of SKB's requirements management. It must be detailed enough to enable technology development, design and assessments of safety, radiation protection and environmental impact to be carried out. At the same time it should allow room for improvements and site adaptation.

Design

General term for determining the required size, dimensions, loadbearing capacity etc for a structure for the purpose of satisfying specified requirements. The standard EN-1997-1, Eurocode 7 /6-3/, issued 10 August 2007, specifies which methods should be used in the geotechnical design of hard rock facilities. The standard also clarifies what steps should be included in the design process. The most important steps are:

- Collection, recording and interpretation of geotechnical data.
- Design of loadbearing structures (including hard rock facilities).
- Supervision of workmanship, monitoring of structure performance and maintenance plan.

Inspection programme

The inspection programme describes what measurements and observations shall be carried out to determine whether the structure is performing as expected or whether measures described in the plan of action need to be taken. These measures must be defined before the start of construction.

Facility documentation

In addition to finished underground openings, design and construction result in a large body of facility documentation. This documentation consists of up-to-date drawings of the facility, its building structures, systems, components and devices, as well as documents showing how these items have been manufactured, installed and inspected. Where applicable, information on modifications in the facility should also be included in the documentation /6-2/.

6.3 Design and construction of underground openings

Design and construction of the final repository shall be executed so that:

- The repository's rock openings – particularly deposition tunnels and deposition holes – are located and configured with a view to the requirements and restrictions that apply to the repository's long-term safety.
- The repository is configured and built so that it meets the requirements that apply to operational safety, working environment and radiation protection.
- The rock structure meets stipulated requirements regarding stability, water seepage, geometry, etc.

A carefully thought-out work methodology that is adapted to the final repository's rock facilities is required to achieve this.

6.3.1 Previously applied design methodology

In RD&D Programme 2004 SKB described the design methodology with a stepwise, increasingly detailed design process that has been applied both before and during the site investigation phase. Table 6-1 provides an overview and summary of the scope of the design steps and what products result from the different steps. Work is currently under way with Layout D2, which will serve as a basis for SR-Site and an application for the final repository.

Design during the site investigation phase according to Table 6-1 can be described as the process of placing the planned facility in a model of the site and adapting it to that model. In each step, all parts of the envisioned facility have been processed to a comparable level of detail as far as possible.

Table 6-1. SKB's design methodology before and during the site investigation phase – design step, scope and products (adapted from /6-4/).

Design step	Scope	Products
Layout E	Integrated non-site-adapted design.	Facility description based on theoretical layouts for the surface and underground parts /6-5, 6-6, 6-7/.
Layout D0	Site-adapted design of the surface parts.	Compilation of possible positions and layouts for the surface parts.
Layout D1	Site-adapted design of the underground parts based on data from the initial part of the site investigation.	Layout for selected alternatives for surface and underground parts /6-8, 6-9, 6-10/. Facility descriptions based on alternative layouts /6-11, 6-12, 6-13/. Basis for preliminary safety evaluation and SR-Can /6-8, 6-10/.
Layout D2	Continued site-adapted design of facility based on complete data from site investigation, safety assessment SR-Can /6-14/ and environmental studies.	Layout of proposed facility with site plan for surface parts and placement of accesses. Facility description based on proposed layout. Background material for SR-Site and EIS. Supporting material for final repository application. Supporting material for tendering documents for above all accesses to the repository.

6.3.2 Basis for work methodology during construction and operation

During construction and operation the actual facility will be built on the actual site. This transition from an envisioned facility in a model to a physical facility on the site will have consequences for how the activities can and should be carried out. Different parts of the facility will be in different phases of planning and production. When certain parts are ready, rock excavation works will be under way for others, investigations and detailed design for others, while some have only been preliminarily designed. Another methodology than the one applied to date is needed for this reality.

Another factor that imposes high demands on the choice of methodology for designing and building the final repository is that the actual properties and behaviour of the rock will not be completely known until rock excavation is completed. The influence of the rock conditions (geology, hydrogeology, groundwater chemistry etc) on the placement of deposition tunnels and deposition holes and on the layout and geotechnical design of the structure gives rise to considerable uncertainties. The investigations that precede rock excavation can reduce these uncertainties. But it is necessary to take full advantage of the knowledge of the rock – and its response to rock excavation – that is gained during rock excavation. Design and construction of the repository's rock openings must therefore be pursued as an iterative process.

The methodology for designing and building facilities under ground must thus be adapted to the fact:

- that the different parts of the repository will be in different construction phases,
- that rock construction is associated with uncertainties,
- that the final layout, including canister positions, cannot be determined until the rock excavation work in the deposition tunnels is finished and the requisite investigations have been conducted.

Other important points of departure are:

- The requirements and restrictions from laws, regulations, owners and other stakeholders on which design is based (site adaptation, layout and engineering) must be managed in a systematic and traceable fashion.
- The site description and the underlying models must be interpreted so that they can be used as a basis for design and construction of the facility. This work has been commenced, and a first site engineering report has been produced as a basis for the ongoing design work in layout step D2.
- The facility must be designed so that the final repository and its engineered barriers can be built and other activities executed in a safe, efficient and environmentally sound manner.
- Data and experience from the excavation works must be fed back to design quickly and efficiently. This requires efficient collaboration and interaction between investigations, modelling, design and safety assessment.

6.3.3 Methods for geotechnical design of rock facilities

Based on the above points of departure, SKB intends to use for each facility part the geotechnical design method that can handle uncertainties in the most reliable and economical fashion while protecting human health, the environment, plant and machinery. The choice of method depends on the type of design issue and the function of the hard rock facility (for example deposition tunnel or central area). According to /6-3/, geotechnical design of hard rock facilities can be carried out with one or several of the following methods:

- calculations based on the partial coefficient method or probability-based calculation methods,
- time-honoured methods based on comparable structures and proven experience,
- model tests and trial loading,
- the Observational Method.

Design by calculation is common in the design of rock facilities. The final layout of the structure is then determined in advance. The structure is built as designed. The method can be employed for structures (for example a rock block that is fixed in place by a rock bolt) where it is possible to accurately determine loadbearing capacity (what load the rock bolt is capable of supporting) and load (the weight of the individual rock block).

Design using time-honoured methods can also be applicable for certain of the final repository's design issues, particularly in early phases. These methods include experience-based systems such as the Q-system /6-15/.

Model tests and trial loading are not feasible for designing the final repository's rock facilities.

The Observational Method may be suitable to use when it is difficult to predict the properties of the structure and its responses to relevant loads. The fundamentals of the method are in principle the same as in the methodology known as "active design" in Sweden and that includes the three fundamental concepts prediction, observation and corrective action. The Observational Method includes prediction of preliminary design, which is reported in the form of geotechnical design reports, drawings and technical specifications. Since there are uncertainties in the designed structure, it is a requirement in the Observational Method that contingency measures that may be required in the execution phase when the behaviour of the structure deviates from what is expected be devised in advance and comprise a part of the construction documents. The design requirements are checked in the execution phase by means of relevant observations. This involves making observations, recording and analyzing measurement data and communicating significant events so that contingency measures can be adopted when needed. The principle of the Observational Method and the sequence of steps followed in applying it are illustrated in Figure 6-3.

The Observational Method should be used when it has the potential to reduce uncertainties in using the right engineering solution in the right context and in the right way. It should be given a clear role and be an integral part of both design and production, since the final design is established by active adaptation to actual site conditions. The choice of parameters to be observed should be based on a clear analysis of what issues are critical. Measurement data and analysis should be of sufficient quality to permit qualified decisions. Only in this way can observations and measurements contribute to reducing uncertainties in the layout and geotechnical design of tunnels and rock caverns. Design using the Observational Method is therefore normally more demanding than design using other methods /6-16/.

Table 6-2 shows as an example an outline of how the observational method can be applied to rock sealing by grouting.

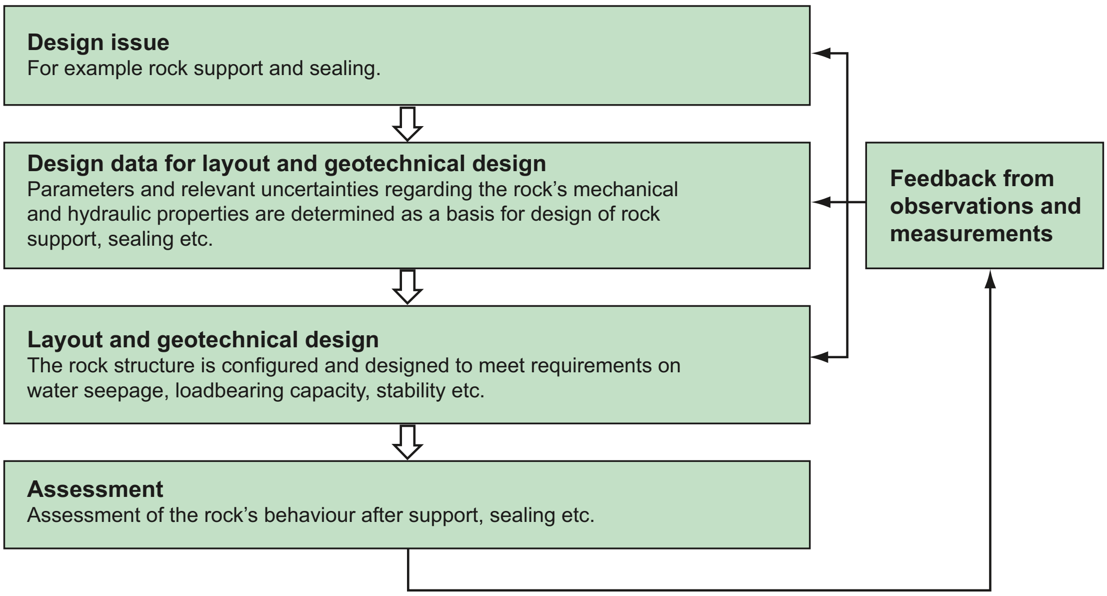


Figure 6-3. *The principle of the Observational Method and the sequence of steps followed in applying it.*

Table 6-2. The Observational Method applied to sealing of rock. The behaviour of the rock is checked against the expected behaviour before, during and after grouting.

When	Prediction to be verified	Requirements	Observation, criteria	Contingent measure when requirement not met
Before grouting	Behaviour of the ungrouted rock	Measurement values should be within stipulated limits for predicted class	Hydraulic data and fracture data from measurements in probe holes	Confirmation or modification of grouting class
During grouting	Penetration of grout into fractures in rock mass	Specifications for pressure, flow and volume	Pressure, flow, volume, backflow	Adjust grouting measures within grouting class
After grouting, before rock excavation	Sealing effect in tunnel to be blasted	Impermeability in grouted zone	Water loss in control hole	New injection round in same screen position
After grouting, after rock excavation	Inflow to blasted tunnel	Inflow to tunnel section	Flow measured in measuring weir	Post-grouting, lining

6.4 Design methodology for other facilities

Conventional design methodology can be used for large parts of the final repository's facilities where conditions are sufficiently well known from the start. This mainly applies to infrastructure and surface buildings as well as technical installations. Conventional design entails that structures are designed and engineered with a gradually increasing level of detail until a complete basis exists for building the facility.

6.5 Main processes and important sub-processes

6.5.1 Main processes

In the ongoing planning for construction and operation of the final repository, the activities have been divided into two main processes:

1. **Construction and operation**. Construction of the repository must always take place in accordance with permits/licences and conditions issued under the Nuclear Activities Act, the Radiation Protection Act and the Environmental Code. This means that construction must conform to the principles adopted in SR-Site or subsequent safety assessments and other requirements and restrictions for the repository's different parts and structures. This requires a clear, traceable and quality-assured work methodology. By continuously cross-checking actual outcome against the assumptions underlying detailed design, construction can be carried out with good control.
2. **Safety assessment and site modelling**. This means that the site description is regularly updated and cross-checked against the premises and assumptions in SR-Site and that the assumptions that have served as a basis for "preliminary operational safety analysis report" are cross-checked against the actual designed and built facility. An updated safety analysis report – concerning both long-term safety and operational safety – is prepared prior to application for a permit for trial operation or if conditions in any phase are judged to deviate from what has been specified in the application.

The two main processes have in turn been divided into a number of sub-processes. Important activities and actors have been clarified for each process. Furthermore, everything needed to implement the process has been identified, along with existing requirements and other constrictions and limitations, the resources needed and the outcome of the process, i.e. the results. So far the planning has focused on construction of underground facilities and the main task during operation: deposition of canisters and backfill.

An overall picture of the two main processes and the relationships between them is shown in Figure 6-4. The two main processes generate a continuous flow of information. Construction-related information is dealt with daily by design and construction. The facility is constantly adapted to the conditions at hand. The site description's models (local, discipline-specific models and detailed models for each tunnel section, part of deposition area, etc) will be updated and cross-checked against the prerequisites in SR-Site at designated times. Based on the up-to-date site description, the results of long-term safety assessment and information and experience from construction, the site engineering report is prepared and updated. This provides the prerequisites for controlled feedback from the main process "safety assessment and site modelling" to the main process "construction and operation". Figure 6-5 illustrates the iterative mode of working as well as important relationships and the information flow between the two main processes.

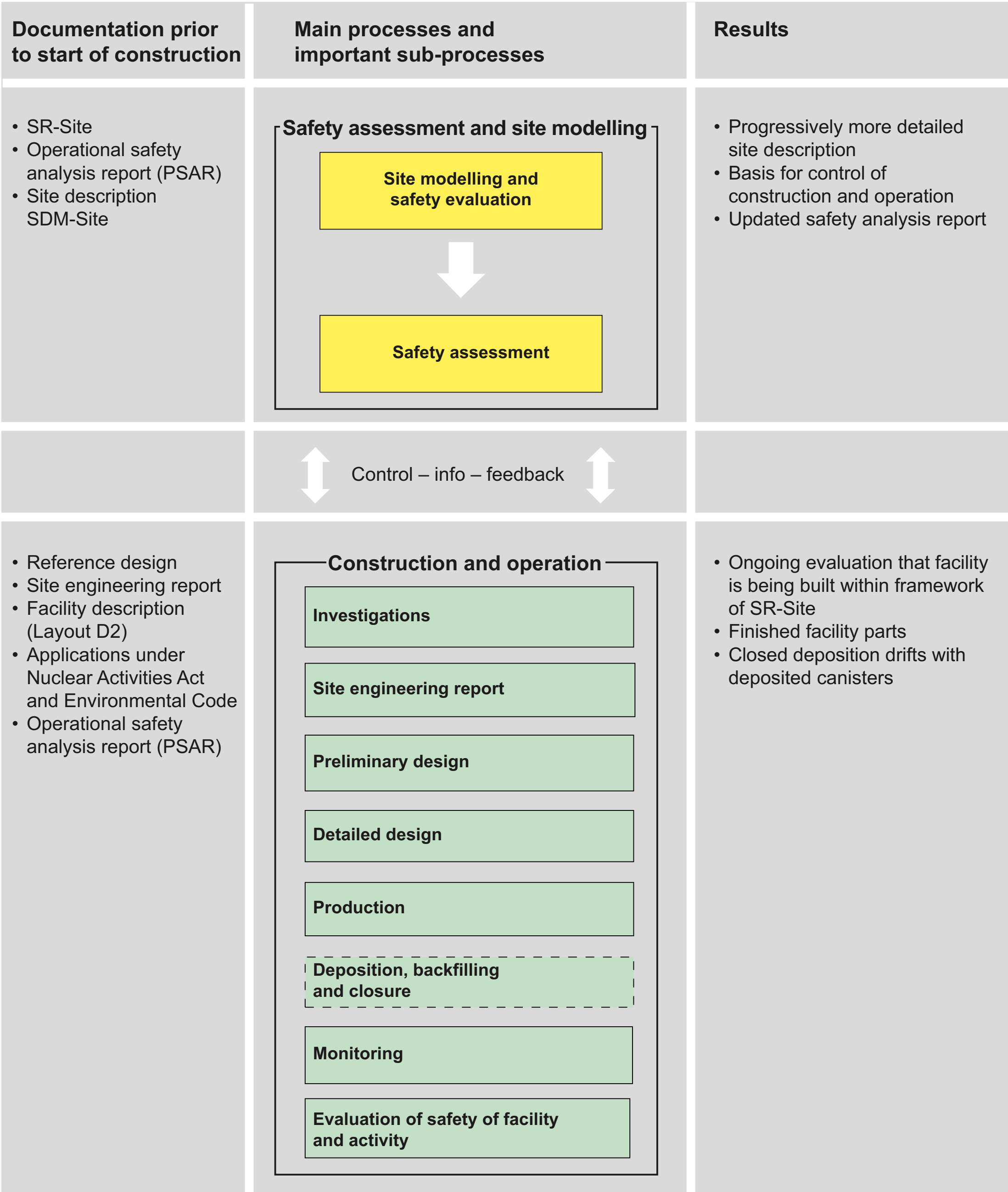


Figure 6-4. *Main processes and important sub-processes during construction and operation. Important relationships exist between the two main processes and their sub-processes. This is illustrated in simplified terms in the figure by the text "control, info, feedback". The dashed line around the sub-process "Deposition, backfilling and closure" illustrates that it is not applicable during the construction phase.*

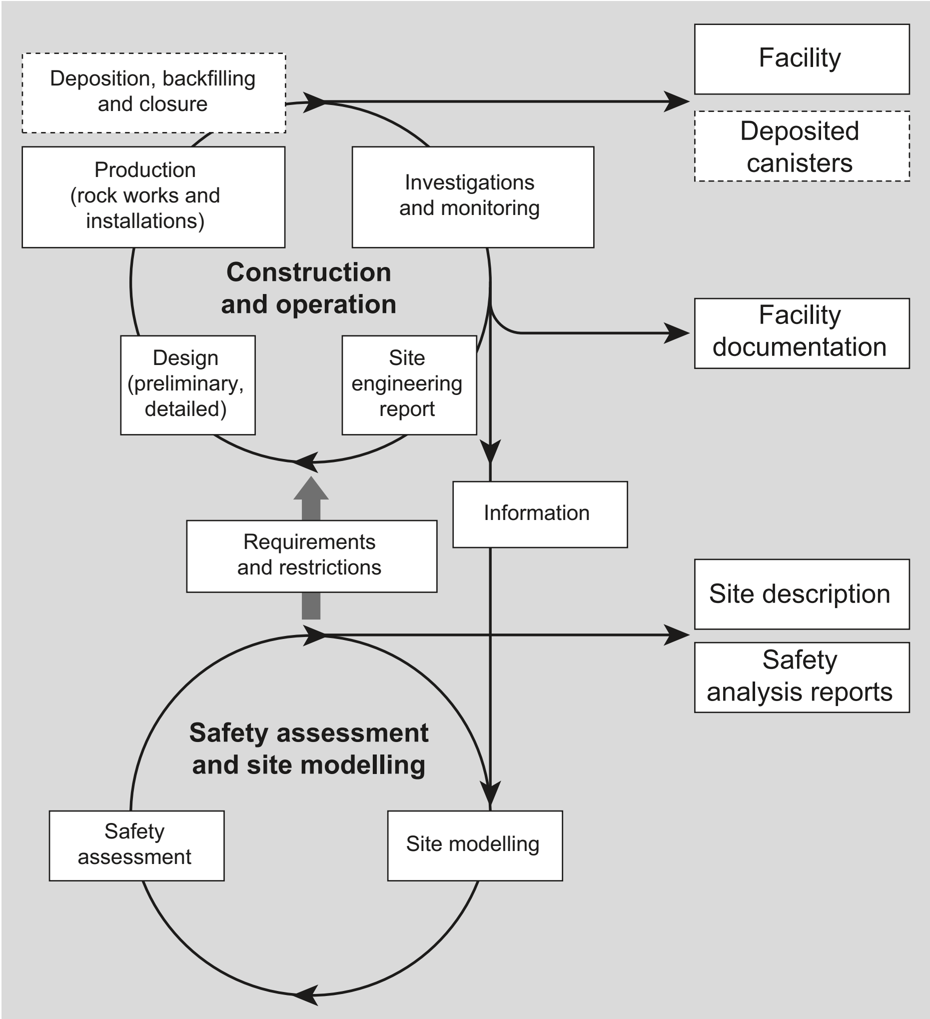


Figure 6-5. *Important relationships and information flow between the two main processes during construction and operation. The dashed line around the sub-process "Deposition, backfilling and closure" illustrates that it is not applicable during the construction phase.*

The main process "construction and operation" includes the following sub-processes during the construction phase, see Figure 6-6:

- Investigations
- Site engineering report
- Preliminary design
- Detailed design
- Production (construction with all included activities)
- Monitoring
- Evaluation of safety of facility and activity

The operating phase also includes the sub-process "deposition, backfilling and closure" with associated activities, see Figure 6-7.

The main process "safety assessment and site modelling", see Figure 6-8, includes the sub-processes:

- Site modelling and safety evaluation
- Safety assessment – long-term safety

Main process "construction and operation" – construction phase

Background documentation	Sub-process	Results
• Up-to-date site description • Conditions in permit/licence decision • Investigation programme • Results from production	**Investigations**	• Investigation results • Basis for updating the site description • Basis for detailed design
• Up-to-date site description • Investigation results	**Site engineering report**	• Site engineering report • Basis for preliminary design
• Up-to-date site engineering report • Up-to-date reference design • Results from production	**Preliminary design**	• Basis for detailed design (layouts, inspection programmes etc.) • Basis for procurement • Basis for assessing the need for new investigations
• Preliminary design • Results from investigations • Results from production	**Detailed design**	• Construction documents • Basis for revision of monitoring programme
• Results from detailed design (construction documents)	**Production**	• Finished facility part • Documentation • Basis for main process to update the safety analysis report
• Up-to-date site description • Conditions in permit/licence decision • Investigation programme • Results from production	**Monitoring**	• Measurement data • Basis for updating the site description • Basis for detailed design
• Results from production	**Evaluation of safety of facility and activity**	**The process is only activated when conditions deviate from given assumptions** Alt. 1: Production can continue after the layout and geotechnical design of the facility have been revised Alt. 2: The layout and geotechnical design of the facility must be assessed in the sub-process "site modelling and safety evaluation"

Figure 6-6. *Main process "construction and operation" – background documentation, sub-processes and results during the construction phase.*

Main process "construction and operation" – operating phase

Background documentation	Sub-process	Results
• Application • Up-to-date site description • Conditions in permit/licence decision • Investigation programme	**Same sub-processes as during construction**	• Finished facility part • Documentation • Basis for main process to update the safety analysis report
• Finished deposition tunnel • Finished canisters with spent nuclear fuel • Safety analysis report • Operating procedures and instructions	**Deposition, backfilling and closure**	• Deposited canisters • Backfilled deposition tunnels • Documentation
• Results from production and operation	**Evaluation of safety of facility and activity**	**The process is only activated when conditions deviate from assumptions** Alt. 1: Production/operation can continue after the layout and geotechnical design of the facility have been revised Alt. 2: The layout and geotechnical design of the facility must be assessed in the sub-process "site modelling and safety evaluation"

Figure 6-7. *Main process "construction and operation" – background documentation, sub-processes and results during the operating phase.*

Main process "safety assessment and site modelling"

Background documentation	Sub-process	Results
• Up-to-date site description • Results from investigations and monitoring • Results from production • Background material and questions from the process "evaluation of safety of facility and activity" in those situations where the conditions deviate from given assumptions and the main process "construction" is unable to handle the question	**Site modelling and safety evaluation**	• Site description with models on detailed scale, tunnel scale, repository scale and regional scale • Basis for investigations • Basis for detailed design • Control of main process "construction and operation" • Basis for safety assessment
• Built and designed facility • Up-to-date site description • RD&D results	**Safety assessment**	• Updated safety analysis report prior to application for trial operation and if the repository deviates from what is established in SR-Site • Control of main process "construction and operation"

Figure 6-8. *Main process "safety assessment and site modelling" – background documentation, sub-processes and results.*

6.5.2 Important sub-processes

Investigations

The sub-process includes all investigations, both those needed daily for construction and those needed to verify and update the site description.

During the different construction and operating phases, the purpose and focus of the investigations will be different for different parts of the repository. The needs of design and construction will constantly be in focus. Investigations that primarily yield information with a bearing on long-term safety will vary with time. In both cases it is important that the investigations be conducted on the site, at the depth and on the scale that provide the best chances of answering the relevant questions.

On a general level the purpose of the investigations during construction and operation is to provide the background documentation that is needed to build the final repository and update the safety analysis report. In somewhat greater detail – and in view of the design premises for the final repository – the main purposes of the investigations are as follows:

- to provide data from investigations under ground to verify the site description from the site investigation phase and update it,
- primarily via updated site descriptions, to provide a basis for renewing and updating the safety assessment,
- to provide whatever other data are needed for the stepwise design and construction of the final repository and documentation of the built facility,
- to provide information for detailed models on different scales as a basis for final positioning of deposition tunnels, deposition holes and other rock openings,
- to provide a basis for judging the consequences (impact on environment and buildings, altered groundwater level and groundwater chemistry etc) of facility construction.

Site engineering report

In the site engineering report, the information in the site description has been analyzed and interpreted to produce descriptions of and parameter values for the stability, hydrology and thermal properties of the rock. Results and experience from rock construction on the site are taken into account in the interpretation and analysis. The site engineering report stipulates and explains any limitations regarding site adaptation with a view towards construction and long-term safety. The site engineering report will be updated based on investigation results, updates of the site description, results from long-term safety assessment and experience from the construction process.

The site engineering report and the current reference design serve as a basis for designing and building each facility part. Ramp and shafts will be built based on the material in the site description and the site engineering report that applies at the time of the application as well as the results of supplementary site engineering investigations. Facility parts that are built later – the central area and above all the deposition areas – will be built based on information from the then up-to-date site description and an updated site engineering report.

Preliminary design

Preliminary design is the first design step during construction and operation. One or more of the facility parts are then designed in accordance with the site engineering report and the reference design. Preliminary design leads to schematic drawings and general technical specifications. The documents shall be so detailed that the ones for ramp, shafts and central area can serve as a basis for procurement of suppliers and for planning the required investigation work in time and space.

Preliminary design includes analyses of how built tunnels and rock caverns behave, in other words the rock's reaction to excavation, support and sealing.

Detailed design

The second design step during construction and operation is detailed design. It is based on preliminary design and the up-to-date site engineering report. Detailed design serves as a basis for production in the form of drawings and technical specifications as well as inspection programmes and plans of action.

The fundamental philosophy for adapting tunnels and rock caverns, with associated support and sealing measures, is that uncertainties should be reduced based on observations of critical design parameters and how the structures behave during construction. By means of inspection programmes and plans of action, production is controlled within the outcome limits defined on the basis of assumptions in safety assessment, reference design, etc. The results of the inspection programme serve as a basis for determining whether the structure behaves as expected, whether measures described in the plan of action need to be adopted, or whether the structure needs to be adapted or modified.

Production

Sealing, rock excavation and support works are carried out during production of the various facility parts, see Figure 6-9. After each operation the quality of execution is checked by means of inspection programmes. The choice of rock or grouting class for the next production cycle is described in drawings or technical specifications. Investigations and measurements performed within the framework of the inspection programme focus on production but also furnish information to safety assessment and site modelling.

Operation

Operation includes all activities that are needed to deposit canisters and close the repository. The activity is described in Chapter 10.

Monitoring

Monitoring provides knowledge on undisturbed conditions in nature and seasonal variations. Monitoring is used to detect changes in relation to previously collected primary comparison data and to distinguish natural changes from those caused by humans. It is thus a means of gaining a better understanding of the site and showing that requirements are met. Another important function is to provide information for decisions to proceed to the next step.

Monitoring was initiated during the site investigations and will continue in both Forsmark and Oskarshamn up to application. It will then continue on the selected site until the start of construction. When construction commences, there will thereby be a known starting situation with time series that describe natural variations on the selected site.

Monitoring will then proceed continuously during the construction and operating phases of the final repository. An important part of the monitoring programme is to accurately record – during construction and operation – all relevant events that can affect a measurement parameter. The scope of the monitoring programme will be regularly adapted on the basis of results and other experience gained from observations made. In order to study natural variations, certain measurements will also be made within a reference area.

Evaluation of safety of facility and activity

For certain situations it is possible that the work methodology that is described in section 6.3 does not provide the background documentation that is needed to continue design and construction. If investigations and measurements show that the rock or a structure does not lie within the outfall limits that have been adopted for the structure and that can be handled with predetermined plans of action, SKB must nevertheless be able to assess and decide what measures are to be adopted. The process “evaluation of safety of facility and activity” has been created for this purpose. The process will have access to competence in safety assessment, site modelling, design and production. In cases where more extensive analyses are required to determine whether the layout and geotechnical design of the facility must be modified, the question will be left to the process “site modelling and safety evaluation”.

Production process		
Background documentation	**Sub-process**	**Results**
• Detailed design including inspection programme	**Sealing**	• Sealed tunnel section
• Inspection programme, sealing • Plan of action, sealing	**Inspection of sealing**	Alt. 1 • Seepage to tunnel section and water loss in probe holes lie within stipulated limits => Approved sealing Alt. 2 • Sealing does not meet stipulated requirements => Reseal. Sealing measures according to inspection programme may need to be adjusted
• Detailed design • Sealed tunnel section • Drilling plan • Charging and detonating plan	**Rock excavation**	• Blasted and mucked tunnel section
• Inspection programme, rock excavation (stability, geometry, vibration, EDZ etc.) • Plan of action, rock excavation, verification	**Inspection of rock excavation**	Alt. 1 • Tunnel section lies within stipulated limits Alt. 2 • Tunnel section does not meet stipulated requirements => adopt necessary measures
• Detailed design including inspection programme	**Rock support**	• Supported tunnel section
• Inspection programme, rock support (load, stability etc.) • Plan of action, rock support	**Inspection of rock support**	Alt. 1 • Finished tunnel section • Facility documentation Alt. 2 Rock support does not meet stipulated requirements => implement measures according to inspection programme. Sealing measures according to inspection programme may need to be adjusted

Figure 6-9. *Production process broken down into sub-processes.*

Site modelling and safety evaluation

Site modelling includes analysis and evaluation of both the information that is continuously produced during construction and operation of the repository and the information that is obtained by targeted investigations in, for example, cored boreholes. The work is based on the site description that is prepared after concluded site investigations (SDM-Site) and that will serve as a basis for SR-Site.

If the actual conditions deviate at any time during construction from the applicable design premises – and the situation cannot be handled in the main process "construction and operation" – the assessment is made within the sub-process "site modelling and safety evaluation".

Safety assessment – long-term safety

The permit to build and licence to operate the repository is based on SR-Site, among other things. An updated safety analysis report is required in support of the application for trial operation. As long as the prerequisites in SR-Site are still satisfied, SKB will not prepare an updated safety analysis report for the interim period. Ongoing follow-up and inspection take place within the process "evaluation of safety of facility and activity", see above.

Continued development of the safety assessment, including methods and models used in the assessment, will proceed during virtually the entire time the repository is being built and operated. This development is based on the results of the ongoing RD&D programme and on the experience provided by construction and operation of the repository.

6.6 Quality control

High demands will be made on control of the activities during construction and operation of the final repository. The information flow between all processes – design, construction, investigations, modelling and safety assessment – must take place according to established procedures and in conformance with strict requirements on documentation and quality assurance. Furthermore, the mode of working must be adapted to the special conditions that apply to the design and construction of underground facilities.

The mode of working which is planned to be used by SKB for construction of the final repository, and is described above, is aimed at meeting these requirements. To this end SKB will need a carefully planned organization with a clearly designated division of responsibilities and an efficient and user-friendly management system. The organization and the management system will be designed to meet the requirements that apply to construction and operation of nuclear facilities. The requirements will be particularly tough when trial operation starts and rock construction proceeds in parallel with the deposition of spent nuclear fuel canisters.

SKB has a management system today that is certified to the quality and environmental management standards ISO 9001 and ISO 14001. SKB took over the operation of Clab on 1 January 2007. At that time a new management system was introduced with procedures that are required to operate nuclear activities, in other words a management system that lives up to all relevant requirements in SSI's and SKI's regulations.

Today's management system will constitute an important base for the organization and the management system that SKB needs to build the final repository, as well as other facilities within the nuclear fuel and LILW programmes. In an appendix to the application under the Nuclear Activities Act for Clab and the encapsulation plant, SKB gave an account of how the company intends to comply with the safety requirements /6-2/ when it comes to organization, management and control during construction and commissioning of the encapsulation plant. Construction and commissioning will take place in parallel with the ongoing operation of Clab. An equivalent account will be provided in the application under the Nuclear Activities Act for the final repository.

SKB's management system contains functions and procedures for further development of the management system. Within the framework of this improvement work, the efficacy and efficiency of the management system will be regularly evaluated. New and changed internal requirements and regulatory requirements, as well as experience from both internal and external organizations, will be continuously evaluated. The results of the evaluations may result in changes in the organization and the management system.

6.7 Safeguards for the final repository

By safeguards is meant measures to prevent nuclear material from falling into the wrong hands. Requirements on measures related to safeguards are found in SKI's regulations concerning safety in nuclear facilities /6-1/ and SKI's regulations on the physical protection of nuclear facilities /6-17/.

Through the IAEA, SKB is participating in international efforts to define the requirements for the safeguards system for a geological repository. Furthermore, SKB is cooperating with Posiva with regard to safeguards for encapsulation and final disposal and is following the development of the Onkalo facility.

A well-functioning safeguards system adopts a holistic view of the entire fuel handling chain, from fuel factory up to and including final disposal of the spent nuclear fuel.

The principle for safeguards at the final repository is continuity of knowledge, Cok. The filled canister can be provided with a seal at the encapsulation plant, and by verifying that the seal is unbroken at deposition assurance can be obtained that the canister with contents has arrived at the final repository in unaltered condition.

In conjunction with the design and construction of the final repository, concerned authorities and SKB will determine places for key measurement points for the safeguards system so that continuity of knowledge is assured and the regulatory authorities' monitoring requirements can be satisfied.

From a safeguards viewpoint it is important to be able to verify that the final repository has been built in accordance with the drawings that have been presented so that there are ways out of the facility that have not been described or areas where other activities occur than those described. This can be done in a similar manner as is now being done in connection with the construction of the Finnish final repository Onkalo, for example by measurements of the underground openings and determination of the quantity of excavated rock. Regulatory authorities can then carry out inspections on regular occasions before and during construction, operation and closure of the final repository to verify the information.

The canister comprises an accounting unit in the system. Each canister has a unique designation which is recorded and its contents documented. The movement of canisters is documented in the safeguards accounts. The canister's unique designation is documented and the seal is checked to make sure it is unbroken when the canister is lifted up out of the transport cask in the deep repository and deposited.

A possible retrieval of deposited canisters also imposes demands on the safeguards system. It is vital to be able to establish unambiguously the identify of the canisters retrieved. This means that the marking of the canisters must be durable in the long-term perspective. The same applies to the information on the canister's contents. Otherwise, the same principles can be applied to retrieval as to the various steps in deposition of the canisters.

7 Main phase: Licensing

Licensing of the final repository, the encapsulation plant and Clab will be an extensive process, since the activity to be reviewed is complex, unique and extensive. The licensing process began in the autumn of 2006 when SKB submitted an application under the Nuclear Activities Act for the encapsulation plant and Clab.

In order to establish and operate the activity at the final repository – as well as the one at the encapsulation plant and Clab – permits/licences are required under both the Nuclear Activities Act and the Environmental Code. Furthermore, the activity must comply with the municipality's detailed development plan and area regulations, and must have been granted building and site improvement permits. Figure 7-1 illustrates the licensing process for the final repository, Clab and the encapsulation plant.

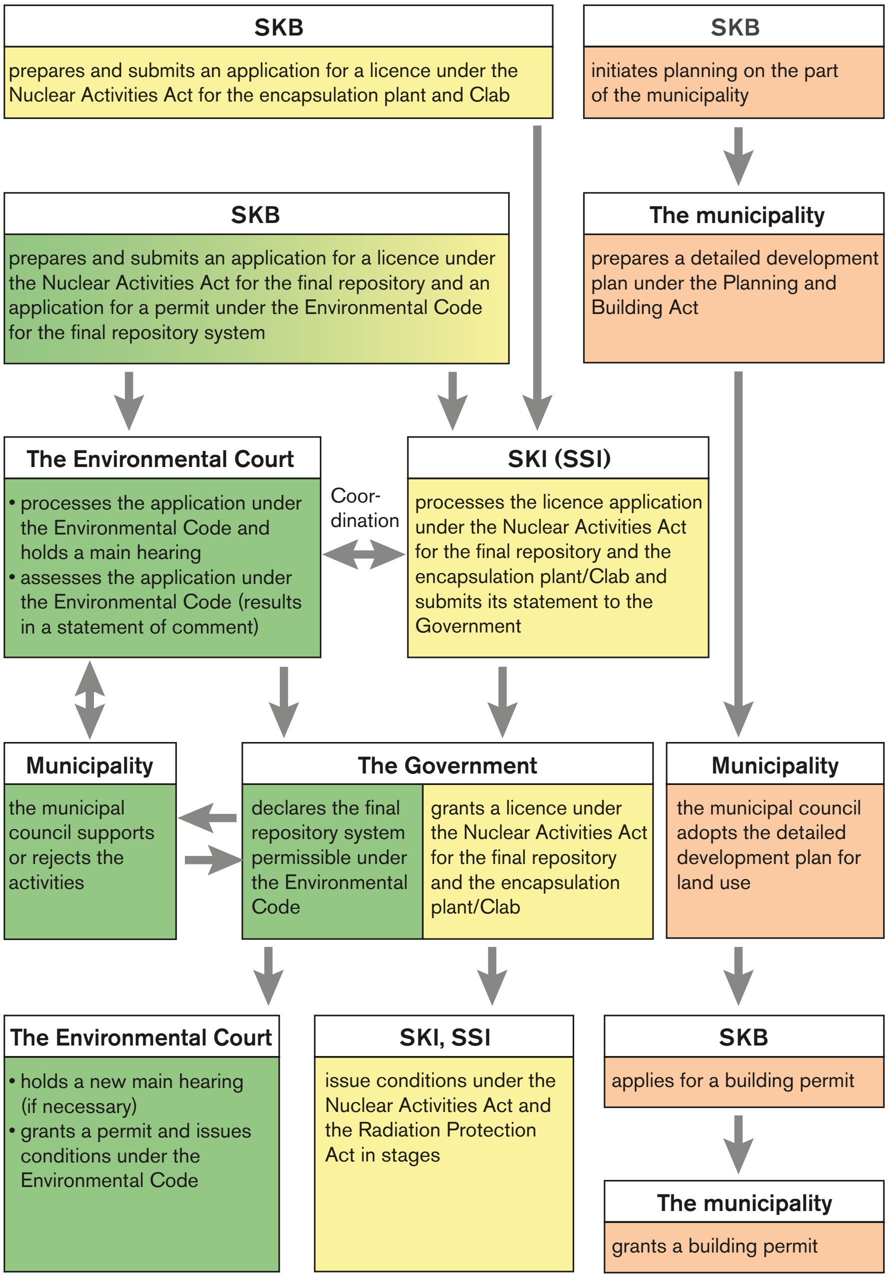


Figure 7-1. The licensing process for the final repository, the encapsulation plant and Clab.

An application for a licence under the Nuclear Activities Act is submitted to the Government after being processed by SKI. When SKI has received an application for the final repository, they begin their review of the application. SKI may send the material on a supplementary round to other regulatory authorities who serve as reviewing bodies in the licensing process. Then SKI can request supplementary material from SKB. When SKI judges that the material is complete, they circulate it for review and comment, after which SKB is given an opportunity to respond to the comments of the reviewing bodies. Then SKI turns the matter over to the Government with its own comments.

An application for a permit under the Environmental Code is submitted to the Government and processed by the Environmental Court. The Environmental Court may also send the material on a supplementary round before the application is referred to regulatory authorities and concerned parties for review and comment. SKB is given an opportunity to respond to comments received. The Environmental Court holds a main hearing, after which the Environmental Court turns the matter over to the Government with its comments.

Formally the Government is supposed to decide on:

- a licence under the Nuclear Activities Act for the encapsulation plant and Clab,
- a licence under the Nuclear Activities Act for the final repository, and
- whether the applied-for activity is permissible under the Environmental Code.

An important basic principle in the Government's permissibility assessment under Chapter 17 of the Environmental Code is that the Government may only permit an activity if the municipal council in the concerned municipality has supported the activity.

According to the travaux preparatoires to the Environmental Code, licensing under the Nuclear Activities Act and permissibility assessment under the Environmental Code should be coordinated so that both the Environmental Court and the concerned municipality have access to SKI's and SSI's statements of comment in the case concerning a licence under the Nuclear Activities Act before they take a stand and issue their statements of comment on the question of permissibility under the Environmental Code. The Government's decisions under the two laws should also be coordinated /7-1, p. 271/. How this will be done in practice is a question which SKB will discuss in greater detail with the concerned bodies. Questions pertaining to coordination and delimitation between the Environmental Code, the Nuclear Activities Act and the Radiation Protection Act have so far only been considered in a few matters.

If the Government grants a licence under the Nuclear Activities Act and permissibility under the Environmental Code, the matters will be referred back to SKI and the Environmental Court, respectively. The Environmental Court determines what conditions are to apply to the activity under the Environmental Code. This can be done in a final judgement or in a separate judgement. The latter applies if the court finds that certain questions relating to the conditions for the activity must be investigated during a probationary period. When the applicant has then submitted supplementary material, the final conditions are established in a final judgement. When it comes to licensing under the Nuclear Activities Act, the Government, SKI and SSI may issue conditions or regulations governing the activity.

In order for a licence to be issued for the activity, it must be compatible with the current detailed development plan or area regulations. This is also a prerequisite for a building permit to be granted by the municipality. Matters concerning development plans and site improvement and building permits will be dealt with in parallel with processing and licensing under the Nuclear Activities Act and the Environmental Code by regulatory authorities, the Environmental Court and the Government.

7.1 Milestones

Important milestones during this phase are:

- The municipal council decides to support the activity.
- The Government rules on permissibility under the Environmental Code and a licence under the Nuclear Activities Act.
- The municipality adopts a detailed development plan.

- The Environmental Court grants a permit and issues conditions under the Environmental Code.
- SKI issues conditions under the Nuclear Activities Act.
- SSI issues conditions under the Radiation Protection Act.
- SKB submits an application for a building permit.
- The municipality grants a building permit.

7.2 Activity

When the applications for the final repository under the Nuclear Activities Act and for the final repository, the encapsulation plant and Clab under the Environmental Code have been submitted, SKB will participate in the licensing process and prepare for the task of building the final repository. Participating in the licensing process entails answering SKI's, the Environmental Court's, the reviewing bodies and the public's questions, providing any supplementary material requested by the regulatory authorities and participating in the main hearing in the Environmental Court.

The fact that licensing proceeds at the same time SKB plans, organizes and designs the facilities and activities in the final repository system entails limitations and uncertainties. An obvious limitation is that SKB cannot commence activities that anticipate outcomes and conditions in future permit/licence decisions. The duration of the licensing process and its outcome once the application has been submitted is an uncertainty we must accept. However, by responding rapidly to requests for supplementary material etc, SKB can keep the process from being prolonged unnecessarily.

In order to be able to make efficient and effective preparations for building the repository, we are to do planning preparatory work on the site. SKB may need to apply for and obtain the requisite permits (excavation permit, site improvement permit, building permit, permit to build roads etc) for these preparations before the activity can commence.

The construction of the final repository will impose different demands than today's on SKB's organization and activities, see Chapter 6. An example is the flow of information between work on environmental and licensing matters, investigations, modelling, design, construction and safety assessment. A central task will therefore be to build up an organization for the construction phase by recruitment and training.

Design of the final repository will continue. Construction documents for the facility parts to be built first will be finished and procurement of contractors and other suppliers will be prepared. This applies to the accesses to the repository area.

Monitoring of groundwater in boreholes and other monitoring will continue on the same scale as during the final phase of the site investigations. A task early during this phase will be to carry out supplementary site engineering investigations in support of the detailed design of shafts and ramp.

7.3 Technology need

After the applications have been submitted, the results of the safety assessment SR-Site can serve as a basis for updating the requirements on technology. Technology development therefore enters a new phase aimed at developing machinery and processes that meet the revised requirements. Another important task will be to prepare the inspection programmes that are needed to verify that the requirements are met during construction and operation.

The phase is concluded when SKB has obtained all permits needed for the start of construction. The technology for building the accesses to the repository – skip shaft and ramp – must then be chosen and well prepared. These facility parts are time-critical during the construction phase, and their excavation will therefore be started as soon as possible. The timetable presumes that the skip shaft is excavated using shaft sinking technique.

Tables 7-1 through 7-4 summarize the planned status that will be achieved during licensing for technology to be used in construction and operation. This is equivalent to the status prior to the start of construction. The format for the tables is the same as in section 5.3.

Table 7-1. Technology for rock engineering – planned status prior to permit/start of construction.

Technology	Planned status prior to permit/start of construction	Reference to section in Part III
Investigations		
The goal of SKB's efforts in the area is to have developed and tested instruments and methods for investigations from shafts and ramp well in time before the start of construction.		
Investigations in boreholes	Instruments and methods that are needed for investigations from ramp and shafts are ready to be put into use.	12.3
	Adaptation and development is under way for instruments and methods that are needed for investigations during construction at repository level.	12.3
Investigations in tunnels and deposition holes	A well functioning system for laser scanning with simple transfer of data to SKB's modelling system has been tested and is ready to be put to use.	12.3.2
	Efficient methods for determining the state of stress in the rock during tunnelling have been chosen and are ready to be put to use.	12.3.4
	An improved method for measurement of water flows in ramp and tunnels has been tested and is ready to be put to use.	12.3.7
	Development of methodology and methods for measurement of inflow to deposition tunnels and deposition holes is under way.	12.3.7, 12.3.8
Information systems and information technology	Information systems that are needed prior to the start of construction are tested and ready to be put into operation.	12.3.11
Rock excavation		
The goal of SKB's efforts in the area is to have demonstrated (in the Äspö HRL) and chosen methods for rock excavation in accesses and central area by the start of construction. Reference method for rock excavation in deposition tunnels chosen. Methods for characterization of excavation-disturbed zone (EDZ) chosen.		
Technology for drill-and-blast	Running-in of personnel and machinery for controlled tunnelling under way.	11.1, 12.5
Excavation-disturbed zone	Method and technology for characterization of excavation-disturbed zone chosen and tested.	12.5
Boring of deposition holes	Prototype of equipment for boring manufactured. Running-in of personnel and machine prepared.	11.1, 12.7
Rock support		
The goal of SKB's efforts in the area is to have tested chosen materials with low pH at the Äspö HRL and to have begun long-term testing.		
Materials for rock support	Rock support (shotcrete, wire mesh and rock bolts) with material that complies with the requirements on low pH demonstrated. The test areas are monitored and changes in the material are recorded.	12.6
Shotcrete	Equipment for low-pH grout tested.	12.6
Sealing technology		
The goal of SKB's efforts in the area is to have chosen and demonstrated sealing technology, including material, for the conditions expected on the site in question.		
Technology and material for sealing of water-conducting fractures and zones	Knowledge and experience of grouting, from Onkalo among other places, has been compiled. Some additional grouting materials (in addition to silica sol) chosen, tested and evaluated from a grouting viewpoint.	11.1, 12.4
Technology and material for sealing of large zones with heavy water flow	Sealing technology for zones/properties expected on the site in question chosen.	11.1, 12.4

Table 7-2. Technology for buffer – planned status prior to permit/start of construction.

Technology	Planned status prior to permit/start of construction	Reference to section in Part III
Production and handling above ground		
The goal of SKB's efforts in the area is that the facilities and equipment that are needed for production and handling at the final repository should be designed in detail.		
Handling chain from mining to final repository	Preliminary design finished. Known and commercially available technology.	–
Treatment and interim storage – raw material	Preliminary design finished. Known and commercially available technology.	–
Compaction – blocks, rings and pellets	Production plant designed in detail and erection prepared.	11.2, 13.3
Interim storage – blocks, rings and pellets	Warehouse and equipment designed in detail and ready to be built/manufactured.	13.4
Handling and application – deposition holes		
Fitting-out	Testing under way.	13.5
Installation – blocks and rings	Possible continued verification that the reference method meets the design requirements. Prototype of gripping tool tested and prototype machine for buffer emplacement under construction.	13.6 11.2
Closure – temporary buffer protection	Possible heating tests under way.	13.5
Installation – pellets/granules	Tests of reference method and equipment under way.	13.7

Table 7-3. Technology for canister handling and deposition at the final repository – planned status prior to permit/start of construction.

Technology	Planned status prior to permit/start of construction	Reference to section in Part III
The goal of SKB's efforts in the area is to have tested the entire handling chain, from transfer of the canister from the transport cask to the deposition machine's radiation shielding tube and deposition of the canister in a deposition hole with buffer, well in time before the construction of the deposition area.		
Handling of transport casks above ground and descent on ramp	Detailed engineering and preparations for manufacture of equipment for terminal building and vehicle for ramp transport under way.	14.8
Transloading station and equipment for moving canisters from transport casks to deposition machine.	Simplified transloading station built at Äspö HRL and important components tested.	14.8
Deposition machine and other equipment for installing buffer and depositing canisters	New machine and other equipment manufactured in prototype version. Tests with this equipment are carried out at the Äspö HRL, as a basis for final design.	11.3, 14.8

Table 7-4. Technology for backfilling – planned status prior to permit/start of construction.

Technology	Planned status prior to permit/start of construction	Reference to section in Part III
Production and handling above ground		
Handling chain from mining to final repository	Preliminary design finished. Known and commercially available technology.	–
Treatment and interim storage – raw material	Preliminary design finished. Known and commercially available technology.	–
Compaction – block for upper part of deposition hole	Production plant designed in detail and erection prepared.	15.3
Compaction – blocks for deposition tunnel	Production plant designed in detail and erection prepared.	15.3
Interim storage – blocks, pellets/granules	Storage facility and equipment designed in detail and ready to be built/manufactured.	15.4
Handling and application – deposition tunnel		
Removal of drainage and temporary buffer protection	Possible long-term test of consequences of stray material under way.	15.5
Backfilling – upper part of deposition hole	Possible further verification that the reference method satisfies the design requirements.	15.6
Backfilling – blocks in tunnel	Possible further verification that the reference method satisfies the design requirements. Possible new prototype installation carried out.	11.4, 15.6
Backfilling – pellets/granules in tunnel	Carried out in possible new prototype installation	15.7
Closure – temporary plug in tunnel	Closure according to reference built in Äspö HRL.	11.4, 15.8

8 Main phase: Construction

When SKB has obtained the necessary permits, procured the first contracts and completed other preparations for start of construction, the construction phase can begin. The phase has a duration of between six and seven years and is dominated by extensive rock excavations. Approximately 0.5–0.7 million cubic metres of rock spoil (solid measure) will be hauled out via the accesses to the facility. At the same time, mapping and investigations will be conducted to acquire more detailed knowledge of the site.

8.1 Milestones

Important milestones during this phase are:

- Establishment and start of construction.
- Skip shaft finished.
- Start excavations at repository level.
- Ramp finished.
- Central area finished.
- Production building finished.
- Updated safety analysis report.
- Facilities and installations (including deposition positions) for integrated testing finished.
- Surface facilities finished.

8.2 Activity

8.2.1 Investigations

The scope and focus of the investigations is dependent on what uncertainties remain after the site investigation phase. The investigation programme is therefore site-specific and cannot be drawn up in detail until modelling, design and safety assessment (SR-Site) – based on data from the site investigations – have been completed.

The investigations that may be required can be roughly divided into the following categories:

1. Investigations (tunnel mapping, probe drilling etc) that are directly related to the advance of the rock works. Such investigations are performed continuously.
2. Investigations that are related to detailed design of a tunnel or another facility part. Such investigations (for example long cored boreholes drilled within the tunnel periphery) are performed solely to answer specific questions, for example to verify the feasibility of tunnelling (passage of water-conducting zone, high rock stresses, etc).
3. Investigations for safety assessment and site modelling. Such investigations will be performed for various reasons, for example to address key issues formulated before the start of construction or answer questions identified in the main process "safety assessment and site modelling" or in design.
4. Investigations related to the deposition process. These investigations are aimed at providing a basis for detailed design of deposition tunnels and setting out of deposition positions. Detailed mapping of deposition tunnels and deposition holes is aimed at both verifying that the tunnels and holes meet stipulated requirements and documenting them.
5. Monitoring is performed to document how construction and operation of the final repository affects the area's ecosystems, soil and bedrock. Monitoring is performed continuously and also supplies important information to the hydrogeological and hydrochemical models.

8.2.2 Monitoring

Monitoring during the construction phase focuses on understanding how hydrogeological, hydrogeochemical and rock mechanical factors affect the long-term performance of the repository, but also include documentation of the disturbances caused by the construction of the repository and assessment of environmental impact. Temperature, microseismic events, groundwater pressure etc can be monitored during the operating phase, along with resaturation and pressure build-up in the backfill.

8.2.3 Design

Preliminary design and detailed design are carried out for facility parts in accordance with the description in sections 6.2 through 6.5. The facility parts will be in different phases, which means their design will be more or less detailed, see Figure 8-1. The Observational Method is applied for those facility parts and design issues where uncertainties remain, see section 6.2. It will not be known exactly which facility parts and issues this applies to until Layout D2 and SR-Site are finished.

8.2.4 Site modelling, safety evaluation and safety assessment

Site modelling and safety evaluation, as well as assessment of long-term safety, will be carried out more or less continuously. The safety analysis report will be updated prior to the application for trial operation. By continuously updating models (local, discipline-specific models and detailed models for tunnel section, part of deposition area etc), SKB will always have a basis for determining whether the prerequisites in SR-Site are still satisfied. If information from the construction process shows that this is not the case, the construction plans may need to be adjusted. The safety analysis report may then also have to be updated. For other cases, issues with a bearing on long-term safety will be handled within the process "evaluation of safety of facility and activity", see section 6.5.

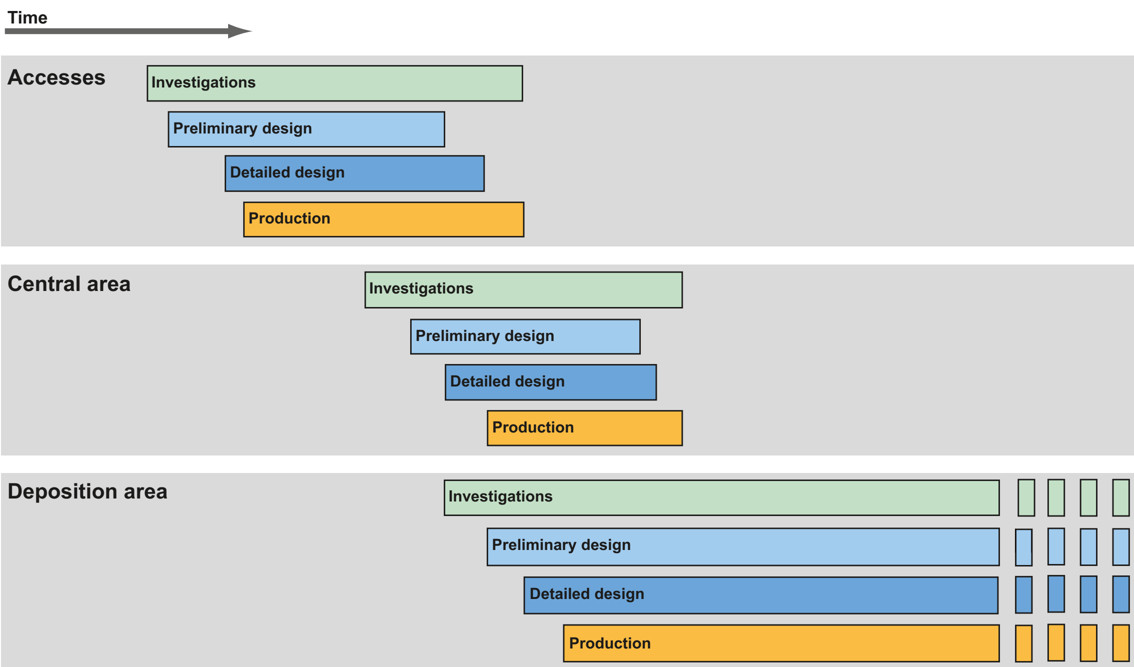


Figure 8-1. *During the construction phase, the different facility parts will be in different phases of design and build. The figure shows as examples accesses, central area and deposition area.*

8.2.5 Rock engineering

During the first part of the construction phase, rock excavation works are mainly carried out by contractors. The accesses to repository level are time-critical. The construction of these accesses therefore starts as soon as the preparations on the construction site are completed. Figure 8-2 shows estimated progress after about three years.

When the shaft has reached repository depth and the rock haulage station is finished, rock excavation on the repository level will begin. Based on the information that has been obtained during the construction of the ramp and the shafts, the layout of the central area may have to be adjusted in relation to Layout D2. During the latter part of the construction phase – after the location of the first deposition area has been determined – rock in the deposition area is extracted via the transport tunnels that connect to the central area. The technology for driving deposition tunnels and boring deposition holes, including verification of criteria for them, will be tested and fine-tuned as soon as possible. As far as is possible, this will be done in the Äspö HRL. A running-in phase will nevertheless be needed, where the technology is adapted to the conditions prevailing on the selected site.

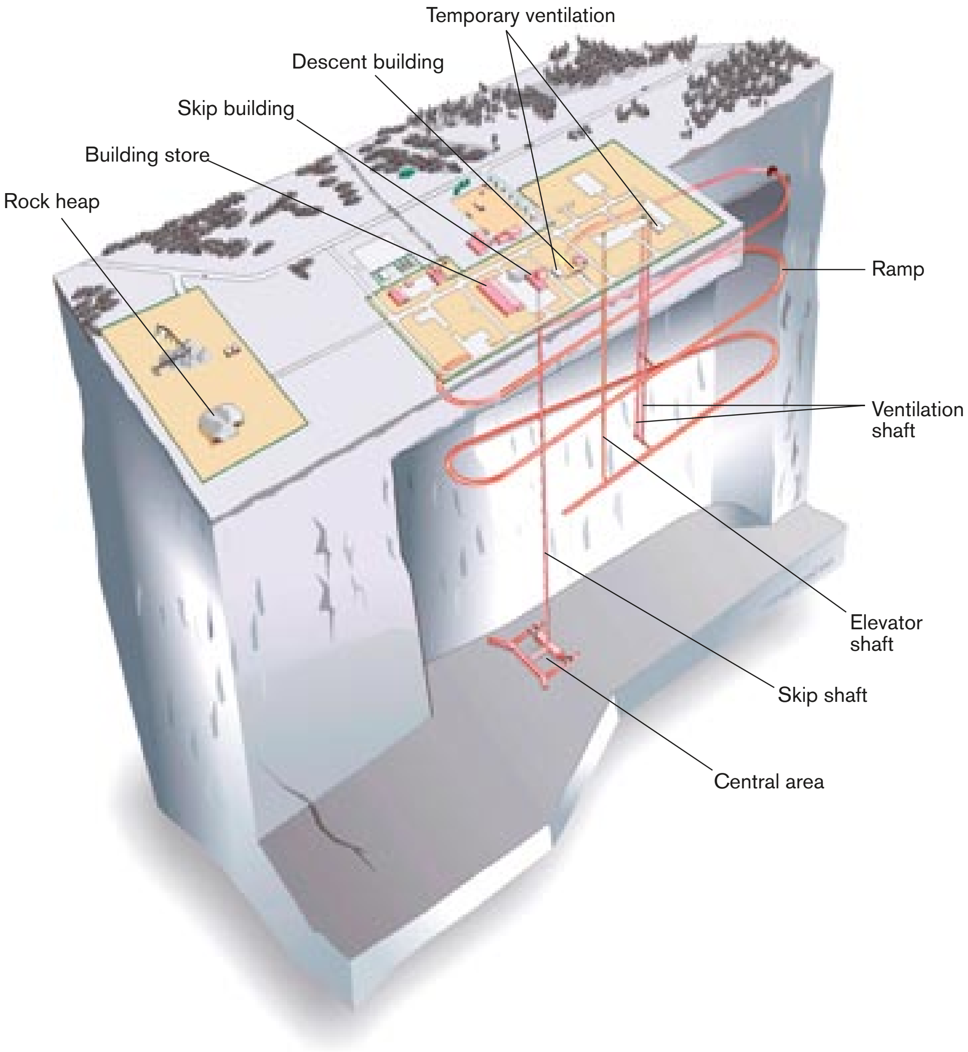


***Figure 8-2.** Construction of skip shaft, ramp, elevator and ventilation shaft and part of surface facility. If the skip shaft for rock spoil is excavated by shaft sinking technique, it will provide the first access to repository level.*

8.2.6 Technical installations

Technical installations include ventilation, water supply and sewerage, elevators, electric power, fire protection and so on. Based on a system function programme, mainly traditional design methodology will be applied. As the underground parts are finished, temporary installations for water supply, sewerage and ventilation will be replaced with more permanent installations.

8.2.7 The surface part

The first activities on the site involve preparations for rock excavation and establishment of infrastructure to and within the operations area. The preparations include establishing the construction site including temporary arrangements, site protection, roads, a possible sewage treatment plant and rock spoil heaps. Moreover, the surface part needs to be fenced in and power and water supplies arranged. The surface buildings are erected as they are needed with a view to their function and purpose. When the central area have been completely excavated, most of the buildings on the surface will also have been erected. The same applies to facilities and infrastructure for reception, storage and transport of bentonite etc.

8.3 Technology need

The construction phase extends over a long period. Different technical systems will be taken into service as construction of the repository progresses, and the subsystems will be commissioned towards the end of the phase. The planned development status for the important subsystems at the start of construction is summarized in Tables 7-1 through 7-4. The technology for building the accesses (sunk shaft and ramp) is then put into use. Construction of the ramp and shafts will furnish data and experience on driving technology, rock support and sealing that is of importance for adapting the technology to the rock works that will later be carried out at repository level.

At the same time as the accesses are built, parts of the surface facility, including the production building for manufacturing buffer and backfill, are also built. Materials and methods for this manufacture must therefore be chosen at an early stage.

The next milestone, with respect to technology need, occurs when there is access to the repository level. First the central area and nearby transport tunnels are excavated. The construction technology is largely the same as for the ramp, but there are some differences. The central area's rock caverns, with their large dimensions, require larger-scale technology for rock excavation etc. When the first deposition tunnels are driven and deposition holes are bored, technology and equipment for this are introduced, along with site-adapted investigation methods and acceptance criteria for deposition positions.

Access to the repository level can thus be seen as an important checkpoint for the development and implementation of a large part of the technology that will be used in the final repository. Tables 8-1 through 8-4 summarize the planned status of important methods and subsystems at the point when the particular method or subsystem can be introduced at the repository level. The tables have the same structure as equivalent tables in Chapter 5 and Chapter 7.

Table 8-1. Technology for rock engineering – planned status when there is access for rock works at repository level.

Technology	Planned status – start of construction at repository level	Reference to section in Part III
Investigations		
The goal of SKB's efforts in the area is that methodology, methods and instruments for investigations of deposition areas and deposition positions are ready to be put into use. This includes methodology and methods for verifying acceptance criteria for the deposition positions.		12.3
Rock excavation, support, sealing		
The goal of SKB's efforts in the area is to have run-in at the Äspö HRL technology for rock excavation, support and sealing for all facility parts at repository level (central area, transport tunnels, deposition holes). The technology should further have been adapted to experience from ramp and shaft driving and information from investigations at repository level.		12.5–12.7

Table 8-2. Technology for buffer – planned status when there is access at repository level.

Technology	Planned status – access to deposition tunnel	Reference to section in Part III
Production and handling above ground		
Handling chain from mining to final repository	Agreements signed with contractors. Programme is developed for inspection of material qualities.	–
	Construction of facilities and infrastructure for reception, transport and storage of material for buffer finished.	–
Treatment and interim storage – raw material	Production plant under completion.	–
Compaction – blocks, rings and pellets	Production plant under completion.	13.3
Interim storage – blocks, rings and pellets	Warehouse and equipment under construction/manufacture.	13.4
Handling and application – deposition holes		
Fitting-out	Technology tested and under running-in.	13.5
Installation – blocks and rings	Technology tested and under running-in.	13.6
Closure – temporary buffer protection	Technology tested and under running-in.	13.5
Installation – pellets/granules	Technology tested and under running-in.	13.7

Table 8-3. Technology for canister handling and deposition at the final repository – planned status when there is access at repository level.

Technology	Planned status on access to deposition tunnel	Reference to section in Part III
The goal of SKB's efforts in the area is that the technology for canister transport, transloading and deposition should be tested and run-in as far as possible when it is transferred from the Äspö HRL to the final repository.		
Handling of transport casks above ground and descent on ramp	Transport vehicle and other equipment built, tested and under running-in.	14.8
Transloading station and equipment for moving canisters from transport casks to deposition machine.	Detailed design finished, preparatory work under way.	14.8
Deposition machine and other equipment for installing buffer and depositing canisters	Machine and other equipment built, tested and under running-in.	13.6, 14.8

Table 8-4. Technology for backfilling – planned status when there is access at repository level.

Technology	Planned status – access to deposition tunnel	Reference to section in Part III
Production and handling above ground		
Handling chain from mining to final repository	Agreements signed with contractors. Programme is developed for inspection of material qualities.	–
	Construction of facilities and infrastructure for reception, transport and storage of material for backfilling finished.	–
Treatment and interim storage – raw material	Production plant under completion.	–
Compaction – block for upper part of deposition hole	Production plant under completion.	15.3
Interim storage – blocks, pellets/granules	Storage facility and equipment under construction/manufacture.	15.4
Handling and application – deposition tunnel		
Removal of drainage and temporary buffer protection	Technology tested and under running-in.	15.5
Backfilling – upper part of deposition hole	Technology tested and under running-in.	15.6
Backfilling – blocks in tunnel	Equipment under manufacture. Running-in of technology begun. Possible prototype installation under water saturation.	15.6
Backfilling – pellets/granules in tunnel	Equipment under manufacture. Running-in of technology begun.	15.7
Closure – temporary plug in tunnel	Detailed design completed, based on experience of closure built at the Äspö HRL.	15.8

9 Main phase: Commissioning

Commissioning of the final repository begins when the construction work at repository level has come so far that this is possible. Furthermore, the necessary machines, handling equipment and parts of the surface facilities are in place.

9.1 Milestones

Important milestones during this phase are:

- Start integrated testing.
- Updated safety analysis report.
- Application for trial operation submitted.

9.2 Activity

Commissioning of the final repository entails that the activity transitions from primarily comprising design and construction to primarily focusing on the deposition process, in other words deposition of canisters and progressive construction. Commissioning is concluded with the issuance of a permit to SKB for trial operation, which marks the transition to the next phase.

Commissioning entails that all technical systems are taken into operation and tested, first one by one and then together, for the purpose of running in the systems with each other. Running-in is concluded with integrated testing of the final repository, followed by integrated testing of the entire nuclear fuel system, i.e. the encapsulation plant, the transportation system and the final repository.

A part of the integrated testing for the final repository is depositing a number of canisters without nuclear fuel. Integrated testing includes all steps of the deposition cycle, i.e. rock excavation, installation of buffer and canister and backfilling. Experience from integrated testing serves as a basis for updating of the operational safety analysis report. An application for a licence to take the facility into operation is submitted to the regulatory authorities towards the end of the commissioning phase.

Tests, trials and demonstration of machines and technology and training of personnel for deposition are carried out as far as possible at the Äspö HRL. Some adaptation of the technology to the on-site conditions at the final repository will nevertheless be necessary. This may involve, for example, fine tuning of methods for investigating and verifying deposition positions and tunnelling methods for deposition tunnels.

In parallel with the commissioning of the facility, the operating organization must be established, educated and trained for their duties. The procedures and instructions that will apply during operating of the final repository now begin to be used.

The construction of the deposition area (including investigations, site modelling and safety assessment) continues in accordance with the description in Chapter 8. An important task during commissioning is to site-adapt and fine-tune the methodology for investigating, judging and approving the deposition positions.

9.3 Technology need

When the technical systems are commissioned they must be ready to be used on a full industrial scale. Commissioning involves running-in of systems and organization with adaptation to on-site conditions, first one by one and then in combination (integrated testing). Results and experience from commissioning will determine what efforts are required to further improve the technology on the site. The work is mainly expected to involve fine tuning and detailed improvements, but more extensive modifications may be required in some respects.

10 Main phase: Operation

When the operating phase starts, SKB has received a permit for trial operation. Radioactive material, consisting of canisters with spent nuclear fuel, arrives for the first time at the final repository. Furthermore, SKB's operating organization has assumed responsibility for the facility.

10.1 Milestones

An important milestone during this phase is the transition from trial operation to routine operation. Routine operation will then continue for many years. Updates of technology and activity can be expected during this period, but it is not possible to predict today what they will entail and when they will occur.

10.2 Activity

10.2.1 Trial operation

During trial operation, the deposition and construction cycles will be fine-adjusted and the requisite operating documentation will be updated. When SKB is able to show that operation can be routinely carried out in the planned manner and with the desired capacity, an application for routine operation is submitted.

The final repository is designed for a capacity of 200 canisters per year, which can be compared to the long-term deposition requirement, which is expected to be 150–160 canisters per year. During trial operation, capacity is gradually increased from 25–50 canisters per year initially.

With the exception of the fact that capacity is lower, especially in the beginning, the activity during trial operation is the same as during routine operation.

10.2.2 Routine operation

Routine operation is defined as the operational activity that takes place after SKI has issued a permit for routine operation of the KBS-3 system until all spent nuclear fuel from the Swedish nuclear power programme has been deposited in the final repository. During this phase, the activity at the final repository includes manufacture of buffer and backfill material, stepwise construction of the facility, deposition of canisters and backfilling, as well as operation and maintenance of the final repository's technical systems.

The use of specified methods and procedures ensures that important requirements on the activities during operation are met. These requirements include:

- simultaneous construction and operation must be able to be carried out safely, efficiently and in an environmentally sound manner,
- good radiation protection must be maintained,
- mishaps must be prevented and their consequences mitigated.

The activity during operation has been divided into three main processes:

- Manufacture of buffer and backfill.
- Deposition.
- Operation and maintenance of technical systems.

The deposition process has four component sub-processes. The first, rock excavation, takes place during a construction cycle for a number of deposition tunnels. The three subsequent sub-processes – deposition of canisters, backfilling and closure of deposition tunnel – take place during a deposition cycle. This is illustrated schematically in Figure 10-1.

Routine operation can be divided into a number of stages, where each stage comprises one deposition cycle and one construction cycle. A deposition cycle comprises deposition of a number of canisters plus backfilling and closure of deposition tunnels.

A construction cycle comprises construction of the deposition tunnels and other tunnels, as well as any ventilation shafts, that are needed to carry out the next deposition cycle. The construction cycle includes excavating tunnels and shafts, cleaning the deposition tunnels and carrying out the installations and building the structures that are needed to carry out deposition, backfilling and closure of deposition tunnel. The construction cycle also includes investigations, monitoring, site modelling and safety evaluation as well as safety assessment – long-term safety, in principle in accordance with the description in Chapter 8.

The reason for the subdivision into deposition and construction cycles is that transloading and deposition of canisters with spent nuclear fuel should be able to be done separately from rock excavations and other preparations. During a deposition and construction cycle, it should be possible to carry out deposition, backfilling and closure in parallel within a delimited portion of a deposition area. At the same time, it should be possible to excavate tunnels and deposition holes in another part of the deposition area. To enable this to be done, the facility is configured so that those parts where construction is taking place can be shut off from other parts and activities, see Figure 10-2.

The deposition and construction cycles are carried out in periods that vary in length from one to five years. A new deposition cycle begins when deposition tunnels and deposition holes for the canisters to be deposited during the cycle have been built, cleaned and approved and the installations and structures that are needed for deposition and backfilling are in place. The deposition cycle is concluded when all deposition tunnels included in the deposition cycle have been sealed with approved concrete plugs. The scope of the cycles is adjusted so that the progressive construction of the final repository can be carried out efficiently.

Rock excavation

Rock excavation refers to all activities that are required to build deposition tunnels from main tunnels, including preparations and boring of deposition holes. The activity also includes providing the deposition tunnel with a roadway (or a wire-sawn bottom) and temporary installations for ventilation and electricity.

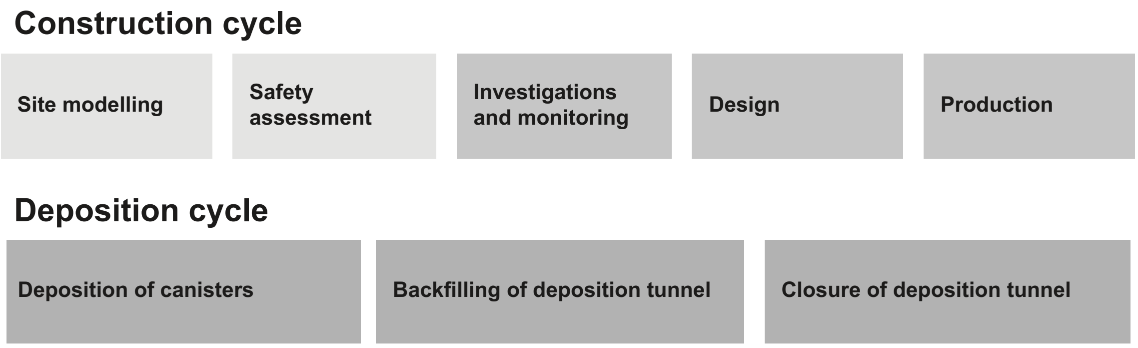


Figure 10-1. *The activity during the operating phase is divided into a construction cycle and a deposition cycle. Construction and deposition proceed in parallel in different parts of the repository.*

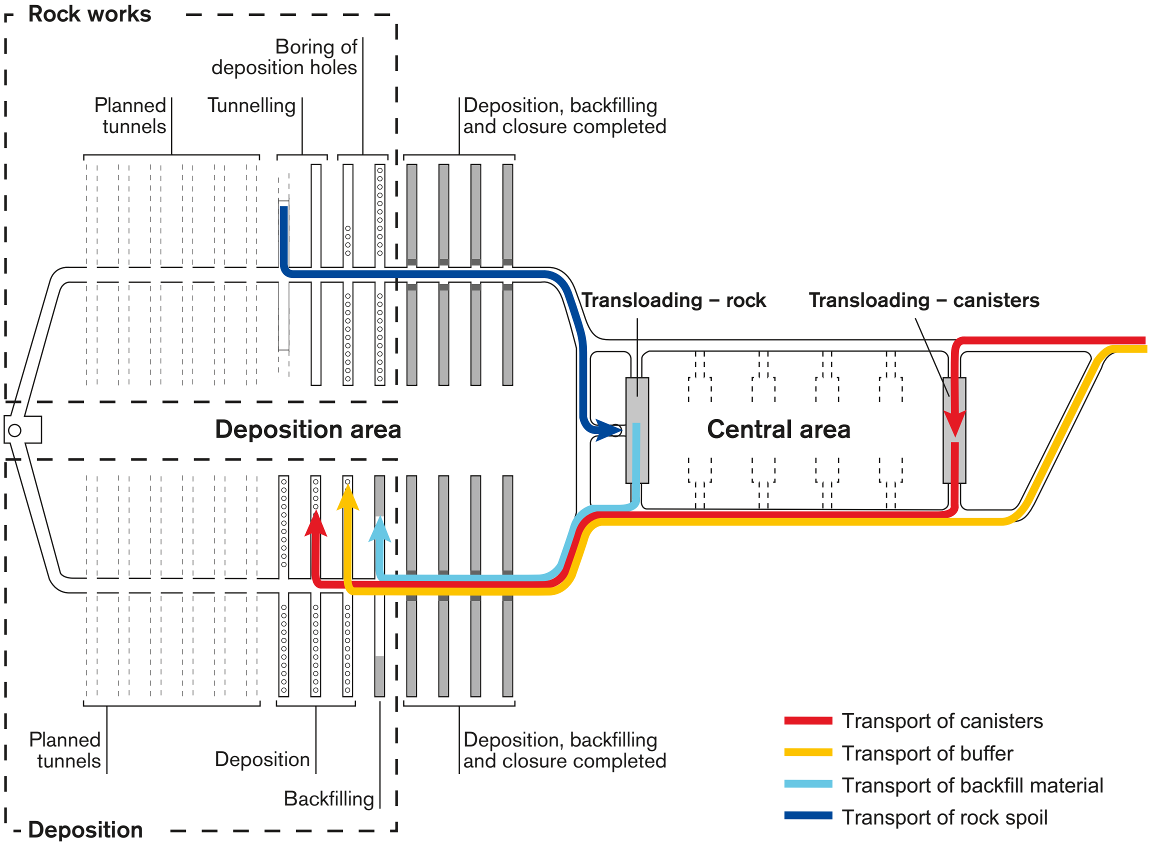


Figure 10-2. *Separation of deposition and rock works.*

SKB plans to do the work under private management using mainly standardized equipment. An exception is the equipment for boring deposition holes. SKB is developing new equipment for this work operation based on experience from the equipment that has been used at the Äspö HRL.

When rock excavation is finished the tunnel should have been cleaned and provided with installations for handover to the deposition cycle.

Deposition

The sub-process "deposition canisters" refers to those activities that are carried out to install buffer and canisters in the deposition holes and to backfill any rejected deposition holes with crushed rock. Deposition is performed with a special vehicle that collects the canister and buffer at the transloading station in the central area and transports the components to the deposition tunnel.

Backfilling of deposition tunnel

Backfilling takes place when all deposition holes in a deposition tunnel have been filled with canisters and buffer. According to the current reference design, most of the backfill consists of compacted blocks, while the remaining volume along the tunnel periphery consists of pellets.

Closure of deposition tunnel

The sub-process "closure of deposition tunnel" begins when backfilling is concluded. The closure consists of a site-cast concrete plug that is supposed to ensure that the tunnel is sealed mechanically and hydraulically. The swelling pressure that builds up in the backfill must not cause material to be displaced towards the open transport tunnel or water to leak out from the deposition tunnel.

10.2.3 Transport and receiving inspection

The following types of transport will take place during operation of the final repository:

- Transport casks with canisters are transported from the operations area on the surface to the central area by a special vehicle that runs on the ramp.
- Rock spoil is transported from the tunnel faces to the primary crusher in the central area and further via skip to the surface part and the rock heap.
- Backfill material and buffer are transported via shaft from the production building down to the central area and further out to the deposition area.
- Other building and operating materials, such as concrete, are transported down – primarily via the ramp.
- Passenger and service transport.

All material arriving at the final repository's operations area will be inspected to meet the requirements of SKB's own receiving inspection and those in SKIFS 2005:1.

10.2.4 Physical protection

SKB must prepare a plan for physical protection to meet the requirements in SKI's regulations and in relevant acts and ordinances, but also to protect employees, contractors and visitors as well as the facilities. The plan must include organizational, administrative and technical measures. Examples of measures are that special rules and procedures will apply to access for all categories (employees, consultants, contractors, suppliers and temporary visitors). Furthermore, everyone who works at the final repository will receive training in protective security. The area in and around the final repository will be divided into three zones with different protection requirements: industrial area, guarded area and protected area, see Figure 10-3.

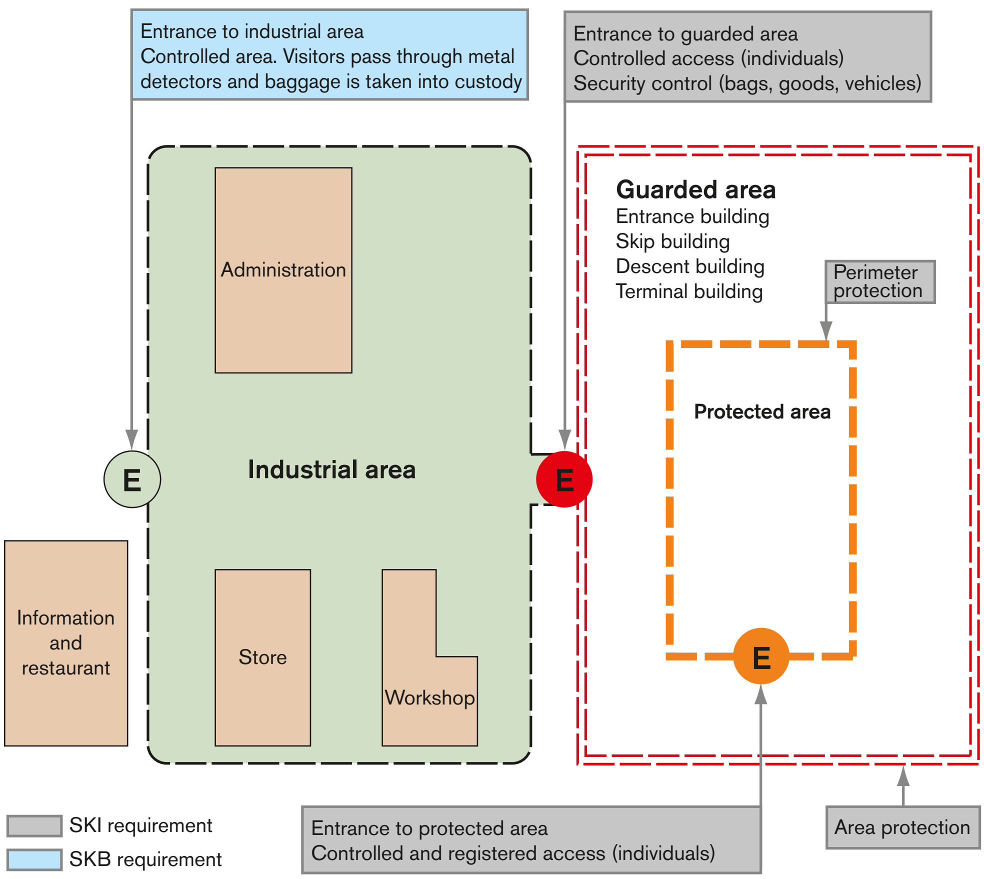


Figure 10-3. Schematic illustration showing how the facilities in the final repository's operations area can be subdivided with respect to protection class.

10.2.5 Manufacture of buffer and backfill

The operating process includes manufacture of buffer and backfill. This takes place in the operations building, to which the raw materials are delivered. High demands will be made on execution and inspection of the process for manufacturing and installing buffer and backfill. The buffer comprises one of the barriers in the final repository. It is intended to prevent water flow and protect the canister. If there are any leaky canisters, the buffer is supposed to prevent and retard the transport of radionuclides from the canister to the rock. The purpose of backfilling deposition tunnels and other rock caverns is so that the barrier functions of the rock will be retained. The backfill is not a barrier in itself, however.

10.2.6 Operation and maintenance of technical systems

A prerequisite for being able to carry out deposition in the final repository is that the facility – both above and below ground – is operated, maintained and developed as the underground part is expanded. Because the facility's operating period is long, the technical systems must eventually be replaced. This is controlled by the main process for operation and maintenance of technical systems. This process will be optimized so that operation and maintenance are as efficient as possible.

Maintenance of the final repository's buildings, vehicles, machinery and systems is expected to be a large part of this activity. According to the plans, maintenance will be performed on the following items in the facility:

- Buildings and grounds.
- Rock excavations.
- Special vehicles for bentonite blocks, transport casks etc.
- Standard vehicles such as wheel loaders, trucks and articulated haulers.
- Machines – deposition machine for canisters, press for bentonite, rock crusher, boring machine for deposition holes, emplacement machine for backfill, etc.
- Transport equipment – conveyors, overhead cranes, electric hoists and elevators.
- Mining machines – drilling machines, grouting equipment, loaders, excavators, articulated haulers, etc.
- Installations for electric power, lighting, ventilation, rock drainage, extinguishing water.

The maintenance activities can be divided into three types:

- Licence-based maintenance.
- Preventive maintenance.
- Maintenance based on inspections.

These three types of maintenance are planned and controlled via a maintenance schedule that is integrated in the system that supervises the day-to-day operation of the final repository.

Some of the operations area's buildings are directly linked to operation, while others are intended for service and administrative purposes, such as information. Aside from the operations area there are external facilities such as rock heaps, ventilation stations and bentonite stores. Infrastructure such as roads, water supply, electric power, tele- and data communications etc are also needed in order for the facility to function.

Part III

Technology development within the nuclear fuel programme

11 Overview – technology development

In parallel with the work of designing the final repository, SKB is conducting technology development in order to be able to build, operate and close the final repository in such a way that the requirements on long-term safety, low radiation dose during work in the facility and a good external environment on the activity site are satisfied. Technology development entails that we develop methods and systems – in the form of machinery and equipment, for example – which we then manufacture, test and refine.

The KBS-3 system is being designed to satisfy, and be evaluated against, the stipulated requirements. Technology development and research are required so that the facility can be built and evaluated. The role of technology development is to contribute to a safe final disposal method. Figure 11-1 illustrates the role of technology development. The figure is schematic and illustrates a flow principle which is rooted in a technical description of the deposition method. By “reference design” we mean the current design of the KBS-3 system and its parts. The reference design is updated continuously as the results of research, technology development and safety assessment become available. The reference design is based on both technology development in the design of the final repository and site data and information. This result, supplemented by information on machines and their function, is analyzed with respect to radiological safety during operation. Feedback takes place to technology development and design until we can show how safe operation can take place under given conditions. This is followed by an assessment of long-term radiological safety. The most recent safety assessment (SR-Can) of a final repository for spent nuclear fuel in Forsmark and Laxemar was published in 2006 /11-1/. This work also requires feedback. Since it takes several years to go through the entire cycle, there is time for improvements to occur in the meantime. In practice, they are introduced in connection with iteration between the steps, instead of waiting until a flow cycle has been completed. As the figure illustrates, technology development supplies information to the following beneficiaries in particular: design, assessment of operational safety and assessment of long-term safety. The information which serves as a basis for the assessment of long-term safety primarily concerns the ability of the technology to live up to the description (with deviations) of the initial state of the parts of the final repository, see Chapters 23–26 in Part IV.

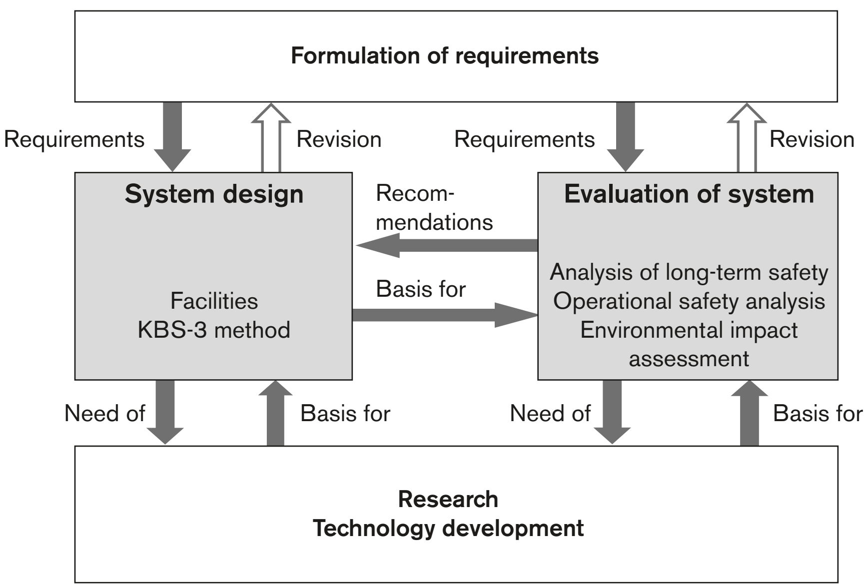


Figure 11-1. *The role of technology development in the cycle of planning, construction and operation of the final repository.*

After many years of research and a number of completed cycles, the major features of the alternative technologies have been tried out and tested. The work that remains concerns machines, methods and other equipment that are needed to build and close the final repository, but are not available on the commercial market or in a commercial application. Issues that are addressed in technology development are also characterized by the fact that it is not obvious how SKB should use the technology, what risks there are of mistakes, or what consequences different errors can lead to. Technology development thus has to do with issues where further information is needed on the function and capacity of different components before reliable assessments of their application in the final repository can be made.

The remaining work has to do with arriving at what the best choice is for different technical solutions on a more detailed level. We must also verify that predictions and assumptions that have been made can be achieved in the final repository. SKB's plans for technology development naturally extend up to repository closure, in other words further in the future than the timespan covered by RD&D Programme 2007. The entire activity is described in SKB's plan of action in Part I, where all important milestones are identified. Based on the milestones, it has been possible to specify the technology need (see sections 5.3, 7.3, 8.3 and 9.3 in Part II) in preparation for the three most important occasions for technology development:

- Application for the final repository under the Nuclear Activities Act and for the final repository system under the Environmental Code.
- Start of construction.
- Start of trial operation.

The system parts in the final repository – such as canister, canister, backfill etc – must meet special requirements which are stipulated in SKB's requirements database, see section 2.4 in Part I. The properties of the parts are determined by the design premises and specifications that are formulated, but also by the production and inspection methods that are used and by any impact during deposition and transport. This is illustrated by the use of the concept "production lines", which describe the production flow for the different system parts. The purpose of the production lines is to promote clarity in the growing body of documentation. SKB has chosen to define six production lines:

- The rock line.
- The buffer line.
- The fuel line (included in the canister line in this RD&D programme).
- The canister line.
- The backfilling line.
- The closure line.

The above breakdown also comprises the platform for describing technology development in this part of the RD&D programme. Figure 11-2 provides a schematic description of the activities included in the different production lines. The activities are described in greater detail in Chapters 12–16. The fuel line contains only the steps "decay heat determination" and "drying". For practical reasons, the fuel line is therefore included in the canister line in this RD&D programme.

Our knowledge and conclusions regarding technology for retrieving deposited canisters where the bentonite buffer has swelled and immobilized the canister in the deposition hole are presented in Chapter 17.

The technology development described in the different production lines pertains to a KBS-3 repository where the canisters are emplaced vertically (KBS-3V). SKB is also investigating the possibility of depositing the canisters horizontally (KBS-3H), see Chapter 18.

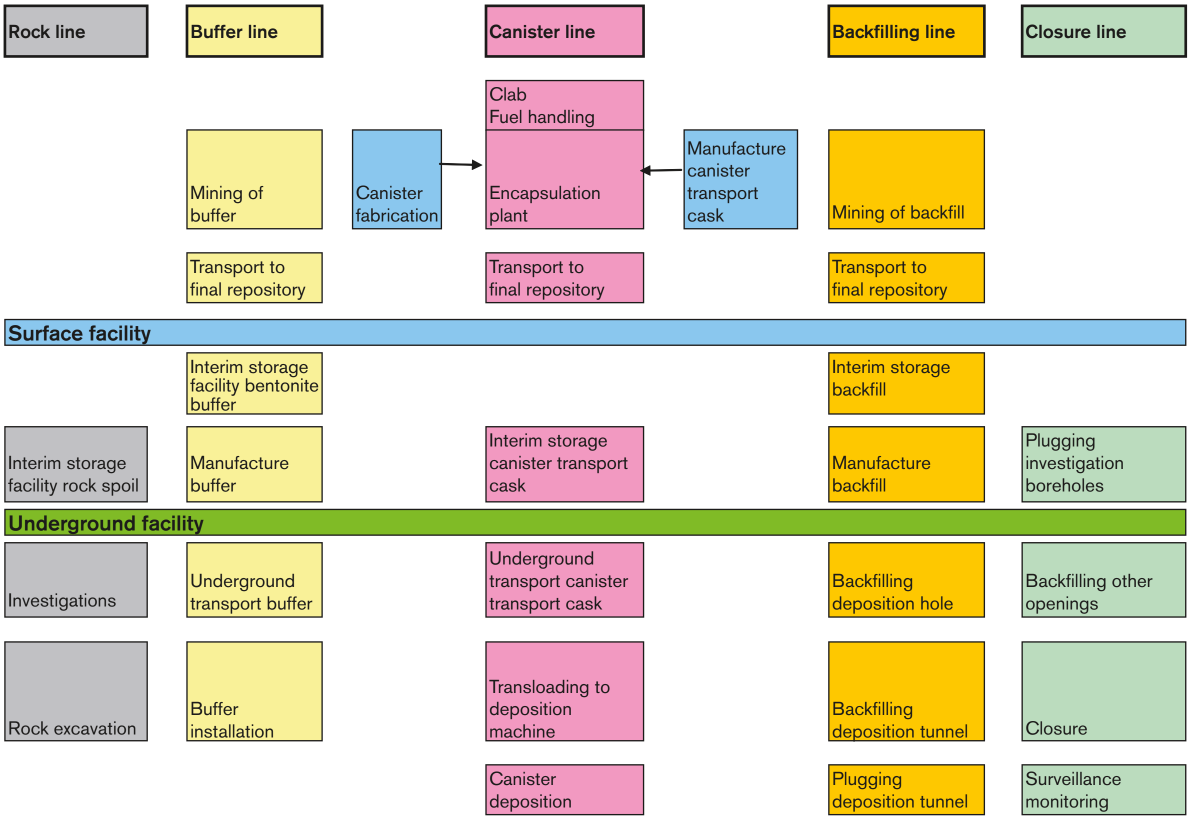


Figure 11-2. *The production lines.*

11.1 The rock line

The rock line includes mining and construction of the deposition area and other openings in the final repository under ground. Swedish engineers have long experience of building in rock and the Swedish mining industry has developed world-leading technology. We will now be able to use this knowledge for rock characterization, drilling, blasting, scaling and rock support. However, great precision will be needed to satisfy the requirements that are made on the final repository.

A well-known phenomenon is the formation of an excavation-disturbed zone (EDZ) around tunnels and rock caverns in connection with rock excavation. The size of the EDZ will depend on what method is used and the conditions in the rock. If the disturbance is very great, the hydraulic properties of the zone may affect the performance of the repository in the long term. Today we know how to limit the extent of this zone. However, we do not know enough about how the hydraulic properties are altered if the degree of disturbance changes. Nevertheless, we believe that the importance of the EDZ can be minimized by careful and controlled technology for drilling and blasting.

The floor of the deposition tunnel must be made flat to make it easier for the deposition machine to drive in the tunnel and for the backfilling machine to build straight stacks of blocks of backfill material. An alternative to controlled drill-and-blast of a smooth tunnel floor is to remove the bottom slice by wire sawing. Wire sawing in rock is used in various contexts, but needs to be demonstrated specifically for this purpose in a deposition tunnel before the method can be said to be available for the final repository.

We have shown that boring of deposition holes works well in full-scale tests in the Äspö HRL. However, it remains to be shown that the method can also achieve the capacity that is required in the final repository.

The problem of water inflow into the underground facility will only be able to be partially solved with existing technology. The difficulty is that the water pressure at the depths at which the repository is located is high. Even small fractures are water-conducting. This means that we must be able to grout the small fractures as well. Furthermore, the grouting material may not give rise to a pH higher than 11 in the groundwater when it is leached out, see Figure 20-2 in Part IV. If the pH is higher, long-term safety may be threatened. We must therefore develop a low-pH grouting material that can be used in small fractures.

When the first important milestone is reached – the applications under the Nuclear Activities Act and the Environmental Code – SKB must have a reference method for drill-and-blast of deposition tunnels. We must also have established acceptance criteria for the perimeter of the deposition tunnel in cooperation with the backfilling line and shown that we can stay within them. Handling and use of explosives must be safe and expedient. We must have proven methods and materials for sealing fractures of the size expected in the final repository. The sealing materials must have a low pH (< 11). SKB intends to use silica sol to seal the finest fractures. The materials to be used for rock support and other structures must also be tried and tested and of low pH. A method for boring deposition holes must have been chosen and we must have finished a basic design of the machine we plan to use.

Prior to the start of construction, SKB must have shown that machines and personnel can apply the methodology for controlled blasting which we intend to use to build the ramp and shafts. We must also have shown that the grouting works in the face of repeated blasting rounds and that we can seal the large water-conducting zones we expect to pass during construction of the repository. Prior to the start of the rock works in the deposition area we must have commenced a dress rehearsal with machines and personnel to excavate deposition tunnels. We must also have manufactured and commissioned a machine for boring deposition holes.

11.2 The buffer line

The buffer line includes manufacture, handling and installation of the buffer – in the form of rings, blocks and pellets or granules of highly compacted bentonite – that surround the canister the deposition hole.

The world's bentonite resources are very large. Many suppliers on the market can deliver a product that satisfies SKB's requirements on the material. Technology and methods for treating the bentonite before it can be compacted to blocks – such as crushing, sieving, grinding, drying etc – are known and proven. SKB has tested two methods for compacting the blocks and rings for the buffer: uniaxial pressing and isostatic pressing. Both of the methods will be further developed before either of them is used in the final repository. Technology for compacting pellets is available on a commercial scale, but must be adapted to meet the needs in the final repository.

Prior to submission of an application, the question of how the buffer material is to be protected from water in the rock must be solved – with no deterioration of properties until the deposition tunnel is backfilled. The temporary buffer protection must have been tested under realistic conditions. A reference method for manufacturing blocks and rings must also have been chosen by then. We must also know under what conditions the manufactured blocks and rings can be stored without drying out or starting to swell. A prototype lifting tool for depositing the bentonite will be in operation and a prototype buffer emplacement machine.

Prior to the start of construction of the final repository, SKB will have completed detailed design of the plant where the blocks and rings will be manufactured so that it can begin to be built.

11.3 The canister line

The canister line describes how the canister is fabricated, sealed, transported and deposited and how quality assurance takes place in the different phases. Quality assurance of the canisters is aimed at showing that the canisters satisfy the specifications. This ensures both handling safety and long-term safety. Quality assurance is accomplished by control of processes and inspection of results.

Methods for fabrication, inspection and sealing of canisters have been under development for many years. The work entails developing quality-assured industrial processes for various suppliers. As far as the welding process used for sealing the copper canister is concerned, SKB has decided to conduct its own development of this process.

It is important to be able to verify the properties of the canister, which is done by means of various standardized methods such as chemical analysis of material composition, microstructure examination, inspection of dimensions and determination of strength properties. However, these methods can only be performed locally and on parts of the canister that would be machined off anyway. General testing must be done using nondestructive methods such as ultrasonic testing and radiography. SKB has chosen to conduct its own development and adaptation of these methods.

In the encapsulation plant, SKB plans to use calculated values of decay heat as a basis for the selection of fuel assemblies for the canisters. If necessary, it must be able to verify the decay heat by means of gamma measurements. In the encapsulation plant, the spent nuclear fuel will also be dried before it can be placed in the canister. In its application for a permit to build the encapsulation plant, SKB has shown that vacuum drying is a method for drying the fuel. The planning for the coming year includes a study of alternative drying methods for the purpose of achieving a more efficient drying process, above all in the case of leaking fuel.

A specially designed transport cask is needed to transport the canisters from the encapsulation plant to the final repository. This transport cask – like all other transport containers used by SKB – is designed to comply with the rules in the IAEA's transport recommendations. SKB engages established cask designers to design and manufacture the casks.

A prerequisite for SKB to obtain an operating license for the future encapsulation plant and final repository is that suppliers, systems and processes for fabricating and sealing the canisters meet all stipulated requirements. A part of this work takes place within the framework of SKB's programme for qualification of fabrication and sealing of the canisters /11-2/, see also section 2.4 in Part I. The programme also includes qualification of the nondestructive testing. Prior to submitting an application, SKB will present its strategy for the qualifications. Reliability analyses of the canister's components will also be available at this time. The basic design of transport vehicles and other equipment for transport, handling and deposition of canisters must have been developed. The deposition machine in the Äspö HRL will be rebuilt so that it runs on wheels instead of rails.

Prior to trial operation, SKB will have tested the entire canister handling chain from the encapsulation plant to deposition in the final repository.

11.4 The backfilling line

The backfilling line includes manufacture, handling and installation of backfill material in deposition tunnels and installation of temporary plugs in the tunnel mouths.

SKB has studied several ways for backfilling deposition tunnels. They include a mixture of crushed rock and bentonite that is compacted in the tunnel, and pre-compacted blocks of either swelling clay or a mixture of crushed rock and bentonite. The two methods based on pre-compacted blocks were analyzed in the safety assessment SR-Can /11-1/. The results of this analysis showed that both alternatives meet the requirements, but that blocks of swelling clay had a greater margin to the function indicators that were used in the analysis. Further technology development will now be focused on developing methods and equipment for the concept employing blocks of natural swelling clay.

Technology and methods for preparing the clay prior to pressing to blocks are known and proven. The blocks can be compacted by means of uniaxial pressing, according to the method that is used in industry for manufacturing refractory brick. It is not possible to fill up the whole tunnel with blocks; the gap between the stacks of blocks and the rock wall will be filled with pellets or granules.

The temporary plug in the tunnel mouth can be designed according to different principles. SKB is studying two designs: a reinforced plug that is anchored in a slot in the rock, and a friction plug.

Prior to application, reference designs for the backfilling concept and plugs must have been chosen. For backfilling, this means that the concept and material in the backfill must have been chosen and that the equipment needed for installation must exist in a prototype version. In order for the question of where the borderline goes for the highest permissible inflow of water to the deposition tunnel that can be handled during installation to be regarded as having been solved, the chosen concept must have been tested in the Bentonite Laboratory at different rates of water inflow to a tunnel.

Prior to the start of construction of the final repository, the reference methods that have been chosen for backfilling and plugging will have to be installed in a trial setup in the Äspö HRL.

11.5 The closure line

The closure line includes backfilling and plugging of all other openings than the deposition tunnels, such as main tunnels, transport tunnels, central area, and ramp and shafts for transport and ventilation. It also includes closure of investigation boreholes drilled from the surface and from openings in the final repository.

Closure of the other openings in the final repository will not take place until all spent nuclear fuel has been deposited. This means that the closure activities lie well in the future. So far SKB has prioritized the work on the backfilling of the deposition tunnels. Experience gained from these studies will be applied in the continued work of backfilling other openings as well. The materials being considered for this purpose are swelling clay, non-swelling clay, crushed rock and combinations of these materials. Handling, manufacture and backfilling can largely be done using the same methods as those developed for the backfilling line.

Investigation boreholes drilled from the ground surface and in the final repository must have been sealed by the closure of the final repository. SKB has studied and developed several concepts for this. The most promising concept, bentonite in combination with quartz-based concrete, has been tested together with Posiva in a 500 metre deep borehole in Olkiluoto in Finland. The quartz-based concrete is placed in zones with poor rock.

Prior to submission of an application, reference designs for closing different parts of the final repository must have been chosen. For closure, this means that both material and method for emplacement of backfill and plugs must have been chosen. It is also important that we study where the borderline goes for water inflow into the tunnel in order for the requirements on closure to be satisfied and how the closure in ramp and shafts should be designed in order for its function to be retained even after the next ice age.

Prior to the start of construction, the materials to be used in the upper parts of the shafts and the ramp must be tested for the conditions that prevail under permafrost.

11.6 Retrieval

The final repository for spent nuclear fuel must be designed in such a way that it does not need to be monitored. If future generations should wish to retrieve the fuel again, this must be technically feasible, even though Sweden does not formally require that it should be possible to retrieve a deposited canister.

How retrieval takes place depends on when the decision is made. Before the buffer has swelled and immobilized the canister, it can be pulled up with the deposition machine as soon as the canister lid has been freed. When the buffer has swelled, the canister must be freed along its entire length before it can be lifted up. SKB has studied and evaluated various methods for freeing the canisters from the bentonite buffer. We have chosen a hydrodynamic method as a reference method where the bentonite is slurried with salt water and pumped away. The method has been tested and demonstrated in the Äspö HRL, both in connection with the slurrying test (which preceded the Canister Retrieval Test) and in connection with the mining of the Canister Retrieval Test. The method can be time-consuming, but no technical difficulties have been identified.

We therefore believe that we have shown that retrieval within the framework of trial operation is feasible and that we can build equipment that can free canisters from a swelled buffer. If the canisters should need to be retrieved, there is time to build the equipment and demonstrate it before retrieval takes place. For this reason, no additional development work is planned in this area within the next six years.

11.7 Alternative repository design – KBS-3H

The KBS-3 method permits canisters to be emplaced either vertically (KBS-3V) or horizontally (KBS-3H). In both cases the canister is surrounded by a buffer of bentonite. No deposition tunnels are needed in KBS-3H; instead, the long horizontal deposition drifts are excavated directly from the main tunnel. This means that a much smaller volume of rock needs to be excavated. The part of the final repository located above ground is not affected by whether the canisters are deposited horizontally or vertically.

SKB and Posiva have been collaborating since 2002 to conduct the research programme for KBS-3H that SKB published in 2001. The programme includes design of the repository's components and a general repository layout. A full-scale demonstration of the deposition technology is being conducted in the Äspö HRL. The required equipment was designed and manufactured in preparation for this demonstration. The programme for KBS-3H includes not just technology development but also a safety assessment and associated questions for an envisioned repository in Olkiluoto.

The programme will be concluded at the end of 2007 and the results of the different activities will be reported. Feasibility and long-term safety will be evaluated. Based on this report and evaluation, SKB will then make a decision as to whether KBS-3H will be further developed or not. If the decision is that KBS-3H is to be further developed, a programme for this will be prepared with the objective of raising the technical level of the knowledge to the same level as for KBS-3V. We estimate that such knowledge can be available at the earliest by the middle of the second three-year period covered by this RD&D programme.

11.8 Technology development in SKB's laboratories

The technical development activity is being increasingly focused on full-scale tests, demonstrations and dress rehearsals. For this purpose among others, SKB has built the Bentonite Laboratory, the Äspö HRL and the Canister Laboratory and equipped them in such a way that much of the remaining technology development that is needed can take place there, see section 1.3.3 in Part I. But there are also other places where this is possible, such as the Onkalo facility in Finland, which is being excavated. There are also a number of laboratories in hard rock and for metallurgical research in other parts of Europe and the world. In addition there are production plants in many countries that have equipment and knowledge in the issues facing SKB. Since our laboratories are specially designed for our purposes and requirements, we will do most of our work in them.

The development and the demonstrations being conducted or planned in the different laboratories are shown in Table 11-1.

Table 11-1. Work being conducted or planned in SKB's laboratories.

Development and demonstration	Bentonite Laboratory	Äspö HRL	Canister Laboratory	See text in section
The rock line				
Instruments in boreholes				
Stabilization of boreholes		X		12.3.1
Geophysical borehole instruments		X		12.3.3
Rock mechanics measurements		X		12.3.4
Measurement of thermal properties		X		12.3.5
Equipment for hydraulic tests		X		12.3.6
Instruments in tunnels and deposition holes				
Laser scanning		X		12.3.2
Rock mechanics measurements		X		12.3.4
Measurement of water inflow in tunnels and ramp		X		12.3.7
Measurement of inflow to deposition holes		X		12.3.8
Determination of sorption parameters		X		12.3.9
Determination of pH and redox potential		X		12.3.10
Fine sealing of tunnel at great depth		X		12.4
Drilling for blasting round		X		12.5
Explosive and detonator		X		12.5
EDZ hydrotechnology measurement		X		12.5
EDZ link between disturbance and hydraulic conductivity		X		12.5
Wire sawing		X		12.5
Boring equipment for deposition hole		X		12.7
Shotcrete		X		12.6
Rock bolting		X		12.6
Road surfacing		X		12.6
The buffer line				
Lifting tool for buffer block	X	X		13.6
Crane for buffer block	X	X		13.6
Fitting-out deposition hole	X	X		13.5
Buffer protection	X	X		13.5
Buffer installation	X	X		13.6
Spraying of pellets/granules	X	X		13.7

Development and demonstration	Bentonite Laboratory	Äspö HRL	Canister Laboratory	See text in section
The canister line				
Nondestructive testing of canister components			X	14.3.2 14.4.2
Optimization of the welding process and lid/bottom design			X	14.5.1
Nondestructive testing of weld			X	14.5.2
Transport vehicle on ramp		X		14.8
Transloading station under ground		X		14.8
Deposition machine		X		14.8
Temperature evolution in deposition hole	X	X		13.5
The backfilling line				
Installation tool for blocks in tunnel	X	X		15.6
Spraying of pellets/granules	X	X		15.7
Mock-up size scale 1:4	X			15.6
Tests on size scale 1:1		X		15.6
Installation of plug		X		15.8
The closure line				
Crushed rock and other candidate materials	X	X		16.3
Freezing of borehole material		X		16.4
Freezing of shaft and ramp material		X		16.3

12 The rock line

The rock line includes mining and construction of all openings in the underground facility. This involves rock excavation for deposition tunnels, main tunnels, transport tunnels, central area, shafts and ramp. The rock works include grouting the rock around the openings in order to reduce the inflow of water and supporting the rock with rock bolts, shotcrete and wire mesh. The rock line also includes the investigations and the geological mapping that are undertaken in conjunction with construction.

The colour coding of the rock line for the deposition area shows the areas within which there is known and proven technology that can be applied to the final repository and the areas for which technology development is required, see Figure 12-1. The figure describes SKB's assessment of the situation for technology development today. In the areas coloured grey or green, normal design efforts are assumed to suffice in order to specify and execute the necessary measures. Verifying tests may be warranted in a few cases. In the areas coloured yellow or red, technology development is needed. Tests have been carried out in a number of the areas coloured yellow, but SKB deems that further development or optimization measures are warranted.

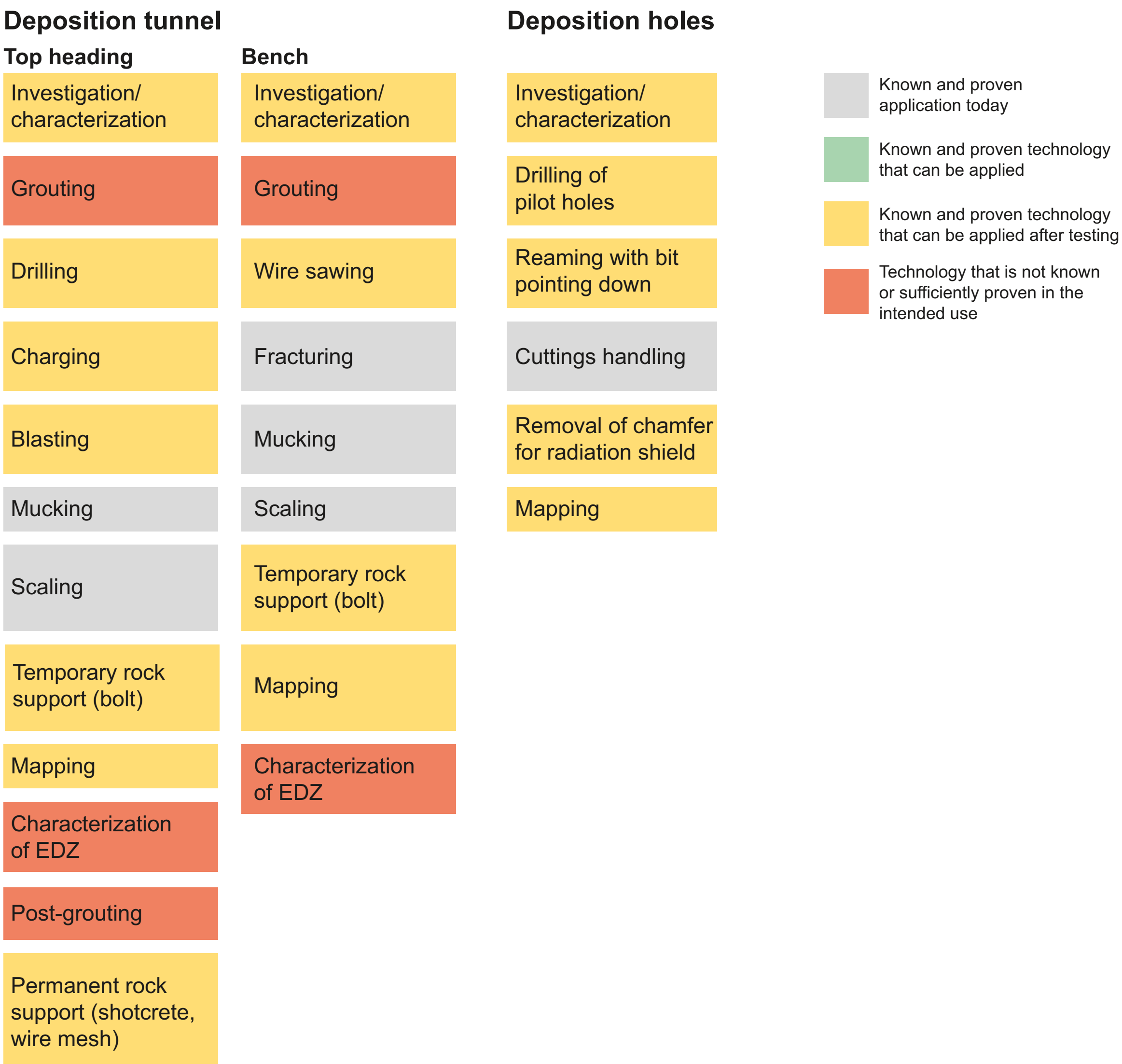


Figure 12-1. Rock line for deposition area – SKB's assessment of the situation for technology development today.

12.1 Current situation

Swedish engineers have long experience of underground constructing and mining. The Swedish mining industry has developed world-leading technology. We will be able to use this experience to characterize the rock and then drill, blast, scale and support it. The work must however be done with great precision in order to satisfy the requirements made on the final repository.

A well-known phenomenon is the formation of an excavation-disturbed zone around tunnels and rock caverns in connection with rock excavation. What the zone looks like depends on whether the tunnel is blasted or bored. If the disturbance is very great, the hydraulic properties of the zone may affect the performance of the repository in the long term. Today we know how to limit the influence of the EDZ. However, we do not know enough about how the hydraulic properties are affected by the size of the EDZ and how we can show this. Nevertheless, we believe that the importance of the EDZ can be minimized by careful and controlled technology for drilling and blasting. Another important question is being able to check and measure the hydraulic properties of the EDZ around tunnels and other openings. This is of particular importance around deposition tunnels and deposition holes.

The bottom of the deposition tunnel needs to be made smooth and level so that the deposition machine can drive on a smooth, flat surface with low rolling resistance. In the backfilling line as well it is preferable to be able to place the bentonite blocks directly on the rock. To minimize the excavation-disturbed zone in the bottom of the tunnel, rock excavation is done in two steps. First a top heading (the uppermost part of the tunnel, nearest the roof) is drilled and blasted. The remaining part of the cross-section, the bench, can then be excavated either by smooth drill-and-blast or by wire sawing. Wire sawing leaves a very smooth bottom. But SKB needs to demonstrate the method in a realistic environment before we can say whether it can be used in the final repository.

We have shown that the boring of the deposition holes works well, but we still have to show that the method can also handle the capacity for which the final repository will be designed: one deposited canister per day.

We will not be able to completely solve the problem of water inflow into the underground facility with existing technology. The water pressure at the depth at which the repository is located is very high. Even small fractures, or systems of interconnected fractures, conduct water. Since the grouting material and the grouting method need to be adjusted to the properties of the fractures and fracture systems, the question becomes complex from a scientific perspective. Moreover, the grouting material may not lead to a pH higher than 11 in the groundwater when it is leached out. Otherwise the long-term performance of the repository may be adversely affected.

Two issues are particularly challenging in the development work in the rock line: grouting at great depths and in situ determination of the hydraulic properties of the EDZ. Sealing must be successful to make it possible for the final repository to be built and backfilled. However, the determination of the hydraulic properties of the EDZ does not affect the safety of the final repository per se, since the rock engineering is expected to result in properties in the EDZ that do not jeopardize the long-term safety of the final repository. In the determinations of the properties of the zone, it is important to be able to show that they lie within given limits. Verifying measurements in the field are above all of importance in deposition holes and deposition tunnels.

12.2 Requirements and premises

Rock structures are defined by SKB as the openings in the rock that are needed for the underground facility. The rock structures must be designed so that they do not significantly impair the barrier functions of the repository rock. In summary, the requirements entail that the environmental impact of construction and operation must be limited, and the rock structures must accommodate the underground facility, permit deposition and be adapted to the rock in such a way that the repository's isolation and retardation functions can be maintained. The rock structures must not degrade the natural capability of the rock to retard radionuclide transport from the repository to the biosphere. The requirements influence both choice of materials and choice of methods for execution.

The requirements on the methods and equipment to be used in building the final repository are:

- Characterization methods and instruments must be developed prior to the investigations of the rock.
- The inflow of water to different parts of the repository must not exceed specified values. This will be achieved by grouting where necessary.
- The materials and methods used to support the rock must not jeopardize long-term safety.
- The construction of the repository must have a limited impact on the rock. Excavation of deposition tunnels must be done in such a way that the excavation-disturbed zone in the deposition area satisfies specified requirements.
- The deposition holes must be able to be bored according to specified requirements on geometry.

Chapter 26 in Part IV describes the processes that can affect the rock in the long term and the properties the rock in the near field should have in the initial state in order to ensure the best long-term performance. In order to be able to prove in advance that our technology development leads to methods and machines that really meet the stipulated requirements, we will go through and compile the inspections and the documentation needed for quality assurance during operation.

Technology development in the rock line is currently focused on an initial state with an excavation-disturbed zone around tunnels, ramp, shafts and deposition holes that possesses the specified hydraulic properties. The key characteristics are the extent of the zone and its hydraulic conductivity. Indicators are the depth and porosity of the zone and the smoothness of the perimeter surface. Other indicators are the performance of drilling machines and the precision of the blasting technology. A complication is that sealing with grout will have to be done. Observations of water inflow can therefore only be done to limited extent in rock with solely natural properties. The initial state in the deposition tunnel also includes the smoothness of the tunnel floor, which in turn is of importance for quality in the backfilling line.

12.3 Investigation and characterization

This section describes the technology development of methods and instruments that SKB deems necessary for being able to conduct geoscientific investigations of the rock during construction and operation of the final repository.

Conclusions in RD&D 2004 and its review

SKB has not previously given an account of the need to develop the methods and instruments that are needed for the investigations that will be done during construction and operation of the final repository. However, RD&D-Programme 2001 contained a brief account of the situation prior to the upcoming site investigations.

Newfound knowledge since RD&D 2004

SKB developed, improved and tested investigation methods and measurement instruments in preparation for the site investigations. We built up systems and procedures for data management and site descriptive models, and to transfer information between investigations, design and safety assessment /12-1, 12-2/.

Experiments and measurements in the Äspö HRL have provided experience of investigations in shafts and tunnels. The investigation methods that were used in the construction of the Äspö HRL are described in /12-3/. The report presents the main area of application for different investigation methods. There is also an assessment of the particular method's suitability for exploring key issues for the different site models (geology, hydrogeology etc). The report principally describes the state of knowledge in 1997, so the experience lies many years back in time. Additional experience has been gained since then. Among other things, the True project has yielded important knowledge on how the transport properties of the rock are determined.

Against this background, SKB concludes that we have access to and solid experience of methods and instruments for the investigations that will be conducted in conjunction with construction of the final repository. However, the mode of working will have to be developed due to the increasing demands on speed and efficiency in conjunction with construction and operation. At the same time, certain instruments and methods need to be improved. In some cases new methods are needed, since new or tougher requirements have been introduced. New, better technology may also have become available. SKB plans to continue using the Äspö HRL for various kinds of research and demonstration.

SKB plans efforts in the following areas:

- Stabilization of boreholes.
- Laser scanning.
- Geophysical borehole instruments.
- Rock mechanics measurements.
- Measurement of thermal properties.
- Equipment for hydraulic tests (single-hole tests).
- Measurement of water flow in ramp and tunnels.
- Measurement of inflow to deposition holes.
- Determination of sorption parameters.
- Determination of pH and redox conditions.
- Information systems and information technology.

A current situation description of the enumerated areas is given in sections 12.3.1 to 12.3.11, followed by SKB's programme to develop instruments and methods in these areas.

12.3.1 Stabilization of boreholes

Boreholes that pass deformation zones with weak and perhaps also water-conducting rock volumes may need to be stabilized so that equipment doesn't get stuck. The boreholes may also need to be stabilized before they are closed. This applies to holes drilled from the surface as well as from tunnels. What differentiates holes drilled the ground surface from holes drilled from tunnels may be borehole directions and the fact that the mouths of the tunnel boreholes lie below the groundwater table. Furthermore, the high water pressures and the potentially high water flows at great depths can cause problems getting equipment into the borehole. Horizontal and slightly inclined holes entail a greater risk of collapse (falling stones etc) and thereby that the equipment will get stuck.

More than one method is probably needed for stabilizing borehole walls. Several factors influence the choice of method, such as whether the hole is drilled from the surface or down in the rock, how much the hole is inclined, what types of measurements will be performed in the hole and the type of crushing.

During the site investigations, SKB has developed technology for stabilizing borehole walls. One method involves installing perforated stainless steel plates in the part of the borehole where the rock is weakened. Figure 12-2 illustrates how this is done. The technique has been used in both Forsmark and Oskarshamn with good results. Another method is stabilizing the borehole with cement where it passes the weak zone. First the hole is widened, after which the section is plugged with cement and then the plug is drilled through. This method was developed at the Äspö HRL and has been tested in Onkalo.

Programme

Both of the methods described above will be further developed. There is also new technology in the conceptual stage. Since the choice of material used to stabilize the boreholes may affect the performance of the repository, it is urgent to analyze the consequences when the technology is designed. Similarly, it is important to test the methods under realistic conditions all the way down to repository depth.

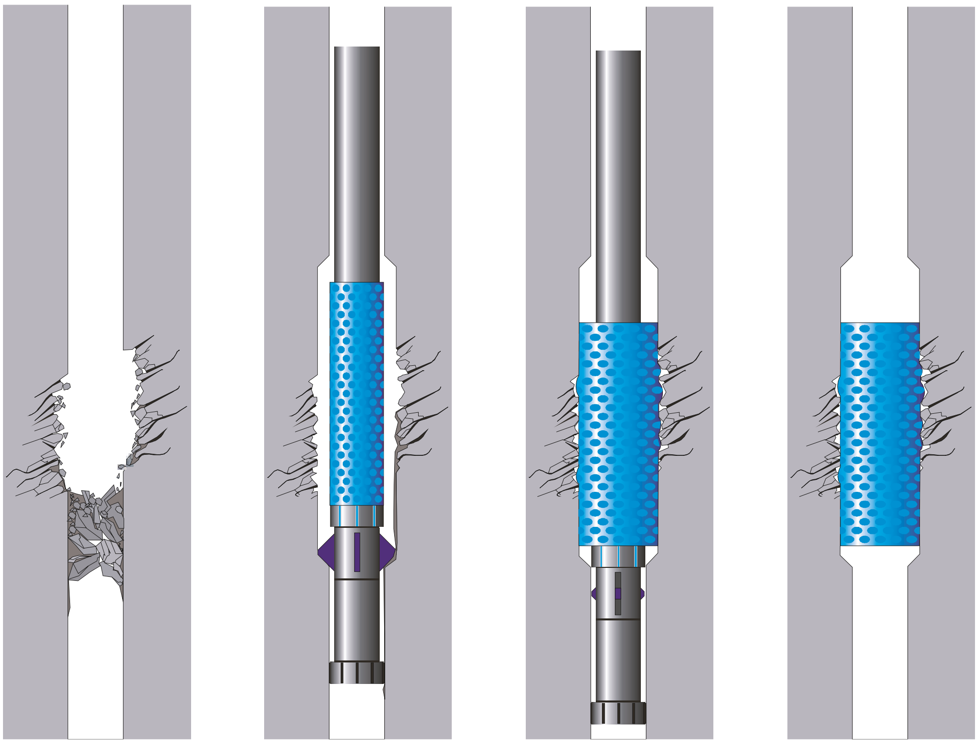


Figure 12-2. Illustration of the sequence of steps that are carried out to stabilize borehole walls in deformation zones /12-4/.

The subject of stabilization of investigation holes is also taken up in the discussion of the closure line in section 16.5.

12.3.2 Laser scanning

In the project "Rock Characterisation System – RoCS", SKB conducted a feasibility study of different systems for rock mapping of tunnels and deposition holes together with Posiva. The study was primarily concentrated on digital photogrammetry and laser scanning in combination with digital photography. The feasibility study focused on geological mapping, but the results were supposed to be able to be used by other disciplines than geology /12-5/.

The feasibility study recommends that laser scanning, combined with digital photography, should be included in a new mapping system. This combination provides an image reminiscent of a colour photograph in three dimensions, where the coordinates of each point are given, see Figure 12-3. The recommendation is based on the fact that the investigation method is fast and that geological mapping can be done with greater precision than with the current method.

The feasibility study has identified a number of existing mapping systems that work in two dimensions. SKB's TMS (Tunnel Mapping System) is one of them. Only a few systems can handle three dimensions. Modelling is done in three dimensions, however. Moreover, there are several programs that can convert laser scanning data to formats that can be handled by different CAD systems.

Programme

SKB's goal is to have a new mapping system for tunnels and deposition holes ready by the start of construction. The system should utilize of laser scanning and data should be able to be transferred to and used by SKB's RVS modelling system (Rock Visualisation System) or a successor to RVS.

A continuation of the RoCS project is planned. Each discipline – geology, hydrogeology, rock mechanics etc – will impose its demands on the characterization system. The first step will be to compile a requirements specification.

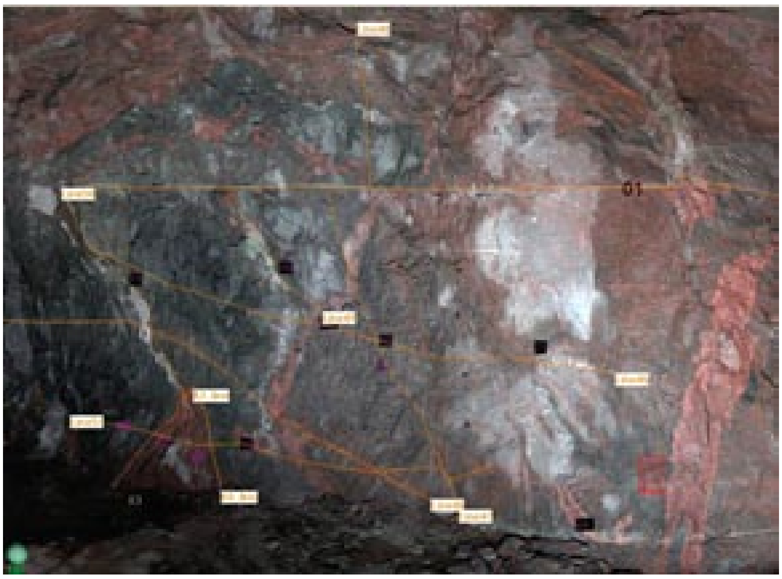


__Figure 12-3.__ Combination of laser-scanned image and digital photo. A number of lines (mostly fractures) have been drawn in with the aid of the drawing tool included in the scanner's software.

12.3.3 Geophysical borehole instruments

At the site investigations in Oskarshamn and Forsmark, geophysical borehole logging with six different probes has been performed in all boreholes. These probes produce 15 different borehole logs (density, susceptibility, resistivity etc). In addition to these logging methods, TV logging with BIPS (Borehole Image Processing System) and radar logging have been carried out. These geophysical logging methods have proved to provide important support for geological interpretation.

A central method is TV logging (BIPS). This method has been vital in the geological mapping and identification of fracture orientation. BIPS is a well-known system of which SKB has great experience. Ultrasonic investigations (Acoustic Televiewer) have previously been regarded as an odd instrument without a defined area of application. However, this instrument has shown potential for measurement of fracture orientation and as a logging tool for precision measurement of the diameter of a borehole along its entire length. It can also be used as support in measuring the borehole's position along its length.

Programme

SKB's BIPS equipment was procured in 1994. It is therefore time to have a look at today's market for TV logging systems. An important feature – aside from image quality and resolution – is the probe's ability to record the orientation correctly. An alternative to buying a new probe is to investigate whether SKB's equipment can be updated so that the software automatically corrects the BIPS image when the probe rotates.

Certain questions have arisen with regard to Acoustic Televiewer during the site investigations. They need to be explored before the method can be used routinely.

12.3.4 Rock mechanics measurements

Neither of the two main methods, overcoring and hydraulic fracturing, that have been used in the site investigations have performed optimally at great depth. The problem has been studied thoroughly in conjunction with the evaluation of measurement data, particularly in results from Forsmark /12-6/.

A main theory is that the occurrence of microfractures in the overcoring core disturbs the results, which seems to be a plausible explanation. From an in situ state with high stresses, a rapid destressing takes place at the same time as overcoring in quartz-rich hard rock, such as in Forsmark, raises the temperature. This causes inelastic strains, and assumptions of elastic response in connection with overcoring are not fully valid. Instead, microfractures occur in the specimen. The overcoring method also has problems with the gluing technique and controlled drilling at great depth. One solution that has been considered is designing a probe for large-diameter boreholes, for example 86–100 millimetres, in order to obtain thicker, and thereby less sensitive, overcoring cores. SKB has therefore carefully evaluated the possibilities and the benefits of measuring rock stress by means of the overcoring method on drill cores of larger diameter. The evaluation has included both numerical calculations and experience from measurements in the URL in Canada. The conclusion is clear: the problem of ring discing persists when the diameter of the drill core is increased in rock stress measurements using the overcoring method. Drill cores with diameters of 76 and 150 millimetres were studied in the numerical calculations, and the measurements in the URL were performed on diameters of 96 and 50 millimetres. Increasing the diameter of the drill core is associated with a considerable increase in costs. In view of this, SKB does not intend to continue studying the feasibility of extracting a larger core in overcoring.

As far as hydraulic methods are concerned (HF-HTPF measurements), SKB has utilized both traditional technology for fracture identification and orientation (impression packer) and modern technology (Mosnier tool). The latter technology is much more sophisticated in its ability to analyze the test results than the old technology. But the hydraulic methods have also proved to have great limitations in conditions such as those in Forsmark /12-6/.

Programme

SKB does not consider further development of methods for measuring rock stresses from the ground surface to be motivated. Instead we plan to obtain information on the stress state on the final repository site through deformation measurements in conjunction with tunnelling. However, it should be noted that a large part of the total deformation in tunnels takes place instantaneously when the rock is excavated, and that part of the deformation can therefore not be measured.

12.3.5 Measurement of the rock's thermal properties

Characterization of the bedrock's thermal conductivity and its variations in space is costly and time-consuming if it is done by determinations in the laboratory. There is therefore a need to develop more efficient and inexpensive methods. Within the framework of the site investigations, development work has been pursued on other ways to determine the thermal conductivity of the rock.

The thermal conductivity of a crystalline rock is generally dependent on the composition, density and thermal conductivity of the minerals in the rock. Based on idealized mineral compositions for igneous rock types, a general correlation has been demonstrated between density and thermal conductivity. This correlation has been verified by values measured in the laboratory. These measurements have been performed on rock cores from the site investigation areas. It has then been possible by means of geophysical borehole logging (gamma-gamma probes) to measure density variations to determine both thermal conductivity and spatial variations for above all felsic and intermediate igneous rocks /12-7, 12-8/.

Programme

Different methods for measuring the thermal conductivity of the rock in the field have been discussed during the site investigations. One alternative is to modify existing methods for measurement on outcrops (single- and multi-probe method). In situ measurements by means of the multi-probe method have been performed in Forsmark and Laxemar. Another alternative is to develop the hydrogeological measurement system PSS (Pipe String System) to be able to measure the thermal conductivity of the rock surrounding a borehole. Pulse tests with hot water in existing boreholes have not yet been performed.

An analysis will be made of what method development may be needed. Among other things, the possibilities of using both the multi-probe method and the method with heat pulses in cored boreholes will be evaluated.

12.3.6 Equipment for hydraulic tests (single-hole tests)

The equipment that was used in the construction of the Äspö HRL performed in accordance with the original requirements, which prescribed that the hydrotests for underground purposes should primarily be performed as so-called outflow tests. But the equipment was not optimally designed when it came to minimizing measurement and setup times.

A number of groups with different areas of responsibility (design, construction, modelling and safety assessment) will collaborate in the construction of the repository. The groups will have different preferences concerning which measurements should be performed, measurement ranges, accuracies etc. In the Äspö HRL SKB has determined the hydraulic properties of the rock mainly by means of sectional measurements with a packer system, but also – although to a lesser extent – by flow measurements along the borehole using the Posiva Flow Log (PFL). By means of sectional measurements it is possible to measure both large (up to about 50 litres per minute) and small flows. It is also possible to evaluate the type of flow regime for the particular flow anomalies, but the labour input is great if the exact position of hydraulic anomalies has to be determined along the entire borehole. In flow measurements along the borehole with PFL, it is not possible to measure flows of hydraulic anomalies that are greater than 5–10 litres per minute. Both methods will be needed during the construction of the final repository.

Programme

SKB plans to develop two types of hydrotest equipment prior to the construction of the final repository. Both must be quick to set up and functional.

- Equipment for measurements in long investigation holes. In its function it should be similar to SKB's existing equipment that has been used in the Äspö HRL. Measurements are performed in the form of outflow tests. The whole borehole is sealed off at the borehole mouth and sectional measurements are performed along the hole. The section inside the active measurement section is connected with the outer section so that the pressures in the sections surrounding the measurement section are equal.
- Equipment for measurements in probe holes in particular. It must be very durable, flexible and extremely quick to set up so that it can be used when important flowing fractures are encountered. It must be possible to perform single- or double-packer measurements with positive or negative pressure.

12.3.7 Measurement of water flows in ramp and tunnels

The method used at the Äspö HRL to measure flows along tunnels did not work perfectly at the start of the construction of the Äspö HRL, partly because the measuring dams that were built quickly filled with fine material from the construction work. The method involves collecting water leaking into the tunnel in dams placed straight across the tunnel. The outflow from the dam is measured by a measuring weir. The equipment and method have been improved, but further improvements are needed.

Programme

The objective is that the measurement systems should be sufficiently accurate. They should also be easy to install, easy to adapt to the progressive construction of the tunnel, and easy to clean and calibrate. The measurements should cause as little disturbance to the construction work as possible, and vice versa. The work includes an inspection of sensors and a revision of manuals for use and calibrations. At the same time, other methods for collecting and measuring water flows along tunnels should be investigated. But the water must be collected in dams. It should be possible to improve the measurement system, however. This can, for example, be done by conducting the water into a pipe after the dam and measuring with inductive flow meters.

If any of the surveyed methods is sufficiently promising, it is tested – preferably in the Äspö HRL.

12.3.8 Measurement of inflow to deposition holes

The hydraulic properties of the rock are of great importance for whether a deposition position can be accepted or must be abandoned. Important hydraulic parameters are the inflow to the deposition hole, the flow distribution and the transmissivity of the surrounding rock.

Measurements and determinations of hydraulic parameters have been performed in the Prototype Repository in the Äspö HRL /12-9/. The results can be summarized in the following points:

- The total flow into the hole was determined by measuring the change of water volume in the hole by time. The method worked well and should be able to be applied in the final repository.
- The flow distribution along the borehole wall was measured with the aid of sorbing material. The work was time-consuming and further development is needed.
- The transmissivity of the hole was calculated on the basis of measured total inflows and pressure conditions adjacent to the hole. The calculation of the hole's transmissivity was considered somewhat uncertain.

The conclusion is that more efficient methods need to be developed.

Programme

The development and choice of methodology and methods for investigations and measurements in deposition tunnels and deposition holes will be coordinated in a joint project for all concerned disciplines. Development efforts are needed for the following measurements:

- Qualitative survey of flows and positions for points of leakage in the borehole wall. The work includes developing a scanner function that can be used for other documentation of the borehole wall.
- Quantitative measurement of the two to three largest flows along the borehole wall. The work includes developing collecting devices for water. They must be able to be installed quickly and easily on the borehole wall.
- Determination of transmissivities by means of hydraulic tests. In order for reliable data to be obtained, the rock must be water-saturated. This means that the hole must have been water-filled for a long time before measurements are performed so that all air has been dissolved in the water.

12.3.9 Determination of sorption parameters

In the general site investigation programme /12-2/, a need was identified to be able to show that the retention parameters (K_d and cation exchange capacity) that are determined in the laboratory agree with the parameters that are determined under repository-like conditions. Measurements in the laboratory are done on drill cores taken from repository depth, but pressure release and preparation of the specimens can create microfractures and change the chemical conditions in the specimens. Sorption measurements are mainly performed on crushed rock material. Only a few measurements are performed on intact pieces in an initial attempt at upscaling. The next step in the upscaling process is to carry out in situ tests under repository-like conditions.

Programme

Experiments during the site investigations have revealed the difficulties of performing in situ determinations in boreholes at great depths. Development of methods in accordance with the proposal in /12-2/ has therefore been abandoned. An alternative is to use the methods developed within the LTDE (Long Term Diffusion Experiment) project in the Äspö HRL. The equipment and methods used are complicated, however. They cannot be used directly on several sites. Simplified equipment for determining sorption parameters, k_d, and/or cation exchange capacity (CEC) will be developed.

12.3.10 Determination of pH and redox conditions

Apparatus for in situ measurement of pH and redox conditions has been developed within the framework of several projects at the Äspö HRL /12-10, 12-11/. These instruments were developed to measure continuously during the entire duration of the project. An initial test with a portable instrument that could be used for pH and Eh measurements anywhere in the Äspö HRL was performed in the Prototype Repository. All instruments so far have contained specially customized electronics. Commercial instruments have proved to have problems in the tunnel environment, even though they have worked well in the laboratory.

Programme

There is a need to develop and test several instruments for in situ measurements of pH and Eh. The purpose is to be able to perform measurements even in borehole sections with a small groundwater flow. Prior to the final repository's construction phase, SKB will continue its efforts to develop new instruments for groundwater characterization – mainly for pH and Eh measurements in direct connection with boreholes in tunnels.

12.3.11 Information systems and information technology

Through the years SKB has procured, customized and developed several information systems that are specially adapted to our needs. In preparation for the construction of the Äspö HRL as well as the site investigations, major efforts were made to gain access to modern and efficient systems. In order to reduce the risks of errors in the transfer of information between the systems, but also to streamline the work, the systems have in several cases been integrated.

Programme

SKB will continue its efforts to improve and optimize information systems. Construction and operation of the final repository will proceed for a long time. There are therefore considerable gains to be made by obtaining access to well integrated and efficient systems. This also enhances quality and safety. The information needs will be identified on the basis of planned work processes in the construction and operation of the final repository. The support that is needed in the form of information systems and storage structures will then be identified.

SKB believes that it is sufficient in many cases to adapt existing systems. But certain systems, such as the tunnel mapping system, must undergo greater changes when new technology (laser scanning) is put into use. Integration between the systems must be given special consideration, due to the short time cycles with demands on rapid interaction between investigations and measurements, modelling and design, construction and operation.

Storage structures and storage methods in the form of databases must be further developed to handle the large quantities of data that will be collected during construction and operation of the final repository. In connection with this, the information technology (computers and networks with software) must also be further developed to enable large quantities of data to be handled directly at the tunnel face and to enable collected data to be visualized in real time.

12.4 Sealing by grouting

The final repository will be located in rock of mainly good quality with a low frequency of water-conducting fractures. Sealing measures will nonetheless be necessary if we are to manage deposition and backfilling with the stipulated quality. We intend to seal the rock by means of grouting.

Requirements on watertightness are the same as those that apply to virtually all hard rock facilities: limited lowering of the groundwater table with a view to subsidence, water supplies and the environment, and limited water inflow with a view to the use of the facility. Furthermore there are requirements associated with long-term safety. One is that the penetration of deep-lying saline water should be limited with a view to its impact on buffer and backfill. Inflows in any point and cumulative flows must also be limited to prevent erosion of buffer and backfill. The requirements on the long-term performance of the final repository lead to certain restrictions on grouting materials, for example with regard to the pH of the leachate from the grout and additives used.

Some of the information needed to determine the scope of the sealing measures that will be needed will be obtained from the ongoing site investigations. The sealing requirements will be dependent on the properties of the selected site and of the buffer and backfill. Design step D2 and current research activities are based on the assumption that we need to limit water inflow in ramp and shafts, the central area and tunnels up to the deposition area to ten litres per 100 metres of length, and in deposition tunnels to ten litres per 300 metres of length. In the deposition tunnels we also need to limit the leakage in any one point to one litre per minute.

The combination of tiny fractures and high water pressures found at repository depth is not found in rock where conventional tunnels (such as road or rail tunnels) are built. In order for us to be able to meet the tightness requirements, we must develop technology to seal these tiny fractures with high water pressures. We also expect to pass zones with more conductive rock that must be sealed. This also requires modified technology, but this technology has a lot in common with existing conventional technology.

Conclusions in RD&D 2004 and its review

In RD&D-Programme 2004, SKB drew the conclusion from our collaboration with Posiva and Numo that cementitious grouts that give leachates with a pH lower than 11 must be developed for the sealing of fractures with a fracture aperture down to about 0.1 millimetre. Other, non-cementitious materials need to be investigated for finer fractures. Silica sol had the greatest potential to be successful.

In its review, SKI commented that SKB should have an alternative plan for how grouting is to be done in the final repository if the development efforts do not lead to the expected results. SKI also said that SKB should acquire knowledge about sealing of major zones or fractures. A detailed programme for research, development and demonstration of grouting was called for.

Newfound knowledge since RD&D 2004

The requirements have become clearer since RD&D-Programme 2004 as a result of the fact that the sites being considered for the final repository have been further investigated and as a result of analysis of what will be required in the construction of a final repository.

Developing methods to obtain a better understanding of the conditions that control the spread of the grout in the rock mass and its penetration into the individual fracture has been of central importance. Another important area has been low-pH grouts, both cementitious and non-cementitious. Stiftelsen Svensk Bergteknisk Forskning (SveBeFo, the Swedish Rock Engineering Research Foundation) has published a book on cement grouting in hard rock /12-12/. The purpose of the book is to disseminate knowledge about the findings of recent years to a larger circle of users.

A number of activities in SKB's programme have yielded new and important information. SKB has compiled the available knowledge and analyzed the need for further information on grouting in preparation for the planning and construction of the final repository /12-13/.

In a sealing experiment in the Äspö HRL, a methodology for rock characterization was used that predicts grout spread /12-14/. The results have now been further followed up by overcoring and studies of the actual grout spread. As expected, large quantities of grout were found where the characterization indicated large fractures and where the tunnel wall is now tight. Fine fractures were also encountered. It was found that they did not contain any grout. The grouting results agreed well with the predictions. In the characterization method that was used, a prediction is made of the transmissivity distribution of the fractures /12-15/ and the smallest fracture that must be sealed to achieve the desired tightness is identified. This approach has also been applied in other projects, for example in the Törnskog Tunnel in Sollentuna /12-16/.

A theoretically based criterion has been developed that describes when the grouting of a single hole should be stopped. The criterion is based on the relationship between grout penetration and grouting time /12-17/. The relationship is relatively new and under evaluation. It has been tested against field data from the sealing test in the Äspö HRL /12-18/.

Suitable grouting materials for a final repository have been studied in a cooperation project between SKB, Posiva and Numo /12-19/. Based on extensive laboratory work, it was concluded that there now exist cementitious grouts for large fractures (wider than 0.1 mm) and non-cementitious grouts for smaller fractures. After optimization, it is expected that these materials can be recommended for use in the final repository. The cementitious grout consists of microfine grouting cement and finely divided silica fume with a possible addition of superplasticizer. The non-cementitious grout consists of colloidal particles of silica in an aqueous solution that forms a gel when salt is added (silica sol). The report states that silica sol does not pose a threat to human health or the environment. A thorough study has been focused on gaining a better understanding of the mechanical properties of silica sol as a basis for grouting design and of its performance with respect to drying-out /12-20/.

Much has been learned about the key properties of cementitious grout, such as its ability to penetrate into fine fractures, its rheological (fluid) properties and its strength growth. /12-21/ shows and explains how finer grinding of the cement does not enable the grout to penetrate into finer fractures. Instead it leads to reduced penetration due to increased chemical surface activity. The old rule of thumb that grout is filtered when it tries to penetrate into a fracture opening smaller than three times the grout's grain size is also confirmed. A description is provided in /12-22/ of the mechanisms that lead to grouting problems that are linked to the strength of the fresh and the cured grout. With the aid of these relationships, it is possible to determine which grout is theoretically suitable in a given situation. /12-22/ also sheds light on the necessity of having a grouting pressure that is large enough in relation to the prevailing water pressure.

Large water-conducting zones will have to be passed during the construction of the final repository. A study has been made of different technical solutions and their feasibility /12-23/. The study indicates that water inflow can be controlled by grouting, and that ground freezing combined with a lining may be an alternative.

A conceptual description of the pre-grouted rock mass and the pressure situation as a basis for a theoretically based design of post-grouting is presented in /12-24/.

The understanding of the ability to control the grouting system – fractures, grout, method and equipment – has deepened. The grouting system should be controlled in an organizational context. An attempt at controlled adaptation of grouting to the rock conditions encountered according to the Observational method is described in section 6.3.3 in Part II.

Programme

The goal of SKB's efforts in the area is to develop methods, grout and equipment to be able to handle the inflow situations that can arise in the final repository. The purpose is to be able to show that knowledge, methods, materials and equipment exist that enable the specified requirements for grouting to be met.

Since SKB is a one-time purchaser of underground facilities, we have to cooperate with the industry. Based on the general competence that exists in the industry, SKB as an organization must develop its competence and adapt its procedures for the construction of the final repository. Contributions made by actors other than SKB are therefore described below.

Methods

A broad development and demonstration initiative is under way in the project "Sealing of tunnel at great depth" in the Äspö HRL. The goals of the project are to investigate whether silica sol is a suitable material to use at repository depth and whether it is possible under the prevailing water pressure to meet the preliminary tightness requirements adopted for a deposition tunnel. A tunnel just under 100 metres in length will be built in the Äspö HRL for this purpose. Construction will proceed stepwise and is planned to include a conventional grouting fan, a fan with holes drilled inside the tunnel perimeter, post-grouting and drip sealing. If the fracture conditions are suitable, cementitious low-pH grout will also be tested. The previously presented characterization and grout spread models are implemented in the project. The project will also yield experience for improvement of results follow-up and equipment, among other things.

A post-doc project concerned with post-grouting is continuing with field tests based on the conceptual model presented above for the purpose of being able to propose suitable strategies for post-grouting measures.

Another special application is the passage of highly water-conducting zones. A study is planned where data and experience from grouting of zones in connection with the construction of the Äspö HRL will be analyzed.

Results from the use of high grouting pressures in a number of projects are planned to be collected. The doctoral project where a conceptual model for how the rock mass reacts to high grouting pressures and how the grout spreads is continuing.

The possibilities of achieving a better rock characterization methodology with the aid of a three-dimensional model are being explored in an ongoing licentiate project.

The following activities related to the grouting process are being conducted by principals other than SKB:

- A doctoral project focused on droplet formation and drip sealing.
- A licentiate project about how today's knowledge can be converted into practical and economic guidelines for grouting.
- A post-doc position has been created in the field of characterization and fracture description of the rock.

Materials

An evaluation of the cementitious low-pH grout used by Posiva will be carried out with a view to SKB's needs. Regarding low-pH grout and passage of zones, Posiva has presented a programme as a basis for selecting materials for passage of the so-called R20 zone in Olkiluoto /12-25/.

The consequences for long-term safety of organic additives in cement are being evaluated in a joint project with Posiva and Numo.

Moreover, grout penetration is being investigated in an ongoing doctoral project entitled "Grout penetrability and separation" (in Swedish only).

The following studies related to materials are being conducted by principals other than SKB:

- Erosion of grout and fracture-filling material. This project has a direct bearing on SKB's project with high water pressures and hydraulic gradients.
- Long-term durability of grout. By long-term is meant in this project about 100 years, so the long-term safety of the final repository is therefore not a primary issue, but the final repository will be in operation for many years and the durability of the grout is therefore of interest for SKB. The project is aimed at evaluating mechanisms and times for degradation of silica sol and cement based on analyses of thermodynamic stability.

Equipment and execution

The availability of suitable grouting equipment must be ensured prior to construction of the final repository. A survey is planned as a complement to the experience that is expected to be gained in the project "Sealing of tunnel at great depth" in the Äspö HRL.

Planning and execution of grouting is necessarily an iterative process, both between the design phases and within the driving cycle. Clear processes must therefore be established for design, control and documentation of the grouting work. Based on new theoretical knowledge and verifying experience in the field, a possible design process for the final repository should be described. The iterative process is conditioned by the need for adaptation to the actual conditions encountered and will, according to SKB's plans, be expressed in terms of the Observational Method. No formal application of the Observational method to grouting is known, and the interpretation of the Observational method for grouting that is presented in /12-13/ must be tried and developed, see also section 6.3.3 in Part II.

12.5 Drill-and-blast of rock openings

Large volumes of rock will be excavated in the construction of the final repository. Stress redistributions and deformations will occur around the cavities that are created in the rock. Water-conducting fractures cause inflow if they are not sealed. It is our opinion that the drill-and-blast method can master these difficulties in a satisfactory manner. SKB therefore recommends this method for mining of the central area, transport tunnels, main tunnels and deposition tunnels.

Conclusions in RD&D 2004 and its review

SKB drew the conclusion from the mining of the Apse tunnel in the Äspö HRL that conventional drill-and-blast can be controlled so that it causes limited damage in the rock. In its review of RD&D-Programme 2004, SKI commented that in view of the stipulated requirements, SKB should nevertheless consider full-face boring of deposition tunnels and deposition holes.

SKI also pointed out that freedom of choice with regard to methods for rock excavation persists all the way up to excavation of the deposition openings. In practice, however, freedom of choice is severely limited since SKB must, in the process of designing the underground part of the final repository, propose methods for rock excavation of the various openings in the design phase. This is because the rock excavation method influences the design of the equipment for boring deposition holes, the equipment for installing buffer, the deposition machine and finally backfilling and closure of the deposition tunnels.

Newfound knowledge since RD&D 2004

We have continued to analyze various advantages and disadvantages and have, with the support of, for example, the results of the SR-Can safety assessment, observed that the excavation-disturbed zone (EDZ) appears to be of little importance for nuclide transport, compared with natural fractures intersecting a deposition tunnel. Nevertheless, controlled drill-and-blast is recommended in all tunnel systems in the final repository, and quality requirements must be formulated for this. Furthermore, a horseshoe-shaped cross-section permits a more efficient utilization of the cross-sectional area.

The requirements on deposition tunnels, with a view to excavation damage in the country rock, were analyzed in SR-Can /12-26/. The results showed that damage of the magnitude detected in the Zedex experiment /12-27/ and in the Apse tunnel /12-28/ in the Äspö HRL does not jeopardize the long-term performance of the final repository. However, changes in mechanical and hydraulic properties in the rock beneath the floor of the deposition tunnel are particularly crucial, since that zone is in contact with the deposition hole. Added to this are quality requirements and preferences during deposition and closure to permit good mobility for the deposition machine and sufficient evenness in connection with emplacement of the backfill's bottom block. In reality, the preference is a smooth and even surface with only a slight lateral inclination. Longitudinal slope is determined by the preference of natural drainage, which means a slope of 1:100 to 1:50 upward counting from the transport tunnel.

From experience in the Apse tunnel we draw the conclusion that the easiest way to meet the requirements on minimization of the excavation-damaged zone in the tunnel floor is by dividing the tunnel section into a top heading and a bench instead of blasting the entire cross-sectional area all at once. The top heading is driven first. The technology for driving the top heading doesn't differ from the previously described technology for controlled drill-and-blast. The roof is supported before the bench is mined. If the excavation-disturbed zone in the tunnel floor is no more than 0.8 metre deep, the remaining bench should be of at least that thickness.

Experience and results from the Apse project have been compiled and analyzed. The project included driving of an approximately 70 metre long tunnel in the Äspö HRL at a depth of 450 metres. Due to strict requirements on controlled blasting, the driving process was special. The tunnel was driven so that we could study the stability of the rock in a pillar between two vertically bored holes 1.8 metres in diameter and 6 metres deep /12-29/. We wanted to have high stress concentrations in the area between the holes, so the tunnel was configured with a high cross-section and a semicircular bottom. The holes in the tunnel were charged with explosive and initiated mainly with Nonel. To investigate if the excavation-damaged zone (EDZ) could be further reduced, the three last rounds were set up for initiation with electronic detonators. Blasting precision was very good and was a prerequisite for the success of the controlled blasting. Figure 12-4 shows some results from the investigations of damage in the rock.

Stiftelsen Svensk Bergteknisk Forskning (SveBeFo, the Swedish Rock Engineering Research Foundation) has studied the extent of the EDZ, and in Onkalo there is experience from practical ramp driving by drill-and-blast /12-25/.

The evaluation of excavation damage from the Apse tunnel in the Äspö HRL /12-28/ showed that macroscopic fractures were induced along the contour holes. In a cross-section to the contour holes, the induced fractures that were nearly parallel to the walls tended to be longer than those that were induced at a large angle to the walls. Only in exceptional cases had the induced fractures from two nearby contour holes propagated so that they intersected. The frequency of induced fractures declined rapidly with the distance from the contour holes. The maximum fracture length in the walls was about 0.3 metre for blasting with Nonel and 0.2 metre for blasting with electronic detonators.

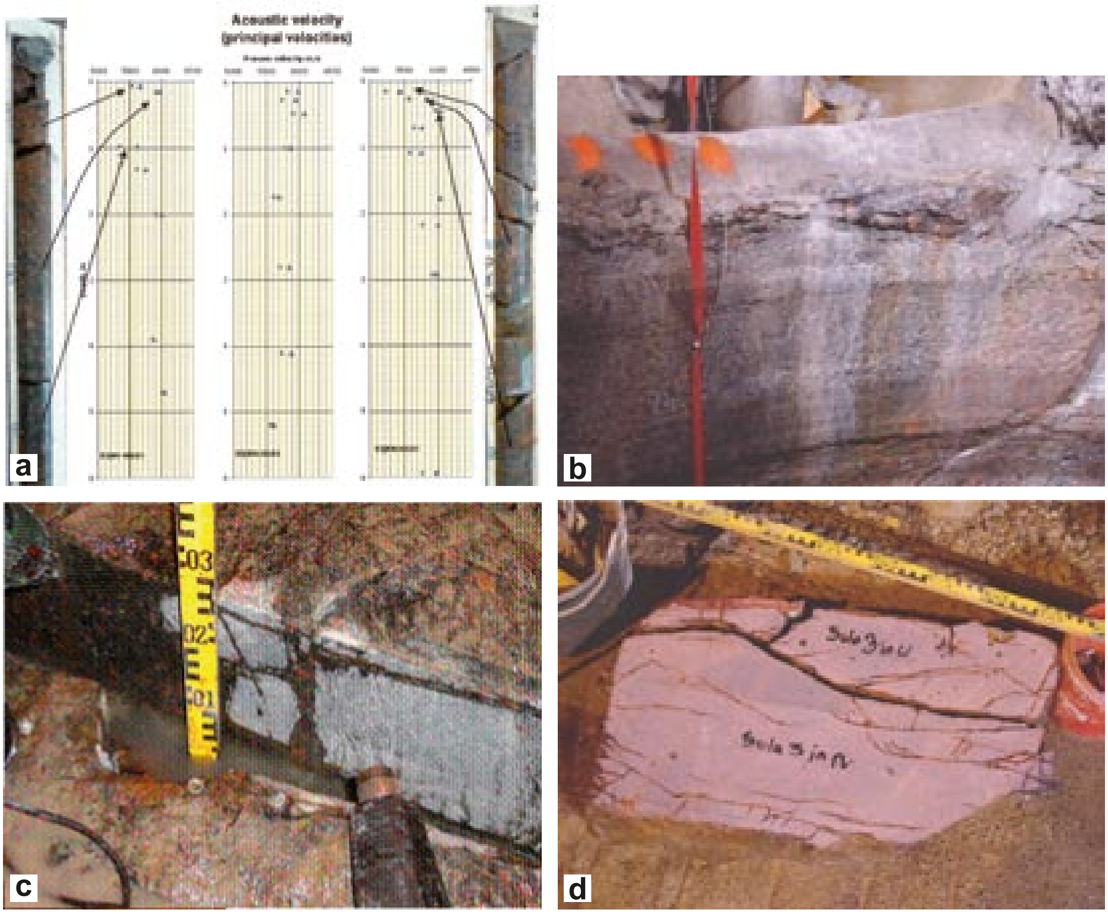


Figure 12-4. *Observed excavation-disturbed zone (EDZ) in the Apse tunnel. a) photos of drill cores and results of P-wave measurement in them, b) observed damage in 1.8 metre diameter deposition hole for the Apse experiment (a thin concrete layer evens off the rock surface), c) observed fractures in slot sawn in the floor in a drill pipe, and d) a slice from the floor across the drilling direction in which two blast holes can be seen (at the top of the slice).*

The former result agreed with previous results from Zedex /12-27/ where Nonel was also used. The macroscopic fractures in the floor were gently-dipping, see Figure 12-4. This is believed to be due to the fact that the tunnel was excavated with top heading and bench, in other words the rock volume nearest the floor was blasted separately. Only an occasional induced fracture was directly connected with a contour hole. It is judged that the circular cross-section of the tunnel floor, whose purpose was to cause high secondary stresses in the floor /12-29/, may have caused some stress-induced fracturing. After measuring in a longitudinal section in the wall over two rounds, we were able to conclude that the macroscopic fractures that were induced along the contour holes were not continuous across the boundary to the next blasting round. Instead, short macroscopic fractures were observed at a large angle to the tunnel, probably sub-parallel to the tunnel face. The fact that excavation-induced fractures are not continuous along several rounds is explained by the fact that the drilling geometry leads to a greater discontinuity between drill pipes in the perimeter than the depth of the excavation-induced fractures. The impact of blasting and stress redistribution also leads to microscopic fractures, probably of an order of magnitude within and between mineral grains. These are not observable without a microscope, but their presence is indicated via seismic velocity. In the Apse tunnel, reduced P-wave velocity was observed down to 0.4–0.5 metre beneath the floor, see Figure 12-4. Hydraulic properties on a relevant scale have not been determined to be affected by macro- and microscopic fractures in the EDZ, but sensitivity analysis of their possible influence was done in SR-Can.

In order to satisfy the quality requirements on the true perimeter of the tunnels, as opposed to with the theoretical perimeter, and limit the influence of the near-field rock it is extremely important to have:

- Good precision in drilling of the round so that the explosive comes as close to the intended position in the round as possible. To achieve this, a system is being developed with higher precision than today's alignment and positioning systems.
- Good control in the charging of the different holes so that the blasting effect is as intended. This is a matter of keeping track of the quantity of explosive charged in each hole.
- Good control over the initiation of the round so that the blast goes as planned, with a view to the damage to the perimeter caused by vibration. Electronic detonators have very good precision and high potential for reducing fracturing in remaining rock. But they need to be made more user-friendly.
- Measurable requirements on the above parameters that together contribute to minimizing the EDZ. Indirect parameters such as drilling tolerance and good control of charging are deemed to be of great importance for controlling the development of the EDZ, even though they are indirect parameters. In addition, verifying observations of the depth of the excavation-damaged zone are required, but this can only be done in the form of spot observations. Geophysical methods for indirect estimation of the depth of the EDZ are another possible method.
- Good knowledge of the hydraulic properties of the excavation-disturbed zone. Low hydraulic conductivities are very difficult to measure in situ. We nevertheless consider it important to confirm our knowledge of the extent of the excavation-disturbed zone, particularly in deposition tunnels and deposition holes, by field observations of the zone's hydraulic properties. Measurements in the laboratory are planned on small rock samples from the tunnel periphery. The possibility of using gas, which has a much faster transport velocity, is being investigated with respect to the relevance of the interpretation of measured values in hydraulic terms. The method using surface packers is being investigated with respect to measurement of sawn-out blocks or rock surfaces.

SKB has no intention of studying TBM boring for excavating deposition tunnels during the current design phase, D2, but only intends to study technology for drill-and-blast tunnelling.

We persist in our opinion that ventilation and elevator shafts should be mined by means of raise boring, for practical and economic reasons. Little impact on side walls is a bonus. With regard to excavation of deposition holes, SKB persists in its recommendation that these holes be mined mechanically by means of reverse raise boring as a reference alternative.

Programme

SKB will study drill-and-blast technology during the current design phase D2. By collaboration in different industry organizations, SKB is gaining further know-how of how to build tunnels with minimal impact on the near-field rock:

- Emulsion explosive (Site Sensitized Emulsion – SSE) is gaining wider use in the mining and civil engineering industries. This explosive has several advantages. An obvious advantage for progressive construction in parallel with operation of the final repository is that SSE is not active until it is mixed, normally at the working face. This means that no attention has to be given to requirements regarding storage and transport of explosive substances. By gasifying the emulsion more or less, varying density and thereby charging concentration can be obtained. However, the application of SSE explosives is not completely trouble-free today.
- The Swedish Blasting Research Centre (Swebrec) is a centre of excellence at Luleå University of Technology. They are conducting research on the impact of SSE explosives on the excavation-damaged zone in a collaboration project between manufacturers, construction companies and contractors. The goal is to formulate guidelines for assessing the excavation-damaged zone on the basis of different charging concentrations with SSE explosive. SKB is participating in this industry research project.
- Nordic Rock Tech Centre (RTC), whose biggest owner is the Swedish Mining Research Foundation, MITU (Mineralindustrins teknikutveckling), with the mining companies LKAB, New Boliden and Lundin Mining as founders. RTC is conducting the project "Faster and better tunnel drifting" on behalf of mining companies and contractors. SKB is participating in this work in order to gain practical experience of quality work in conjunction with rock works, which we believe is an important aspect of ensuring a minimal excavation-damaged zone.

Preliminary studies have also been made of suitable drill-and-blast plans for limiting the excavation-damaged zone in the rock. We believe that we can remain within the values that could affect long-term safety for the final repository. In addition to the projects mentioned above, SKB is privy to Posiva's experience from the construction of Onkalo, where much is being learned about how to optimize a modern drilling rig to meet the quality requirements for drilling. SKB intends to keep track of the results of the rock excavation work in Onkalo and station a representative on the site. Posiva is establishing a programme there for control of the excavation-disturbed zone /12-25/. Experience and results from experiments and tests conducted in Onkalo will supplement the programmes for research and development in the Äspö HRL.

During construction of the final repository, the actual properties and behaviour of the rock will not become fully known until rock excavation has been completed. A systematic work methodology is needed in order to handle the uncertainty regarding the site conditions. This methodology is described in section 6.3 in Part II. The Eurocode standard for geotechnical design /12-30/ will apply in Sweden starting in 2009. A project is being pursued within the trade organization SveBeFo on the application of the Observational Method – one of the methods that may be applicable in connection with the design and construction of the repository's hard rock facilities. SKB is following this work and has introduced it in the design premises for design phase D2.

The hydraulic properties of the excavation-damaged zone (EDZ) have been investigated in several projects previously and are currently being studied in the joint international Decovalex project. The focus lies on understanding the connection between the mechanical disturbance and the change in hydraulic conductivity in both the radial and axial directions in relation to the tunnel. Since every blasting round has weak stemming in the outer part of the boreholes, the zone is intermittent along the tunnel. But the zone may be in radial connection with fractures that are of hydraulic importance for the performance of the final repository. Above all the zone in the floor is an important area. The knowledge from Decovalex will be used to design field tests in zones with various degrees of excavation disturbance in the Äspö HRL, including the zone formed by a controlled excavation of the bottom bench in deposition tunnels.

The ambition during this RD&D period is also to design and execute a large-scale measurement test on the excavation-disturbed zone around a drill-and-blast tunnel with a realistic rock stress situation and realistic geohydraulic conditions.

SKB will need access to additional tunnels in the Äspö HRL in order to carry out different types of experiments and demonstrations. Our intention is to exploit the construction of these tunnels in order to demonstrate possible drill-and-blast plans and thereby verify that the desired quality is achieved. The plan is that these tunnels should have the same dimensions as the future deposition tunnels and that the programmes to execute the rock excavation work will constitute preliminary programmes for similar works in the final repository.

The plan to try out sealing technology in a tunnel in the Äspö HRL will provide an opportunity to test selected aspects which are currently considered quality-critical for achieving a smooth perimeter and a minimal EDZ. After evaluation of the experience, SKB intends to drive another tunnel in the Äspö HRL in order to test a total quality approach in tunnelling before the construction of the final repository begins. In addition, a special experimental tunnel will be needed to develop explosives and electric detonators.

For excavation of the bottom bench in the deposition tunnel, we have analyzed two methods for controlled excavation: controlled drill-and-blast and wire sawing. Both methods will be tested in field tests in the Äspö HRL. In drill-and-blast excavation, high demands are made on drilling precision and follow-up so that the floor will be smooth. Deviations from the theoretical profile are of importance and are monitored by means of laser measurement of the tunnels. Wire sawing of the floor and removal of the bench will probably be done in increments of about 50 metres. After removal of the loosened rock, the next sawing stage can be carried out until the whole floor has been sawn and the bench removed. The wire pulley runs in two holes on either side of the floor.

In order to establish an efficient and streamlined operation, SKB intends to organize a group at the Äspö HRL that specializes in tunnelling with grouting.

12.6 Rock support

The main rock support methods that will be used are conventional support elements such as rock bolts, shotcrete and wire mesh. The rock support will be left when the repository is closed so that backfilling can be done under secured rock conditions. The strategy for rock support is based on the principles of the Observational method, see section 6.3.3 in Part II.

The durability of the underground facility during the construction and operating phases is determined by, among other things, the technical lifetime of the different parts of the facility. The need for rock support is a part of the design-basis information gathered for the underground part of the facility. This need is dependent on such factors as the properties of the rock mass, loads in the form of rock stresses and the geometry of the openings. The need for rock support is also dependent on the performance and technical lifetime of the openings, as well as maintenance and environmental requirements.

The general requirements on rock support are formulated in the design premises. The recommended service life requirement is five years for a deposition tunnel, since it will be backfilled after deposition. This is equivalent to the requirements that are normally made on temporary rock support in civil engineering projects and mines. The service life requirement in the rest of the facility has been set at 100 years. This is equivalent to the existing requirement on infrastructure tunnels /12-31/.

Conclusions in RD&D 2004 and its review

In the review of RD&D-Programme 2004, a need was expressed for SKB to specify what pH values are expected in grout for rock bolts and shotcrete for rock support. SKB's objective is that these products should be of a low-pH grade that gives leachate with a pH lower than 11.

Newfound knowledge

The rock support methods being considered for the final repository are all conventional and commercial. The recipes for grout for rock bolts and shotcrete, which meet the requirements on low pH, are being developed.

In the ongoing EU project Esdred, which is a part of the Sixth Framework Programme, there is a sub-project concerned with development of recipes for low-pH shotcrete /12-32/.

SKB has – in cooperation with the Swedish Cement and Concrete Research Institute (CBI) – improved a recipe for shotcrete. The recipe was originally developed by Enresa in Spain. The improved recipe was tested in a pilot test in a concrete laboratory in Älvkarleby and was furthermore used in 2006 in a small field test at the Äspö HRL /12-33/.

The rock support needs on the two candidate sites have been studied in conjunction with the design work (phase D1). One conclusion is that sufficient firmness and stability can be achieved under most conditions by relatively simple measures, such as bolting and surface support with shotcrete or wire mesh. We only expect more extensive rock support to be needed when deformation zones are passed.

Besides in bolt grout and shotcrete, low-pH concrete will also be used in plugs for the deposition tunnels, base slabs at the bottom of the deposition holes and possibly in the road surfacing in the final repository's tunnel system.

Programme

Development of low-pH recipes for cement for rock bolts, shotcrete and road surfacing is continuing. Suitable materials will be tested in the Äspö HRL.

We will also study and try out how modern wire mesh technology can be used to reduce the total quantity of shotcrete. Field tests will be performed in the Äspö HRL, in Onkalo and in other facilities where we can establish cooperation.

12.7 Boring of deposition holes

The straightness and diameter of the vertical deposition hole must be kept within narrow tolerances. This is important in order for the final density of the buffer to be within the stipulated limits. Furthermore, damage to the surrounding rock must be minimized and impurities in the deposition hole avoided. The bottom of the deposition hole should be as horizontal as possible. This facilitates the construction of the bottom pad in the deposition hole, which must be completely flat. If a flat bottom cannot be achieved in the deposition hole, a larger radial space between the canister and the buffer rings will be required.

12.7.1 Boring

Conclusions in RD&D 2004 and its review

The methods for boring deposition holes that are judged to be feasible are shaft boring or drilling of pilot holes with subsequent reaming.

Full-face boring of deposition holes has verified the extent of the excavation-disturbed zone as a function of different boring parameters /12-34/.

Newfound knowledge since RD&D 2004

A feasibility study was carried out in the autumn of 2006 dealing with different technologies for excavation of deposition holes. The following methods were considered possible:

- Reverse raise boring
- Shaft boring machine (SBM) or tunnel boring machine (TBM)
- Water cluster
- Air cluster
- Water jet
- Core drilling

Rock excavation for deposition holes by drill-and-blast or stitch drilling were dismissed, since these methods cannot meet the requirements for the deposition holes.

The results of the feasibility study have led us to choose reverse raise boring as a reference method. Work has begun on a basic design of a machine that meets the requirements of the final repository. We have experience of this method from trial boring of three deposition holes in Posiva's investigation tunnel for the VLJ repository for low- and intermediate-level waste in Olkiluoto /12-35/ and from boring of long horizontal deposition tunnels for KBS-3H in the Äspö HRL /12-36/.

The reason SKB chose reverse raise boring requirement is that the equipment is best able to meet SKB's requirements with regard to:

- safety, geometry and environmental impact,
- efficiency and durability,
- established technology, which leads to reduced development costs and shorter development times as well as more efficient operation and maintenance.

The problem of spalling of the deposition hole walls touches on several disciplines, including boring of the deposition holes. The boring sequence can make the situation either better or worse depending on how the work is done. The design of the boring machine thus depends on whether there is a risk of spalling, and the issue must be considered in this regard as well.

Programme

When the design of the machine for reverse raise boring of deposition holes is concluded, we will conduct an evaluation of the machine's performance and overall efficiency. The plan is to then go on and manufacture a prototype machine, see Figure 12-5.

Development of the water jet and core drilling alternatives will be followed over the next few years, and we may initiate limited testing ourselves.

12.7.2 Removal of chamfer in the deposition hole

Conclusions in RD&D 2004 and its review

RD&D-Programme 2004 did not cover the removal of a chamfer in the deposition hole.

Newfound knowledge since RD&D 2004

The reference design of the deposition machine is based on lowering the bottom part of the radiation shield into the deposition hole when the canister is deposited. The tunnel height can thereby be limited, compared to if the radiation shield is placed above the deposition hole. The tilting movement down into the deposition hole can only take place if a chamfer is removed in the top part of the deposition hole. The chamfer must be 1.1 metres deep and 1.6 metres wide. The function of the deposition machine during deposition is based on a tilting movement, simultaneous forward and downward.

Two alternative methods for removal of the chamfer are wire sawing and water jet. Of these, we consider wire sawing to have the greatest potential. In the demonstration tunnel at a depth of 420 metres in the Äspö HRL, chamfers were made in the holes where SKB's rail-bound deposition machine deposited canisters. They were removed by stitch drilling.

Programme

Suitable technology for removal of the chamfer will be tried out in the Äspö HRL.

Figure 12-5. *Boring of deposition holes by reverse raise boring in Olkiluoto in a joint project between SKB and Posiva.*

13 The buffer line

The buffer line includes manufacture, handling and installation of the buffer, in the form of rings and blocks of highly compacted bentonite, that surrounds the canister in the deposition holes. The line includes compaction of bentonite blocks and rings, fitting-out of the deposition holes and installation. Besides rings and blocks, bentonite in the form of pellets or granules may be used to fill the gaps formed against the rock wall in the deposition holes.

The colour coding of the buffer line shows the areas for which there is known and proven technology that can be applied to the final repository and the areas for which technology development is required, see Figure 13-1. The figure describes SKB's assessment of the situation for technology development today. In the areas coloured grey or green, normal design efforts are assumed to suffice in order to specify and execute the necessary measures. Verifying tests may be warranted in a few cases. In the areas coloured yellow or red, technology development is needed. Studies have been carried out in a number of the areas coloured yellow, but SKB deems that further development or optimization measures are warranted.

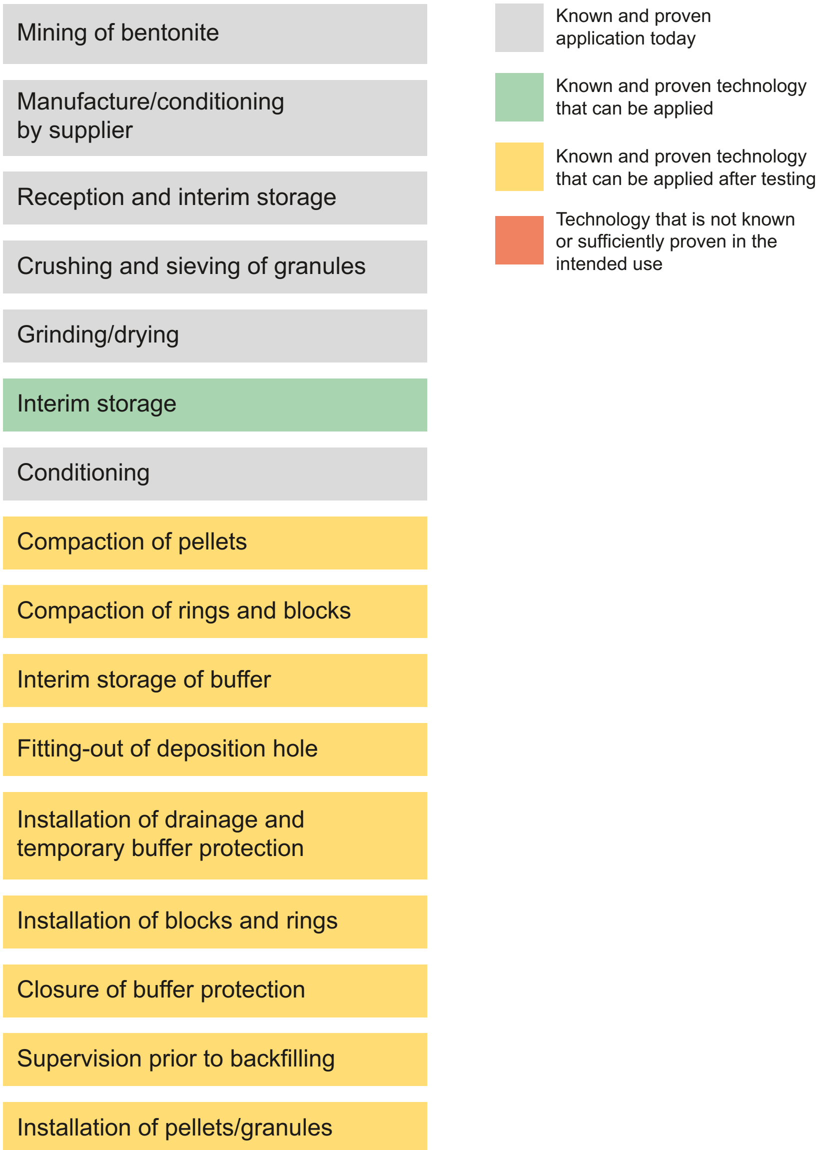


Figure 13-1. *The buffer line – SKB's assessment of the situation for technology development today.*

13.1 Current situation

The world's bentonite resources are very large. Many of the actors on the market can deliver a product that satisfies SKB's requirements on the material.

Methods for crushing and sieving bentonite in the form of granules employ known and proven technology that is being used in the world's bentonite industry today. This is also true of technology for grinding, drying and mixing the bentonite so that it has the desired water content (conditioning).

SKB has tested two methods for compacting the blocks and rings: uniaxial pressing and isostatic pressing. Both methods must be further developed before they can be used in the operation of the final repository. Technology for compacting pellets is available on a commercial scale, but must be adapted to meet the needs in the final repository.

Interim storage of buffer material must take place under controlled conditions to ensure that its properties, particularly water content, are preserved. It is also important to study how the buffer is to be protected to retain its properties after installation in the deposition hole and up until the deposition tunnel is backfilled. The method for installing the buffer also needs to be tried out and fine-adjusted.

13.2 Requirements and premises

The buffer's main functions are to protect the canister and prevent water flow, as well as to retard the transport of radionuclides from a leaky canister to the rock. At the same time, the buffer must not have any properties that have a negative impact on the other barriers. The requirements on the methods and the equipment needed in order for the installed buffer to fulfil its long-term function and to permit handling and installation are:

- The buffer blocks must be compacted to a specified geometry, water content and density.
- The buffer blocks may only contain cracks and other internal defects that can be accepted in view of the lifts and other handling to which the buffer blocks are subjected during operation.
- The installation method and the equipment must result in a vertical stack of blocks with enough space in the middle to deposit a canister.
- The properties of the buffer must be kept within specified limits, regardless of the inflow of water into the deposition hole, up until the deposition tunnel has been backfilled past the deposition hole.
- The gap between buffer blocks and rock must have room for drainage hoses and possible buffer protection.
- The buffer protection must be able to be closed after deposition of the canister and emplacement of the bentonite buffer. A vapour barrier must then be in place around the deposited buffer-canister package.
- It must be possible to continuously measure the relative humidity inside the buffer protection in representative points. Acceptable intervals in the measurement series must be specified.
- The buffer protection and the drainage lines must be able to be removed in a safe manner.

If the gap is filled with pellets or granules, they must meet the following requirements:

- The pellets must conform to a pre-specified shape and density and the granules to a pre-specified size distribution.
- The gap between the buffer blocks and the rock must be filled with pellets and granules in such quantity that the total specified quantity of bentonite in the deposition hole is sufficient to meet the requirements on density and swelling pressure.

Chapter 24 in Part IV describes the processes that can affect the buffer in the long term and the properties the buffer should have in the initial state in order to ensure the best long-term performance. In order to be able to prove in advance that our technology development leads to methods and machines that really meet the stipulated requirements, we will go through and compile the inspections and the documentation that will assure quality during manufacture, interim storage and installation.

Technology development is currently aimed at achieving an initial state with a buffer around the canister that consists of a specified quantity of bentonite of a specified homogeneity in the deposition hole. In addition to the chemical properties of the bentonite, which are a given premise in technology development, the dry density and the water ratio are important parameters. The quality of pellets, granules and large blocks is characterized by these parameters. Other indicators are the size of the pellets and the grading curve of granules.

13.3 Manufacture of buffer

Manufacture of the buffer consists mainly of two activities: compaction of rings and blocks and manufacture of pellets and granules. The activities are described in sections 13.3.1 and 13.3.2.

13.3.1 Compaction of rings and blocks

SKB has tested two methods for compacting bentonite blocks and rings: uniaxial pressing and isostatic pressing. Blocks and rings for nine deposition holes of natural size were made from sodium bentonite (MX-80) by uniaxial pressing. They were then used in the Canister Retrieval Test, the Prototype Repository /13-1/ and the Lasgit test in the Äspö HRL.

Conclusions in RD&D 2004 and its review

There is no isostatic press in Sweden where full-scale blocks and rings can be manufactured. Twelve blocks on a scale of 1:4 were pressed in a press at Ifö Ceramics in 2000 /13-2/. The results showed that the technique should also be applicable on a larger scale. SKB concluded that manufacture of the buffer by isostatic pressing along with the handling process would be further studied.

SKI pointed out in its review of RD&D-Programme 2004 that SKB needs to develop technology and procedures for manufacturing buffer blocks, for example test its reference method for compaction on a full scale. Furthermore, the buffer concept that will be included in future permit/licence applications should be prioritized.

Kasam said that SKB should explain how they can ensure that the density of the buffer can be maintained at a sufficiently high level.

Newfound knowledge since RD&D 2004

Manufacture of blocks and rings has not been prioritized by SKB during the current period. A small number of studies have been conducted, however. Among other things, blocks of alternative buffer material have been manufactured on a small scale for a field test in the Äspö HRL.

Completed analyses of the density of the water-saturated buffer in the six deposition holes in the Prototype Repository have shown that the desired buffer density has been achieved. The analyses also showed that the variation in density is small within and between the deposition holes /13-3/. This means that we have shown that we can manufacture and install buffer components.

Large composite blocks, with ring and bottom in a single unit, could be an alternative. But with such a design there is a great risk of problems with cracking and disintegration during wetting and during drying after deposition. Moreover, the use of such blocks means that the mean density and the swelling pressure will be higher in the bottom than around the canister, since the difference in density between rings and blocks that has been achieved for the tests in the Äspö HRL cannot be achieved in the manufacture of a composite block.

Programme

SKB has not chosen a reference method for manufacturing blocks and rings. This means that both uniaxial and isostatic pressing of bentonite blocks and rings will be further developed in parallel. This development work is being pursued in cooperation with Posiva.

The first overall goal is to gather data to permit evaluation and comparison of the potential of the two technologies. The results of the studies will be used to justify the selection of the method that will be described in the application for the final repository under the Nuclear Activities Act and the application under the Environmental Code for the final repository system.

The planned development work for isostatic pressing can be divided into the following steps:

- Press blocks on a scale of 1:4 in an existing press, for example the one at Ifö Ceramics in Bromölla. The possibility of compacting even larger blocks, near full scale, in a press inside or outside Europe will also be explored.
- Investigate the need of, and develop technology for, machining the blocks to the desired dimensions.
- Test, in a small existing press, how the conditioning of the bentonite affects the quality of the blocks.

The planned development work for uniaxial pressing can be divided into the following steps:

- Develop the method so that the need of lubricant is minimized.
- Improve the geometry of the blocks, in other words eliminate or reduce the tapered shape of the blocks resulting from compaction today.
- Develop the compaction technology so that the blocks can be made higher than the 50 centimetre high blocks that have been manufactured so far.

13.3.2 Manufacture of pellets and granules

Methods and technology for manufacturing pellets and granules are known and are available on the commercial market. Pellets are pressed from finely ground bentonite and are given a smooth surface. The size of all pellets pressed with the same die is the same. The granules are graded in connection with crushing and grinding of the bentonite. They are irregular particles, but their particle size can be combined to get a favourable size distribution or density.

Conclusions in RD&D 2004 and its review

There was no account of the manufacture of pellets or granules in RD&D-Programme 2004.

Newfound knowledge since RD&D 2004

The gap between rock and buffer blocks may be filled with pellets or granules of bentonite. No particular technology development has been conducted during the period in question.

Programme

Up until the submission of the applications for the final repository under the Nuclear Activities Act and for the final repository system under the Environmental Code, the advantages and disadvantages of the two products will be determined by testing in the Bentonite Laboratory. Different particle size distributions for granules and different sizes of pellets will be evaluated.

13.4 Interim storage

The manufactured bentonite blocks and rings must be interim-stored in such a manner that their properties are preserved. This applies to pellets and granules as well. Bentonite absorbs water so that it swells in humid air and dries out in dry air. For every water content of the bentonite there is an equilibrium value for the relative humidity of the surrounding air. Interim storage can take place in hermetically sealed rooms where this relationship is utilized. Hermetically sealed steel containers that also served as transport protection were used for interim storage of the blocks for the different tests in the Äspö HRL.

Conclusions in RD&D 2004 and its review

No account was given of interim storage of buffer blocks and rings in RD&D-Programme 2004.

Newfound knowledge since RD&D 2004

There has been no RD&D during the period.

Programme

Laboratory tests will be conducted prior to the choice of method for interim storage. The purpose of these tests is to determine the equilibrium values of different buffer products with the surrounding atmosphere. In addition, different methods for containing the buffer products will be studied.

13.5 Fitting-out of deposition hole

After the deposition hole has been bored and rock characterization has been done, certain internal fittings need to be on hand before the first bentonite block can be installed. The internal fittings comprise a horizontal bottom in the deposition hole, equipment for dealing with inflowing water and a temporary protection around the buffer to prevent it from swelling before the backfill in the deposition tunnel is installed.

Conclusions in RD&D 2004 and its review

No account of the fitting-out of the deposition holes was given in RD&D-Programme 2004.

Newfound knowledge since RD&D 2004

Currently the internal fittings in the deposition hole consist of:

- A horizontal bottom pad of low-pH concrete and a vapour barrier of, for example a copper sheet.
- A pump sump for collecting inflowing water.
- A hose for drawing off drainage water.
- A buffer protection that is fastened around the bottom pad. The protection is fastened so that it can be taken up from the tunnel at a later opportunity, before the tunnel is backfilled. The buffer protection should be able to be closed temporarily.

This type of internal fitting was used in the deposition holes in the Canister Retrieval Test and the Prototype Repository in the Äspö HRL /13-4, 13-5, 13-6/.

Programme

During the coming period we will investigate how large a water inflow to the deposition holes can be handled without our having to resort to technical solutions such as drainage and buffer protection. Furthermore, we will study how large water inflows can be handled by technical means.

Different temporary installations for protecting the bentonite from inflowing water and from the high humidity in the deposition hole will be studied, compared and ranked. In conjunction with the development and testing of different buffer protections, closure of the protection will also be investigated. The purpose is to learn more about its resistance to rising temperature and different climate situations.

The Bentonite Laboratory will be used for the fundamental tests that need to be done. Before the chosen solution is used in the final repository, it will first be demonstrated in a realistic underground environment in the Äspö HRL.

13.6 Installation of blocks and rings

Before the canister is placed in the deposition hole, the buffer, which consists of highly compacted bentonite in the form of blocks and rings, must be in place. Emplacing the buffer requires equipment that is capable of lowering and, if necessary, retrieving bentonite rings and blocks from the deposition holes. The equipment consists of a gantry crane and a lifting tool. The lifting tool is equipped with a positioning system so that the blocks will end up in exactly the right position in the deposition hole.

Conclusions in RD&D 2004 and its review

SKB concluded in RD&D-Programme 2004 that the equipment in the form of lifting tool and gantry crane that had been used to emplace blocks and rings in tests in the Äspö HRL /13-5, 13-6/ was good and has good development potential.

SSI pointed out that prior to trial operation, SKB needs to be able to show that all steps in the deposition process can be carried out under realistic conditions and with the machines and procedures that will be used in routine operation.

Newfound knowledge since RD&D 2004

The larger blocks which SKB plans to manufacture are now being used as a basis for the further development of the lifting tool and the gantry crane for buffer installation. A basic design has been arrived at for both the tool and the crane.

Programme

The programme for installing the buffer includes manufacture of the equipment and testing and demonstration of the method in the Bentonite Laboratory and the Äspö HRL. The planned demonstrations are aimed at confirming that the chosen method and the handling equipment will work as planned. The programme will be carried out partially in cooperation Posiva.

The lifting tool will be developed to start with. A new prototype tool will be ready in 2008, see Figure 13-2. This tool will initially be used in the Bentonite Laboratory.

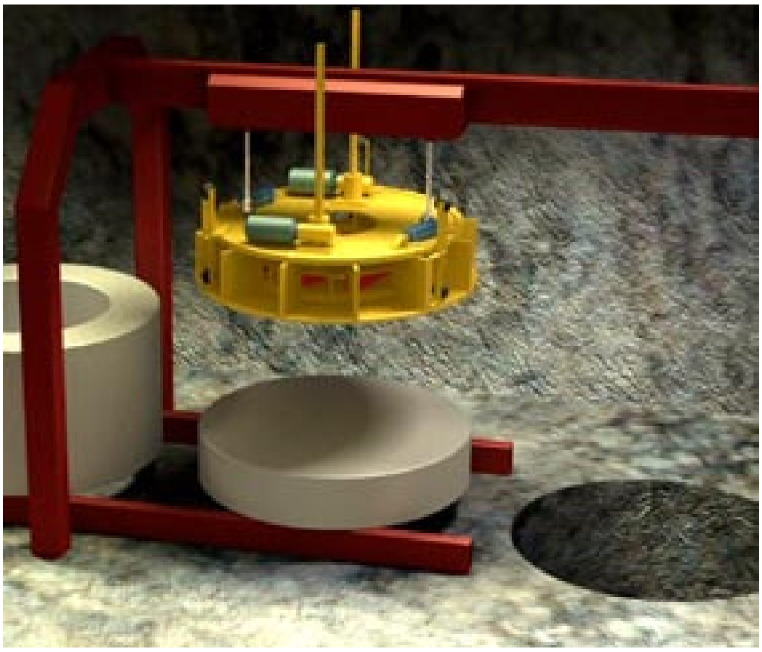


Figure 13-2. *Illustration of the prototype lifting tool that is being developed for blocks and rings.*

In a later phase the prototype lifting tool will be tested together with a prototype buffer emplacement machine. This can be done at a depth of 420 metres in the existing tunnels in the Äspö HRL. SKB has plans to build new tunnels at this level. If this is done the demonstration can be carried out there. The timetable for building the new tunnels has not been established, but construction will tentatively start in 2008.

The programme also includes developing a radiation shielding hatch, see Figure 13-3. The hatch is supposed to prevent direct radiation up into the deposition tunnel after the canister has been deposited, but before the uppermost bentonite blocks have been put in place. The need for radiation shielding after all bentonite buffer is installed will be studied. First, however, the permitted radiation level from a canister must be specified and the radiation-shielding capacity of the buffer measured.

13.7 Installation of pellets or granules

The buffer blocks contain so much bentonite clay that the initial state (see section 24.1 in Part IV) can be achieved without any supplementary filling in the deposition holes being necessary. In some cases, however, there is a risk that the canister's heat output will cause spalling of the rock wall before the buffer has had time to cool. As a result, pieces of rock could fall down into the gap between the buffer blocks and the rock wall. This can be prevented by filling up the gap from the start with pellets or granules.

Conclusions in RD&D 2004 and its review

Installation of pellets or granules between the bentonite blocks and the rock wall in the deposition holes was not discussed in RD&D-Programme 2004.

Newfound knowledge since RD&D 2004

No efforts have been targeted directly at this area during the period. Current knowledge is based on the good results of gap filling with pellets in the Canister Retrieval Test, the Temperature Buffer Test and the Prototype Repository in the Äspö HRL. Additional experience has since been gained from tests with spraying of pellets during backfilling in the Äspö HRL.

Programme

Installation of pellets or granules in deposition holes will be further developed and tested on a full scale in the Bentonite Laboratory. The goal is to develop methods and equipment for installation that minimize dust and result in high and even filling of the deposition hole. How different conditions, such as water inflow and the risk of spalling in the deposition hole prior to water saturation, affect installation will be studied.

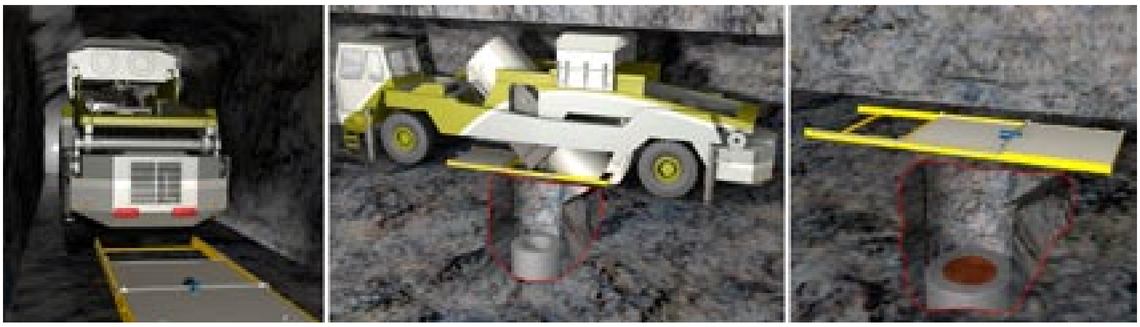


Figure 13-3. *Radiation shielding hatch that prevents direct radiation before the uppermost bentonite blocks are put in place. The figure shows the radiation shielding hatch before, during and after deposition.*

14 The canister line

The canister line describes how the canisters in which the spent nuclear fuel will be encapsulated are fabricated, sealed, transported and deposited. The line also includes such activities as transport of encapsulated fuel and handling and deposition in the final repository. The technology needs are also presented for two process steps in the encapsulation plant that really belong to the fuel line: drying of fuel and measurement of decay heat.

The colour coding of the canister line shows the areas for which there is known and proven technology that can be applied to the final repository and the areas for which technology development is required, see Figure 14-1. The figure describes SKB's assessment of the situation for technology development today. In the areas coloured grey or green, normal design efforts are assumed to suffice in order to specify and execute the necessary measures. Verifying tests may be warranted in a few cases. In the areas coloured yellow or red, technology development is needed. Studies have been carried out in a number of the areas coloured yellow, but SKB deems that further development or optimization measures are warranted.

14.1 Current situation

The work of developing canisters for the final repository has been going on for many years. The work is being pursued on a broad front.

Knowledge about different processes in the final repository and the stresses which the canister must resist is increasing due to research, see section 23.2 in Part IV. Information regarding loads on the canister in the final repository's handling system will be acquired as development and design of this system progresses. The canister must comply with the specifications that are derived from the design premises. Different tests and analyses that provide a basis for the specifications for the canister are being carried out. Current areas are corrosion testing and creep testing.

The basic concept for the canister is not being changed, but the detailed design is the subject of different studies. An example of this is that it is desirable for easier deposition, though not necessary, that the bottom of the canister is flat. It is now being studied whether this is possible to achieve by conducting fabrication and welding tests and evaluating testability. Another example is that certain deformations of the fuel channels can occur during casting of PWR inserts. The size of the channels may need to be adjusted on account of this.

Different suppliers' fabrication processes are being progressively developed so that the components will comply with the specifications. Several alternative and complementary methods for fabrication are being developed. An assessment has been made for every component as to which fabrication method has come the farthest in development and is judged to have the potential to meet the quality requirements in production (reference methods).

SKB has chosen friction stir welding (FSW) as the reference method for sealing the copper canister /14-1/, and optimization of this process is under way. The welds have very good mechanical properties and the probability that they will contain discontinuities is small. The welding machine in the Canister Laboratory has high reliability.

Nondestructive testing is an important tool for evaluation of material structure and the presence of discontinuities. Previously it was only possible to test the canister's welds regularly in the Canister Laboratory, but nowadays the canister components – copper tubes, inserts and lids and bottoms – can also be tested. Efforts to optimize the testing methods and evaluate their reliability are being pursued at the same time as preliminary results from testing of canister components are beginning to become available.

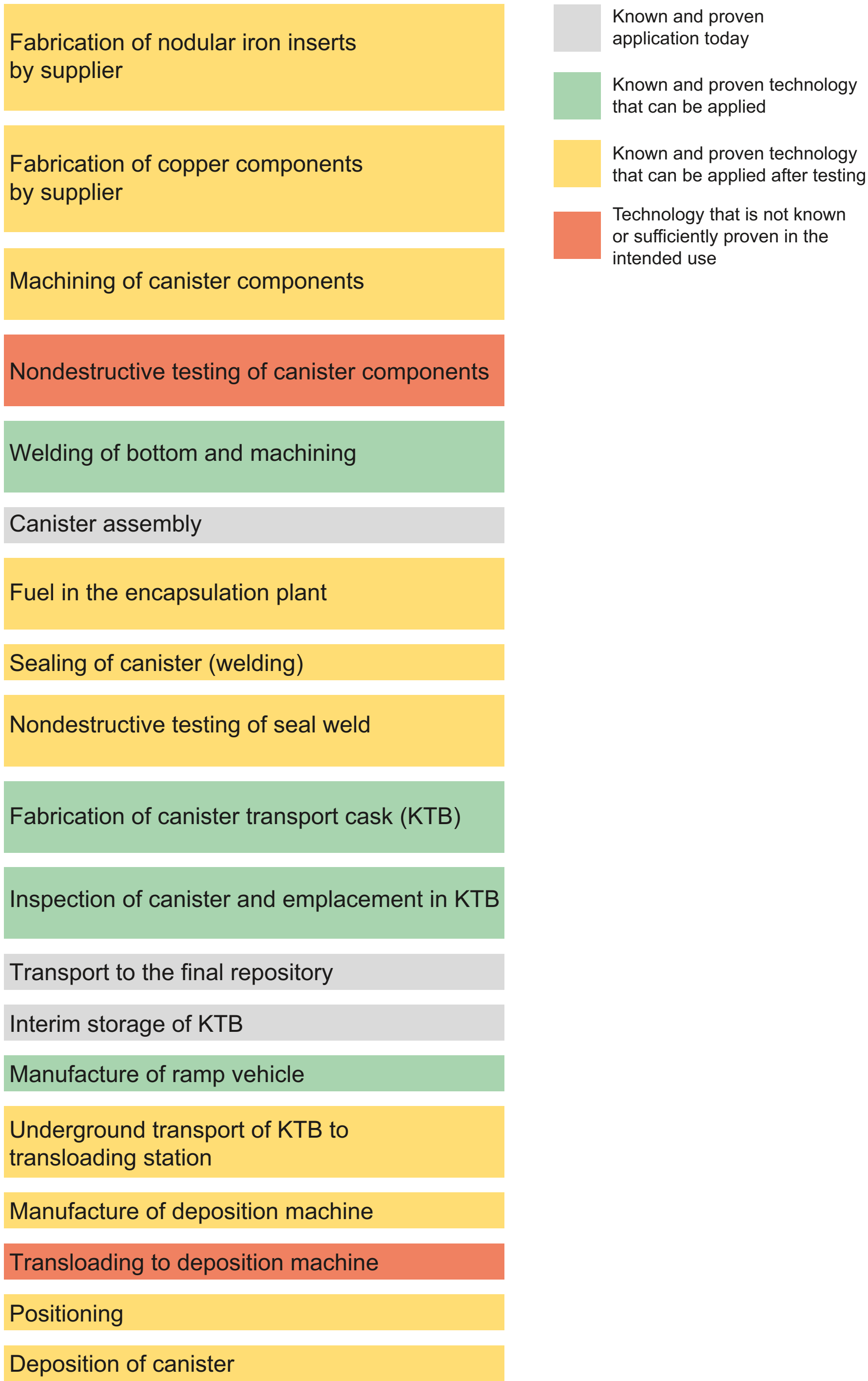


Figure 14-1. *The canister line – SKB's assessment of the situation for technology development today.*

The methods for nondestructive testing (NDT) that have been developed are being applied as tools in the development work. SKB has presented a programme for demonstrations and associated prequalification /14-2/. As planned, the first industrial demonstration of the fabrication process for BWR inserts and prequalification of the casting process are being conducted by one of our suppliers during 2007.

In the encapsulation plant, the spent nuclear fuel will be dried before it can be placed in the canister. In its application for a permit to build the encapsulation plant, SKB has shown that vacuum drying is a method for fuel drying. The planning for the coming year includes a study of alternative drying methods for the purpose of streamlining the drying process, mainly with regard to leaking fuel.

A specially designed transport cask is needed to ship the canisters from the encapsulation plant to the final repository. Like all other transport containers used by SKB, it must comply with the rules in the IAEA transport recommendations. SKB engages established cask designers to design and manufacture the casks.

Equipment and procedures for handling and depositing the canisters of spent nuclear fuel in the final repository must be designed so that radiation doses to personnel are limited and the sealed canister is not exposed to stresses that affect its properties as a barrier in the final repository. The equipment and procedures must also be designed so that the consequences of mishaps and abnormal incidents are mitigated. SKB is analyzing the entire handling chain, and the design work includes designing and, in some cases, manufacturing prototypes, equipment and vehicles required to execute the activity.

14.2 Requirements on the canister

The purpose of the canister in the final repository is to isolate the spent nuclear fuel from its surroundings over very long periods of time. SKB's reference design for the canister consists of an outer corrosion barrier of copper and a loadbearing insert of nodular iron. The canister has a diameter of just over one metre and a length of nearly five metres, see Figure 14-2.

Both the design of the different parts of the canister and the choice of material in the different components are based on the design premises for the canister /14-3/. By design premises is meant the general requirements stipulated on the function of the canister. These in turn determine the detailed design of the different parts of the canister.

5 cm copper

Estimated weight (kg):	
Copper canister	7,400
Insert	13,600
Fuel assembly (BWR)	3,600
Totalt	24,600

Figure 14-2. *Canister for spent nuclear fuel. The canister consists of an outer shell of copper and an insert of nodular iron. The insert in the figure is intended for BWR assemblies.*

In brief, the design premises are as follows:

- The canister must contain and prevent the dispersion of radionuclides from the spent nuclear fuel.
- The canister must resist the corrosion attacks expected in the final repository.
- The canister must resist the isostatic loads expected in the final repository during a glaciation cycle.
- The canister must resist the shear loads expected in the final repository.
- The canister must have negligible adverse thermal, chemical and mechanical effects on the other barriers and on the fuel.
- The canister must be able to be transported, deposited and otherwise handled in a safe manner.
- The canister must be based on proven or tried and tested technology.
- Canisters with specified properties must be able to be fabricated, sealed and inspected with high reliability in production.
- It must be possible to test the properties of the canister against specified acceptance criteria.
- It must be possible to fabricate, seal and inspect the canisters at the desired pace.

Equipment and procedures for transport, handling and deposition of canisters with spent nuclear fuel must be designed so that radiation doses to personnel are limited. The equipment and procedures must also be designed so that the consequences of mishaps and abnormal incidents are mitigated.

Conclusions in RD&D 2004 and its review

In its review of RD&D-Programme 2004, SKI found that SKB should, as soon as possible, develop design premises for the canister and verify these premises in the next planned safety assessment in 2006. SKI found that "A clear and logical link between the detailed design premises for the canister and the requirements on long-term safety of the repository is still lacking". SKI pointed out in its review that the requirements on fabrication and inspection should be formulated based on investigated events, design premises, material and environmental data, load data and strength analyses.

SKI also had some material-related objections. Among other things, they noted the lack of an explanation as to why an average grain size of 360 micrometres is required in the copper. SKB cited an international standard for copper but gave no reason or reference as to why they had chosen to comply with that particular standard, according to SKI. Nor did they explain whether the requirements regarding grain size and presence of impurities also apply to the weld.

SKI also had a number of detailed viewpoints. When canister strength is calculated, the loads must be clearly specified and the elevated temperature must be taken into consideration. The acceptance criterion that the smallest permissible copper cover is 1.5 cm is unclear. The defect's other dimensions, such as length and width, need to be included. The question of remaining ligaments needs to be examined.

Newfound knowledge since RD&D 2004

SKB has devised a system for requirements management /14-4/. The purpose is to document the connections between long-term safety and design requirements.

We have also presented a new edition of the design premises for the canister /14-3/. The report describes status and state of knowledge. Some work remains to be done to arrive at the final design premises for the canister. The background material must be structured and augmented so that it contains the information that is required to assure the canister's performance and meet the needs of the regulatory authorities for review.

Due to the close relationship between the design premises and the safety assessment and the fact that work on these was pursued in parallel, the design premises /14-3/ do not completely take into account all aspects from the safety assessment SR-Can. Another area where design premises are not complete concerns acceptance requirements for different variables. Some requirements are specified, but efforts are under way to supplement them. Thus, the design premises do not provide a complete basis today for material selection and detailed design of the canister, but efforts to compile a complete body of documentation are under way.

In view of the importance placed by the regulatory authorities on design premises and design basis data in their review of RD&D-Programme 2004, important design premises are presented in Appendix A.

Programme

Prior to permit application for the final repository, SKB continues to work to compile design premises and design basis data in accordance with the requirements set forth in SKI's study report 2006/109 /14-5/.

The design premises /14-3/ contain a line of action for how the background data for the canister will be augmented or refined. The line of action mainly involves issues having to do with materials and strength. Based on this line of action, the following areas where further efforts are required can be identified. For natural reasons, the time periods are approximate as in all research-oriented activities.

Material issues	Programme	Period
Creep properties of copper	Testing of the creep properties of copper has been under way for several years. Recently the investigations have been concentrated on the properties of the FSW weld, effects of extremely slow loading and creep with a multiaxial stress state. The results are being analyzed and summarized and comparisons are being made with the requirements. There have been questions concerning the long-term stability of phosphorus, and the basis of these questions is being further explored. Furthermore, in order to calculate the loads on the canister, a validated creep model must be constructed that takes into account time-dependent courses of events, such as postglacial shearing of the canister. Also of interest is studying creep at low temperature, 0°C.	2008–2013
Effect of hydrogen on copper and nodular iron	Occasional fuel rods may be damaged and water may have entered the rod. Since it cannot be guaranteed that this water will be removed by the drying of the fuel that is planned in the encapsulation plant, there may be water left in the canister after the canister is sealed. The atmosphere in the insert is replaced with argon, but in the long term anaerobic corrosion of the iron in the insert can occur, resulting in the formation of hydrogen. It is therefore of interest to study whether hydrogen affects the mechanical properties of nodular iron and copper. If hydrogen has any effect on the material, permissible concentrations of hydrogen will be determined.	2008–2009
Cold working effects in copper caused by handling damage	Plasticizing of the copper shell can occur in connection with handling. From a mechanical viewpoint, this leads to deformation hardening, accompanied by an increase in ultimate strength and reduced elongation at break. It is of interest to study more closely how creep properties are affected. If cold working has any effect on the long-term properties of the canister, we will determine what degree of cold working can be permitted.	2008–2010
Stress corrosion cracking in copper	Recently the possibility that stress corrosion cracking in the copper shell can occur in the final repository has been discussed again. It is of interest to carry out stress analyses of the copper shell, but also to review the existing chemical arguments.	2008–2010
Time-dependent properties of the insert	The long-term integrity of the canister insert must be verified with respect to creep and other time-dependent phenomena. Experiments are under way to investigate creep in nodular iron.	2008–2012

Strength issues	Programme	Period
Postglacial earthquakes	Postglacial earthquakes can give rise to shear loads on the canister that affect both copper shell and nodular iron insert. The issue is complex and is dependent on both geological conditions and the mechanical properties of the buffer. The impact on the canister has been studied, and refined calculations are being performed where the impact on the copper shell is being studied and the detailed design of the canister is being taken into account.	2008–2012
Margins to threshold effects	Study of the interaction between tolerances in input data and the margin to threshold effects in calculating the collapse load for the insert.	2008–2009
Combined load cases for the insert	The total stress level that can occur in the insert when different loads interact is being determined.	2008–2010
Damage tolerance of the insert	It is of interest to study what discontinuities can be accepted in the insert in view of the total stress level that can arise as well as the interaction between different discontinuities. A project is being pursued aimed at answering the question of what discontinuities can be permitted in the insert. The investigation will provide a basis for quality inspection of the insert by nondestructive testing. This project will also address the effect of possible stress corrosion cracking in the insert.	2008–2009
Criticality safety	The effect of major discontinuities in the insert's partition walls on criticality safety will be investigated. The investigation will provide a basis for quality inspection of the insert by nondestructive testing.	2008
Handling safety	Assurance must be provided that the canister meets the requirements on safe handling and that its long-term integrity is not affected by handling. Possible handling damages are being determined and their effect on the canister's handling safety and long-term integrity is being analyzed. Mishaps during the operating phase are being studied and their impact on the canister's capability to contain the fuel is being determined.	2008–2009

14.3 Fabrication and nondestructive testing of the insert

Fabrication of the insert (subsystem insert in the production system for canister fabrication) consists mainly of two processes: casting of the insert and nondestructive testing. The subsystem also includes supporting processes such as machining of the insert and fabrication of a steel cassette and a steel lid /14-6/.

14.3.1 Fabrication

Conclusions in RD&D 2004 and its review

In RD&D-Programme 2004, SKB presented results from trial fabrication of inserts and from extensive material testing. The results showed a relatively wide range of variation in the material properties of many individual inserts. The greatest variation in tensile testing was found in values for elongation at break. This is due to the fact that the material contains non-nodular graphite and discontinuities in the form of pores and particles. Computer simulations of the casting processes at different foundries have provided a greater understanding of parameters such as temperature and additives. This makes it easier to control the form and distribution of the graphite in the material and the casting processes can be improved.

In its review, SKI considered SKB's focus and programme for the material in the insert to be appropriate. There was also an understanding for the fact that inhomogeneities occur in such a large cast piece as the insert. The goal should be, with expected variations in the structure and with expected discontinuities, to obtain the required mechanical properties.

SKI also expressed its appreciation of the fact that SKB has taken notice of previous comments that the mechanical properties of the insert should be verified thoroughly and that computer simulation programs are used in the development work.

Newfound knowledge since RD&D 2004

The casting method has been developed during the trial castings by improvements of, for example, the fastening of the cassette in the bottom and increased cast length to enable impurities to be cut off. This development work is described in /14-7/.

Since 2004, twelve inserts have been cast in nodular iron: nine of the BWR version and three of the PWR version. As of the end of 2006, 43 inserts have been fabricated altogether (four of the PWR version and the rest of the BWR version). The BWR version with twelve channels is considered more complicated to fabricate. SKB has therefore chosen to concentrate its development efforts primarily on this version.

Certain changes have occurred on the supplier side. One new foundry has been added while two have been dropped. This has permitted more concentrated development efforts and stepped up the pace of the development work.

In order to show that the insert possesses sufficiently high strength, a probabilistic analysis has been carried out of the ability of the insert to withstand the stresses and loads to which it is subjected in the final repository /14-8/. A testing programme was used to determine the statistical distribution of material parameters and discontinuities in three different inserts. Based on this distribution, the probability of plastic collapse caused by high pressure or of fracture caused by crack growth in regions with tensile stresses is calculated. The results show that the probability of fracture is very low in both cases. Furthermore, experiments have been conducted to show the reliability of the canister – and particularly of the insert – when it comes to external pressure. Test loading in the form of two pressure tests was performed on shortened canisters with an insert height of 950 millimetres. In both pressure tests, the load was gradually increased to about 130 MPa /14-9/. The pressure tests show a high margin of safety in relation to the pressure for which the canister is designed, which is 45 MPa /14-3/.

SKB is carrying out a development programme for fabricating canisters in cooperation with our suppliers. The programme includes a total of twelve inserts. Development is under way for PWR inserts and the process needs to be optimized to ensure that the dimensional requirements on the fuel channels can be met before a demonstration series can be carried out. The development work has come farther for BWR inserts, and so far five BWR inserts have been fabricated with good results. Five more BWR inserts will be fabricated under serial production conditions to see what quality can be expected in serial production. The quality of these inserts will be evaluated. Sufficient data are being collected in the programme so that a prequalification of the process can be carried out during 2007. Furthermore, two PWR-type inserts will be fabricated.

Technical specifications and drawings have been produced for other components included in the insert, such as steel cassette, steel lid and bolt. These may be regarded as preliminary, since various kinds of design data are gathered continuously and changes can occur.

Programme

The fabrication of components for the insert will be further developed at several of the suppliers. SKB will need to engage several foundries for future fabrication in order to ensure delivery of the 200 inserts required annually. The technical specifications for the insert have been progressively modified during the development process, and further minor adjustments may be made.

During the coming three-year period, SKB plans to:

- Intensify development of the fabrication of PWR inserts.
- Fabricate BWR inserts in serial production and gather material for a prequalification of the casting process.
- Analyze reliability in the fabrication and inspection of inserts.
- Carry out the necessary technology development to ensure that sufficient capacity exists for machining and testing in the future.
- Secure long-term deliveries by continuing to develop the fabrication process at a new foundry.

In a longer time perspective, SKB will work according to the programme for qualification /14-2/, which includes qualification of the fabrication of inserts.

14.3.2 Nondestructive testing

The insert will be inspected by nondestructive testing (NDT). This testing is done to detect any discontinuities in the material. The primary quality-enhancing measure is to optimize the fabrication processes so that the requisite quality is assured. Nondestructive testing should verify that quality is as intended. Furthermore, NDT is an important evaluation tool during the development work. We must show that we can fabricate canisters that satisfy the design requirements. The work is primarily being conducted at the Canister Laboratory in Oskarshamn.

Different testing methods will be developed to enable the insert's complex geometry to be scanned. It is also important that testing can be automated, since the insert is relatively large.

Certain parts, such as steel lids and bolts, are standard products and can be purchased with associated quality certificates. The load these parts are subjected to determines whether they require some form of testing. This will be looked into.

Conclusions in RD&D 2004 and its review

In their review of RD&D-Programme 2004, SKI and SSI said that the requirements on the NDT methods must be established and concretized. This is an area in which intensive efforts are being pursued. Strength analyses based on the design premises /14-3/ are being conducted, which should lead to requirements on nondestructive testing.

Newfound knowledge since RD&D 2004

SKB is working to develop preliminary NDT methods for the different components in the canister. This was reported in part in /14-10/ and the current state of knowledge is summarized here.

In an initial comparison between different NDT methods, ultrasonic testing emerges as the most suitable technology /14-10/. This agrees well with what is used in other industrial sectors for testing similar components. SKB has procured an ultrasound system with phased array for inspection of welds. This will also be used in development and trials of preliminary testing methods for the components. A mechanized scanning system is needed in order to be able to test the insert in an rational manner /14-10/.

Testing methods

Four methods have been developed for ultrasonic testing of the insert, see Figure 14-3:

- Pulse-echo normal scanning: The area 30–200 millimetres below the outer surface is tested.
- TRL (Transmitter Receiver Longitudinal): A double crystal probe is used to test the region 0–50 millimetres below the mantle surface.
- Through-transmission method: Used to test the inner areas between the channels. This method also uses a pulse-echo technique to provide additional information.
- Phased array: Different areas are scanned at different angles. The method entails that the area at the outer channel tubes is scanned at four different angles.

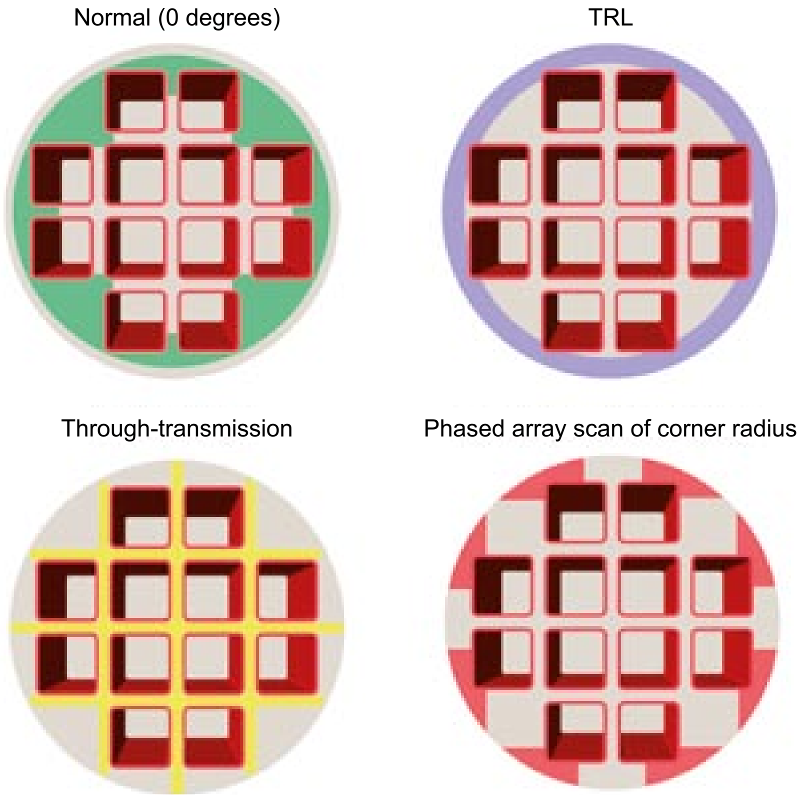


Figure 14-3. *The insert; the different scanning areas for the testing methods are coloured in the figure.*

The TRL method uses a 2 MHz double crystal where the longitudinal wave is refracted to 70° in the nodular iron. The method is used successfully for testing of reactor vessels in the nuclear power industry and is intended for detecting discontinuities in and beneath the surface. Scanning is done by four probes simultaneously in different directions.

Preliminary investigations of the strength of the insert show that it is the areas around the outer channel tubes that are subjected to the heaviest loads. More extensive testing is therefore conducted in these areas, for example by means of sector scanning. A total of four different scans are done.

The different scanning methods are being evaluated.

Manipulator

A general description of the manipulator at the Canister Laboratory is provided in /14-10/. The rotational symmetry of the components is utilized in scanning with the manipulator. A prerequisite for the preliminary testing methods mentioned previously is that the mantle surface of the nodular iron insert is accessible. Two components are needed for the manipulator to do the scan: a mechanical device for moving the object, and fixtures to hold various probes in place during the scan.

At the Canister Laboratory, SKB has set up a station for testing of the components: copper tubes, lids and bottoms, and nodular iron inserts. The mechanical parts of the manipulators are controlled by a PLC system (programmable logic controller). The control system enables the different axes to be controlled and permits automated scanning. Two manipulators are used: one for inserts and copper tubes (rotator), see Figure 14-4, and one for copper lids and bottoms (turntable), see Figure 14-7.

The rotator has a number of functions designed to assure and facilitate testing. On one side of the rotator is a special rig for handling the reference object. The purpose of this part is to handle the reference object in an efficient manner. The conditions for the reference objects should be the same as for the object to be tested. To facilitate fabrication and handling of the reference objects, a module system has been developed that makes it possible to fasten smaller pieces in an insert disc or copper tube.

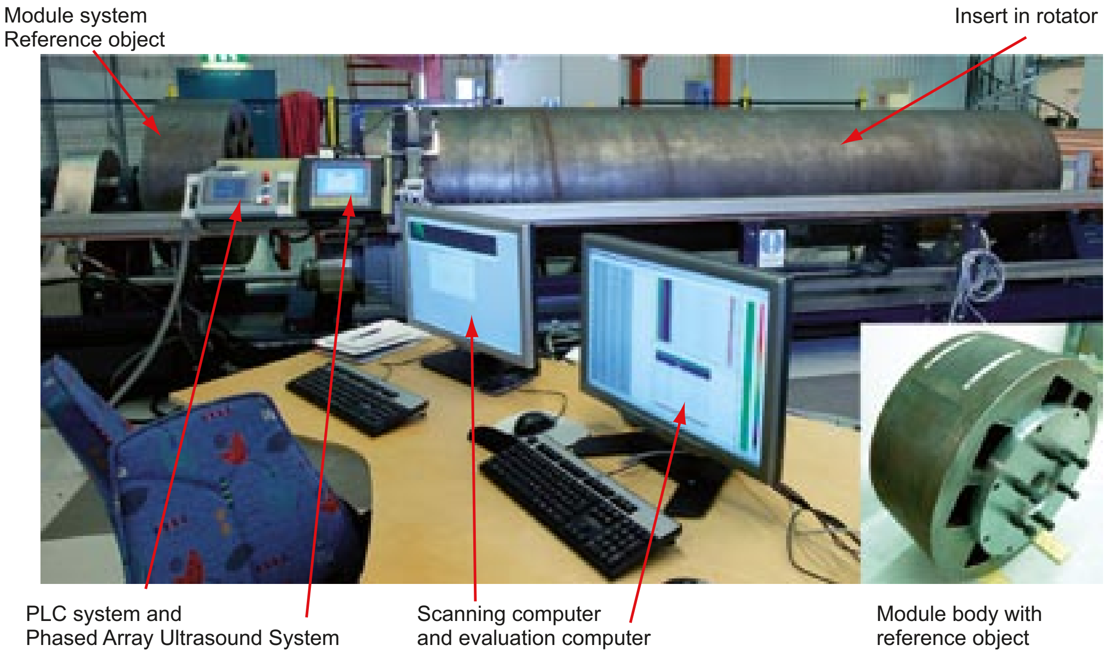


Figure 14-4. *Rotator part of NDT station for inspection of canister components.*

Scanning can be done by spiral scanning or by advancing the scanner after each completed scanning turn. Other scanning modes are also possible.

An immersion tube is used for the testing with pulse-echo (normal scanning), see left-hand picture in Figure 14-5. Its function is to form a water gap between array and object. In order to be able to optimize the position of the array, the immersion tube is flexibly built so that the distance and the angle to the object can be varied in both the tangential and axial directions.

In testing with a TRL scanner, the probes are in direct contact with the object. The function of the fixture is to press the probes against the object and hold them in place so that contact with the object is not lost, see right-hand picture in Figure 14-5.

In through-transmission testing, two arrays are positioned on either side of the insert. At present, one prototype fixture is available, which has been used with success. However, certain modifications must be made to adapt it to production conditions.

In sector scanning the wedge is in contact with the object, see middle picture in Figure 14-5.

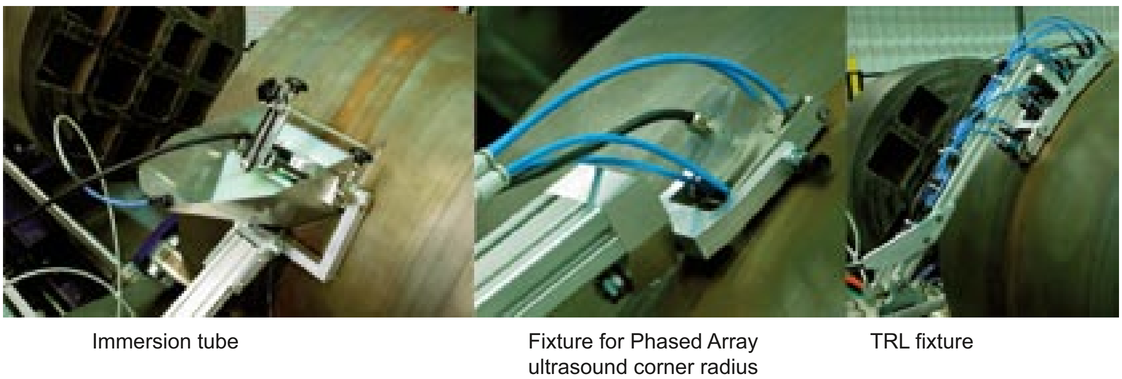


Figure 14-5. *Different fixtures for testing of the insert in the rotator.*

Supporting information

The microstructure of the material affects ultrasonic testing. An important factor for the material structure is the nodularity of the iron. It is possible to measure the nodularity of nodular iron, but existing methods assume that the wall thickness is known. SKB has investigated whether it is possible to measure nodularity with different ultrasonic techniques. The results of the study will be evaluated during 2007.

We are evaluating whether it simplifies testing to have a special machining phase before volumetric testing is carried out. This means that the insert must have a certain geometry (adapted for testing).

The spacer plates that fix the fuel channels during casting of the nodular iron insert prevent testing of certain areas. Ongoing damage tolerance analyses indicate that the material that cannot be tested does not add anything from a strength viewpoint. A final decision is expected to be made on this matter during the first half of 2008.

Programme

The purpose of the coming work is to develop reliable testing methods for the nodular iron insert. It must be possible to qualify these testing methods so that they can be used in the canister factory.

The activities that are planned during the next three years (2008–2010) are described in /14-10/. In an initial phase, test configurations will be determined and consideration will be given to expected discontinuities and preliminary acceptance criteria. Certain prerequisites (material structure, geometry and testing system) will also be determined. In order to gain further understanding of results and possible limitations in the testing procedure, modelling runs will also be carried out.

During the period 2008–2010, the reliability of the selected methods will also be studied. Background material for tentative strategies for qualification of methods for nondestructive testing will also be compiled and presented.

Other activities will be pursued during the second three-year period (2011–2013). For example, activities are planned to compile background data for qualifications. In order for this to be possible, the testing systems must be established and technical justifications must be available. When the canister factory is to be designed, background material for the testing systems for this purpose must also be compiled.

14.4 Fabrication and nondestructive testing of the copper shell

Fabrication of the reference canister’s copper shell includes the following reference processes: casting of copper ingot, extrusion of copper tube, forging of copper lid and bottom, welding of bottom by friction stir welding (FSW) and quality inspection of components and bottom weld by nondestructive testing (NDT). In addition, rough and finish machining of components and finish machining of the bottom weld are needed.

Besides extrusion and FSW, SKB also has supplementary methods for both fabrication of copper tubes and welding. These are pierce and draw processing and forging to fabricate copper tubes and electron beam welding to attach the bottom of the canister. Depending on the outcomes of the development work and evaluations, changes may be made in the classifications of reference versus supplementary method.

14.4.1 Fabrication

Cylindrical copper ingots are used as starting stock for hot forming of copper components. SKB has tested four different methods for fabricating the tubes for the copper canisters: roll forming of copper plate to tube halves that are welded together, and fabrication of seamless tubes by extrusion, pierce and draw processing and forging. Since 1998, attention has been concentrated on the latter three alternatives. Fabrication of copper lids and bottoms is done by forging.

Conclusions in RD&D 2004 and its review

In RD&D-Programme 2004, SKB presented results and experience from the continued work of developing the methods for fabricating copper components by optimizing and improving tools, process parameters and material yield. Copper tubes with integral bottoms had been fabricated by pierce and draw processing, and a number of tubes had been fabricated by forging. As far as fabrication of lids and bottoms is concerned, computer simulations and tool optimization had been used to develop forging into a feasible method for this.

SKB has chosen a pure oxygen-free copper that conforms to the standard EN 1976:1988 for Cu-OFE or Cu-OF1 with a number of additional requirements. One of the additional requirements concerns the average grain size in the material, which affects the properties of the material and the potential for ultrasonic testing. In its review, SKI stated that a full explanation of the grain size requirement was lacking. Another additional requirement stipulated maximum oxygen concentration. This had been chosen so that the material could be electron-beam welded. SKI pointed out that it was not clear from SKB's account what requirements had to be made on the oxygen concentration in the copper if friction stir welding is used.

Newfound knowledge since RD&D 2004

Trial casting of copper ingots for the fabrication of copper tubes for the canister has been done in cooperation with Outokumpu Poricopper Oy, now Luvata. Nineteen copper ingots were fabricated during the period 2004–2006. The trials involved semicontinuous casting of ingots with a diameter of 850 millimetres and weighing up to 13.5 tonnes. In the trial fabrication of tubes with a wall thickness of 50 millimetres, it has sometimes been difficult to get sufficiently long tubes. The capacity of ingot fabrication was therefore recently increased to 16 tonnes. This has also allowed the area at the starting end of the ingot, which may contain defects, to be cut off with sufficient margin. This has made it possible to solve previous problems in meeting the requirement on low oxygen content in the entire ingot as well as problems with an uneven phosphorus concentration and the occurrence of cavities in the middle parts of the ingots. Subsequent ingots have exhibited good results. The chemical composition of the fabricated ingots has been analyzed. The results show that the ingots satisfy the requirements on chemical composition /14-11, 14-6/.

Wyman Gordon Ltd in Livingston, Scotland, have a large press for vertical extrusion (press force of about 30,000 tonnes) in which SKB's copper tubes can be extruded. In addition to tubes with a wall thickness of 50 millimetres, several tubes with smaller wall thicknesses (40 and 30 millimetres) have also been fabricated. Extrusion produces copper tubes with a fine-grained microstructure that easily meets the requirement in the design premises of 800 micrometres /14-3/. SKB's specification of a grain size < 360 micrometres is also met by specimens taken from the tube ends. The design premises take into account the material's strength properties, while the specification also takes into account the fact that a finer structure is required in order for the components to be tested by ultrasound. The latter grain size requirement may be modified when more knowledge is available from ultrasound measurements. As of the end of 2006, a total of 23 tubes had been fabricated by extrusion, of which eight after RD&D-Programme 2004. The eight most recently extruded tubes were fabricated in series of four tubes, which was a smoothly functioning production pace.

In developing methods for ultrasonic testing of copper tubes, we have discovered local changes in the material structure along extruded tubes. Ultrasound attenuation has been found to be high in certain areas. Metallographic examinations of some of these areas have revealed an altered microstructure. This must be further studied. The extrusion process must also be developed to get better control over the geometry of the tube.

In cooperation with Vallourec & Mannesmann Tubes in Düsseldorf, copper tubes have been fabricated by pierce and draw processing. What is special about this method is that the mandrel is not pressed all the way through the ingot, leaving a 200–300 millimetre thick bottom. This tube therefore has an integral bottom, eliminating the necessity of fabricating a bottom and welding it on. One difficulty has been to get a thoroughly worked and fine-grained microstructure in the bottom material. Development work is being pursued including new fabrication trials for the purpose of obtaining a fine-grained structure in this part as well. This requires a more powerful working of the bottom material and thereby also greater strain. If this succeeds, the method can probably be used to fabricate tubes with integral bottoms in which the microstructure is fully approved. So far, one tube with approved bottom structure has been fabricated. As of the end of 2006, a total of nine tubes have been fabricated by pierce and draw processing.

Trial fabrication of copper tubes by forging has been done in cooperation with Scana Steel Björneborg AB in Värmland, Sweden. As a result of development efforts, the tubes can now be forged in a few work operations. Forging produces a fine-grained copper material. As of the end of 2006, a total of seven tubes have been fabricated by forging. Continued development of the forging process is necessary in order to obtain better control over the geometry of the tube.

During the past three-year period, 117 ingots for lids and bottoms have been fabricated at Norddeutsche Affinerie AG. The development work for fabricating copper lids and bottoms has been pursued in cooperation with Scana Steel Björneborg AB. The preformed blanks have been forged from continuously cast copper billets with a diameter of 500 millimetres and a weight of about 1,100 kilograms. Efforts have been focused on forging in a closed die at about 650–700°C. In order to keep the force needed in the forging press as low as possible and to get better material filling of the die, an extra upsetting step with a spherical mandrel has been introduced. Otherwise the force required on the large surface area of the lids is relatively high. The process is concluded with cogging, where the surface of the lid blank is forged in several steps. Cogging produces better filling in the bottom of the die and a lower total force requirement. The method produces copper blanks that are machined into finished lids and bottoms with good microstructure and elongation values. Lids have been fabricated in a series of 19 consecutive lids. Methods for ultrasonic testing of whole lids have been developed at the Canister Laboratory. Ultrasonic testing has shown that fabricated lids have uneven attenuation due to local structural variations in the lid. The forging process needs to be further developed by, for example, increased process control.

Recently the introduction of friction stir welding as a sealing method has increased the requirements on the lid and bottom forgings. These requirements are met by using a modified die with a different distribution of the volume from the ingot (taller and more slender). This has in turn required changes in the forging process. An ejector has been introduced to expel the forging from the die, which can deform the forging. Modifications of the die are expected to solve this problem, however. A development effort is under way with friction stir welding aimed at being able to weld lids with the same geometry as the lids used in electron beam welding. The forging process will be further optimized.

SKB plans to use the same reference method for welding on the bottom as for welding on the lid (the seal weld), i.e. friction stir welding. This method has been shown to be a repeatable and reliable method, at the same time as it produces a good microstructure and good quality of the weld. On difference is that the bottom weld is made before the spent nuclear fuel is placed in the canister. This is therefore not done in a nuclear facility.

The development of laser technology for measuring the dimensions of the copper tubes has continued. To measure the straightness and roundness of the fabricated copper tubes, a laser measurement apparatus was previously developed in cooperation with the Royal Institute of Technology in Stockholm (KTH). It is described in a status report /14-11/. The equipment, which is still just a prototype, has since been improved in the following ways, see also Figure 14-6:

- The round bar on which the laser head travels inside the tube has been replaced by a carriage with wheels, which greatly facilitates transport and handling.
- The laser head rotates automatically.
- The risk of operator error has been reduced in the new version, since the adjustments at the start of the measurement have been simplified.

Programme

Development of the alternative fabrication methods for copper tubes, forging and pierce and draw processing, will continue. A number of fabrication trials are planned for the coming years.

During the coming three-year period we will work to improve geometric accuracy in the extrusion process. Furthermore, studies will be conducted of local microstructure variations along extruded tubes.

Figure 14-6. Laser measurement apparatus at the Canister Laboratory, December 2006.

The method of forging lid and bottom blanks needs to be further developed in order to achieve even lower microstructure variations and thereby more uniform sound attenuation. One step in this work is to improve the process control of key parameters during forging.

It is desirable that the canister have a flat bottom to facilitate deposition. The current bottom design is similar to the lid design with a collar on the periphery. A development project aimed at investigating fabricability, weldability and testability by NDT for a flat-bottomed canister is under way.

Moreover, the forging die for the lid will be further developed.

Studies of the reliability of the fabrication and testing methods are being conducted in a similar manner as the studies that have been conducted of welding.

SKB further intends to do the following during the coming three-year period:

- Investigate how machining and testing of a large number of copper components can be done.
- Establish another long-term supplier of large copper ingots.
- Execute activities under the qualification programme /14-2/.

14.4.2 Nondestructive testing

All copper components will be inspected by nondestructive testing (NDT). This is done to find any anomalies, or discontinuities, in the material and to verify that fabrication functions as intended. The work is mainly being done at the Canister Laboratory.

Different testing methods will be used, since the different components have different geometries. It is also important that testing can be automated, since large areas/volumes must be examined.

Conclusions in RD&D 2004 and its review

See section 14.3.2 for general information on nondestructive testing of the components.

Newfound knowledge since RD&D 2004

SKB is working to develop preliminary methods for nondestructive testing of the different copper components. This is described in part in /14-10/, and the current state of knowledge is summarized here.

Ultrasonic testing seems to be the most advantageous technique for the copper components /14-10/. This agrees well with what is used in other industrial sectors for testing similar components (tubes, pipes etc). SKB has a phased array ultrasound system, which is used for the preliminary testing methods. Experience from the testing activities at the Canister Laboratory has served as a basis for the choice of parameters for testing of copper components.

The same rotator is used for testing of the copper tube as for the insert. The copper lids and bottoms will, on the other hand, be tested on a turntable. The turntable is adapted to the same control system as the rotator.

For further information on the rotator, see section 14.3.2.

Testing methods

SKB is developing and trying out two different ultrasonic methods for the copper tube:

- Pulse-echo normal scanning.
- Pulse-echo with angled incidence 45° in four different directions.

The procedure is taken from standardized tube testing.

Normal scanning (longitudinal waves) is done at a frequency of 5 MHz. The copper tube's entire volume is examined with this method. The testing primarily provides information on discontinuities extending in the axial direction of the tube.

Transversal waves with a frequency of 2.25 MHz are used for angled incidence. The angle of refraction of the sound is 45° and sound is sent in four different directions: ± 45° in the axial direction and ± 45° in the tangential direction. The copper tube's entire volume is examined with this method. Testing is primarily done to detect discontinuities extending in the radial direction of the tube.

Lids and bottoms are tested in a phase of fabrication when they have a simple a geometry as possible. After testing, the components are finish-machined to their final shape. Due to the geometry of the copper lid, several scans must be done. The plane-parallel parts of the lid in the centre are scanned in the same way as the copper tube, while several scans are required of the area at the periphery. A frequency of 5 MHz is used in the normal scan (longitudinal waves). The testing is performed from two different directions, perpendicular to each other.

Manipulator

Testing of lids and bottoms is done with the object immersed in a tank of water, see Figure 14-7. The ultrasound technique used is called immersion. A linear module moves the probe in a radial direction at the same time as the object rotates.

Supporting information

The microstructure of the material affects ultrasonic testing. An important factor for the material structure is the grain size in the copper material. The influence of grain size on ultrasonic testing has been studied /14-12/. More studies are required in this area so that we can impose reasonable requirements on the material structure and say with certainty how it affects the ultrasonic testing.

Programme

The coming work is aimed at making sure that reliable testing methods are available for the copper components. It should be possible to qualify the testing methods. Furthermore, it should be possible to use the methods for future qualification of systems for testing in the canister factory.

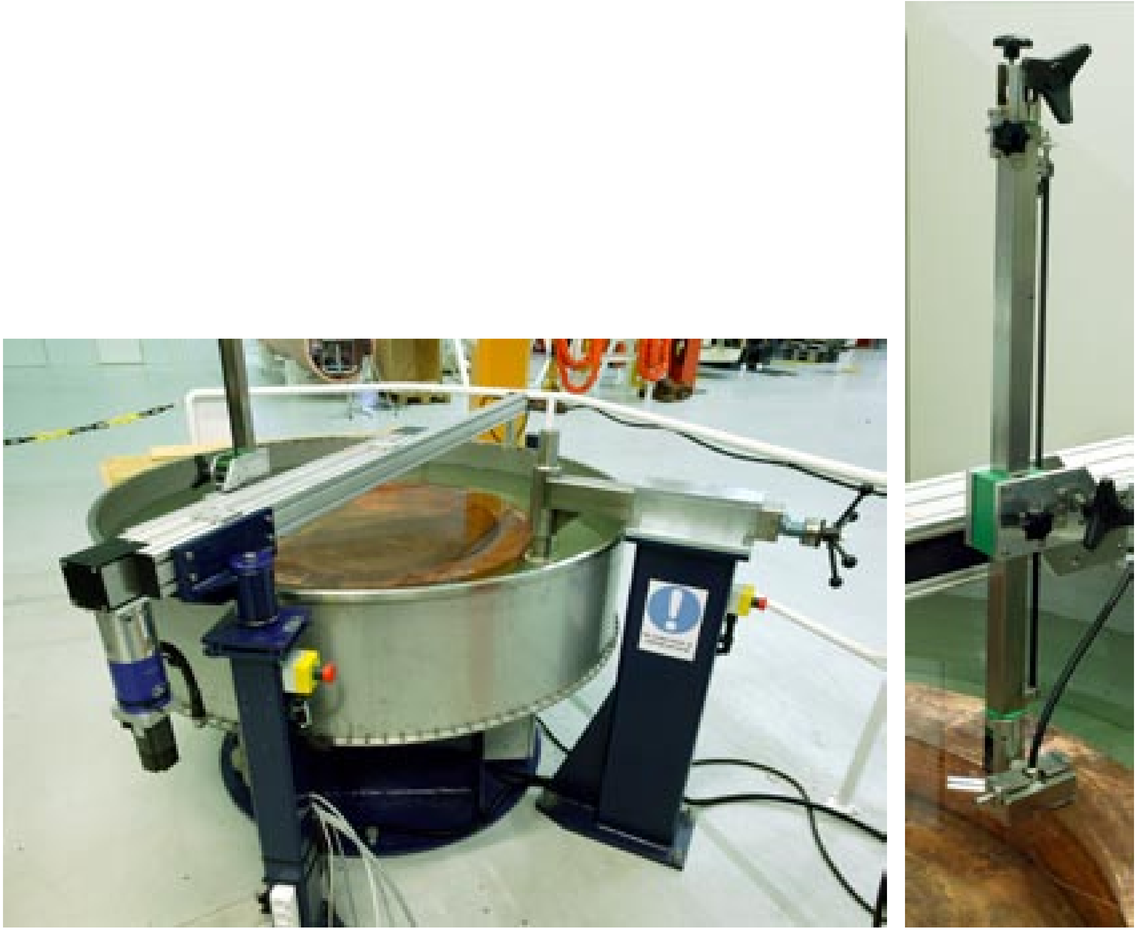


Figure 14-7. *The turntable. Lids and bottoms are immersed in a water-filled tank where they are examined by ultrasound.*

Future activities for the copper components do not differ much from what will be done for the nodular iron insert, see section 14.3.2. Certain material-specific aspects are not the same for the insert and the copper components. In the copper material it is mainly the grain size that influences the testing. Studies are therefore planned to learn more about how the microstructure of the material influences the testing and what can be done to make the testing more reliable. The activities that are planned during the next three years are described in /14-10/.

14.5 Sealing and nondestructive testing of the weld

The canister is sealed by friction stir welding and the quality of the weld is inspected by ultrasonic and X-ray testing (radiography).

In the future production line, SKB plans to do its own welding, which means that welding procedures and systems must be developed and welding systems must be installed both in the canister factory and the encapsulation plant. The same welding method is planned to be used in both plants. The system that is installed in the encapsulation plant is, however, included in a nuclear activity.

14.5.1 Welding

SKB has been developing two methods for welding of the canister for several years now. One is a thermomechanical solid-state process called friction stir welding (FSW). The other is a fusion welding method called electron beam welding (EBW) /14-1/. There is equipment for friction stir welding and electron beam welding in the Canister Laboratory.

Conclusions in RD&D 2004 and its review

Since the welding equipment influences the design of the encapsulation plant, SKB had to choose a reference method before the application under the Nuclear Activities Act for Clab and the encapsulation plant was submitted.

SKI's assessment was that SKB has made considerable progress in the development of friction stir welding as a sealing method and that the programme is being conducted in a reasonable manner. Results from the development work were lacking, however. For friction stir welding, it remained to be demonstrated if – and how – the properties of the weld material differ from those of the parent metal, as well as how any impurities in the weld affect quality. SKI assumed that all of this would be presented in conjunction with the application for the encapsulation plant.

In its review, the regulatory authorities pointed out that SKB has made considerable progress and improvements when it comes to electron beam welding, but that the reliability of the method has not been convincingly demonstrated. SKI further said that the presented programme for further development was too briefly described to judge whether electron beam welding will be able to be developed into a usable method.

Newfound knowledge since RD&D 2004

In 2005, after having carefully analyzed the results of the welding tests with the two methods, SKB chose friction stir welding as a reference method in the encapsulation plant. The most important criteria for choosing this method are the high reliability of the welding process and the equipment, and the fact that the quality of the welds is very high in both serial welding and other welding. Friction stir welding thus satisfies all requirements with regard to both process and system /14-1/.

Another advantage is that friction stir welding, which is a non-fusion welding process, gives very good material properties in the weld metal. Electron beam welding satisfies the requirements made on the actual process, but not the requirements on system reliability and demonstrated weld quality. The estimated costs are similar for the two methods. The environmental effects are also judged to be equivalent. Detailed information on the choice and the grounds on which it is based have been published /14-1/.

Following the choice of friction stir welding as a reference method, the focus of further research, development and demonstration is on this method. Since certain questions remained at the time of the choice of reference method, development of electron beam welding has also continued to some extent. Following is an account of the results of the welding tests that have been performed with the two methods.

Friction stir welding

A large number of welding tests (59 lids) have been performed. The tests have shown that the process is very stable with high repeatability, which is explained by the fact that the process has adaptive control. Temperature is an important process parameter which is monitored continuously, and the process is constantly adjusted to keep the temperature within a given interval. No disturbances or parameter changes in the welding tests at the Canister Laboratory have affected the quality of the weld. This shows that the process window is relatively wide. The process window is the interval within which the welding factors and welding results are allowed to vary without the welding result being affected.

The welding process is evaluated statistically in preparation for the choice of reference method. The methodology for this is described more fully in a report dealing with reliability in the sealing process /14-13/. The purpose of the evaluation was to optimize the process, determine the process window and demonstrate the potential of the welding process in a production-like welding series consisting of 20 lid welds, see Figure 14-8. The process window that was determined at the optimal welding speed of 74.3 millimetres per minute can be seen in Table 14-1.

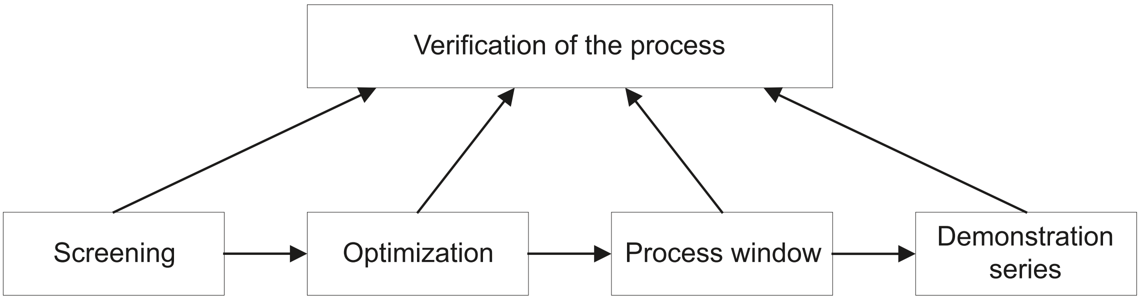


Figure 14-8. *Methodology for verification of the welding process.*

Table 14-1. Process window for FSW and influence of the welding factors on the process and weld quality.

Factor	Window	At high value	At low value
Spindle speed (rpm)	350–450	Risk of high tool temperature	–
Axial force (kN)	78–98	Risk of high tool temperature	Risk of discontinuities
Tool temperature (°C)	790–910	Risk of tool failure	Risk of discontinuities
Shoulder depth (mm)	0.4–1.5	Risk of discontinuities	Risk of discontinuities

The welding equipment at the Canister Laboratory has had nearly 100 percent availability since installation. This is a very good result considering that the system is based on a new concept. The tool is regularly replaced after each welding operation. Normal variations in the tool have not been linked to any effects on the welding result.

Different tests have been performed on lid welds done by friction stir welding in order to assess the mechanical and chemical properties of the welds in the short and long term:

- Metallography: The microstructure of the weld metal – with a focus on grain size – has been examined in some fifty-odd macrosections. All macrosections have a fine-grained recrystallized microstructure with a grain size of about 75 micrometres /14-11/. The grain size is on a level with that of the parent metal or even slightly finer.
- Strength testing: Tensile testing has been performed on 45 and 20 millimetre wide flat test bars and on round test bars with a diameter of 10 millimetres /14-14/. The results show that welds made by friction stir welding have strength properties similar to those of the parent metal: ultimate strength (206–209 MPa), yield strength (68–82 MPa) and elongation at break (48–53 percent). The test bars, which were taken from both the overlap sequence and the joint line sequence, have gone to rupture in the heat-affected zone (i.e. outside the weld).
- Creep testing: Creep testing at different loads and temperatures shows that the weld metal has creep properties similar to those of the parent metal /14-15/. All specimens that went to rupture had more than 40 percent creep ductility and uniform elongation. None of the specimens exhibited brittle rupture /14-16/.
- Corrosion testing: Corrosion testing has been performed on specimens taking from four lid welds. The specimen showed no tendency to grain boundary corrosion in the weld metal or galvanic corrosion between the parent metal and the weld metal /14-17/. Additional investigations show that any impurities from the welding tool do not cause increased copper corrosion or degraded corrosion properties in the weld metal /14-18/.
- Residual stress measurement: Residual stress measurement was performed on a lid weld /14-19, 14-20/. The highest tensile residual stresses noted amount to 39 MPa with an uncertainty of ± 23 MPa method-bound uncertainty (diffraction – grain size), in other words well below the yield strength of the weld metal. Further investigations are being conducted and will be summarized in 2008.

- Chemical analyses: Chemical analyses of the weld metal were performed on several lid welds. Traces of nickel particles from the tool probe (up to 20 ppm) and copper oxide particles (up to 25 ppm) were detected /14-21/.
- Welding with shielding gas: To investigate the possibility of eliminating oxide inclusions, a lid was welded in shielding gas in an argon gas chamber, see Figure 14-9. The weld metal is being analyzed, but preliminary results show that a weld metal without oxide inclusions can be produced. The concentration of metal particles from the probe also decreases.
- Surface treatment of welding tool: Different types of surface treatments of the welding tool have been tested. With a suitable coating, the layer withstands a whole welding cycle and the weld metal is free of traces of metal particles from the tool probe /14-22/. Further investigations of the influence of the surface treatment and of the composition of the weld metal are under way.

Both nondestructive and destructive welding have been performed to evaluate the homogeneity of the lid and bottom welds. The welds have been examined by both X-ray and ultrasonic inspection both before and after machining. As a whole the weld metal is very homogeneous. Only one type of recurrent discontinuity has been detected by nondestructive testing and metallographic examinations of the welds: joint line hooking /14-13/. This occurs when the tip of the probe penetrates too deeply and the material flow pulls the vertical joint line out towards the surface, see Figure 14-10.

The NDT results from the serial welding show only indications of joint line hooking. They are then located in the overlap sequence. Their extent does not exceed 4.5 millimetres in the 20 lid welds, with a mean value of 3.8 millimetres, see left-hand photo in Figure 14-10. After the serial welding, development of the welding procedure was focused on reducing joint line hooking by optimizing the length of the probe. A supplementary study with an improved probe produced much less joint line hooking, see right-hand photo in Figure 14-10. During 20 welding cycles with the modified probe, joint line hooking varied between 0.4 and 1.5 millimetres /14-23/.

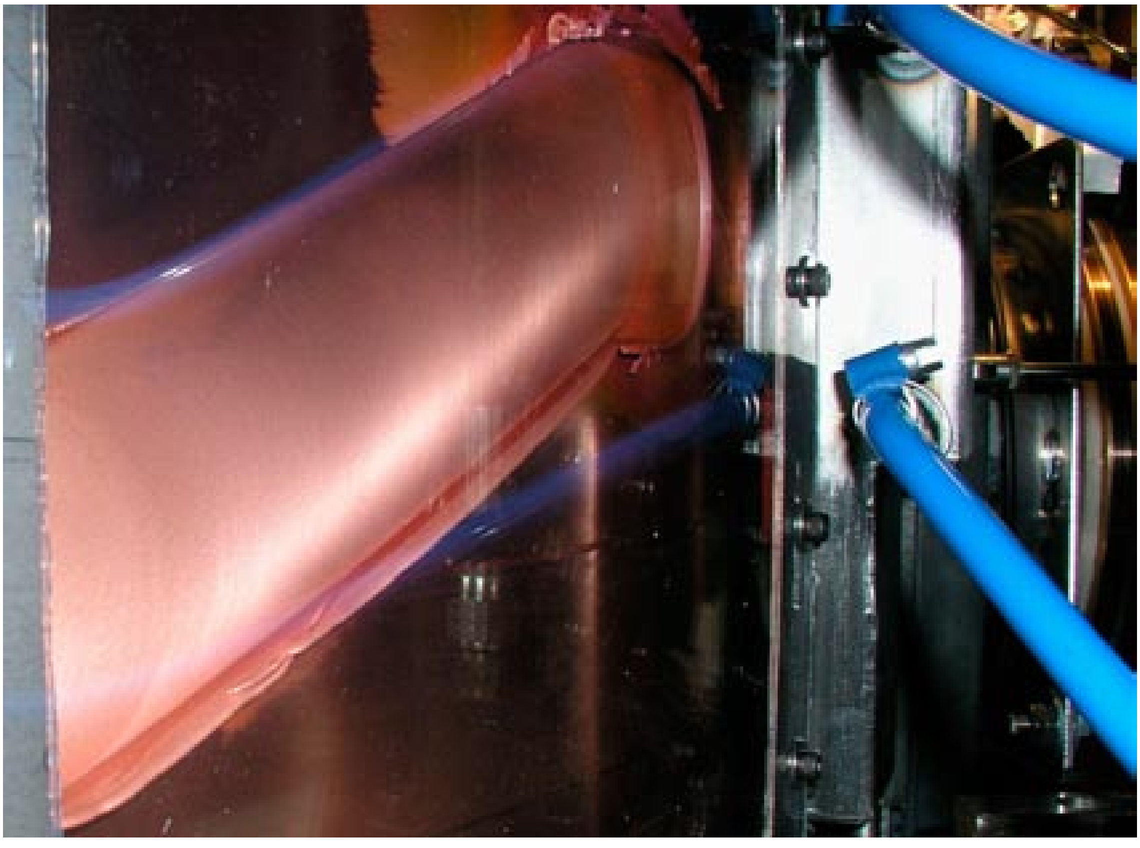


Figure 14-9. *FSW with argon gas chamber.*

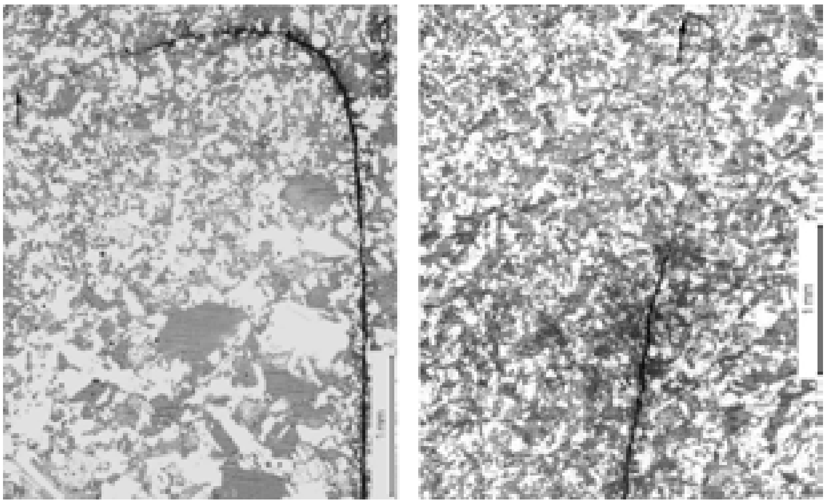


Figure 14-10. Joint line hooking occurs when the tip of the probe penetrates too deeply and the material flow pulls the vertical joint line out towards the surface.

At the time when SKB selected a reference method, the choice was based on the results from a relatively short development period. Some of the results on which the choice was based were preliminary. Further technology development was thus required. During the subsequent period, SKB has therefore prioritized work on the following issues:

- Verification of mechanical properties in the weld metal by continued creep testing at Kimab. The investigations have been concluded and the conclusion was that the creep properties satisfy stipulated requirements /14-24/ by a good margin /14-16/.
- Technical development to minimize discontinuities (joint line hooking) in the weld metal with the conclusion that joint line hooking can be mastered and limited to acceptable levels /14-23/.
- Investigations of the influence of oxides and metal particles in the weld metal and technical development of the welding procedure. The conclusion was that there is no risk of galvanic corrosion, that occasional oxide and metal particles are of no importance /14-18/ and that oxides and metal particles can be eliminated from the weld metal /14-22/.

In view of the positive results in the above investigations, there will be no change in the choice of reference method for welding.

If an FSW weld fails to satisfy the requirements, it may be necessary to repair the weld by rewelding. How rewelding affects the weld metal has been thoroughly investigated by studies of the overlap zone that arises in connection with all full-turn welds. The investigations show that this regular rewelding does not affect the weld metal. Parameters such as microstructure, creep properties, corrosion properties, ultimate and yield strength, residual stresses etc were covered by the investigations. Detailed criteria have not yet been formulated for what discontinuities can be accepted in a weld.

Electron beam welding (EBW)

Parameter studies carried out at the Canister Laboratory show that the welding process is reliable within the tested tolerance range and that a suitable process window can be defined. A full-scale test, i.e. welding of a canister of natural size with insert, shows that no difference in quality or penetration is obtained compared with welding of short tubes without insert. Serial tests, all with the same parameters, show that the welding process is stable and produces uniform results. A change of cathode during the course of the series led to a certain change in the weld root, however. The cathodes, which are currently made manually, are of uneven quality, which affects the welding result.

The fact that the welding system at the Canister Laboratory was not fully developed on delivery has been reflected in problems with unreliability and the lack of important functions. After the choice of friction stir welding as a reference method, development of electron beam welding has continued in several areas, although at reduced intensity.

Two modifications have been made in the welding equipment to improve the reliability of the welding system. In September 2006 a beam sleeve that had been causing problems with high temperature leading to interruption in operation was replaced. The new beam sleeve has a larger centre hole and substantially increased the process window for installation of one of the focus coils. There was no pressure increase in the welding gun, as had been feared. In February 2007, the system for logging of the welding parameters was replaced. The old system worked with too low a frequency and also sometimes lost contact with the control computer, causing disruptions.

Different tests have been performed on lid welds done by electron beam welding in order to assess the mechanical and chemical properties of the welds in the short and long term:

- Metallography: All lid welds were examined in macrosections at the Canister Laboratory. Two lid welds were examined with a focus on microstructure and grain size /14-25/. The examination shows that the weld metal has a normal solidification structure with typical columnar grains at the fusion boundary. The grain size lies in the interval 353–639 micrometres with a mean value of 535 micrometres.
- Strength testing: Tensile testing was performed on two early lid welds and four lid welds from the welding series. Two different types of test bars were used: flat test bars with a width of 20 millimetres and round test bars with a diameter of 10 millimetres /14-14/. The results show that welds done by EBW have slightly lower strength properties compared with the parent metal: ultimate strength (179–187 MPa), yield strength (47–66 MPa) and elongation at break (29–33 percent). The test bars taken from both the overlap area and the single weld area have gone to rupture in the weld metal.
- Creep testing: Creep tests /14-15/ were performed on an early lid weld, which is not representative of current welding technique. The lid welding was done with several welding revolutions, causing the grain size in the weld metal to become very large, around 2,000 micrometres compared with 535 micrometres which is the mean value with the current technique, which is done in one revolution. Even though the large grain size reduces the material's creep strength, the margin to cracking is very good. Creep ductility in the weld metal has been measured at up to 20–30 percent.
- Corrosion testing: Corrosion testing /14-17/ was performed on four early lid welds. The test shows that it is highly unlikely that grain boundary corrosion will be a problem for long-term safety in the final repository. However, the measurements revealed a relatively great difference in surface potential between the weld metal and the parent metal. This could lead to a corrosion cell with the weld metal as an anode. Subsequent investigations have been able to dismiss these fears. The differences in the first measurements were probably due to differences in conditions at the surfaces in the weld and the parent metal /14-18/.
- Residual stress measurement: Measurement of residual stresses was performed /14-19, 14-20/ on a lid weld. The highest tensile residual stresses noted amount to 33 MPa, which is well below the yield strength of the weld metal.
- Chemical analyses: Chemical analyses of the weld metal were performed on several lid welds /14-25/. The chemical composition of the weld metal is comparable to that of the lid and tube. The presence of oxide was also investigated by means of a hydrogen embrittlement test on a lid weld /14-21/. The results showed that the weld metal does not contain oxide.

Programme

The FSW process and system will be developed with the goal of meeting the same requirements as those made for production welding of copper canisters. The weld metal in friction stir welding will continue to be examined. The following development work is planned:

- For the canister factory, procedures will be developed for welding the bottom onto the canister. There are two options for welding: welding with the canister standing or lying down. The choice of alternative will depend on the design of the factory.
- Technology for repairing defects in the weld by local rewelding will be developed. Initial tests with a machined defect of 2×35 millimetres showed that this defect could be repaired, but a more thorough study will be conducted. This work also includes performing a number of reweldings and evaluating quality and the material properties of the weld metal. Another important part of the development work is being able to start in an exit hole at the joint line without discontinuities being formed. The activities will be carried out during 2008–2010.
- Development work to increase the permissible process temperature and determine the tool probe's useful life and safety factor. The activities will be carried out during 2007–2009.
- The process's adaptive control is partially manual. The goal is to reduce the manual aspect and if possible develop an automatic control. The activities will be carried out during 2007–2009.
- When development of the welding cycle is finished, there will probably be a need to optimize the process with regard to stability and repeatability within as wide a process window as possible. The activities will be carried out during 2008–2010.
- Formulate specifications for equipment for remote control of the welding system in the encapsulation plant, for example automatic tool change. The activities will be carried out during 2009–2010.
- Programme for qualifying the welding procedure /14-1/. The activities will be carried out during 2008–2013.

Since several problems for friction stir welding have been straightened out during 2005–2006, development efforts for electron beam welding will be limited. The work that is planned for 2007–2008 can be briefly described as follows:

- Development of a method for precision manufacture of cathodes in order to increase repeatability in connection with cathode replacement is being pursued jointly with TWI.
- Trials of welding with full penetration against detachable backing bars in the copper lid's lifting groove are planned to eliminate the risk of root defects.
- Development of the design of the drip edge to minimize the risk that the molten weld will run over the edge and cause discontinuities in the weld metal.
- The welding programme for lid welding will be developed to reduce the risk of discontinuities in the overlap area.
- Technology for automatic adjustment of the electron beam and joint tracking will be studied.

14.5.2 Nondestructive testing

The purpose of nondestructive testing (NDT) is to check that the welds do not have any discontinuities in the weld metal that affect the function of the canister. In the Canister Laboratory, SKB is conducting activities to develop, test and demonstrate systems for NDT /14-26/. There are systems at the Canister Laboratory for digital radiography (commissioned 1999) and phased array ultrasonic testing (commissioned 1998 and replaced 2002 and 2005) for examination of welds made by electron beam welding and friction stir welding.

Conclusions in RD&D 2004 and its review

SKB is developing the nondestructive testing methods in parallel with the welding methods. Efforts have been devoted to developing and specifying ultrasonic testing of welds made by friction stir welding. The testing methods are being progressively improved by comparison with the results of destructive testing. SKB has also carried out a thorough study to determine the detection capacity of the NDT methods.

SKI made positive comments on the work done by SKB to develop the weld testing methods. But the programme is unclear. SKI assumed that SKB will describe and document the testing methods that will be used, as well as their reliability, in connection with the permit application under the Nuclear Activities Act for Clab and the encapsulation plant.

SKI also pointed out that it was urgent that the development work be focused on testing methods for the chosen reference method for welding. This is in line with the work being pursued by SKB and is further described in /14-26/.

SKB also described its development work for inductive testing of welds. However, SKI found that its role was not evident from the programme. At present, SKB does not believe inductive testing is needed for nondestructive testing of the canister's welds. The reason is that sufficient information is obtained with the expected detection targets and detection capability from the ultrasonic methods used.

SKI also considered that the role of machining in connection with nondestructive testing of the seal weld was unclear. SKB assumes that final testing of the weld will be done after machining, but that nondestructive testing will probably also be performed before the canister has been finish-machined. Trials are currently being carried out to investigate the possibilities of sealing the canister using friction stir welding and a lower lid than has so far been used. This may result in a change in the role of machining in connection with nondestructive testing of the weld.

SKI stressed that models used to simulate different processes must always be verified. This is included in SKB's plan for the work of modelling nondestructive testing. The models used to support the arguments for different testing configurations will be verified.

SSI said that inspection of the bottom weld needed to be studied. SKB is currently investigating different designs of the bottom of the copper shell. One goal in this investigation is to define a phase during the fabrication process when nondestructive testing can be carried out with the same parameters as for the seal weld.

Newfound knowledge since RD&D 2004

A milestone has been reached in that preliminary testing procedures have been established for radiographic and ultrasonic testing of a seal weld done by friction stir welding. The reliability of these testing methods has also been determined. The reliability of the proposed testing methods has been reported in /14-27, 14-13/.

An account of the work done in the area of nondestructive testing of the canister welds is given in /14-26/. The account describes efforts up to and including 2005 and plans up to and including 2012. The account, which is based on the requirements made on the canister and how they can be applied to testing, deals with experience from system and process development and testing of more than 100 welds (> 60 EBW and > 50 FSW). Between December 2004 and January 2005, series of 20 lid welds each were performed with both EBW and FSW. The welds were then examined by both radiographic and ultrasonic inspection in January and February 2005. We were thereby able to show that the NDT systems had good potential for working in a production-like environment.

The X-ray equipment is very stable and gives high reproducibility. The equipment is built for continuous use. The problems that have been experienced with the system are a consequence of the fact that the linear accelerator was idle for long periods of time. The ultrasound equipment has generally lived up to SKB's specifications, but some limitations have been identified. Transfer of the large quantity of data generated by the system to the computer limits the testing speed, for example, and the software for evaluation is not optimally developed to perform efficient evaluations. The phased array ultrasound technology has undergone great development in recent years, as a result of which more suppliers are available and the performance of the equipment is increasing.

By "NDT reliability" is meant the ability to detect and determine the size of defects and to estimate the risk of false calls /14-28/. This has been studied in a project entitled "NDT Reliability" at BAM Bundesanstalt für Materialforschung- und Prüfung) /14-27/. The project comprised an evaluation of nondestructive testing of welds done by both electron beam welding (EBW) and friction stir welding (FSW). The purpose was to determine Probability of Detection (POD) and precision in estimation of the size of the discontinuities. Because friction stir welding was chosen as the reference method for sealing, the end of the study was focused on nondestructive testing of welds made by this method. Consequently, the results obtained for welds made by electron beam welding have greater uncertainties.

The requirement of a remaining copper thickness of 15 millimetres was used as a point of departure for the reliability study /14-24/. In order to obtain specimens with sufficient discontinuities, welds were performed under abnormal conditions. Examples of disturbances that were introduced are contamination and mechanical damage on joint surfaces and deviations from normal process variables. The purpose was to generate a large number of realistic discontinuities that could conceivably arise in the processes. Furthermore, material from other welds where defects were indicated by nondestructive testing was used to provide a large enough body of data for the analysis. The welds were examined by radiographic and ultrasonic testing. Specimens and examination results from NDT were delivered to BAM, where the specimens were examined by different reference methods. Finally, metallographic examinations were also carried out to verify the occurrence, shape and extent of the discontinuities. In summary, we can note that the study showed that the only normally occurring discontinuity in welds made by friction stir welding, joint line hooking, can be detected 90 percent of the time ($a_{90/95}$) at a size of 4 millimetres and its size can be determined with an accuracy of 2 millimetres.

In the project at BAM, SKB's system for radiography was also analyzed in relation to international standards. This analysis shows that the system meets the criteria (according to EN 1435) for conventional radiographic examination.

Modelling of ultrasound has been carried out at both BAM and SKB. The main purpose of modelling for nondestructive testing of welds made by friction stir welding has been to gain a better understanding of the configurations that are used in weld testing.

No activity is currently being pursued in the area of inductive testing, inasmuch as the requirements on the surface of the canister are not higher for the weld than for the rest of the canister. Furthermore, the results of the project "NDT Reliability" show that ultrasonic and radiographic testing provide sufficiently high reliability. One methodology has, however, been developed that can when necessary be adapted so that weld testing can be done economically.

Programme

Inasmuch as the study of reliability /14-27/ of nondestructive testing of the seal weld was carried out with high intensity during 2005 and early 2006, further development in this area has been limited. Based on the results of the reliability study and greater knowledge concerning possible discontinuities in welds made by means of friction stir welding, further development activities are currently being identified.

The purpose of the future work is to ensure that a reliable method for testing of the canister's seal weld will be available in accordance with SKB's qualification timetable /14-2/. Furthermore, the NDT systems will be adapted to make it possible to qualify future processes in the canister factory and the encapsulation plant.

The programme for the upcoming period (2007–2010) is described in the canister report /14-26/. It includes a general overview of the scope of the nondestructive testing of the welds in the copper shell. The purpose is to define which testing methods are relevant. Moreover, existing methods for both ultrasonic and radiographic inspection will be investigated and optimized by means of both practical trials and modelling. In addition, alternative methods such as TOFD (Time-Of-Flight-Diffraction) will be evaluated. An important area is to formulate requirements on the copper material to permit reliable testing. This includes investigating within what limits grain size may vary and whether disturbances are caused by nearby discontinuities. SKB is planning to present a preliminary strategy for qualification of methods for NDT during 2007.

In the coming years (2011–2013), the focus will be on gathering material to permit qualification of the testing. This includes, for example, establishing specifications for testing systems and formulating technical justifications. Another important area is gathering material as a basis for designing the encapsulation plant and the canister factory. This includes formulating principles for remote control of the equipment and coupling mediums for ultrasonic testing, as well as investigating what effects canister temperature and radiation have on ultrasound sensors.

14.6 Fuel in the encapsulation plant

SKB's application for a permit to build the encapsulation plant and Clab includes an account of the technology development that has taken place during the design process and since RD&D-Programme 2004. The requirements and technical solutions that satisfy the requirements are described in the application. The detailed technical solutions may be changed during system and detailed design of the plant, which is the next phase in the design process.

Conclusions in RD&D 2004 and its review

In the review comments on RD&D-Programme 2004, the regulatory authorities called for a description of how the fuel assemblies will be distributed in the different canisters. SKB has conducted an initial study to optimize the canister contents.

Like SSI, SKI wanted SKB to describe how measurement of nuclear materials and verification of decay heat will be done in the encapsulation plant. There are currently no formal requirements on measuring the fuel. According to SKB's plans, there will be equipment for gamma measurements in the encapsulation plant. Such measurements can then be performed if the need should arise. Calorimetric measurements and gamma measurements of individual fuel assemblies have been carried out for several years at Clab. The purpose is to develop a method for verifying decay heat by means of gamma measurements. The measurements are also aimed at validating the methods for decay heat calculation. Visual verification is planned to take place in the plant's handling cell when the canister is filled with fuel assemblies and before the steel lid is lifted into place and screwed onto the insert.

SKI also commented on the lack of information on what special measures might be necessary in connection with the encapsulation of odd fuel types and damaged fuel that has been lifted out of its special cans. When odd-sized fuel assemblies are to be encapsulated, spacers are placed in the channels in the insert before the canister is brought into the process. Leaking fuel, which is stored in special cans, is handled in basically the same way as other fuel. The lid of the can is removed in the plant's handling pool, after which the can with its contents is transported up to the drying position in the handling cell. After drying the fuel assembly is lifted out of the can and down into the canister. The cans are inspected on the outside and any remaining material is taken out of the can by manipulators and placed in the canister or disposed of by other means in the waste management system.

14.6.1 Drying of fuel

Conclusions in RD&D 2004 and its review

Drying of fuel was not dealt with in RD&D-Programme 2004.

Newfound knowledge since RD&D 2004

The drying process for fuel was previously designed as a hot air system where the air circulated and the moisture was condensed in chillers. Then the air was heated again. During the design process for the encapsulation plant, the possibility of using a vacuum system for drying the fuel was investigated. The calculations that were carried out showed that it was fully possible to dry the fuel by means of vacuum. The method simplifies the process system compared with the hot air variant.

Programme

Leaking fuel rods may contain water inside the cladding tubes. Since there is a limit to how much water may be present in a canister, it is important that the drying process should guarantee that the maximum permissible quantity of water is not exceeded. If a fuel rod has very small holes there is a risk that all water will not be evaporated by drying.

SKB will study the drying process further. Contact has been made with a company that has developed a new successful method for drying fuel prior to dry interim storage.

14.6.2 Measurement of decay heat

Conclusions in RD&D 2004 and its review

Measurement of decay heat was not dealt with in RD&D-Programme 2004.

Newfound knowledge since RD&D 2004

Measurement equipment for calorimetric measurements of decay heat in individual fuel assemblies has been in operation at Clab since 2003. A total of about 100 measurements have been performed on both PWR and BWR assemblies. All fuel assemblies have also undergone gamma measurement. The purpose of the measurements has been to improve the calculation methods and to develop a reliable method for verification of decay heat by means of gamma measurements. For improvement of the calculation models, SKB is collaborating with Oak Ridge National Laboratory, which is informed of the measurement results and uses them in its development of the fuel calculation programme Origen-S.

In the encapsulation plant, SKB plans to use calculated values of decay heat as a basis for selecting fuel assemblies for the canisters. If necessary, it must be possible to verify the decay heat by means of gamma measurements.

In the measurements performed to date, calculated and measured values show good agreement. But a small systematic discrepancy has been found in the measurements for PWR assemblies. The accuracy of the measurements is currently estimated to be between two and five percent.

Programme

Plans call for the measurements in Clab to continue for several more years. The purpose is to obtain a better body of statistics and to find the reason for the systematic discrepancy in the measurements of the PWR assemblies. The measurement programme will be extended to new fuel types as they reach a cooling and decay period of about ten years.

14.7 Transport cask for encapsulated fuel

Transport of encapsulated fuel /14-29/ will take place in a similar manner to transport of unencapsulated spent fuel, which has been going on since 1985 from the Swedish nuclear power plants to the Clab interim storage facility. This means that SKB's transportation system will be used at the same time for canister shipments and other shipments, such as shipments of spent fuel to Clab and waste to SFR.

A specially designed transport cask is needed for canister shipments to the final repository, which must, like all other transport packagings, be designed to comply with the rules in the IAEA's transport regulations /14-30/.

14.7.1 Requirements on the transport cask

The main requirements on the canister transport cask (KTB) is that it must:

- Be adapted to handling and loading of the canister in the encapsulation plant.
- Be adapted to handling and unloading to the deposition machine in the final repository.
- Be able to be transported between the encapsulation plant and the final repository.
- Protect the canister during transport.
- Protect the environment from radiation during transport.
- Protect the environment in the event of accidents.

According to the IAEA's transport regulations, the requirements for "type B packages" must be met due to the total activity content of a canister. This means that the design cannot be varied within particularly wide limits.

The spent nuclear fuel in the canister emits alpha, beta, gamma and neutron radiation. The canister shields alpha and beta radiation completely, but gamma and neutron radiation levels are high even outside the canister. Gamma and neutron radiation must therefore be shielded so well that the cask can be handled and transported without further protective measures. This results in a heavy cask with thick walls. The surface dose rate on the average canister transport cask during transport will be low (below 2 mSv/h, usually far below). The canister must also dissipate the heat generated by the fuel in the canister.

The mechanical requirements on cask, lid and shock absorbers are defined for the most part on the basis of the tests undergone by a type B package to guarantee its integrity even in an extreme accident situation. Certain tests are performed with a prototype cask, while certain properties are verified by calculations. All this is done by the cask designer and is included in the requirements for licensing.

Inspection programmes exist for today's shipments, as well as for the design and manufacture of transport casks for spent nuclear fuel. They entail the following in brief. Manufacture shall be certified to ISO 9001. Manufacture is subject to an inspection plan approved by the authority and is overseen by an independent inspection body. The independent inspection body certifies that manufacture has taken place according to the specification which is included in the certification (licensing).

14.7.2 Design of the transport cask

Conclusions in RD&D 2004 and its review

The transportation system was described relatively thoroughly in RD&D 2004, and that description still applies for the most part.

SKI pointed out in its review that a timetable for the entire manufacturing and certification procedure should be established so that approved transport casks do not constitute a bottleneck.

Newfound knowledge since RD&D 2004

During 2004–2005, SKB carried out feasibility studies regarding the design of canister transport casks at two internationally established cask designers. The two proposed transport casks are quite similar, even though they differ in materials and design details. Detailed qualification of the cask's design takes place within the framework of the licensing process.

Both feasibility studies are conservative in many respects, in other words the proposed transport casks represent a "maximum" cask in terms of weight and dimensions. The cask consists of a forged thick-walled mantle of carbon steel or cast iron lined on the inside with a low-friction material against the canister's copper shell to minimize any mechanical impact on the shell. A bottom of the same material as the mantle is welded to the mantle. The cask is provided with two lids: an inner lid and an outer lid that protects the inner one.

The KTB, see Figure 14-11, has six trunnions, four in the lid end used for lifts inside the plants and two in the bottom end. During transport the cask rests in a horizontal position with four lifting pins anchored to the transport frame's supports. Each of the shock absorbers, which are screwed to the ends of the cask when it is resting on the transport frame, consists of an outer steel shell filled with wood. In this way the shock absorber also contributes to radiation shielding of neutrons.

Programme

The work of optimizing the KTB will continue up until the start of design so that it:

- meets all requirements that apply to type B packages used for transportation of canisters,
- meets the requirements that derive from SKB's facilities and transport procedures,
- is designed for simple, safe and efficient handling in both the encapsulation plant and the final repository,
- is easy to maintain and keep clean,
- weighs as little as possible – taking the above requirements into consideration – in order to reduce the total weight of the transport rig during tunnel descent and road driving,
- can function together with SKB's existing transportation system, i.e. with the shipments of fuel and waste that will take place in parallel with the canister shipments.

All design requirements for licensing are satisfied by the casks developed in the feasibility studies. What is lacking is a further optimization with respect to the canisters, the transportation system and the facilities aimed at reliable and smooth co-functioning during many years of operation.

At the same time, SKB will continue to participate in and follow the work being done internationally on development of cask designs and revision of transport regulations. The first cask will be used in conjunction with commissioning and trial operation of the encapsulation plant and the final repository, after which the remaining casks will be delivered successively. At least five casks should have been delivered by the time the facilities are put into operation.

14.8 Handling of the canister in the final repository

Handling of the canister in the final repository refers to the entire handling chain from the time the canister arrives at the terminal building in the final repository's guarded area in a licensed canister transport cask (KTB) until the time the canister has been deposited, all inspections have been performed and documented and an empty KTB has been returned to the terminal building. The design of and requirements on the KTB are discussed in section 14.7. Handling of the canister in the final repository thus includes reception of the KTB at the facility, transport of the KTB in the ramp

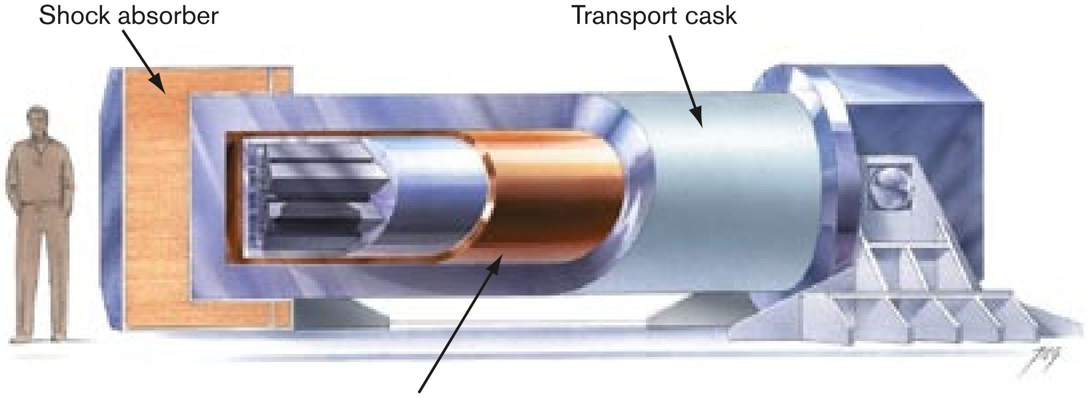


Figure 14-11. Transport cask (KTB) and transport frame.

down to the transloading station at repository level, transloading of the canister from the KTB to the deposition machine's shielded tube and transport out to the current deposition area with a prepared deposition hole.

Equipment and procedures for handling and deposition of canisters with spent nuclear fuel must be designed so that radiation doses to personnel are limited. The equipment and procedures must also be designed so that the consequences of mishaps and abnormal incidents are mitigated.

Conclusions in RD&D 2004 and its review

Handling of the canister in the final repository is not described in detail in RD&D-Programme 2004.

SKI has pointed out that SKB needs to work with the entire handling chain for the canister in the final repository so that the activity can take place in a manner that is safe in all respects. SKI also pointed out that SKB should describe how loading and unloading of the canister should be carried out, what needs to be automated due to radiation etc.

Newfound knowledge since RD&D 2004

SKB has investigated the entire handling chain for the canister in the final repository. In the design work for the final repository, the design of equipment and vehicles required to execute the activity has been studied.

Transport on the ramp has been studied and a feasibility study has been carried out for a future ramp vehicle for transport of the KTB on the ramp from ground level down to deposition level.

During the design work, the space requirement for relevant equipment has also been incorporated into the preliminary layout for the underground part of the facility with transloading hall, transport and main tunnels and deposition tunnels.

A basic design of the next generation of deposition machine was arrived at in 2005. As a result, in December 2006 SKB procured detailed design and manufacture of a modified deposition machine, runs on rubber wheels instead of rails.

Programme

Underground transport and transloading

Work on the basic design of the ramp vehicle will continue during 2007–2008. A preliminary choice of vehicle type is expected to be made in 2008, see Figure 14-12. The chosen vehicle solution will then be studied with respect to operational safety. We will also study different types of mishaps in conjunction with transport on the ramp, including different fire scenarios and how they can be prevented or mitigated so that the consequences of a fire are acceptable. The ramp vehicle is planned to have a navigation system, the objective being that the vehicle can be driven on ramp without a driver.

Figure 14-12. *Ramp vehicle for transport of the canister to the underground facility.*

Transfer of the canister from the KTB to the deposition machine's shielded tube has been studied as a part of the design of the final repository's underground part. Three-dimensional drawings and simple video animations have been made to describe the activity in the transloading hall so that the whole process can be analyzed and the dose load to the personnel can be calculated.

The future programme includes building a complete transloading hall in the Äspö HRL in order to demonstrate the entire chain with transloading and then deposition of the canister in a prepared deposition hole.

Deposition

The modified deposition machine, see Figure 14-13, will be delivered to the Äspö HRL at the end of 2007. This demonstration machine will then be used to test the entire handling chain from transfer of the canister from a KTB to the deposition machine's radiation shielding tube to deposition of the canister in a deposition hole with buffer.

Simplified equipment is planned to be used in the initial phase, but the handling chain involves the same sizes and weights as in the future final repository.

Some of these tests will begin during 2008 and will later be expanded to show that SKB can execute all steps of the deposition process under realistic conditions and with machines and procedures that will be used in routine operation. These tests will be carried out in a demonstration tunnel at a depth of 420 metres in the Äspö HRL.

The deposition machine is equipped with a navigation system and a positioning system that will undergo extensive testing. The objective is to be able to execute navigation and positioning so that deposition can largely be done by remote control. The tests with the equipment during the next few years are aimed at demonstrating that this is realizable.

The continued programme will be carried out partially in cooperation with Posiva, since they intend to handle similar canisters and buffer units. Planned demonstrations are aimed at verifying that the chosen method and equipment for handling will work as planned.

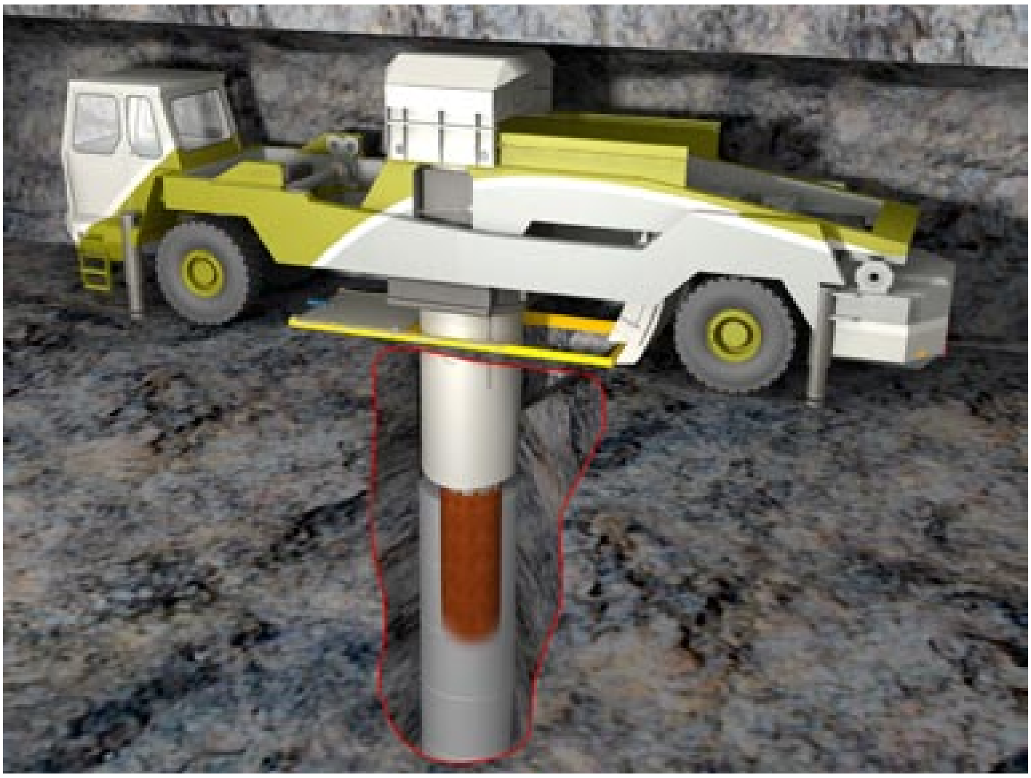


Figure 14-13. The next version of the deposition machine will be equipped with wheels.

15 The backfilling line

The backfilling line includes manufacture, handling and installation of backfill in deposition tunnels and in the top part of the deposition holes. When the deposition tunnel is backfilled, a temporary plug is installed in the mouth of the tunnel opening into the main tunnel.

The colour coding of the backfill line shows the areas for which there is known and proven technology that can be applied to the final repository and the areas for which technology development is required, see Figure 15-1. The figure describes SKB's assessment of the situation for technology

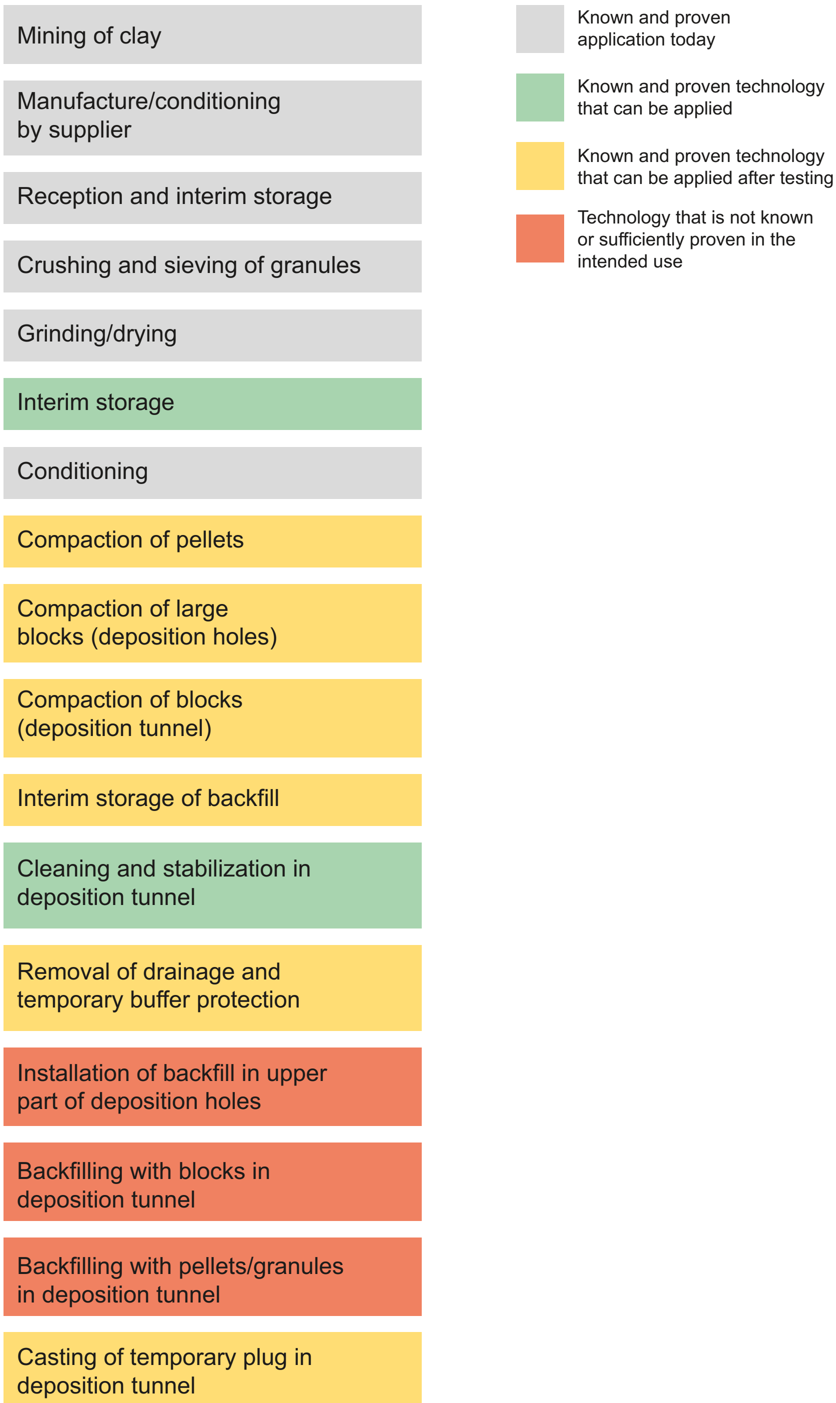


Figure 15-1. *The backfilling line – SKB's assessment of the situation for technology development today.*

development today. In the areas coloured grey or green, normal design efforts are assumed to suffice in order to specify and execute the necessary measures. Verifying tests may be warranted in a few cases. In the areas coloured yellow or red, technology development is needed. Tests have been carried out in a number of the areas coloured yellow, but SKB deems that further development or optimization measures are warranted.

15.1 Current situation

SKB has previously developed a concept for backfilling of deposition tunnels with a mixture of crushed rock and bentonite, which was tested on a full scale in the Backfill and Plug Test /15-1/ and the Prototype Repository /15-2, 15-3, 15-4/. The concept has proved to have too small a margin to the stipulated requirements.

SKB has since studied other concepts for backfilling deposition tunnels /15-5/. In RD&D-Programme 2004, we observed that a concept based on emplacement of pre-compacted blocks (that can be lifted out manually) was promising and would be further investigated. This concept with blocks of either swelling clay (Friedland clay) or a mixture of crushed rock and bentonite was analyzed in the safety assessment SR-Can /15-6/. The results of this analysis showed that both alternatives meet the requirements, but that blocks of swelling clay had a greater margin to the function indicators that were used in the analysis.

Further technology development will now be focused on developing methods and equipment for the concept with blocks of natural swelling clay.

Technology and methods for preparing the clay prior to compaction to blocks are known and proven. The blocks can be compacted by means of uniaxial pressing, according to the method that is used in industry for manufacturing refractory brick. Pellets and granules are manufactured in the same way as in the buffer line. The same also applies to interim storage of backfill material. Cleaning and stabilization in deposition tunnels is judged to be possible using proven technology. The temporary plug in the tunnel mouth can be designed according to different principles. SKB is studying two designs: a reinforced plug that is anchored in a slot in the rock, and a friction plug.

It is important to determine where the borderline goes for the highest permissible inflow of water to the deposition tunnel during installation of the backfill to ensure that the backfill will meet the stipulated requirements.

15.2 Requirements and premises

In summary, the requirements on the backfill are that it should limit the upward expansion of the buffer into the deposition hole and prevent the development of hydraulic transport pathways in the deposition tunnels so that the water flux at repository level is affected. The requirements on the methods and the equipment that are needed in order for the backfill to be able to perform the expected functions and to be installed during operation of the final repository are that:

- The backfill blocks that will be used in the uppermost part of the deposition hole must be compacted to a specified geometry, water content and density.
- The backfill blocks that will be used in the uppermost part of the deposition hole may only contain cracks and other internal defects that can be accepted in view of the lifts and the handling to which the blocks are subjected during operation.
- The backfill blocks that will be used in the deposition tunnel are compacted to a specified geometry, water content and density.
- Granules must be produced with a specified size distribution and pellets compacted to a specified shape and density.
- Installation of blocks and pellets or granules must result in the emplacement of specified quantities of material in the tunnel so that the desired density is achieved.

The temporary plugs in the mouth of the deposition tunnel have three purposes: to bring about a water pressure in the deposition holes as quickly as possible in order to facilitate the wetting of the buffer, to reduce the groundwater's pressure gradient in the backfill so that piping is prevented, and to keep the backfill in place during the construction and operating phase until the main tunnel has been backfilled.

The processes that can affect the backfill in the long term and the properties the backfill should have in the initial state in order to best serve its purpose in the long term are described in Chapter 25 in Part IV. In order to be able to prove in advance that our technology development leads to methods and machines that really meet the stipulated requirements, we will go through and compile the inspections and the documentation that will assure quality during manufacture, interim storage and installation.

Technology development in the backfilling line will for the time being be focused on a backfill in the deposition tunnels that consists of a specified quantity of natural swelling clay with a specified homogeneity per unit length of the tunnel. Important properties of the backfill are dry density, water ratio and compressibility. An indicator of the latter property is the quantity of material in different products: blocks, pellets and granules. The function of the temporary plug is determined by its water-tightness, i.e. the amount of groundwater that leaks through the plug and between rock and plug.

15.3 Compaction of backfill blocks

Conclusions in RD&D 2004 and its review

In RD&D-Programme 2004 we wrote that SKB and Posiva will continue the ongoing development programme and that three backfilling concepts would be further studied:

- A mixture of bentonite and crushed rock that is compacted in the tunnel.
- Swelling clay that is compacted in the tunnel.
- Pre-compacted blocks that are emplaced in the tunnel.

SKI supported SKB's plans to study the latter two alternatives, i.e. swelling clay that is compacted in the tunnel and pre-compacted clay blocks, and commented that it is good that SKB has intensified its programme to find a working concept to backfill the deposition tunnels. In both alternatives, Friedland clay is used as an example. Regarding the third alternative above, SKI also pointed out the importance of studying the question of what an upscaling of the alternative entails.

SKI also thought that SKB should present a concept for backfilling of tunnels prior to future applications. The concept should meet the requirement made on the performance of the final repository.

Newfound knowledge since RD&D 2004

Since RD&D-Programme 2004, the backfilling concepts listed above have been further studied. The alternative of emplacing pre-compacted blocks in the deposition tunnels appears most promising, and the work has therefore been focused on this concept.

The method that is planned to be used to compact the blocks for the deposition tunnels is based on known technology: uniaxial pressing.

Manufacture of blocks has been tested on both a laboratory scale and an industrial scale. One purpose of the laboratory tests was to determine the optimal water content for achieving maximum dry density. The tests were performed at two different compaction pressures: 25 and 50 MPa /15-7/.

An inventory has been conducted of technology for producing backfill blocks on an industrial scale, and trial manufacture of 25 blocks has been carried out in Germany /15-8/, see Figure 15-2. The main conclusion from this manufacturing trial is that it is possible to manufacture blocks with a high enough density and production rate. The trial also showed that blocks with a size of 80×60×50 centimetres (0.24 m^3) can be produced at a pressure of 30 MPa in commercially available equipment.

Figure 15-2. Some of the manufactured backfill blocks (300×300×160 millimetres).

The backfill blocks that will be emplaced in the upper part of the deposition hole have roughly the same diameter as the buffer blocks and can therefore be manufactured in the same press, see section 13.3.1.

Programme

All technology development for compacting the blocks for the upper part of the deposition hole will be coordinated with the activities in the buffer line.

How the chamfer that may be made in the upper rim of the deposition hole to allow for the radiation shield's deposition movement will be backfilled will be studied. The method used to remove the chamfer (drill-and-blast, wire sawing or another method) must be taken into account. Development and testing of the manufacture of blocks for this purpose will be conducted in the Bentonite Laboratory.

In the industrial-scale tests that have been performed, SKB has demonstrated that blocks for use in the deposition hole can be manufactured with commercially available equipment. SKB therefore does not plan any major efforts to develop the technology for this type of block compaction during the coming six-year period. We will, however, study what properties blocks of possible backfilling materials may have after compaction.

All blocks for coming large-scale tests of backfilling, for example in the Bentonite Laboratory, will be manufactured in existing presses.

15.4 Manufacture of pellets and granules

Development of production methods for pellets and granules is described in section 13.3.2. For backfilling, however, pellets or granules may be manufactured of another clay material than pure bentonite.

15.5 Removal of drainage and temporary buffer protection

Before backfilling of the deposition tunnel can begin, the drainage and the buffer protection in the deposition holes must be removed. This does not entail any problems under normal circumstances.

Conclusions in RD&D 2004 and its review

This preparatory work was not described in RD&D-Programme 2004.

Newfound knowledge since RD&D 2004

No efforts have been targeted directly at this area during the period. The current state of knowledge is based on experience from Prototype Repository in the Äspö HRL /15-3, 15-4/. There the buffer protection and drainage could be removed, despite the fact that the gap between buffer block and rock wall was often crowded with instrument cables.

Programme

The goal in the final repository is that it should be possible to remove drainage and temporary buffer protection by remote control. Development of equipment for this will be based on analyses of events and scenarios that are judged to have a high probability of occurring or to lead to serious consequences. For example, there must be an emergency plan and equipment for removing stuck buffer protection. Prior to application for the final repository we tested different ways to handle problems and what to do in the most difficult situations.

15.6 Installation of backfill blocks

Conclusions in RD&D 2004 and its review

Besides the conclusions and comments that are presented in section 15.3, SSI pointed out that before trial operation SKB needs to be able to show that they can carry out all steps in deposition and backfilling under realistic conditions and with the machines and procedures that will be used in routine operation.

SKI also pointed out that SKB should take into account the fact that the quality of materials, handling, application etc can vary during the long operating period.

Newfound knowledge since RD&D 2004

Since 2004, machines and methods for backfilling deposition tunnels have been evaluated in a programme for backfilling and closure (Baclo). SKB and Posiva are carrying out the programme together. An account of technology for backfilling the tunnels with blocks is provided in /15-8/. The tunnels are backfilled with block units sized 120×80×50 centimetres. This is equivalent to the size of two blocks that can be made with commercially available technology. The dimensions of the blocks will be adapted to the dimensions of the tunnel when the latter have been established. The blocks are loaded onto a transport vehicle under ground and driven out to the deposition tunnel. In the tunnel the blocks are transferred to an installation rig, see Figure 15-3. The block units are placed in the right position in the tunnel by means of an installation tool, see Figure 15-4. Normally 80 percent of the tunnel cross-section is filled with blocks and other parts with pellets or granules. To fulfil the function indicator (see Chapter 25 in Part IV), 90 percent of the remaining volume needs to be filled up with the type of pellets used so far in the tests in the Bentonite Laboratory. The capacity for which the final repository is currently designed entails that six metres of deposition tunnel will be backfilled per day.

Figure 15-3. Rig for transport and installation of blocks.

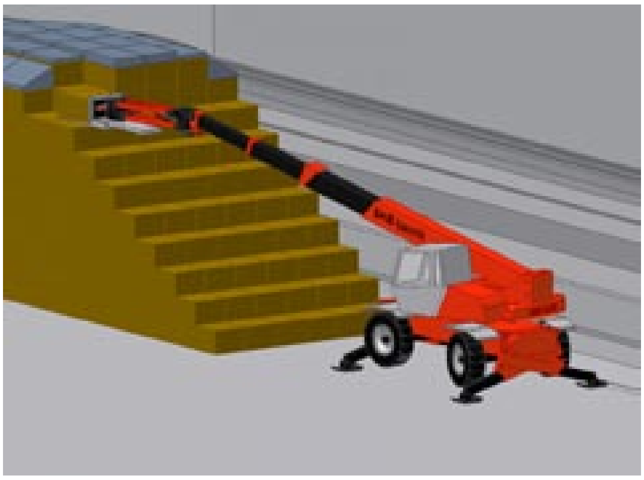


Figure 15-4. Emplacement of blocks in tunnel with an installation tool.

Programme

The installation of whole backfill blocks in the upper part of the deposition hole is done in the same way as the installation of buffer blocks. The development of a rig consisting of gripping tool and crane is described in section 13.6.

Thorough work will be required to design the concept for backfilling of the chamfer by the time of the applications for the final repository under the Nuclear Activities Act and for the final repository system under the Environmental Code. Practical tests will be conducted in the Bentonite Laboratory during the coming three-year period.

The development work will focus on developing technology and methods for installing blocks in the deposition tunnels according to stipulated requirements. The influence of water inflow on backfilling of the tunnels will be studied both conceptually and by practical trials. Among other things, the relationship between how much water inflow can be permitted and the backfilling rate will be determined. The Bentonite Laboratory was built to enable us to simulate water inflow in different positions around a tunnel and different-sized flows in different positions.

The backfilling method will be tested and demonstrated on a full scale in the Äspö HRL. The first tests will be done in the Bentonite Laboratory, where probable water inflow scenarios will be simulated. There we will work both with a mock-up on a scale of 1:4 and full-scale tests (1:1).

15.7 Installation of pellets or granules

Conclusions in RD&D 2004 and its review

There was no account of the installation of pellets or granules in deposition tunnels in RD&D-Programme 2004.

Newfound knowledge since RD&D 2004

During the period, SKB's cooperation with Posiva has led to a main alternative for backfilling of deposition tunnels, which is also recommended after having been analyzed in SR-Can /15-6/. This alternative for backfilling of deposition tunnels assumes that pellets or granules are installed between the wall of the tunnel and the clay blocks. Different ways to install the pellets or granules are being tested in a series of tests in the Bentonite Laboratory.

Programme

Tests of installation of pellets and granules in the Bentonite Laboratory will continue. The goal is to develop the method and the equipment for installation so that dust is minimized and a high and even degree of filling is achieved. How different conditions, such as point inflows of water and the smoothness of the rock wall, affect installation will be studied.

The tests and demonstrations are a part of the work with backfilling methods that is described in section 15.6.

15.8 Installation of a temporary plug in the deposition tunnel

When all canisters in a deposition tunnel have been deposited, the tunnel is backfilled and plugged. A temporary plug is used until other openings in the underground part have also been backfilled. The temporary plug has no long-term function in itself, but is designed to withstand the water pressure at repository depth and the swelling pressure in the backfill. It is also dense enough that any piping in the backfill that forms during installation can self-heal. The temporary plug will not be dismantled, but rather will be left in place when other openings have been closed.

Conclusions in RD&D 2004 and its review

Two types of plugs were identified in RD&D-Programme 2004. One type is based on a reinforced plug that is anchored in a slot in the rock around the tunnel, see Figure 15-5. Plugs of this type have been installed in the Backfill and Plug Test in the Prototype Repository in the Äspö HRL. The other type of plug is a friction plug that is held in place by the friction between the plug and the rock wall, see Figure 15-6.

We also concluded that performance requirements, technical solutions and methods for building plugs need to be developed.

Newfound knowledge since RD&D 2004

The requirements on and design of the temporary plug have been further defined during the period. The premises on which the further development work will be based are that the plug:

- Does not need to cut off the excavation-disturbed zone, since we plan to use driving technology, drill-and-blast, that does not result in an axially transmissive zone along the tunnel.
- Must be possible to install in tunnels with a water inflow of up to 10 litres per minute.
- Must withstand a swelling pressure of up to 2 MPa and a water pressure of up to 5 MPa.
- May not have axial cracks larger than 0.1 millimetre (tightness requirement).
- pH < 11 (in the leachate from the concrete).

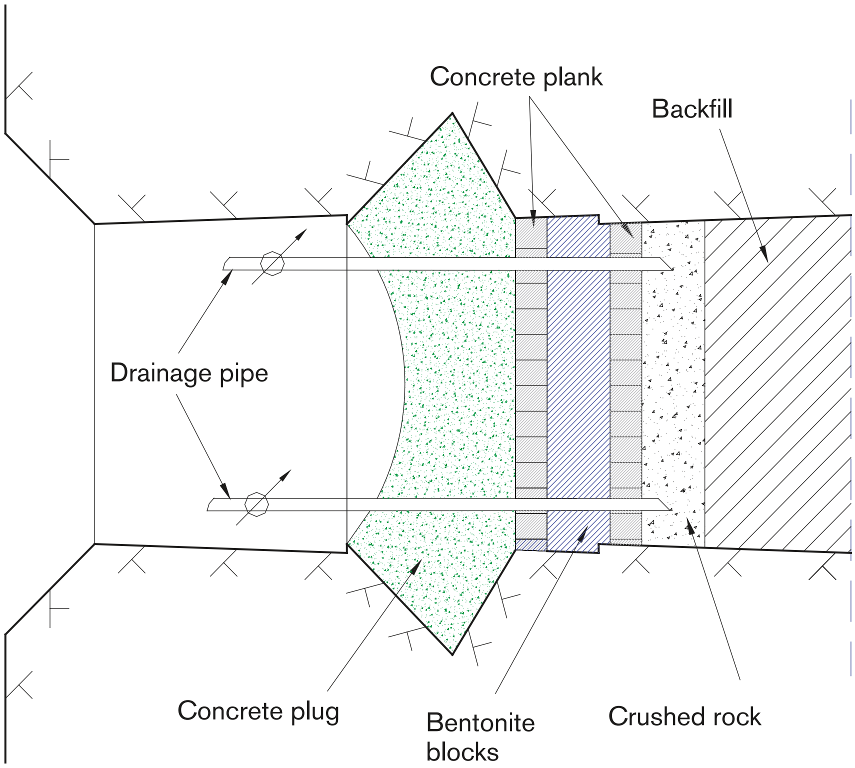


Figure 15-5. *Schematic illustration of a type of plug based on a reinforced plug that is anchored in a slot in the rock around the deposition tunnel.*

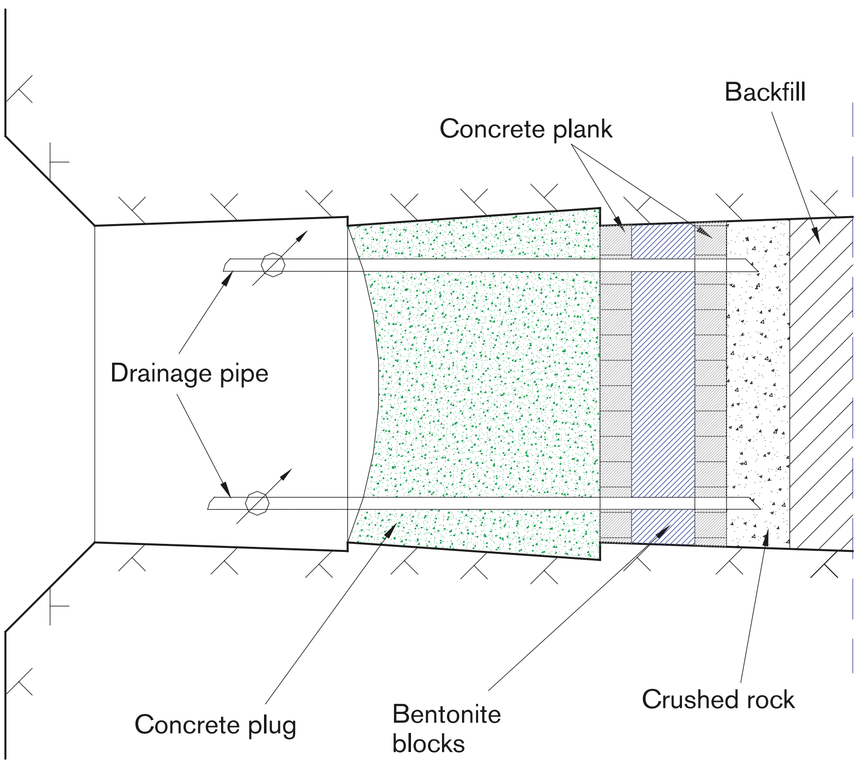


Figure 15-6. *Schematic illustration of a friction plug that is held in place by the friction between the plug and the rock wall.*

A number of requirements are made on the concrete in the plug. For example, it must be of the low-pH type, self-compacting and emit little heat on hydration. SKB has been working on the development of low-pH concrete since 2004, for example in the EU project Esdred and in cooperation with Posiva and Numo /15-9/. However, this development has mainly been focused on injection grout, shotcrete and concrete in plugs in investigation boreholes.

Low-pH concrete has been used in a full-scale plug installed in the URL in Canada within the framework of an international project entitled “Tunnel Sealing Experiment (TSX)” /15-10/.

Programme

Studies and tests are being conducted to develop recipes for low-pH concrete that is suitable for the plugs. Particular attention is being given to evaluating which plasticizer(s) can be used and in what quantities.

The feasibility study of the two plug concepts that was initiated at the end of 2006 will continue. The results of the study will be used to choose a reference concept. SKB plans to design and install a full-scale plug of the chosen reference concept in the Äspö HRL.

16 The closure line

The closure line – i.e. the closure of the final repository – includes backfilling and plugging of all other openings than the deposition tunnels, such as main tunnels, transport tunnels, central area, and ramp and shafts for transport and ventilation. It also includes closure of investigation boreholes from the surface and from openings in the final repository. The closure line describes the required handling, production and installation of backfill.

The colour coding of the closure line shows the areas for which there is known and proven technology that can be applied to the final repository and the areas for which technology development is required, see Figure 16-1. The figure describes SKB's assessment of the situation for technology development today. In the areas coloured grey or green, normal design efforts are assumed to suffice in order to specify and execute the necessary measures. Verifying tests may be warranted in a few cases. In the areas coloured yellow or red, technology development is needed. Tests have been carried out in a number of the areas coloured yellow, but SKB deems that further development or optimization measures are warranted.

16.1 Current situation

Closure of the other openings will not take place until all spent nuclear fuel has been deposited. This means that the closure activities lie well in the future. So far SKB has prioritized the work on the backfilling of the deposition tunnels. Experience from these studies will be used in the continued work of backfilling other openings as well.

The materials being considered for closure of the repository are swelling clay, non-swelling clay, crushed rock and combinations of these materials. Handling, manufacture and backfilling can largely be done using the same methods as those developed for the backfilling line. Commercially employed methods are also available for non-swelling clays and crushed rock. Mixtures of quartz sand and bentonite were tested in the Stripa mine. In tests in the Äspö HRL, SKB has installed backfills consisting of crushed rock and a mixture of crushed rock and bentonite. Different types of plugs may be used when the closure materials have been installed.

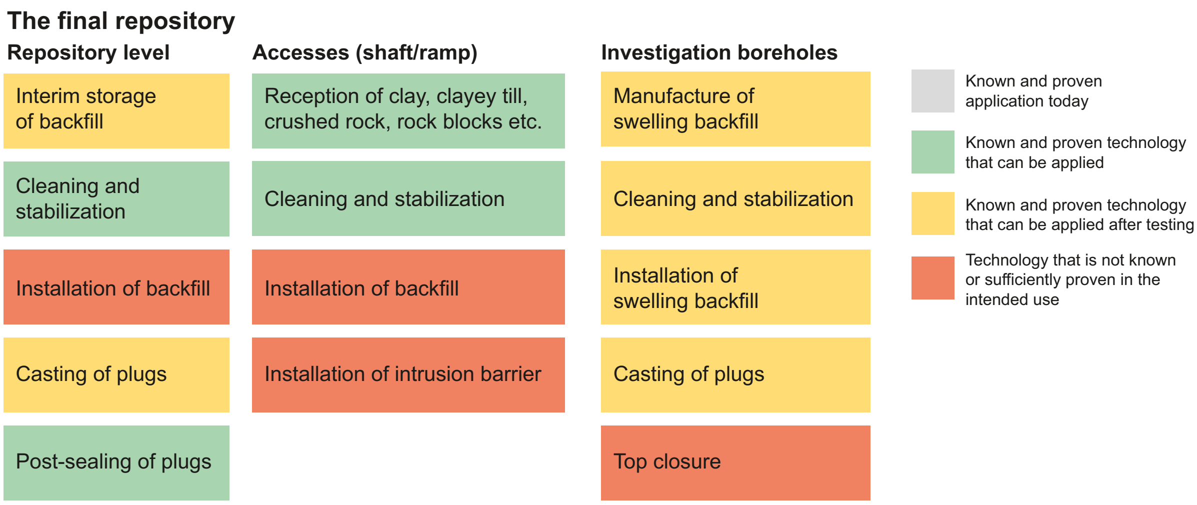


Figure 16-1. *The closure line – SKB's assessment of the situation for technology development today.*

Investigation boreholes from the ground surface and in the final repository must be sealed by the time of the closure of the final repository. SKB has studied and developed several concepts for borehole closure. The most promising concept, bentonite and quartz-based concrete, has been tested in a 500 metre deep borehole in Olkiluoto in Finland.

In the same way as for the backfilling line, it is also important in the closure line to determine where the borderline for water inflow goes if we are to meet the closure requirements. It is also important to study how closure of shafts and ramp should be designed so that the necessary function is retained even during and after the next ice age.

16.2 Requirements and premises

The requirements on backfilling and plugging of other openings will be adjusted to the importance of each opening for radionuclide transport from leaky canisters. This will be analyzed in the safety assessment SR-Site. The conclusions will provide guidance on how the closure should be designed. The requirements on backfilling and plugs in main tunnels in the deposition areas are expected to be similar to those for backfilling in the deposition tunnels, see Chapter 15.

Requirements on methods and equipment for backfilling and plugging other openings have not yet been specified. At present, requirements are only stipulated for the desired performance:

- The closure of the transport tunnels should be designed so that the backfill in the deposition tunnels is held permanently in place.
- The closure in the upper parts of shafts and ramp should be designed to withstand a period of permafrost.
- The closures in the uppermost parts of ramp and shafts should be designed to hinder intrusion in the final repository.
- The borehole seal should provide durable sealing of the boreholes and prevent axial water inflow in them.

The requirements on methods and equipment for installing the closure will only be able to be derived from these performance requirements when the closure concept has been chosen.

16.3 Manufacture and installation of backfill

Conclusions in RD&D 2004 and its review

No distinction was made in RD&D-Programme 2004 between backfilling of deposition tunnels and other openings in the final repository.

Newfound knowledge since RD&D 2004

The newfound knowledge in this area comes from the development work that has been done on backfilling of deposition tunnels. Experience from development, manufacture and installation of different backfill concepts in the Äspö HRL /16-1, 16-2, 16-3/ will be able to be used in the continued work.

Programme

Closure of the final repository lies so far in the future that there is time to await the results of technology development for the backfilling of deposition tunnels before we make a decision on what need exists for technology development.

The performance of the backfill during future ice ages will be investigated. We plan to conduct field studies of the processes and any changes in properties that occur in connection with freezing and thawing of the backfill. The results will comprise a basis for designing the backfill in the superficial parts of the final repository, where there is a risk of freezing.

16.4 Installation of plugs

Temporary and permanent plugs may be important when the final repository is to be closed. Most of the knowledge about these plugs that will be gained during the current RD&D period will be generated by the work being done to develop the plugs for the deposition tunnels, see section 15.8.

16.5 Closure of boreholes

16.5.1 Sealing of boreholes

Conclusions in RD&D 2004 and its review

A programme for identifying suitable technology for cleaning and sealing technology was described in RD&D-Programme 2001. The first stage consisted of a feasibility study which served as a basis for the programme which SKB presented in RD&D-Programme 2004. The goal of the programme was to develop performance requirements and a complete concept, and to conduct studies in the laboratory and in the field.

The comments made by the regulatory authorities have not occasioned any changes in the focus of the programme.

Newfound knowledge since RD&D 2004

SKB has, in cooperation with Posiva, developed concepts for sealing long and short boreholes /16-4, 16-5, 16-6, 16-7/. The concepts are supposed to work in both steeply and gently dipping boreholes /16-8/. The concept is based on the one tested in Stripa /16-9/ and used in SFR.

The basic concept for closing long and short boreholes involves sealing the holes with perforated copper tubes filled with highly compacted smectite-rich clay (of type MX-80). In our judgement, the basic concept can be used for boreholes of arbitrary orientation.

Three other methods for sealing holes have also been studied:

- The container concept involves placing a closed tube containing compacted smectite-rich clay in the borehole. The closed tube isolates the clay from the borehole water during installation. When the tube is in the right position, the bottom is opened and the clay is pressed out. We believe that this concept can be used for sealing both short and long holes.
- The couronne concept involves emplacing cylindrical bentonite blocks that are strung up on a copper bar in the borehole. We judge that this concept can be used in boreholes that are up to 100 metres long and have an arbitrary orientation.
- The pellet concept involves spraying highly compacted pellets of smectite-rich clay (of type MX-80) directly into the borehole. This concept can probably only be used in steeply dipping downward-directed holes.

Manufacture of bentonite blocks does not differ appreciably in the different concepts. We have enough experience of compacting bentonite blocks of this size to be able to manufacture the blocks regardless of concept.

There is a high risk that the clay will erode where the borehole passes water-conducting fractures. There the holes can be filled with silica concrete, which is a permeable material. The necessary conditions for the sealing material to remain mechanically stable is that the cement content is low and the aggregate material is inert. Existing knowledge of manufacturing silica concrete is judged to be adequate.

The sealing in the upper part of the borehole, which is usually of a larger diameter than the lower part, is supposed to protect the clay in the borehole and prevent it from expanding upward. In designing the upper part of the sealing, the effects of external forces, such as a changing climate and rock deformations resulting from tectonic displacements and glaciations, must be taken into consideration. Several materials – such as stone, gravel, sand or till – can be used to protect the clay. Two concepts have been developed for plugging: a plug consisting of reinforced concrete with quartz and an expanding metal plug.

Programme

The research project will continue to be conducted during the coming RD&D period. During the remaining stages we will manufacture all the materials required for borehole sealing and test them in existing investigation boreholes from the site investigations in Finland and Sweden. The goal is that SKB and Posiva together should demonstrate sealing of up to 1,000-metre-deep boreholes.

16.5.2 Cleaning and stabilization of boreholes

Before the boreholes can be sealed they must be cleaned from old measurement equipment and broken-out rock, for example. The borehole may also need to be reamed to its original diameter and the borehole walls may need to be stabilized, especially where they pass zones of weakness.

Conclusions in RD&D 2004 and its review

Cleaning and stabilization of boreholes was not dealt with in RD&D-Programme 2004.

Newfound knowledge since RD&D 2004

A compilation of the methods that can be used to clean boreholes has been prepared by SKB and Posiva. The work has been done within the framework of a cooperation project /16-8/. The conclusion is that technology is available for cleaning boreholes. There is therefore no need today to conduct further development.

SKB and Posiva have developed a method for stabilizing boreholes in the areas where they pass zones of weakness in the rock. Stabilization is achieved by widening the borehole and filling it with silica concrete. A hole of the same diameter as the original borehole is then drilled through the concrete. This method has been used in investigation holes at the site investigations and for sealing of a deep borehole in 2005 in Olkiluoto (KR-24) /16-10/. The method works well and meets the requirements that apply during the short time it takes to install the clay, see also section 12.3.1.

Programme

The method described above to stabilize boreholes has worked well, but needs to be tested in holes deeper than 500 metres. The investigation holes in Olkiluoto, Forsmark and Oskarshamn will be examined from a sealing perspective. A geological characterization of the holes is also planned. The need of future stabilization will then be compiled and suitable test objects below a depth of 500 metres will be identified. The continued work on stabilization technology in new investigation holes is described in section 12.3.1. We will evaluate the results continuously with a view to the possibility of using the technology in deep investigation holes from the ground surface as well.

Grouting with fine-grained silica cement is another possibility for stabilizing zones of weakness. Development of the grouting technology will take place in coordination with development of the technology for grouting of tunnels, see section 12.4.

17 Retrieval

The final repository for spent nuclear fuel must be designed in such a way that it does not need to be monitored. If future generations should wish to retrieve the fuel again, this is fully possible. A small number of canisters will be deposited during trial operation of the final repository. The activity will be evaluated regularly. If the evaluation has a positive outcome, deposition will continue during routine operation. If the outcome is not positive, freeing and retrieving the canisters may be considered. Retrieval would require a permit under the Nuclear Activities Act.

How a canister is retrieved depends on when the decision is made. The longer time has passed since deposition, the more difficult it will be to remove the buffer and free the canisters. The technical difficulties depend on the degree of water saturation – and thereby the swelling pressure – in the surrounding buffer. Another difficulty is the radiation from the fuel, which will necessitate radiation shielding during the work. When the bentonite has been removed, the canister can be lifted up out of the deposition hole and handled behind radiation shielding with the deposition machine. SKB has demonstrated that it is possible to retrieve canisters during the operating phase in a full-scale test in the Äspö HRL. The method developed by SKB offers the requisite radiation shielding. The greatest labour input and the highest costs are associated with retrieval after closure of the repository.

17.1 Current situation

SKB has previously studied and evaluated various methods for freeing the canisters from the bentonite buffer /17-1/:

- Mechanical methods where the bentonite is machined away by, for example, boring or drilling.
- Hydrodynamic methods where the bentonite is washed away with water.
- Thermal methods where the canister's mantle surface is freed by heating or cooling.
- Electrical methods where the bentonite nearest the canister's mantle surface is shrunk by means of an electric current to create a gap between the canister and the buffer.

Of the above methods, the hydrodynamic method is judged to have the highest development potential. It was tested in the Äspö HRL both in the Slurrying Test (which preceded the Canister Retrieval Test) and in the mining of the Canister Retrieval Test. The hydrodynamic method may be time-consuming, but no major difficulties have been observed. The method consists of two parts: slurrying of the bentonite buffer and dewatering of the generated slurry, see Figure 17-1. Installation of the Canister Retrieval Test is described in /17-2/.

Figure 17-1. *Demonstration of freeing of a copper canister by means of the hydrodynamic method in the Äspö HRL. The slurrying of the bentonite buffer is shown at the left and the equipment for dewatering at the right.*

17.2 Requirements

In Sweden there is no formal requirement that it should be possible to retrieve deposited canisters after closure of the repository. Retrieving canisters is regarded as a nuclear activity, which means that a permit under the Nuclear Activities Act is required.

However, SKB has formulated its own requirement that the final repository must be designed in such a manner that it is possible to retrieve deposited canisters before closure, provided this does not lead to technical designs that degrade the long-term performance of the repository. Single canisters may have to be retrieved from a deposition hole if something unforeseen happens during deposition. Retrieval of a large number of canisters in a later phase of operation of the repository must also be possible. If another method for disposing of or making use of the spent nuclear fuel is preferred in the future, technology for retrieving canisters will be needed then as well.

17.3 Freeing of canister

Conclusions in RD&D 2004 and its review

In RD&D-Programme 2004, SKB demonstrated with makeshift equipment in the Äspö HRL that freeing of a canister of natural size is possible. The test confirmed that the hydrodynamic method is a promising method that should be further developed and tested.

In its review, Kasam points out that the repository should be built so that fuel can be retrieved, considering possible future progress in, for example, transmutation technology. Moreover, safety in conjunction with a possible retrieval must be studied.

Newfound knowledge since RD&D 2004

The hydrodynamic method has been developed and tested on a full scale in conjunction with the dismantling of the Canister Retrieval Test in the Äspö HRL /17-3/. In this test, approximately half of the buffer material disintegrated, while the rest was mined mechanically so it could be examined for the purpose of other studies. A schematic illustration of the canister freeing equipment is provided in Figure 17-2.

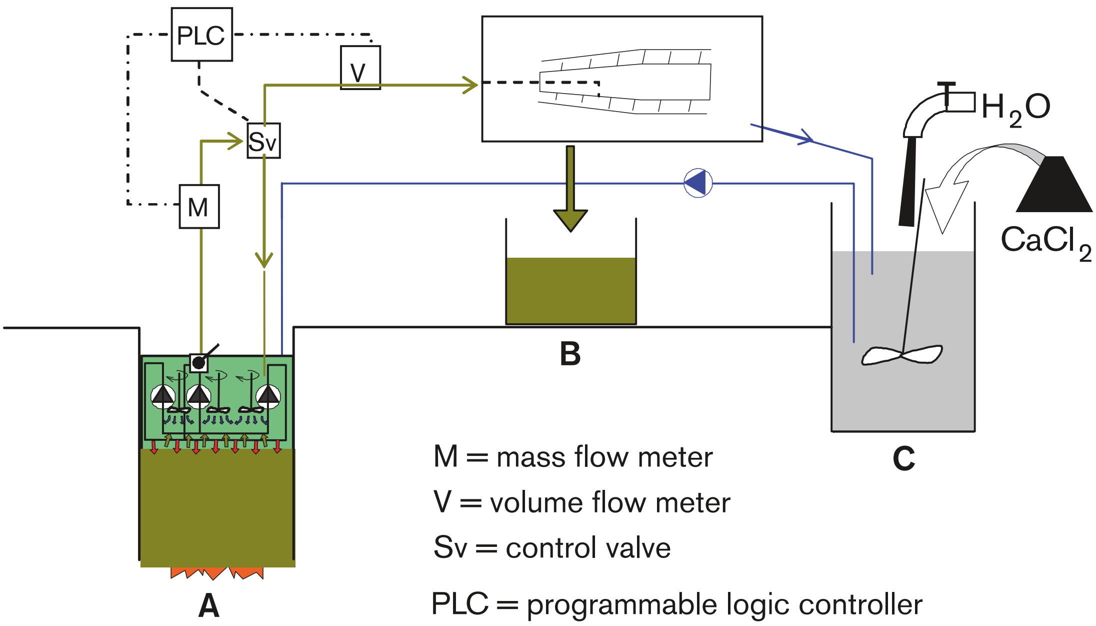


Figure 17-2. *Schematic illustration of the canister freeing equipment. (A) deposition hole with saline solution above the bentonite buffer and with the slurrying equipment in the working position. (B) decanter centrifuge with release of dewatered bentonite and clear liquid. (C) vessel for collection of clear liquid and preparation and testing of saline solution.*

The freeing of the canister carried out in the Canister Retrieval Test showed that the chosen hydrodynamic method works well and offers the following advantages:

- The simultaneous chemical and mechanical action on the buffer erodes the compacted bentonite. The method can be applied in a continuous process.
- The saline solution acts as radiation protection, in addition to eroding and slurrying the bentonite.
- There is very little risk of damage to the canister.
- Sensitivity to the position of the canister in the deposition hole is little.
- No bulky loadbearing or positioning structural parts are needed (compared with equipment that uses some type of mechanical freeing technology).

Programme

No additional large-scale tests are planned during the current RD&D period.

17.4 Dewatering of generated slurry

Conclusions in RD&D 2004 and its review

In RD&D-Programme 2004, SKB demonstrated with makeshift equipment in the Äspö HRL that freeing of a canister of natural size is possible.

Newfound knowledge since RD&D 2004

Dewatering with a decanter centrifuge in a continuous process has been carried out on full scale in the Äspö HRL. The bentonite slurry that was generated during freeing of the canister in the Canister Retrieval Test in the Äspö HRL was dewatered in a large decanter centrifuge with very good results, see Figure 17-3.

Programme

No work is planned during the programme period.

Figure 17-3. *Dewatered bentonite from the decanter centrifuge.*

18 Alternative repository design – KBS-3H

The KBS-3 method permits canisters to be emplaced either vertically (KBS-3V) or horizontally (KBS-3H). In both cases the canister is surrounded by a buffer of bentonite, see Figure 18-1. No deposition tunnels are needed in KBS-3H; the long horizontal deposition holes (deposition drifts) are excavated directly from the main tunnel. This means that a much smaller volume of rock needs to be excavated than in vertical deposition. The part of the final repository located above ground is not affected by whether the canisters are deposited horizontally or vertically.

SKB studied horizontal emplacement of canisters in a final repository in the early 1990s /18-1, 18-2/. A research, development and demonstration programme for KBS-3H was published in 2001 /18-3/ to determine whether horizontal deposition can offer an alternative to vertical deposition.

18.1 Current situation

SKB and Posiva have been cooperating since 2002 to conduct the research programme which SKB published in 2001. The programme, which will be concluded during 2007, includes design of the repository's components and a general repository layout. A full-scale demonstration of the deposition equipment for KBS-3H is being conducted in the Äspö HRL. In preparation for this, the required equipment was designed and manufactured. This work is taking place within the framework of the EU project Esdred in the Sixth Framework Programme. Two horizontal deposition drifts have been bored in the Äspö HRL. They are being used to demonstrate the deposition procedure and other activities, such as grouting and plugging. The deposition equipment was delivered in 2006. After various modifications it was put into operation, and the demonstration was begun in early 2007.

The programme for KBS-3H also includes a safety assessment for a planned repository in Olkiluoto. The assessment is being conducted by Posiva.

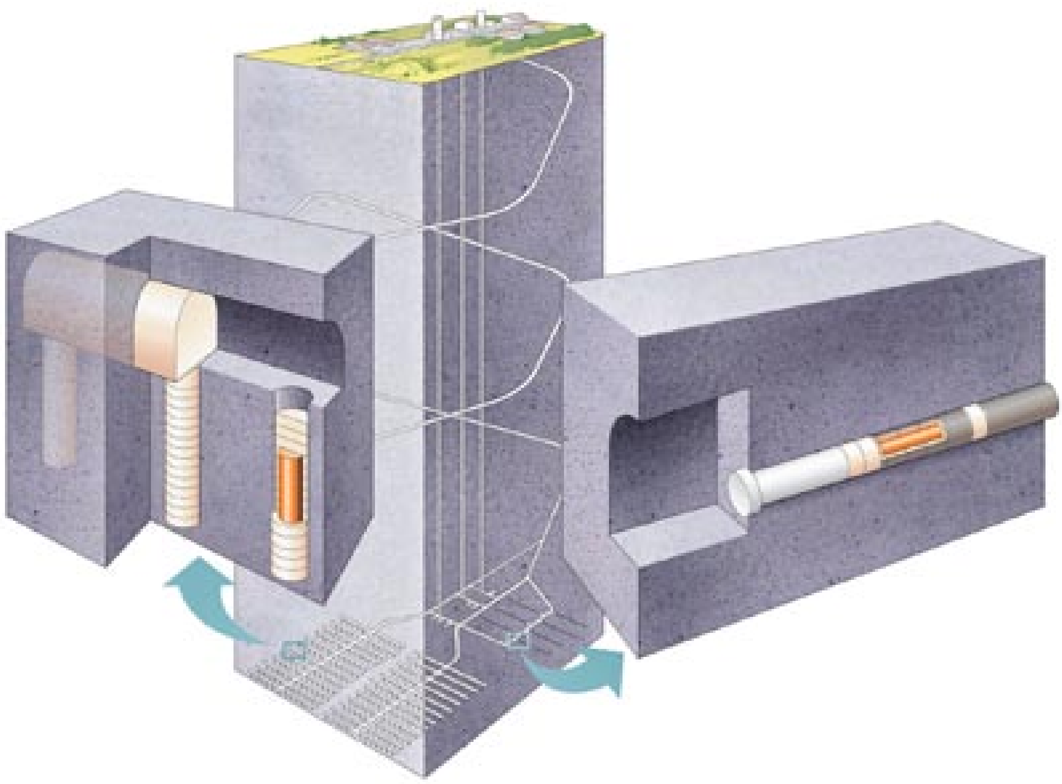


Figure 18-1. The KBS-3 repository with vertical (KBS-3V) versus horizontal (KBS-3H) deposition.

At the end of 2007 the results of the activities in the programme will be reported. Feasibility and long-term safety will then be evaluated. Based on this report and evaluation, SKB will then make a decision as to whether KBS-3H will be further developed or not.

18.2 Design

Conclusions in RD&D 2004 and its review

A design of a KBS-3H repository was presented in RD&D-Programme 2004. The design was based on boring approximately 300 metre long, gently sloping deposition drifts from the main tunnel. The canisters are deposited in the drifts surrounded by a bentonite buffer and a perforated steel cylinder called the supercontainer.

A deposition machine is needed to deposit the supercontainer packages in the deposition drifts. Development of the deposition machine and other equipment is currently under way. The plans call for the deposition machine to utilize water-driven cushions to reduce the friction against the rock in the deposition drift when the supercontainer is emplaced.

There will be a distance block of bentonite clay between successive supercontainer packages to seal off the different supercontainer drift sections so that water flow along the drift is prevented and the temperature in the buffer does not get too high. A concrete plug will be installed at the mouth of the deposition drift. The plug will hold the supercontainers and distance blocks in place until the main tunnel is backfilled. The deposition drifts may be spaced at a distance of 25–40 metres, depending on the properties of the rock.

The concept has a number of uncertainties and problems, such as piping in the buffer material, strict requirements on the water inflow to the deposition drift, heterogeneous water saturation and cracking in the distance blocks.

Newfound knowledge since RD&D 2004

The design of KBS-3H has been further developed since RD&D-Programme 2004. Among other things, tests of how water inflows along the deposition drift affect the buffer have been performed on a laboratory scale /18-4/.

To prevent large quantities of water from getting into the deposition drift via water-conducting fracture zones, these zones will be screened off. Screening is accomplished by placing compartment plugs on both sides of fracture zones in the deposition drift. The compartment plugs are designed to withstand the hydrostatic pressure at a depth of 400–500 metres and the bentonite's swelling pressure. Compartment plugs and other components in a KBS-3H repository are shown in Figure 18-2.

The basic design of the deposition equipment was developed in 2003 and reported in /18-5/. This work constitutes the basis of the detailed design and the manufacture of the deposition equipment.

Furthermore, a so-called megapacker has been developed for post-grouting of the excavated deposition drifts to further reduce the water inflow.

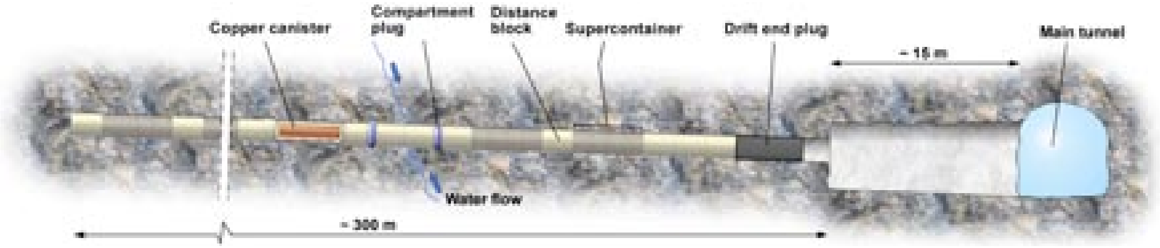


Figure 18-2. *Schematic illustration of a KBS-3H repository.*

Programme

If the decision is made to further develop KBS-3H, a programme for this will be prepared. The development issues which we already judge to be important in order for KBS-3H to achieve a technical level equivalent to that of KBS-3V are presented here. The programme points taken up below must, if implemented, be able to be executed during the coming six years.

The design of KBS-3H will be studied in greater detail. This includes, for example, the compartment plugs that will screen off the water-conducting zones and the distance blocks of buffer material. Furthermore, different ways to handle water inflows by drainage will be developed. How the water inflow is handled also depends on the actual frequency – and properties – of the fractures on the site for the final repository. Layout studies therefore need to be done in both Forsmark and Laxemar. Such studies also serve as a basis for determining what rock stresses we have to take into account, how great the risk of spalling is and how the excavation-disturbed zone around the deposition drifts can be characterized.

Determining the logistics of deposition is important for quality assurance in deposition. An important question is how long a time may pass between the deposition of two supercontainers and how much time may pass from when the last supercontainer has been deposited in a deposition drift until the drift is plugged.

In order to be able to handle error events during the deposition sequence, they must first be identified and analyzed. Based on the results of the analysis, the necessary measures can be described and equipment developed.

Other materials than steel in the supercontainer will be studied. The same applies to other buffer materials. Furthermore, the handling of buffer and canister without supercontainer will be evaluated.

The largest water inflows that can be allowed to the deposition drift without jeopardizing the quality of the buffer is an important question, in the same way as for the deposition holes in KBS–3V. This may consequently be investigated jointly for the two alternatives.

18.3 Demonstration in the Äspö HRL

Conclusions in RD&D 2004 and its review

A full-scale demonstration of KBS-3H was planned in the Äspö HRL at a depth of 220 metres. Preparatory work in the form of drilling of investigation boreholes and blasting-out of a niche where all the equipment will be placed had begun.

Newfound knowledge since RD&D 2004

Two horizontal deposition drifts have been excavated /18-6/. One drift is 15 metres long and is used to test the repository’s components in different ways. A short drift end plug of low-pH shotcrete has been built in this drift, for example. The other drift is 95 metres long and is used mainly for demonstration of the deposition equipment and grouting with the megapacker.

Horizontal reverse raise boring was used to excavate the drifts. A pilot hole was drilled, after which the drift was reamed to full diameter /18-6/. Careful control of the guidance of the drilling of the pilot hole enabled the strict requirements on straightness of the drift to be met.

The components for two filled supercontainers (canister, buffer block and rings plus a perforated steel cylinder) were manufactured and assembled to two packages during 2005. To enable the deposition demonstration to be executed, the buffer was made of concrete. Bentonite could not be used because it will begin to swell in the moist environment in the Äspö HRL and the package has to work throughout duration of the test. The concrete has the same density and compressive strength as bentonite in order to simulate actual conditions in terms of weight and to some extent durability as well.

A French company manufactured the deposition equipment, which was delivered and installed in the Äspö HRL in 2006. After various modifications, for example to correct instability in the equipment and poor function of the water-powered lifting cushions, the equipment could be approved (site acceptance test – SAT) in February 2007. The equipment is shown in Figure 18-3.

A short drift end plug made of low-pH shotcrete was installed in the 15-metre-long deposition drift. The work was carried out within the framework of the EU project Esdred. The test showed that it was difficult to achieve good adhesion between the plug and the rock surface.

Programme

SKB will decide at the end of 2007 whether or not the KBS-3H concept should be further developed. If we decide to continue working on KBS-3H, the following is planned:

Provided the continued work on the design of the method results in promising solutions, SKB will consider how reliable field data can be obtained.

In the existing niche and the deposition drifts at a depth of 220 metres we will be able to test equipment for handling and deposition and conduct installation tests with compartment plug, distance block and drainage solutions.

We also believe long-term tests are needed in order to study the performance of the compartment plugs. Another area that needs to be studied further by long-term tests is how materials peculiar to KBS-3H affect the performance of the buffer, for example.

Certain studies will need to be performed at higher groundwater pressures and higher rock stresses. This includes investigations of the properties of the rock around the excavated deposition drifts, how much spalling occurs and how the rock can be sealed at this depth. Like SKI, SKB believes that a prototype of a KBS-3H repository needs to be installed in a realistic final repository environment. If such a step is taken, the installation can be located in a deeper part of the Äspö HRL. According to current estimates, the installation can be carried out during the coming six-year period.

Figure 18-3. *KBS-3H – deposition equipment in the Äspö HRL at a depth of 220 metres.*

18.4 Long-term safety

Conclusions in RD&D 2004 and its review

A preliminary safety evaluation of KBS-3H has been conducted and reviewed by international experts. The conclusion of this review was that it is judged possible to satisfy the requirements on long-term safety /18-7/.

A preliminary safety assessment of KBS-3H is being conducted under the leadership of Posiva. The safety assessment utilizes the methodology that was developed for SR-Can as well as Posiva's own expertise. The assessment is being done for a final repository in Olkiluoto and site data from there will be used.

In its review of RD&D-Programme 2004, SKI pointed out that the planned safety assessment for a final repository in Olkiluoto will not provide all the answers needed to evaluate safety under Swedish conditions, for example the importance of the high rock stresses in Forsmark.

Newfound knowledge since RD&D 2004

KBS-3H is in many respects very similar to KBS-3V. The similarities include the spent fuel, the copper canister, the bentonite buffer and conditions in the geosphere and the biosphere. For this reason, only the crucial differences between KBS-3H and KBS-3V will be studied in detail in the safety assessment. Specific characteristics of KBS-3H are:

- The deposition drifts are long and there is a risk that piping and erosion will occur in the buffer and distance blocks before the bentonite has become water-saturated.
- KBS-3H has a larger number of steel components. These components will corrode and form hydrogen gas. The iron will also affect the physical and chemical properties of the bentonite.

Programme

Posiva will complete a preliminary safety assessment for a KBS-3H repository (KBS-3H Safety Assessment 2007) applied to the Olkiluoto site during 2007. Provided it is decided that work on KBS-3H is to continue, this assessment will be supplemented by a site-specific safety assessment for the site SKB selects for KBS-3V. The design and scope of the assessment will not be planned until SR-Site has been completed. The assessment will be based to as great an extent as possible on SR-Site and supplementary assessments of the differences between the two concepts. The purpose is to be able to compare the safety of the two alternatives.

Part IV

Safety assessment and natural science research

19 Overview – safety assessment and natural science research

A safety assessment determines whether the final repository for spent nuclear fuel satisfies the requirement on long-term safety by describing the repository's initial state and examining the possible long-term changes. Based on this, the safety assessment then describes the consequences for man and the environment. The safety assessment uses a scientific methodology and obtains knowledge concerning long-term changes from research. The results of the assessment are presented in a safety report.

SKB's natural science research programme spans two fields:

- Long-term safety
- Other final disposal methods than KBS-3

The biggest field is research on long-term safety. This research is directly aimed at furnishing background data for SKB's safety assessments of the final repository for spent fuel. The most recent safety assessment is called SR-Can, and the safety analysis report was submitted to the regulatory authorities on 1 November 2006 /19-1/. SR-Can has provided guidance in the planning of the research programme. By identifying and examining different processes in the repository and its surroundings, the relevant areas of research can be identified.

SKB is following the development of two other methods for disposing of spent fuel: partitioning and transmutation (P&T) and deep boreholes. These alternative methods are described in Chapter 28. Safety assessment and research aimed at low- and intermediate-level waste are dealt with in Part VI of this RD&D programme.

19.1 Safety assessment

Chapter 20 provides an initial overview of the method that was used in the recently reported safety assessment SR-Can. It then goes on to describe how the method will be modified for the coming safety assessment SR-Site, on which the application for the final repository will be based. Large parts of the methodology that is used in SR-Can are regarded as mature and will be reused in SR-Site. The regulatory authorities' report on their review of SR-Can will be published in December 2007. It will serve as an important point of departure for determining the final methodology for SR-Site.

Chapter 20 also describes the status and development programme for some tools for integrated modelling in the safety assessment.

The work in the safety assessment is concentrated on the KBS-3V repository concept. Horizontal deposition of the canisters (KBS-3H) is also being studied, but the long-term safety of KBS-3H is being assessed under the leadership of Posiva. The goal is that Posiva should present a preliminary safety assessment with Olkiluoto as the reference site in 2007. This is discussed in Part III, section 18.4.

19.2 Research on long-term safety

SKB's research on long-term safety is above all focused on the processes (long-term changes) that occur in a final repository and how they affect the repository's ability to isolate the spent nuclear fuel. The climate's impact on the repository is of a general nature. We have therefore chosen to start with a chapter that describes the research being conducted by SKB within the area (Chapter 21). The regulatory authorities require that the impact of an ice age on a final repository be elucidated. SKB's climate programme is therefore aimed at doing this.

Detailed accounts of the programmes for fuel, canister, buffer, backfill and geosphere follow in Chapters 22 to 26. Possible research and development needs for the initial state are discussed for each part of the repository. After the discussion of the research and development need for the initial state, all processes are dealt with. The processes are divided into radiation-related (R), thermal (T), hydraulic (H), mechanical (M) and chemical (C), plus processes related to radionuclide transport. In some cases a treatment of individual processes is not sufficient for understanding the course of events. The subdivision of processes has therefore sometimes been augmented with descriptions that are characterized as integrated studies.

Table 19-1 shows all processes of importance for long-term safety that are dealt with in Chapters 22 to 26. The corresponding information for the initial state is found in Table 19-2. The colour code provides a rough idea of the magnitude of the planned initiatives for the different processes during the upcoming three-year period. Research initiatives that are particularly important for the coming safety assessments warrant great efforts and are therefore often marked in red. In its review of RD&D-Programme 2004, SSI called for a clearer identification of the most important research issues in each area, taking into account their importance for long-term radiation protection and for carrying out the different steps in the nuclear fuel programme. Tables 19-1 and 19-2 are intended to provide some guidance in this. All research conducted by SKB into processes of importance for long-term safety should be important to the extent that the results should make a crucial difference in the assessment of safety, in a positive or a negative sense. Prior to the different steps in the final repository programme, however, certain questions must have been cleared up or at least have come so far that there is agreement to proceed with the overall programme. This is dealt with in the Application Plan /19-2/ that was submitted in August 2006.

Chapter 27 presents SKB's research programme for the biosphere. It is described with a slightly freer format than other parts. The processes are too numerous to be used as a basis for the presentation without losing the overall picture. The format instead follows the ecosystem-based approach that will be used in SR-Site.

The point of departure for the account of the research programme is KBS-3V. Many processes in KBS-3H are the same as far as long-term safety is concerned. This means that the results of investigations started with KBS-3V in mind can also be used for KBS-3H. The reverse can also be true, see sections 23.2.8, 24.2.8, 24.2.9 and 24.2.11.

19.2.1 Climate change

Due to the variations in the Earth's climate, we cannot rule out the possibility of one or more glacial cycles (ice ages) during the timespan of hundreds of thousands of years over which the safety of the final repository must be studied. SKB has therefore studied climate change and climate-related processes in order to be able to define a number of relevant climate scenarios that can be used in the safety assessment. The safety assessment SR-Can evaluated the importance of climate-related conditions under various glaciation scenarios, including a reference scenario based on the most recent glaciation. The results show that the sequences of events during periods of glaciation and permafrost affect both the rock and the engineered barriers under different circumstances. Hydraulic pressure and groundwater composition can change down towards repository depth. Furthermore, permafrost can affect above all the parts of the repository where shafts and tunnels reach the ground surface. The glaciation scenario in SR-Can has thereby influenced the research programme for buffer and fuel in particular. New research projects aimed at providing a clearer picture of the climatic conditions and climate-related processes associated with glacial cycles and the future climate will start prior to SR-Site. The programme will, for example, continue to investigate how the ice load could vary (see section 21.2), how the sea level will change with time (see section 21.3) and the extent and impact of permafrost (see section 21.4) and be extended with new studies to increase our understanding of the more extreme climate scenarios that need to be analyzed in the safety assessment (see section 21.5).

Table 19-1. Research on long-term safety.

	Fuel	Canister	Buffer	Backfill	Geosphere
R	Radioactive decay 22.2.2				
	Radiation attenuation/heat generation 22.2.3	Radiation attenuation/heat generation 23.2.2	Radiation attenuation/heat generation 24.2.2	Radiation attenuation/heat generation 25.2.3	
	Induced fission (criticality) 22.2.4				
T	Heat transport 22.2.5	Heat transport 23.2.3	Heat transport 24.2.3	Heat transport 25.2.4	Heat transport 26.2.2
			Freezing 24.2.4	Freezing 25.2.5	
H	Water/gas transport 22.2.6		Water transport unsaturated 24.2.5	Water transport unsaturated 25.2.6	Groundwater flow 26.2.3
			Water transport saturated 24.2.6	Water transport saturated 25.2.7	
			Gas transport/dissolution 24.2.7	Gas transport/dissolution 25.2.8	Gas flow/dissolution 26.2.4
			Piping/erosion 24.2.8	Piping/erosion 25.2.9	
M		Deformation insert 23.2.4	Swelling 24.2.9	Swelling 25.2.10	Movements in intact rock 26.2.5
		External deformation Cu 23.2.5			Reactivation (earthquakes) 26.2.7
		Inner deformation Cu 23.2.7			Fracturing 26.2.8
					Time-dependent deformations 26.2.9
	Thermal expansion/cladding failure 22.2.7	Thermal expansion 23.2.6	Thermal expansion 24.2.10	Thermal expansion 25.2.11	Thermal movement 26.2.6
					Erosion 26.2.10
C	Advection/diffusion 22.2.8		Advection 24.2.12	Advection 25.2.12	Advection/mixing 26.2.11
			Diffusion 24.2.13	Diffusion 25.2.13	Diffusion 26.2.13
	Residual gas radiolysis/oxygen formation 22.2.9	Corrosion insert 23.2.8	Osmosis (salt effect) 24.2.14	Osmosis (salt effect) 25.2.14	Reactions with rock 26.2.15
	Water radiolysis 22.2.10	Galvanic corrosion 23.2.9	Ion exchange/sorption 24.2.15	Ion exchange/sorption 25.2.15	Dissol./precip. fract. minerals 26.2.16
	Metal corrosion 22.2.11	SCC insert 23.2.10	Montmorillonite transf. 24.2.16	Montmorillonite transf. 25.2.16	Microbial processes 26.2.18
	Fuel dissolution 22.2.12	Radiation effects 23.2.11	Dissolution/precipitation impurities 24.2.17	Dissolution/precipitation impurities 25.2.17	Inorganic decomposition 26.2.19
	Dissolution gap inventory 22.2.13	Copper corrosion 23.2.12	Colloid release/erosion 24.2.18	Colloid release/erosion 25.2.18	Colloid turnover 26.2.20
	Speciation radionuclides/colloid formation 22.2.14	SCC shell 23.2.13	Radiation-induced montmorillonite transformation 24.2.19	Radiation-induced montmorillonite transformation 25.2.19	Gas formation/dissolution 26.2.22
	Helium production 22.2.15	Grain growth copper 23.2.14	Radiolysis pore water 24.2.20	Radiolysis pore water 25.2.20	Methane ice formation 26.2.23
			Microbial processes 24.2.21	Microbial processes 25.2.21	Salt exclusion 26.2.24
Integration		HMC evolution damaged canister 23.2.16	THM evolution unsaturated 24.2.11		HC evolution 26.2.25
Radionuclide transport			Advection 24.2.22	Advection 25.2.22	Advection/mixing 26.2.12
			Diffusion 24.2.23	Diffusion 25.2.23	Diffusion 26.2.14
			Sorption 24.2.24	Sorption 25.2.24	Sorption 26.2.17
			Speciation 24.2.25	Speciation 25.2.25	Speciation 22.2.14
			Colloid transport 24.2.26		Colloid transport 26.2.21
					Gas phase transport 26.2.4
		RN transport near-field 23.2.15			RN transport geosphere 26.2.26

Code:	Major initiatives	Moderate initiatives	Minor initiatives/monitoring during coming three-year period

Table 19-2. Research on the initial state of the repository.

Fuel	Canister	Buffer	Backfill	Geosphere
Geometry 22.1.2	Geometry 23.1.2	Geometry 24.1.2	Geometry 25.1.2	
Radiation intensity 22.1.3	Radiation intensity 23.1.3	Pore geometry 24.1.3	Pore geometry 25.1.3	
Temperature 22.1.4	Temperature 23.1.4	Radiation intensity 24.1.4	Radiation intensity 25.1.4	
Hydrovariables 22.1.5	Mechanical stresses 23.1.5	Temperature 24.1.5	Temperature 25.1.5	
Mechanical stresses 22.1.6	Material composition 23.1.6	Smectite content 24.1.6	Smectite content 25.1.6	
Total radionuclide inventory 22.1.7		Water content 24.1.7	Water content 25.1.7	Site investigations
Gap inventory 22.1.8		Gas contents 24.1.8	Gas contents 25.1.8	
Material composition 22.1.9		Hydrovariables 24.1.9	Hydrovariables 25.1.9	
Water composition 22.1.10		Swelling pressure 24.1.10	Swelling pressure 25.1.10	
Gas composition 22.1.11		Smectite composition 24.1.11	Smectite composition 25.1.11	
		Pore water composition 24.1.12	Pore water composition 25.1.12	
		Impurity levels 24.1.13	Impurity levels 25.1.13	

Code:	Major initiatives	Moderate initiatives	Minor initiatives/monitoring during coming three-year period

19.2.2 Fuel

If the canister's isolation is breached and groundwater enters, radionuclides will be released from the spent nuclear fuel. Dissolution of the fuel is therefore an important process in the safety assessment. SR-Can analyzed a scenario where it was assumed that meltwater from an ice sheet damaged the buffer around some of the canisters, which in turn led to a case where the canister's isolation was breached due to increased corrosion. Fuel dissolution has thereby become even more important for safety. The scenario with a damaged buffer entails higher water flows. This is a slightly different situation than the one that has previously served as a basis for the planning of experiments and evaluations. The research programme is focused on shedding light on such conditions, for example by tests in the presence of corroding iron or with such reducing substances as are found in deep groundwaters.

Another important circumstance is the increasing burnup of the fuel and the planned use of mox fuel in Swedish reactors. Experimental and theoretical evaluations must naturally keep up with these developments. The increasing importance of fuel dissolution also underscores the need to shed light on the impact of higher burnup and use of other fuel types. Section 22.2.12 presents new results and the focus of the new programme for fuel dissolution. The need for additional theoretical evaluations is, for example, described in section 22.2.15, which is concerned with the build-up of helium from alpha particles.

In the very long term, radium, which is generated by uranium via chain decay, is of importance for safety. An interesting relationship is that the quantity of barium in spent fuel is several orders of magnitude larger than the quantity of radium. Co-precipitation of radium with barium could reduce the release of radium. This is dealt with in sections 22.1.9 and 22.2.14.

19.2.3 The canister as a barrier

In an intact canister, the fuel is completely isolated. All processes that could in any way affect and harm the canister are therefore of special importance for the safety assessment. This includes, for example, mechanical loads during a glaciation and in connection with an earthquake, as well as the types of corrosion that could occur, see section 23.2.1.

The ability of the canister to resist deformation due to external load is being investigated both experimentally and theoretically. The cast iron insert is important for mechanical stability, and the strength of both intact and defective inserts is being examined, see sections 23.2.4 and 23.2.5. The canister's ability to withstand shear movements is being examined by probabilistic analyses. Furthermore, we are investigating the possibilities of conducting shear experiments in Sweden or in cooperation with some other country. There are also fears that creep in the copper material could occur as a result of loading of the canister. Models that can describe this phenomenon will be put into use.

The investigations of canister corrosion are continuing. This is described in section 23.2.12. An important part of this is the question of stress corrosion cracking (SCC). The likelihood of stress corrosion cracking under the geochemical conditions that prevail in the investigation areas will be investigated. The consequence of foreign substances in the weld will also be further investigated, see section 23.1.6.

19.2.4 Buffer

After deposition the buffer can absorb additional water, swell and evolve towards a condition of water saturation and homogeneity. This affects the thermal conductivity and other properties of the buffer, which contribute to stabilizing the deposition hole and protecting the canister. Performance indicators with associated criteria are used to evaluate the performance of the buffer in the safety assessment. They provide a good idea of what is expected, see Table 24-1 in Chapter 24. It is important to be able to predict what state the buffer ultimately achieves and roughly how long this takes. The process is studied both in the laboratory and in situ and on different scales. The results are used to test the models that are used to describe the process and to provide the models with values of the material parameters, see section 24.2.5.

There are several processes in the water-saturated buffer that need to be studied in view of the importance of the buffer for safety and the long periods of time that must be considered. Processes that still need to be studied include freezing of the bentonite, see section 24.2.7, and gas transport, see section 24.2.7. The latter will be examined in situ and on a full scale in the Lasgit project in the Äspö HRL. One process that has taken on greater topicality with the studies of the glaciation scenario in SR-Can is colloid release and erosion, see section 24.2.18. Meltwater from an ice sheet can in the worst case disperse the bentonite if relatively large flows of such water reach the buffer. A special project has been started to study this issue as soon as possible.

One of the ongoing studies of the buffer pertains to KBS-3H. The successive deposition of canister-buffer supercontainers with plugs between the packages gives rise to conditions where erosion could occur, see section 24.2.8. Swelling is also an important process for stabilizing the buffer in KBS-3H. The supercontainers have an outer container of perforated steel. The buffer will swell out through the holes and seal against the rock wall in the deposition tunnel. Studies of swelling are described in general terms in section 24.2.9. Both laboratory studies and model development are included.

19.2.5 Backfill

The safety assessment SR-Can analyzed two different compositions of backfill material. In both cases the deposition tunnels were filled with pre-compacted blocks. In one case a natural swelling clay – Friedland clay – was chosen as an example, in the other case a mixture of bentonite and sand in the proportions 30/70 was chosen. The use of pre-compacted blocks was justified by the relative salinity of the groundwater. The salinity requires a high clay content, which in turn leads to difficulties in compacting the backfill in place. The best solution from several viewpoints turned out to be blocks of Friedland clay /19-1/.

An important process in the backfill is swelling, see section 25.2.10. It is supposed to counteract the swelling of the buffer, press against the rock so that no gaps arise, prevent the breakout of blocks of rock from the roof, counteract spalling, which can form fractures near the rock wall, swell and compress the fill of pellets in the gap between the rock and the backfill block – if this backfilling method is chosen – and heal any channels caused by piping, erosion and the subsequent mechanical evolution. Processes that can affect swelling are thereby also important, for example freezing, see section 25.2.5, and erosion, see section 25.2.9.

19.2.6 Geosphere

An earthquake can give rise to shear movements in the fractures in the rock. The size of the displacement depends on the extent of the fractures and the distance from the quake. The importance of this is examined in the safety assessment. Models for calculating rock movements and methods for determining the properties of the fractures in a repository are research areas that are described in sections 26.2.5, 26.2.7 and 26.2.8.

The spent fuel generates heat that is absorbed by the rock in the repository. Changes that can be caused by heating are studied in the Äspö HRL. This is necessary for the safety assessment. If fractures arise in the walls of the deposition holes due to heating and excessively high rock stresses, the transport resistance in the near-field may be degraded. Research in this area is described in section 26.2.6.

The groundwater flow on the investigated sites is simulated by numerical models, which are still being developed and improved. The groundwater flow is of central importance for the safety assessment. Not just today's conditions have to be described, but also future hydrogeological conditions, for example those prevailing during an ice age. The development of models for groundwater flow is described in section 26.2.3. The conditions that prevail during resaturation of the repository are also dealt with, but in a simplified manner. This is described in section 26.2.4.

The safety assessment always examines the importance of a breach in isolation so that water comes into contact with the spent nuclear fuel. In such a case, different transport resistances limit the spread of radionuclides. In order to be able to calculate the transport resistance in the rock, the processes of advection/mixing (see section 26.2.12) and colloid formation (see sections 26.2.20 and 26.2.21) are being studied. Model codes that are needed to calculate transport of solutes, both radionuclides and other substances of importance for safety, are constantly being developed. A new such calculation code is Marfa. Marfa can also handle transport calculations in the transition between different flow situations that can arise as a consequence of major changes in the climate, such as during an ice age.

The geochemical investigations on the site must always be supplemented by studies of chemical changes resulting from the contamination of the natural environment in the rock with foreign substances, see section 26.2.19, and from major climate changes in the future, see sections 26.2.15 and 26.2.16. The site investigations are also being supplemented with investigations of microbial processes, see section 26.2.18, and gases dissolved in the groundwater, see section 26.2.22.

19.2.7 Biosphere

Site data and models that describe the ecosystems were used to a greater extent in the safety assessment SR-Can than previously to calculate the consequences radionuclides will have in the biosphere. The development of our understanding of the component processes and the descriptive biosphere models is dealt with in section 27.2.

Models that take into account the change of the landscape in time and space are needed in order to calculate how radionuclides migrate in the biosphere. The fact that the consequences for flora and fauna are also included nowadays means that the models must also treat the flow of radionuclides in the entire ecosystem. The development and use of the landscape model is dealt with in section 27.3.

The flow of water in the biosphere and in the interface between geosphere and biosphere determine, together with other transport processes, which ecosystems and organisms will be exposed to radionuclides. Transport processes are dealt with in section 27.4. Definitions and descriptions of the most important processes in different types of ecosystems, such as terrestrial and aquatic ecosystems, are taken up in sections 27.5 and 27.6. The interaction between different ecosystems is also of interest for further studies. Long-term variations in climate, land uplift and salinity can impact the biosphere, and such studies are described in section 27.7.

The biosphere programme conducted in advance of SR-Can, and the continuation aimed at SR-Site, is the most ambitious yet for SKB. The research is aimed at achieving a sufficient understanding of processes and phenomena in order to subsequently construct the numerical models that are needed for dose calculations, see section 27.9. The site investigations make conceptual descriptions possible and furnish the calculation models with input data. Another purpose of the biosphere research is to provide guidance for the collection of site data, see section 27.10.

19.2.8 Research in the Äspö HRL

The Äspö HRL is SKB's facility for development, testing and demonstration of technology for deposition of spent nuclear fuel. Several of the projects being conducted there are also aimed at providing knowledge of long-term safety, and a large number of projects are completely focused on such experiments. Most of these experiments concern the function of the buffer and the rock in protecting the canister and serving as barriers to the escape of radionuclides. There are also experiments concerned with the function of the canister and tests aimed at the fuel. Table 19-3 gives a number of examples of projects in the Äspö HRL that are completely or partially focused on long-term safety. The table refers to sections in following chapters where more information is available on the importance of the experiments in understanding and modelling processes of relevance for long-term safety. Sometimes the main purpose of a project is technology development, and sometimes the borderline between technology development and research may be fluid. Long-term safety is naturally the aim point of departure for all development of final repository technology. If we consider new technology, we must simultaneously consider whether it meets the requirements of the safety assessment.

International participation in the Äspö HRL is of great importance. The broad participation of many researchers in different countries means that prevalent theories and achieved results are subjected to both extensive and thorough scrutiny. Here the special task forces have made a valuable contribution. They are put together for special purposes in order to develop the experiments and interpret the results. An example is the Äspö Task Force on Modelling of Groundwater Flow and Transport of Solutes, see section 26.2.26.

Table 19-3. Examples of projects and experiments in the Äspö HRL, all or part of which are focused on research regarding long-term safety.

Project/experiment	Section
Experiments in the Chemlab probes	22.2.12, 26.2.17
Minican experiments	23.2.7, 23.2.16
Prototype Repository	24.2.5, 24.2.11, 24.2.12, 25.2.6, 25.2.7, 26.2.2, 26.2.6, 26.2.18
Lasgit	24.2.7, 24.2.8
TBT	24.2.3, 24.2.5, 24.2.11
Canister Retrieval Test	24.2.5, 24.2.6, 24.2.11, 24.2.21, 26.2.2
Lot	23.2.12, 24.1.2, 24.2.6, 24.2.9, 24.2.14, 24.2.15, 24.2.16, 24.2.17, 24.2.21
Alternative buffer materials	24.1.2, 24.2.6, 24.2.9, 24.2.16
The Colloid project	26.2.21
Backfill and Plug Test	25.2.2, 25.2.7
Apse (Äspö Pillar Stability Experiment)	26.2.5, 26.2.6, 26.2.8
True	26.2.26
LTDE	26.2.14, 26.2.17
Matrix Fluid Chemistry Experiment	26.2.15
Microbe Project	26.2.18, 26.2.22
Micomig Project	26.2.17

The references refer to sections in coming chapters where the particular process is dealt with, i.e. Chapter 22 Fuel, 23 Canister, 24 Buffer, 25 Backfill and 26 Geosphere.

The University of Kalmar's research school is now a feature at the Äspö HRL. The activities of the research school also include studies in those nearby areas where SKB is conducting site investigations. The research school's studies of mechanisms for the transport and migration of pollutants in rock, soil layers and biosphere are generally oriented, but are naturally also of importance for SKB. Hopefully the school will also train researchers to meet our future needs.

19.3 Other methods

SKB's research and development is focused on deposition of spent fuel according to the KBS-3 method, but some studies are also being done of other methods such as partitioning and transmutation (P&T) and deep boreholes. The programmes are described in greater detail in Chapter 28. The following sections provide only a brief sketch.

19.3.1 Partitioning and transmutation (P&T)

SKB has supported research in the area of partitioning and transmutation for the past 16 years. If this method becomes reality one day, it would be one way to reduce the content of long-lived radionuclides in the waste while extracting more energy in the bargain. Developing methods and facilities for partitioning and transmutation requires large resources, however. Sweden does not have the resources to pursue such development work on its own; international cooperation would be required, or the involvement of a major power. So far the research is at a fundamental level, even internationally. SKB's ambition is mainly to keep track of the development of P&T. SKB is supporting research on partitioning and transmutation at the Royal Institute of Technology, Uppsala University and Chalmers University of Technology. The researchers there are engaged in a number of EU projects, where they can participate in the international work in the field. The amount of funding given by SKB to this research in Sweden is sufficient to ensure adequate breadth and scope to be viable. To participate in the international development work, competent partners must be provided and there must be institutions in the country where research is conducted at an acceptable level.

In the 1990s, great hopes were attached to a the possibility of generating neutrons in a proton accelerator to drive a subcritical reactor, which in turn generates the fast neutrons that are required to transform – transmute – the partitioned long-lived nuclides. Interest in this prospect appears to have waned with the development of the fourth generation of reactors, which includes fast reactors that could also bring about transmutation. As far as partitioning is concerned, SKB is particularly interested in wet methods. That is where most international development is taking place. An account of SKB's research programme in the area of partitioning and transmutation is provided in section 28.1.

19.3.2 Deep boreholes

The possibility of disposing of spent fuel in deep boreholes was studied by SKB as far back as the early 1990s. Further studies have been conducted since then without revealing anything to indicate that disposal in deep boreholes would increase the safety of spent fuel disposal. Deeper disposal would utilize to a higher degree the protection provided by the rock barrier against the escape of radionuclides, but at the same time it would increase the stresses on the engineered barriers, the canister and the buffer. At a depth of several kilometres, the consequence is that long-term safety mainly rests on the fact that deep brine (saline groundwater) tends to remain immobile due to its higher density. In the KBS-3 method, safety is mainly provided by the engineered barriers. They are easier to check than conditions in the rock at a depth of several kilometres. The deposition procedure is also much easier to check in a KBS-3 repository than in deep boreholes. In other words, the KBS-3 method emerges as the better solution. SKB is nevertheless continuing to monitor the development of both knowledge of the rock and the technology for drilling holes and depositing waste at a depth of several kilometres. Read more about this in section 28.2.

20 Safety assessment

During the site investigation phase, SKB is conducting two safety assessments of a KBS-3 repository:

- SR-Can, employing site data taken from the preliminary results of the site investigations in Oskarshamn and Forsmark.
- SR-Site, employing data from the completed site investigations.

SR-Can will not be used as a basis for any permit/licence application, while SR-Site is planned to be included in the application for the final repository. SR-Can was published in November 2006 /20-1/ and is currently being reviewed by SKI, SSI and their international experts. A simplified Swedish summary of the SR-Can report was published in May 2007 /20-2/.

Method development for the safety assessment is taking place within these two safety assessment projects. The results of this development work are mainly reported in the form of descriptions of applications in the safety analysis reports. Thus, significant development of the safety assessment method was described in the SR-Can report in November 2006. All remaining method development during the period is aimed at application of the methods in the safety assessment SR-Site.

Plans for both methodology development and development of tools for integrated modelling are described in the following. The plans concern methodology for safety assessments for a final repository for spent nuclear fuel, but much of the resulting methodology should also be able to be used for other geological repositories for radioactive waste. Knowledge acquisition concerning individual processes of importance for long-term safety is described in Chapters 22 to 26. These accounts are by and large structured according to the safety assessment's process reports. Future climate change is described in Chapter 21, while the migration and effects of radionuclides in the environment are addressed in Chapter 27.

20.1 Methodology for assessment of the long-term safety of the repository

20.1.1 Methodology in SR-Can

Overview

A ten-step methodology has been developed for SR-Can for assessing the long-term safety of the repository. It is summarized in Figure 20-1. These steps are carried out partly in parallel and partly sequentially. The ten steps are described in greater detail below.

1. Identification of factors to consider (FEP processing)

   This step consists of identifying all the factors that need to be included in the analysis. Experience from earlier safety assessments and KBS-3-specific and international databases of relevant features, events and processes (FEPs) influencing long-term safety are utilized. A FEP database has been developed for SR-Can where the great majority of FEPs are classified as being either initial state FEPs, internal processes or external FEPs. Remaining FEPs are either related to the assessment methodology in general or judged to be irrelevant for the KBS-3 concept. Based on the results of the FEP processing, an SR-Can FEP catalogue, containing FEPs to be handled in SR-Can, has been established. This step of FEP processing is further described in Chapter 3 of /20-1/ and fully documented in the FEP report in SR-Can.

2. Description of the initial state

   The initial state of the system is described based on the design specifications of the KBS-3 repository, a descriptive model of the repository site and a site-specific layout of the repository. The initial state of the fuel and the engineered components is that immediately after deposition as described in the initial state report. The initial state of the geosphere and the biosphere is that of the natural system prior to excavation, as described in the site descriptive models of the Forsmark /20-3/ and Laxemar /20-4/ sites. Repository layouts adapted to the sites are provided in /20-5/ for Forsmark and /20-6/ for Laxemar, see further Chapter 4 of /20-1/.

3. Description of external conditions

   Factors related to external conditions are handled in the three categories “climate related issues”, “large-scale geological processes and effects” and “future human actions”. The handling of these factors is described in the climate report, the geosphere process report, and the FHA report, respectively. See further Chapter 5 of /20-1/.

4. Description of processes

   The identification of relevant processes is based on earlier assessments and FEP screening. All identified processes within the system boundary that are relevant to the long-term evolution of the system are described in dedicated process reports. For each process, its general characteristics, the time frame in which it is important, the other processes to which it is coupled and how the process is handled in the safety assessment are documented, see further Chapter 6 of /20-1/.

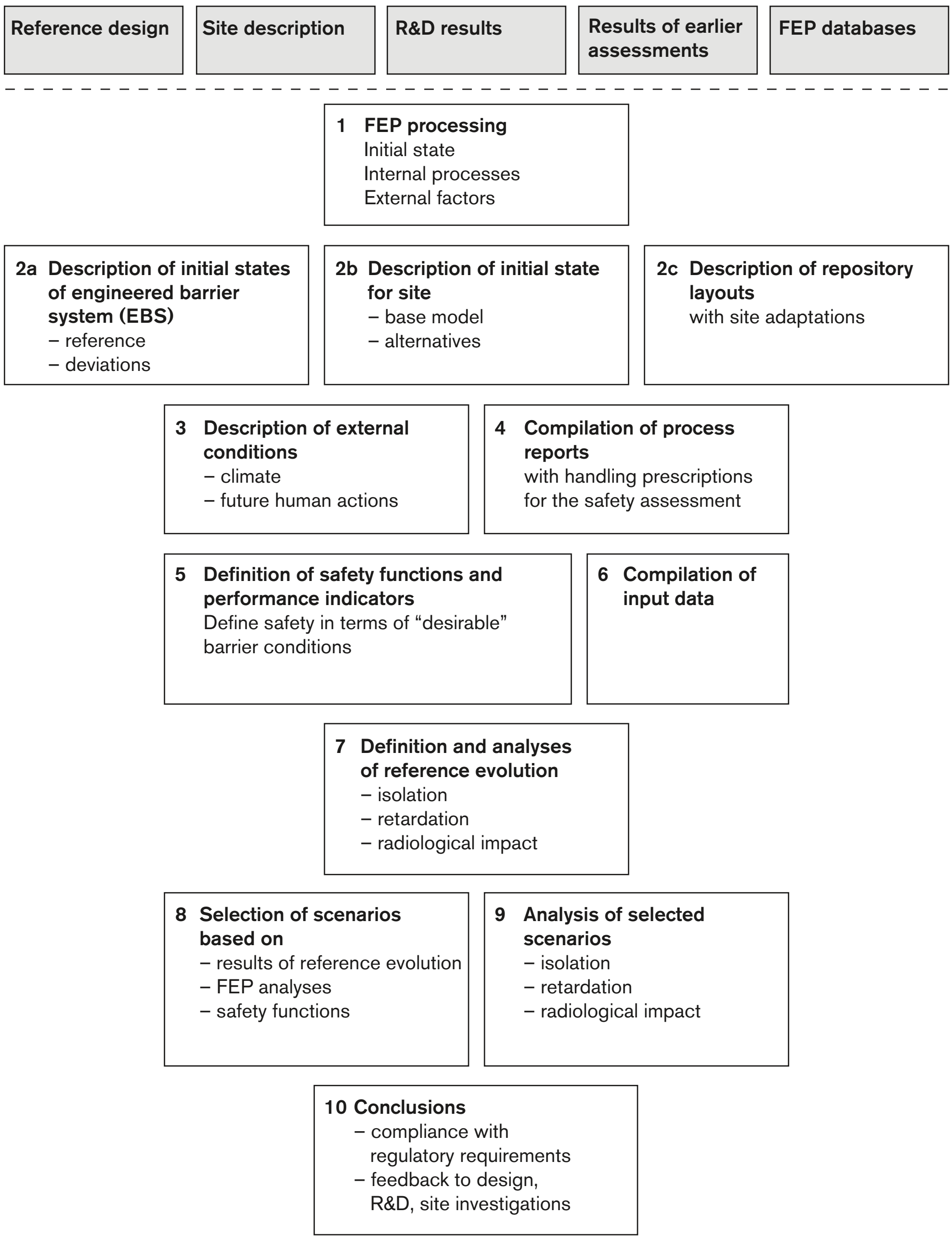


Figure 20-1. *Outline of the ten main steps of the SR-Can safety assessment. The boxes at the top above the dashed line are inputs to the assessment.*

5. Definition of safety functions, safety performance indicators and safety performance indicator criteria

   This step consists of an account of the safety functions of the system and of how they can be evaluated by means of a set of safety performance indicators that are, in principle, measurable or calculable properties of the system. Criteria for the safety performance indicators are provided. The process reports are important reference documents for this step. An FEP chart is prepared showing how FEPs are related to the safety performance indicators. The execution and results of this step are described in Chapter 7 of /20-1/.

6. Compilation of input data

   Data to be used in the quantification of repository evolution and in dose calculations are selected using a structured procedure. The selection process and the chosen data values are described in a dedicated Data Report. A flexible template for discussion of uncertainties in input data has been developed and applied, see further Chapter 8 of /20-1/.

7. Definition and analysis of reference evolution

   A reference evolution, which provides a description of a plausible evolution of the repository system, is defined and analyzed. The isolating potential of the system over time is analyzed in a first step, yielding a description of the general system evolution and an evaluation of the safety performance indicators. If the evolution indicates a breach of isolation, the retarding potential of the repository and its environs is analyzed and dose consequences are calculated for the long-term conditions identified in the first step. Certain canister failure modes that do not occur in the reference evolution are analyzed in order to further elucidate the retarding properties of the system. Each process is handled in accordance with the plans outlined in the process reports. See further Chapter 9 of /20-1/ for an analysis of the general evolution and isolating potential of the repository system and Chapter 10 of /20-1/ for an analysis of its retarding potential.

8. Selection of scenarios

   A set of scenarios is selected for the assessment. A comprehensive main scenario is defined in accordance with SKI's regulations SKIFS 2002:1. The main scenario is closely related to the reference evolution analyzed in step 7. The selection of additional scenarios is based on the safety functions of the repository and the safety performance indicators defined in step 5. For each safety function, an assessment is made as to whether any reasonable situation could arise where the function is not maintained. If this is the case, the corresponding scenario is included in the risk evaluation for the repository. The total risk is determined by summation over such scenarios. The set of selected scenarios also includes e.g. scenarios explicitly mentioned in applicable regulations, such as human intrusion scenarios, as well as scenarios and variants to explore the roles of various components in the repository. See further Chapter 11 in /20-1/ for a description of the scenario selection methodology and the application of the selection method.

9. Analysis of selected scenarios

   The main scenario is analyzed primarily by referring to the reference evolution in step 7. An important result is a calculated risk contribution from the main scenario. Additional scenarios are analyzed by focusing on factors that could lead to situations in which the safety function in question is not maintained. In most cases, these analyses are carried out by comparison with the evolution for the main scenario, meaning that they only encompass those aspects of repository evolution where the scenario in question deviates from the main scenario. For these scenarios, as for the main scenario, a risk contribution is estimated. See further Chapter 12 in /20-1/.

10. Conclusions

    This step includes compilation of the results from the various scenario analyses, conclusions regarding safety in relation to regulatory criteria and feedback with regard to repository design, continued site investigations and SKB's RD&D programme. See further Chapter 13 in /20-1/.

Some important aspects of the methodology are examined in detail in the following sections.

Safety functions

The key safety-related features of the KBS-3 disposal system can be summarized in the safety functions of isolation and retardation. A more detailed description of how the main safety functions of isolation and retardation are maintained by the components in the repository is required for a detailed and quantitative understanding and evaluation of repository safety. Based on an understanding of the properties of the components and the long-term evolution of the system, a number of safety functions that are subordinate to isolation and retardation were identified in SR-Can. They play a key role in the methodology for the assessment in that they:

- contribute to focusing the assessment in an early phase on the issues that are of crucial importance for safety,
- provide structure for the account of the reference evolution of the repository, which in turn serves as a basis for a main scenario in the safety assessment,
- comprise an important basis for the selection of additional scenarios.

The following definitions are used:

- A safety function is the role played by a repository component that contributes to safety.
- A safety performance indicator is a measurable or calculable property of a repository component that indicates the extent to which a safety function is fulfilled.
- A criterion for a safety performance indicator is a quantitative limit. If the safety performance indicator fulfils the criterion, the corresponding safety function is fulfilled.

Figure 20-2 provides an overview of safety functions, performance indicators and criteria.

Safety functions aid in the evaluation of safety, but the fulfilment of all safety performance indicator criteria is neither necessary nor sufficient to prove that the repository is safe. The different safety performance indicator criteria are furthermore determined with different acceptance margins.

Safety functions are related to, but not the same as, design criteria. Whereas the latter relate to the initial state of the repository and primarily to its engineered components, the former should be fulfilled throughout the assessment period and relate to both engineered components and the natural system.

Method for scenario selection

The assessment of repository safety is broken down into a number of scenarios. A comprehensive main scenario represents a reasonable evolution of the repository system. The evolution of this scenario is closely linked to the reference evolution, see step 7 in the above overview of the methodology. A set of additional scenarios are defined in order to cover uncertainties not addressed in the reference evolution, for example more extreme climatic conditions than those studied in the reference evolution.

The safety functions are used to obtain a comprehensive set of additional scenarios focusing on issues of relevance to repository safety. When a scenario is defined, a breach of a safety function is postulated and all conceivable routes to such a breach are then studied. The goal is to answer the question: Is there any reasonable possibility that this scenario could occur? If this is found to be the case, the consequences of the scenario in question are included in a risk summation for the repository. Otherwise the scenario is regarded as a “residual scenario” and the consequences can be analyzed for illustrative purposes.

A scenario with canister failure due to isostatic pressure exemplifies the approach. In this scenario, mishaps in the manufacture of the loadbearing canister inserts, swelling pressures in excess of the reference values for the buffer and very thick ice sheets resulting in high groundwater pressures are considered.

In addition to the scenarios arrived at in this way, scenarios required by government regulations or deemed relevant for other reasons are sought. Table 20-1 provides an overview of the scenarios selected in SR-Can.

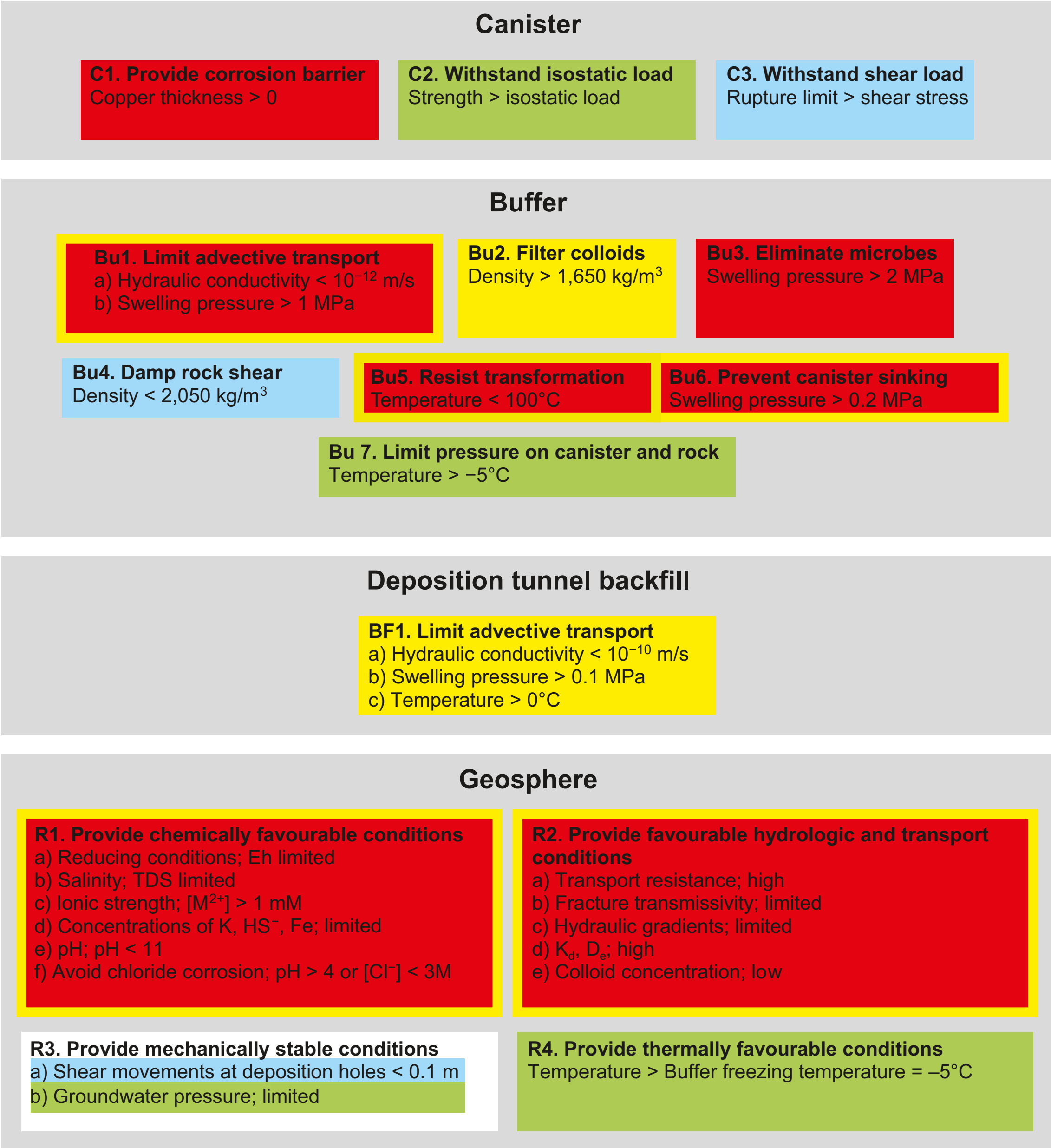


Figure 20-2. *Safety functions (bold), safety performance indicators and criteria for safety performance indicators. When quantitative criteria cannot be given, terms like "high", "low" and "limited" are used to indicate favourable values of the safety performance indicators. The colour coding shows how the functions contribute to the canister's safety functions C1 (red), C2 (green), C3 (blue) or to retardation (yellow). Many functions contribute to both C1 and retardation (red box with yellow border).*

Quality assurance

Within the framework of the work with SR-Can, a quality plan has been developed for the safety assessment. Among other things, a number of control documents are described there stipulating how different steps in the project are to be executed. Several of these procedures, for example instructions for writing process reports and data reports, are based on procedures used in previous safety assessments. New in SR-Can is a "Model Summary Report" /20-7/, which briefly describes the calculation models used in the safety assessment. The report also explains the choice of model and refers to other documents where different quality assurance aspects of the models are described. Links between the models are described in Assessment Model Flow Charts, AMFs. Another innovation is a database of the experts who have contributed to the safety assessment. The following is given for each expert: education, scientific qualifications, experience of relevance to the safety assessment and the project group's reasons for choosing this particular expert.

Table 20-1. Result of scenario selection in SR-Can. Green cells denote conditions for the base variant of the main scenario, red cells denote deviations from these conditions. EBS stands for engineered barrier system, i.e. the canister, the buffer and the deposition tunnel.

Main scenario				
Name	**Initial state EBS**	**Initial state site**	**Process handling**	**Handling of external conditions**
Base variant	Reference ± tolerances	Site descriptive model version 1.2 (with variants/ uncertainties)	According to Process Reports	Reference climate (repetitions of Weichselian glacial cycle). No future human actions (FHA).
Greenhouse variant	Reference ± tolerances	Site descriptive model version 1.2 (with variants/ uncertainties)	According to Process Reports	Extended warm period. No future human actions (FHA).
Additional scenarios based on potential loss of safety functions (“less probable” or “residual” scenarios based on outcome of analysis)				
Name	**Initial state EBS**	**Initial state site**	**Process handling**	**Handling of external conditions**
Buffer advection	Evaluate uncertainties for relevant initial state factors, internal processes and external conditions that could lead to loss of the safety function question. The analysis of the main scenario is the starting point.			
Buffer freezing	See above			
Buffer transformation	See above			
	Consider each of above three buffer states + intact buffer when analyzing the three canister scenarios below			
Canister failure due to isostatic load	Evaluate uncertainties for relevant initial state factors, internal processes and external conditions that could lead to loss of the safety function question. The analysis of the main scenario is the starting point.			
Canister failure due to shear movement	See above			
Canister failure due to corrosion	See above			
Scenarios related to future human actions				
Name	**Initial state EBS**	**Initial state site**	**Process handling**	**Handling of external conditions**
Drilling intrusion	As base variant of main scenario	As base variant of main scenario	As base variant of main scenario, except processes affected by drilling	Reference climate + drilling
Additional intrusion cases, e.g. nearby mining site	As base variant of main scenario	As base variant of main scenario	As base variant of main scenario, except processes affected by intrusion	Reference climate + intrusion
Unclosed repository (not analyzed in SR-Can)	As base variant of main scenario, but incomplete closure	As base variant of main scenario	As base variant of main scenario, modified depending on initial state	Reference climate

20.1.2 Programme

Development needs for the methodology for the safety assessment were described in the main report SR-Can /20-1, section 13.9/. The discussion is structured according to the ten steps described in section 20.1.1 above. No reasons have emerged to revise the judgements made in SR-Can. The development plan will be cross-checked against the regulatory authorities' review report for SR-Can when it becomes available in December 2007. In general, certain system parts dealt with cursorily in SR-Can (backfilling of other repository openings than deposition tunnels, plugs and sealing of investigation boreholes) will be dealt with in greater detail in SR-Site. But this does not require any method development. Knowledge acquisition regarding these system parts is described in Chapter 25.

The following development needs for the different steps of the safety assessment are identified in SR-Can:

1. Identification of factors to consider (FEP processing)

   SKB's FEP database and FEP catalogue, developed for SR-Can, will be updated for SR-Site. These products are regarded as mature, meaning that only minor modifications are foreseen. The comprehensive and time-consuming cross-check against the NEA's FEP database carried out within the SR-Can project led to the identification of a few new FEPs. It is not seen as meaningful to repeat such a cross-check in the SR-Site assessment. The FEP report will be updated, based on the experience gained from SR-Can.

2. Description of the initial state

   The Initial state report, which describes the fuel and the engineered barriers, will be updated. The report for SR-Site will also contain a summary of the production steps undergone by each barrier and how this may have affected the safety assessment's initial state, i.e. the state immediately after deposition.

   Updated versions of the site descriptive models will be used for SR-Site. The handling of the updated site information is foreseen to be similar to that in SR-Can, i.e. a condensed version with a focus on safety-related aspects of the site description in the main report and a qualification of essential data for the safety assessment in the Data Report.

   The repository layouts will be updated to version D2, which will be used in SR-Site. Acceptance criteria for deposition holes that will be applied in layout D2 will be developed based on the experience in SR-Can.

3. Description of external conditions

   The handling of external conditions will be described in updated versions of the climate and FHA reports. Regarding the handling of future human actions (FHAs), only minor, if any, modifications are foreseen.

4. Description of processes

   The purpose of the process reports is to serve as a link between scientific background reports and the safety assessment by condensing the information in the background reports and focusing on the needs of the safety assessment. As such, the process reports are judged to be meaningful and they will therefore, be updated for SR-Site, with essentially the same format as for SR-Can.

   For example, an update is foreseen regarding the understanding of colloid release and erosion of the buffer when it is exposed to dilute groundwaters. This update is based on ongoing experiments and other sources. Most of the material in the process reports is, however, regarded as sufficiently mature to be reused in SR-Site.

   The need for process reports for the additional system components "bottom pad in deposition hole", "plugs", "borehole seals" and "backfill in other repository parts" that were not treated in SR-Can (see section 6.1.1 in /20-1/) will be assessed in the planning of SR-Site.

   The process tables and the assessment model flow charts (AMFs) introduced in Chapter 6 of /20-1/ are considered to be useful tools for condensing information and providing an overview. These will be updated for SR-Site.

5. Definition of safety functions, safety performance indicators and safety performance indicator criteria

   This step constitutes an important basis for the methodology used in SR-Can and is planned to have a similar role in SR-Site. The set of safety functions, indicators and criteria may be revised, based on newfound knowledge in SR-Site.

   The FEP chart introduced in Chapter 7 of /20-1/ is a useful tool for providing an overview of the "safety logic" for the KBS-3 repository. There is some overlap between the information contained in the AMFs (see step 4 above) and in the FEP chart, since the information from modelling is used when safety is evaluated. It could be possible to combine these two instruments into one, but this would presumably require one FEP chart for each time period in the assessment. This will be further considered when SR-Site is planned.

6. Compilation of input data

   The format for presenting input data and discussing uncertainties in input data used in the data report is regarded as mature and is therefore planned to be reused to a high degree in SR-Site. The set of input data entities will be revised based on the results of SR-Can and additional information in SR-Site. The data report will be updated.

7. Definition and analysis of reference evolution

   The format used to analyze the reference evolution in SR-Can covers four time periods. The evolution of external conditions, the biosphere and THMC conditions in the repository system are analyzed for each period. This is followed by an evaluation of the safety functions for each time increment. This format is considered to be appropriate and will be reused in SR-Site.

   The format for analyzing the repository's retarding capacity, subdivided into the different failure modes of the canister, is also considered to be appropriate. Here the method for the analyzing radionuclide transport and dose in the biosphere is new and contains much of the methodology that is planned to be used in SR-Site.

8. Selection of scenarios

   The method for scenario selection based on safety functions was introduced in SR-Can. A major advantage of the method is that it addresses the importance of all identified safety-related issues with a limited number of scenarios. This is achieved due to the fact that the scenarios focus directly on the safety functions and not on all the uncertainties that affect safety. These uncertainties are instead handled systematically in the analysis of the selected scenarios.

   The method was also found to be relatively straightforward to apply and explain, which is important for the transparency of the safety assessment. The same method will therefore be used in SR-Site.

9. Analysis of selected scenarios

   The method used to analyze the selected scenarios is regarded as adequate, and essentially the same method will therefore be used in SR-Site.

   Estimates of scenario probabilities for the risk calculation were often pessimistic. For example, buffer erosion is assumed to always occur under glacial conditions, since the possibility cannot be excluded. Another example is provided by the three possible hydrogeological interpretations of Forsmark that were made in SR-Can. The most pessimistic interpretation in terms of consequences – with regard to buffer erosion and canister corrosion – was used in the risk summation in SR-Can, since the site descriptive models on which the assessment was based did not allow an estimate of probabilities for the different interpretations.

   This approach was primarily warranted by a lack of knowledge. Essentially the same approach is foreseen for SR-Site for similar situations. But it should also be noted that the state of knowledge with regard to the above examples may have improved by SR-Site, allowing a less pessimistic treatment.

10. Conclusions

   An essential part of the concluding chapter in SR-Can consists of a discussion of compliance with regulatory requirements on long-term safety. This is SKB's first account of compliance with the relatively recent Swedish regulations and shows SKB's understanding of how compliance can be demonstrated. A similar format is foreseen for the account in SR-Site.

20.2 Integrated modelling

20.2.1 System development

A so-called system model is described in RD&D-programme 2004 /20-8/ and in greater detail in /20-9/. It consists of a number of submodels, each of which describes a part of the overall evolution of a repository system after closure. The system model is intended to serve as an aid in the safety assessment. Only the thermal submodel and the submodel for canister corrosion were used in SR-Can. Other areas are modelled with other models.

An analytical model for calculation of permafrost depth has been added since RD&D-Programme 2004, see Appendix B in /20-1/.

The role that is foreseen for the system model in SR-Site is to verify by means of simple calculations the results obtained from more advanced models and thereby firstly verify calculation results from complex models and secondly demonstrate which input data and processes are most important for the subareas being modelled, thereby demonstrating an understanding of the processes in question.

Areas that can be studied in this manner include:

- Thermal evolution in fuel, buffer and rock after deposition and onward for a temperate climate.
- Permafrost depth.
- Chemical evolution in the buffer.
- Interaction of the buffer with the backfill during swelling.
- Canister corrosion.
- Internal evolution of the canister after damage.

Only minor development activities around these models are planned for SR-Site.

20.2.2 Radionuclide transport

Both more detailed numerical models and simplified analytical models are available for calculating radionuclide transport in the near-field (canister, buffer and tunnel backfill) and the far-field (geosphere) /20-8/. Furthermore, an analytical model was developed in the framework of SR-Can for handling radionuclide transport under advective conditions in a deposition hole, see Appendix B in /20-1/. All of these models were used in SR-Can. Results from the analytical models were compared with results from numerical models in a number of cases with good agreement. The faster analytical models were then used to calculate a large number of other cases where they were applicable, while certain cases could only be calculated with the numerical models, see further Chapter 10 in /20-1/. A similar approach will probably be used in SR-Site.

The analytical model for advective conditions needs to be developed to include solubility limits. Otherwise no development needs are foreseen as far as the analytical models are concerned. They do, however, need to be fully quality-assured to a level similar to that of other models in the safety assessment. This will be done within the framework of SR-Site.

Further development of the numerical models for the near-field and the far field is described in sections 25.3 and 26.2.26, respectively. Modelling of radionuclide transport in the biosphere is described in Chapter 27.

21 Climate change

The Earth's climate naturally varies over periods ranging from a few decades to more than 100,000 years. The climatic variations are caused by, for example, variations in insolation due to changes in the Earth's orbit around the sun, volcanic eruptions and variations in solar activity. Climate changes in recent decades also have an anthropogenic component consisting of an increase in the quantity of greenhouse gases and aerosols in the atmosphere.

On the time scale for which the performance and safety of a final repository for spent nuclear fuel are being studied, i.e. hundreds of thousands of years and longer, the Scandinavian climate has varied a great deal. This has resulted in repeated glacial cycles (ice ages), among other things. Over the past 700,000 years or so, a cycle has been repeated where periods of roughly 100,000 years with a progressively colder climate (glacials) have been interrupted by a rapid transition to shorter periods with a warm climate (interglacials). Knowledge regarding climate and climate variations is therefore of great importance when SKB assesses the safety of a repository for spent nuclear fuel.

Even if the climate, as such, at the ground surface does not have much impact on repository performance, it is likely that future climate variations will lead to other climate-related processes at the surface that will have an impact. An example is the growth of ice sheets and permafrost and changes in sea level. These processes in turn affect groundwater flow, groundwater chemistry and stresses in the Earth's crust, which are also of importance for repository performance. The repository is therefore designed to resist the impact that can be caused by climate-related processes. The climate at the ground surface also influences the evolution of the biosphere in the area. The biosphere in turn has a great influence on human activities, which should be able to proceed in the landscape without man being affected by nearness to the closed geological repository.

21.1 Climate scenarios in the safety assessment

It is not possible today to reliably predict the future climate in the long time perspectives that are required in safety assessments of a final repository for spent nuclear fuel. It is nevertheless possible to estimate the extremes within wich the future climate may vary, especially based on knowledge of natural climate variations in the past and the suggested future antropogenic climate change. The future climate will also manifest itself as the sum of natural variations, including internal variability, and anthropogenic impact. In estimations of possible future climate changes, it is therefore important also to consider cases where anthropogenic impact is included.

In other words, based on current knowledge, it is possible to describe the bounds within which the Scandinavian climate will vary, even in very long time perspectives. Within these bounds we can identify certain characteristic climate-related conditions that are of importance for repository performance. These conditions can be described as climate-driven process domains, hereinafter called climate domains, see Figure 21-1. The three identified climate domains that are of importance for the repository and its safety are:

- Temperate domain
- Permafrost domain
- Glacial domain

SKB is therefore focusing its research efforts in the climate field on identifying and understanding conditions and processes within these climate domains. It is also important to examine the importance of the duration of the different climate domains and to include possible transitions between them. If it is possible to show that the repository meets the safety requirements given the different conceivable climate domains, and during transitions between them, it is not necessary in the assessment of repository safety to take into account the actual future evolution of the climate in time and space.

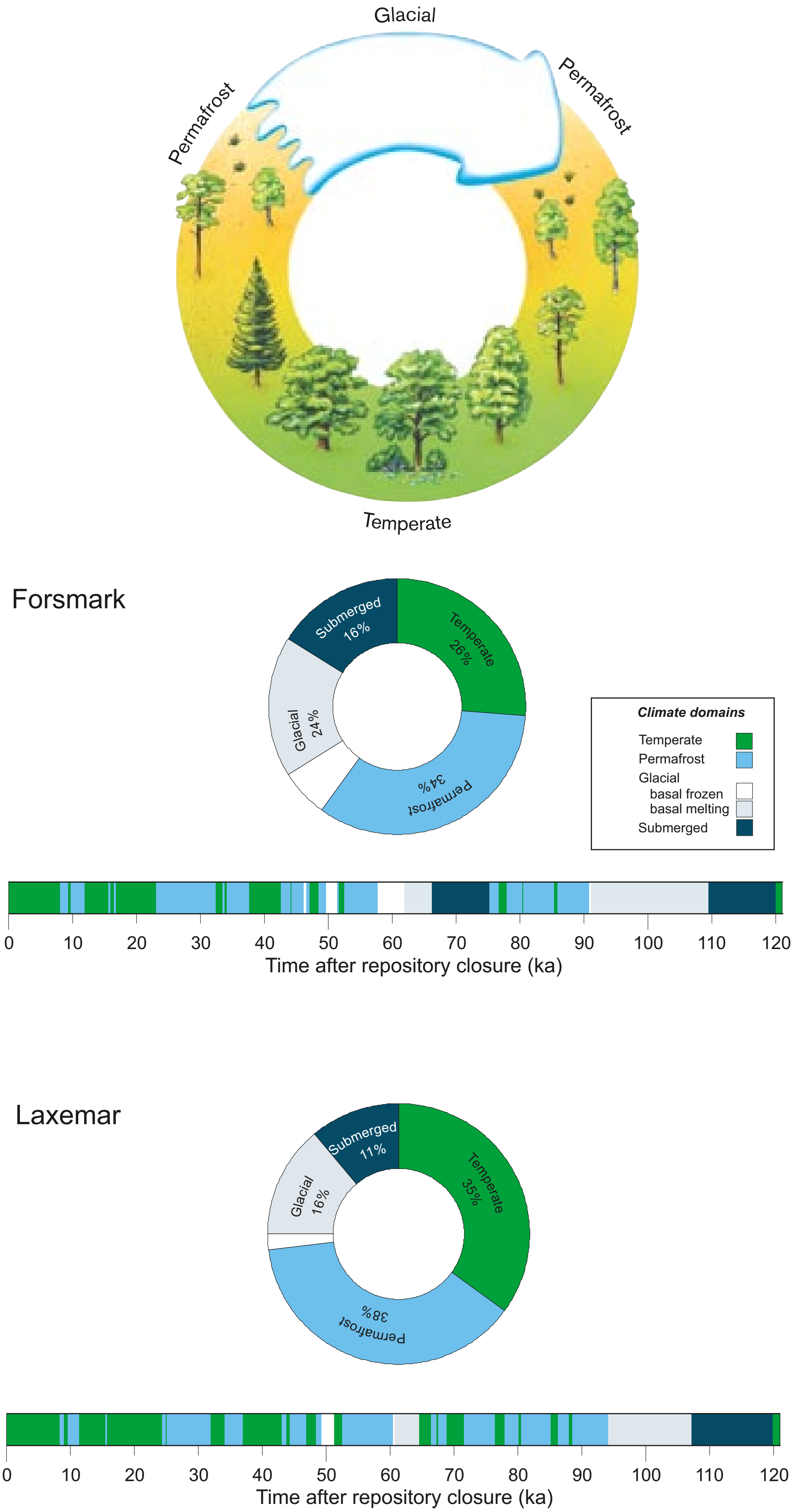


Figure 21-1. *Climate-related changes can be viewed as a cyclical progression with successive transitions between different climate domains, a) schematic illustration, b) example from safety assessment.*

SKB's approach is to first construct a main scenario that shows how the different climate domains succeed each other during a glacial cycle, i.e. a period of about 100,000 years. Two variants of the main scenario have been selected and analyzed. The first variant is a reconstruction of how climate-related parameters varied during the most recent glacial cycle (about 100,000 years). In the second variant a warmer climate dominates initially, caused by an increased greenhouse effect. In both variants of the main scenario, the purpose is to describe how parameters such as ice sheet thickness, permafrost depth and shoreline displacement vary with time. Since it is not possible to describe expected climate change during the coming 100,000 years, the two variants of the main scenario should not be regarded as an attempt to predict future climate evolutions. They are rather examples of future evolutions that describe climate-related processes in a realistic and integrated way in a 100,000-year perspective.

Besides being used in the assessment of long-term safety, the main scenario is also a suitable scientific point of departure for an extended analysis of the impact of the climate on the repository. Based on the evolution in the main scenario and on our knowledge of the repository's performance and safety, a number of other scenarios are selected in a structured manner. The other scenarios cover all possible situations where climate-related processes affect the performance of the repository but are not covered in the main scenario. These scenarios contain alternative site-specific climate evolutions that describe more extreme climates in terms of amplitude or duration. This provides an opportunity to assess the performance of the repository given, for example, thicker ice sheets or deeper permafrost than in the main scenario

Even though there are still uncertainties in how the most recent glaciation affected the Fenno-scandian Shield, a reconstruction of conditions during the most recent glaciation, the Weichselian, is very useful and relevant for constructing the main scenario. The Weichselian is the glaciation we know the most about. This knowledge enables us to test and calibrate the models we use to, for example, reconstruct the extent and thickness of the continental ice sheet based on geological information. In line with the above reasoning, the purpose of the reconstruction of the Weichselian period is not to produce a "true" picture of how the most recent glaciation took place, but rather to define a good scientific starting point for further analyses of how climate-related processes can affect the safety of the repository.

The climate scenario with an anthropogenically influenced climate due to an increased greenhouse effect includes a global rise in sea level caused by increased melting of the Greenland ice sheet in particular. This is necessary in view of the fact that both Oskarshamn and Forsmark are located on the present-day coastline.

The extent of the ice sheet in Scandinavia determines how the climate domains succeed one another in the main scenario. The project "Basal conditions and hydrology of continental ice sheets" was therefore initiated in 2002 to study the ice sheet during the most recent glacial period. The project involves a compilation of glacial geological information on the Weichselian, ice sheet modelling and process studies of ice sheet hydrology. Simulation of the Scandinavian ice sheet using a numerical thermodynamic ice sheet model has been a key project in SKB's climate programme. The project is now in its final phase and a more detailed account of what has been learned is given in section 21.2.

The description of the evolution of the continental ice sheet during the most recent glacial cycle has in turn been used to study shoreline displacement (see section 21.3), permafrost (see section 21.4) and the occurrence of glacial earthquakes (see section 26.2.7). The results of the model studies (see Figure 21-2) have been used to construct the main scenario, where these climate-related parameters are included. As mentioned previously, the analysis of the main scenario has also served as a basis for a selection of alternative climate evolutions for which the evolution of the relevant climate-related processes has also been analyzed.

In order to gain a better understanding of the change and variability we can expect of the climate in the future, SKB has also conducted two of its own studies in the field of climate variations during the period. One project was aimed at studying the evolution of the climate in Sweden during the past 1,000 years of interglacial period, partly in order to study the variability of the climate, see section 21.5. The other project was aimed at compiling northern European climate archives that cover periods of more than 10,000 years, see section 21.5.

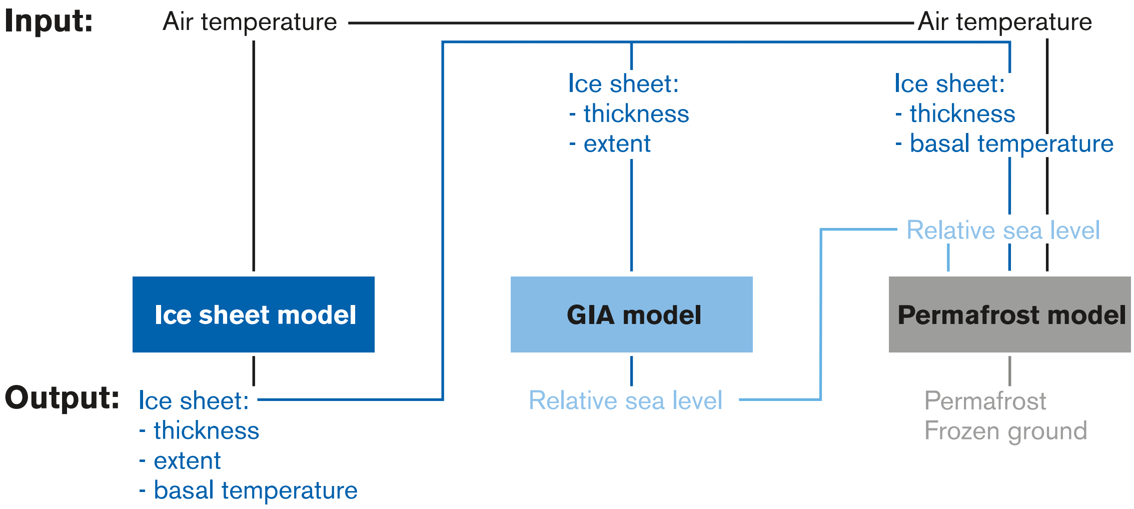


Figure 21-2. *Schematic illustration of the models used to reconstruct conditions during the most recent glacial cycle and the flow of data between them. GIA stands for Glacial Isostatic Adjustment.*

In its review of RD&D-Programme 2004, SSI supports SKB in delimiting the issues that are of particular interest in connection with glaciation, such as possible depth of permafrost, water pressures and flows, possible infiltration of glacial meltwater and upconing of deep brines, changes in rock stresses and tendency towards rock movements, and couplings between hydrological and mechanical processes. With the present-day approach and safety assessment methodology, the identified climate-related domains – and their evolution in time and space in the selected climate scenarios – comprise a basis for the assessment of the safety of the entire repository. The climate is in this way now an integral part of the safety assessment. Moreover, the climate parts also undergo an FEP analysis in the safety assessment /21-1/.

Future and historical climate change is a research area that is undergoing rapid development. SKB therefore keeps track of relevant research in international scientific periodicals and at scientific meetings as well as the work in bodies and organizations dealing with the climate, such as the IPCC (Intergovernmental Panel on Climate Change).

21.2 Ice sheet dynamics and glacial hydrology

The glacial climate domain is defined as areas covered by glacial ice, in other words glaciers or continental ice sheets. The most important research areas are ice sheet dynamics and glacial hydrology. A colder climate normally exists in the glacial climate domain than in permafrost or temperate climate domains. However, the climate is not necessarily drier or wetter. A glacial domain only exists in Sweden today at certain places in the Scandinavian mountain range (the Caledonides) where there are glaciers.

A typical Quaternary glacial cycle spans a period of around 100,000 years. During the glaciation cycle, a continental ice sheet forms which covers parts of the Fennoscandian Shield. The growth of the ice sheet starts in the alpine areas when small glaciers merge to form a single larger ice sheet that ultimately extends into the lowland outside the alpine areas. During the most recent glacial cycles the southern front of the ice reached as far south as northern Germany and Poland. All of Sweden was then dominated by the glacial domain. The average extent of a typical Quaternary ice sheet is much smaller than that, however. The ice margin lay much further north, in the lowlands relatively near the Scandinavian mountain range. During such a Quaternary average ice extent, Forsmark and Oskarshamn were ice-free areas. In large, the deglaciation phase of a Fennoscandian ice sheet was the reverse of the growth phase. The last remnants of the continental ice sheet are found in the highest parts of the Scandinavian Caledonides.

The thermal and hydraulic properties at the base of the continental ice sheet determine how the ice sheet affects its bed and thereby also how it affects the final repository. The ice may be cold-based, whereby the temperature in the basal parts is below the pressure melting point. It may also be warm-based, whereby the basal ice is at the pressure melting point.

In the first case, permafrost may occur underneath the ice sheet. In the cold-based case there is no free water beneath the ice and therefore no subglacial groundwater recharge. A cold-based ice sheet mainly affects the repository by increasing the hydrostatic pressure at repository depth due to its weight. It also affects the stress conditions in the Earth's crust during growth and deglaciation.

A warm-based ice sheet, on the other hand, also makes a contribution to groundwater recharge due to the meltwater that forms beneath the ice. Moreover, in the frontal parts of the ice sheet, meltwater from the surface reaches down to the base through crevasses and moulins. This water, with much greater quantities and greater variation in pressure than the basally generated water, also contributes to groundwater recharge and variations in hydrostatic pressure in the bedrock. The glacial meltwater is very ion-poor and oxygen-rich. Groundwater recharge during periods of glacial climate domain therefore results in the transport of water with such properties downward in the rock. Some of SKB's efforts are therefore spent on studying how groundwater is recharged and transported down through the rock under glacial conditions, see section 26.2.3, and how a groundwater of glacial origin affects, for example, the properties of the buffer clay, see Chapter 24.

When a continental ice sheet advances and retreats, the rock stresses in the concerned area are affected, which could lead to a reactivation of existing fracture zones by glacially induced earthquakes, see section 26.2.7. Figure 21-3 provides an overview of the processes that are being studied within the glacial domain.

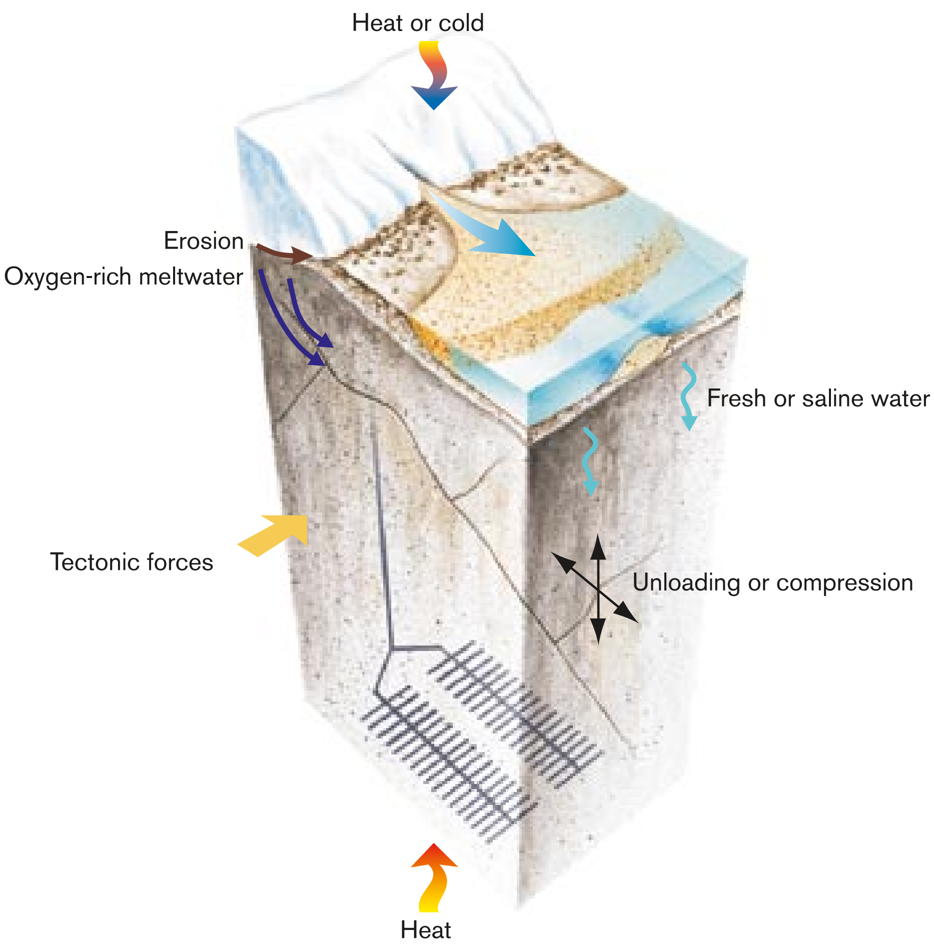


Figure 21-3. *As an ice sheet advances and retreats, changes occur in temperature, hydrological conditions, rock stresses and groundwater composition.*

Conclusions in RD&D 2004 and its review

SKI appreciated the fact that SKB is focusing on the Weichselian glaciation as a first step, but also pointed out that SKB needs to account for alternative climate evolutions. Kasam pointed out that traces of other ice ages than the most recent one should also be taken into account in SKB's work. Furthermore, Kasam appreciated SKB's intentions to investigate issues relating to subglacial drainage and hydrology.

SKI pointed out that SKB only provides a brief description of how changes in hydrology during permafrost and glacial domains will be handled. SKI further noted that the most important goal should be to identify differences between a future climate domain and the existing climate and to analyze the consequences (such as salt exclusion and groundwater flow channelling). SSI thought that predictions should be made of both natural and disturbed groundwater recharge in connection with possible future climate changes.

Newfound knowledge since RD&D 2004

As mentioned above, SKB describes in its current climate programme both a main scenario containing a reconstruction of the conditions during the most recent glacial cycle and alternative climate evolutions. The alternative evolutions that have now been studied are:

- A colder and drier climate than in the reference case, resulting in more and deeper permafrost, see section 21.4.
- A colder climate with precipitation quantities that can build up a thicker ice sheet than during the most recent glacial cycle, see below in this section. Traces of other glaciations than the most recent one are also utilized here, as requested by Kasam.
- A future climate warmer than during the most recent glacial cycle, see sections 21.3 and 21.5.

The project that was initiated in 2002 for the purpose of studying the basal conditions and hydrology of the most recent continental ice sheet involves a compilation of glacial geological information, ice sheet modelling and process studies of ice sheet hydrology.

Glacial geological information

The compilation of glacial geological information is presented in /21-2/. The compilation was carried out in order to get a picture of the current state of knowledge regarding the history of the most recent glacial cycle and in order that this information could be used to calibrate the extent of the ice sheet in the ice sheet model that was used in the reconstruction of the Weichselian ice sheet. The compilation shows that there are still questions surrounding the extent of the ice sheet during the early and middle part of the Weichselian glaciation. But the picture that has become increasingly clear in recent years is that the ice sheet has a more dynamic behaviour than was previously thought, with great variations in ice sheet configuration during the glacial cycle, for example during Marine Isotope Stage 3 (MIS 3) 59,000 to 24,000 years ago /21-2/. Knowledge of the configuration and evolution of the ice sheet at the time of the last glacial maximum about 20,000 years ago and the subsequent deglaciation of Scandinavia is relatively good.

Numerical ice sheet simulation

The current state of knowledge for the theories concerning ice sheet dynamics has been compiled and reported in section 3.1 of /21-3/.

The ice sheet model UMISM (University of Main Ice Sheet Model) was the primary model used for the reconstruction of the Weichselian ice sheet /21-4, 21-5, 21-6/. It is a thermodynamic non-steady-state model that can simulate the behaviour of ice sheets that are not normally in equilibrium with the prevailing climate. UMISM generates results in line with other modern ice sheet models /21-7/. In addition to the climate data that are used in ice sheet simulations of the Fennoscandian ice sheet, a new type of data set has been compiled to be used as input data to the simulations of the Weichselian ice sheet. The data set describes with high resolution the spatial variation in geothermal heat flow over Sweden and has been compiled in cooperation with SGU /21-3, 21-8/. Since the variation in the geothermal heat flow is important for the ice sheet's basal conditions /21-8, 21-9/, such a data set is important in order to reduce the uncertainties in the model's calculations of basal ice temperatures and associated basal melt rates. Prior to this study a spatially variable data set had never been used in numerical simulations of ice sheets. Previously a single assumed value of the heat flow has been used for the entire model domain. The results show that if the purpose of the model study is to investigate the basal thermal and hydrological properties of an ice sheet at a regional and local level, it is necessary to include such a realistic, spatially varying geothermal heat flow /21-8/. Examples of results from the reconstruction of the Weichselian ice sheet are shown in Figure 21-4. The results of the Weichselian reconstruction show that the growth of the ice sheet takes place in a number of phases with intervening periods of more limited ice sheet extent.

The ice sheet model was also used to study extreme climates within the glacial domain, in this case to study the maximum ice thicknesses than can occur in Forsmark and Oskarshamn. In this sub-study the greatest possible ice thickness that has occurred during the past two million years in Scandinavia (during the Saale glaciation) was simulated in order to see how large the extra hydrostatic pressure at repository depth is. Furthermore, a number of sensitivity studies were carried out in which the maximum ice thickness on the two sites was studied in a number of cases with colder climate, where the ice was allowed to grow to equilibrium with the climate. The results show that the maximum expected ice thickness above the sites is 2,600 metres in Laxemar and 3,200 metres in Forsmark, which is equivalent to an extra hydrostatic pressure of 23 and 28 MPa, respectively. For a detailed discussion of maximum ice thicknesses and associated maximum contributions to hydrostatic pressure at repository depth, see the climate report for SR-Can, /21-3, section 4.4.2/. The results of the ice sheet simulations have also been used in the compilation of the climate scenarios in SR-Can /21-3, section 4.2 and 21-10, section 9.4/.

In order to be able to describe a main scenario where all climate-related processes of importance for repository performance are included, the variation in ice extent and ice load history from the ice sheet reconstruction was used as input data in the model simulations of shoreline displacement and permafrost, see sections 21.3 and 21.4, and in studies of glacial earthquakes, see section 26.2.7. Output data from the ice sheet reconstruction (basal melt rates and ice thickness) were also used for simulations of groundwater hydrology and chemistry (salinity) under glacial conditions, see section 26.2.

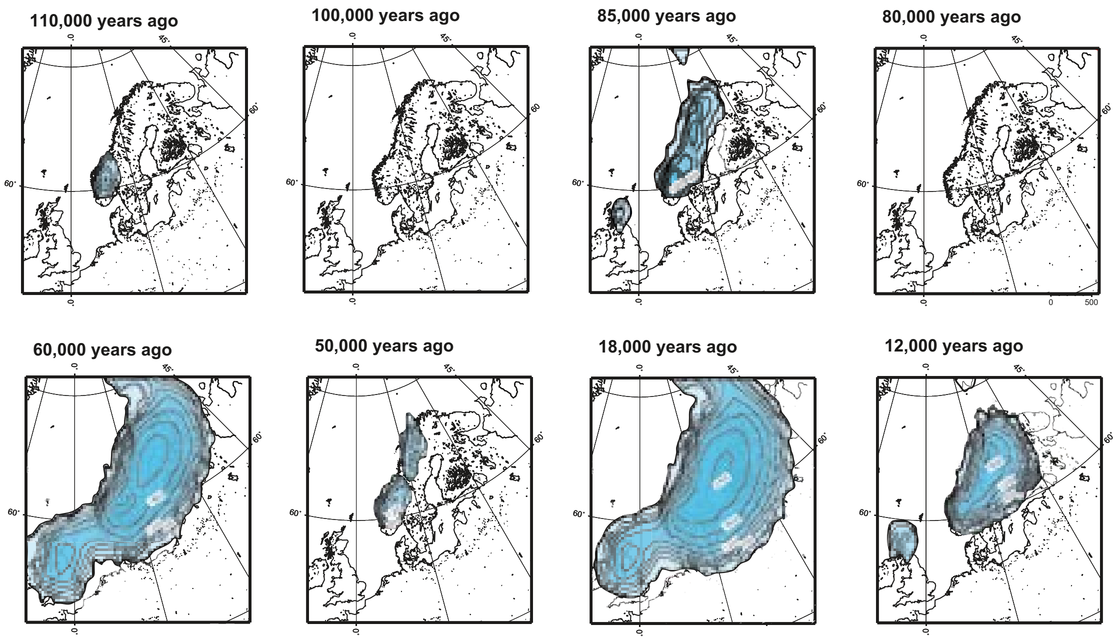


Figure 21-4. *Examples of ice sheet configurations and ice surface elevation (with a 300 metre contour interval) from a reconstruction of the Weichselian glaciation /21-3/.*

In conjunction with glaciations, couplings between mechanical and hydraulic processes are also significant. Mechanical processes that can give rise to glacially induced earthquakes are, for example, dependent on the groundwater's pore pressure, which is affected during glaciations. Mechanical processes are further dealt with in section 26.2.

Process studies of ice sheet hydrology

A review of the current state of knowledge in the area of glacial hydrology has been carried out and reported in /21-3, section 3.2/ and in /21-11/. The latter report comprises an extensive review of the theoretical knowledge concerning how water flows in and beneath a glacier or ice sheet, and how this theoretical knowledge is applied today in model simulations of ice sheet hydrology. The purpose of the report is to present the state of knowledge within the area, but also to identify the gaps that exist today in our understanding of ice sheet hydrology. The main problem is that the glacial hydrological processes that occur on a relatively small scale are difficult to conceptualize in today's large-scale ice sheet models. The important coupling between the complex and glacial hydrological system, which exhibits great spatial variation over time, and the dynamics and flow of ice sheets is therefore largely lacking in today's models.

With the possibility in mind of utilizing the Greenland ice sheet as an analogy for the Scandinavian ice sheet, a preliminary reconnaissance was done on Greenland in the summer of 2005. In conjunction with this, SKB also established contacts with GEUS (the Geological Survey of Denmark and Greenland). SKB is continuing to monitor the possibilities in this area.

Programme

Relatively great uncertainty still exists in the geological interpretations of when, where and with what duration ice-free periods (interstadials) occurred during the most recent glacial cycle in Scandinavia. SKB plans to study the course of events during specific parts of the most recent glacial cycle in Scandinavia in order to reduce the current uncertainty in the geological interpretations. Datings and correlations of existing interstadial sediment samples and stratigraphies from selected key localities in Sweden are therefore planned in order to furnish more supporting data to the safety assessment for the scenario based on a repeat of the Weichselian glaciation.

In the field of ice sheet dynamics and glacial hydrology, SKB intends to continue studying how glacial hydrology can and should be conceptualized in planned geohydrological studies, see section 26.2.3. The springboard for this work consists of experience from geohydrological and glacial hydrological studies conducted during the past period /21-12/ and the current state of knowledge described under the heading "Process studies of ice sheet hydrology" above. In this context, SKB also plans to carry out a project on Greenland aimed at using the Greenland ice sheet as an analogy for the situation we expect in connection with a future glaciation of Forsmark and Oskarshamn. The results would give us a better understanding of the hydrological and geochemical conditions in and around a continental ice sheet, and specifically address issues concerning how an ice sheet affects the groundwater flow and chemistry around a final repository. The project is intended to be carried out in western Greenland near the village of Søndre Strømfjord (Kangerlussuaq). There are rocks in this region, in front of and beneath the ice sheet, that exhibit great similarities to those at Forsmark and Oskarshamn. This similarity is a prerequisite for the studies to be meaningful and provide the desired information on the hydrology and hydrochemistry associated with an ice sheet. The project is planned to be carried out in cooperation with Posiva.

SKB also intends to continue its work of analyzing which cases of ice load history should be selected in planned studies of earthquakes, see section 26.2.7.

The project "Basal conditions and hydrology of continental ice sheets" is planned to be completed in 2007.

21.3 Isostatic changes and shoreline displacement

Shoreline displacement is the most important climate-related process for a repository in the temperate climate domain. The temperate climate domain is defined as a situation without an ice sheet or permafrost. In other words, it consists of areas with a temperate climate in a broad sense, with cold winters and either cold or warm summers. The temperate climate domain has a warmer climate than the glacial domain and the permafrost domain. According to this definition, the temperate domain prevails in all of Sweden today, with the exception of parts of the Scandinavian mountain range.

The position of the shoreline affects the hydrological boundary conditions for the final repository. The salinity in the sea, inland sea or lake corresponding to today's Baltic Sea is also affected by the position of the shoreline, particularly in the inlets in the southern parts. Studies in the biosphere programme have previously shown that the fresh water influx is important for the salinity of the Baltic sea /21-13/.

In the climate scenario that describes a future climate evolution with a warmer climate caused by an increased greenhouse effect, the first 60,000 years or so of the scenario at Forsmark and Oskarshamn consists of a temperate climate domain. After that the climate becomes gradually colder, with at first short, but then increasingly long, periods of permafrost at the two investigated sites. The first period of glacial conditions comes at the end of this approximately 100,000-year-long scenario. In reality, the evolution of a warm greenhouse climate could lead to an initial period with temperate conditions of either shorter or longer duration than in the selected scenario. A warmer climate globally could furthermore entail a colder climate than today regionally across Scandinavia, caused by changes in the thermohaline circulation pattern in the North Atlantic. How these complex issues are handled is described in section 4.3 of /21-3/.

Good knowledge exists concerning conditions and processes in the temperate climate domain and their importance for repository safety and conditions in the biosphere.

Conclusions in RD&D 2004 and its review

SKI appreciated the fact that SKB has initiated projects to understand the causes of shoreline position. SKI pointed out that a future melting of ice sheets due to global warming and the consequences of this for the repository sites need to be described in future safety assessments. Kasam shared this view by pointing out that climate change over a timespan of several hundred to a thousand years can be of interest in view of the risk of global warming and sea level rise, increased precipitation and rising groundwater levels. SSI noted that it is important to describe future sea level changes and whether they could lead to a release of activity accumulated in marine sediments.

Kasam pointed out that predictions should be made of both natural and perturbed groundwater recharge in conjunction with future climate change.

Newfound knowledge since RD&D 2004

The current state of knowledge for theories regarding isostatic changes and shoreline displacement has been reviewed and reported in section 3.3 of /21-3/.

The points brought up by SKI, SSI and Kasam above are all dealt with in the climate scenario with an anthropogenically affected warmer climate due to an increased greenhouse effect, see below.

A project where Global Isostatic Adjustment (GIA) modelling plays a central role and whose purpose is to understand and quantify shoreline displacement was initiated in 2004. Shoreline displacement has an isostatic and a eustatic component, i.e. changes in the level of the Earth's crust and the surface of the sea, respectively. These processes must be studied globally, which can be done with GIA models /21-14 and 21-15/. In this project a two-dimensional GIA model developed at the University of Durham was used /21-14, 21-15 and 21-16/. The cases analyzed with the GIA model are:

- The main scenario based on the repetition of the Weichselian period.
- The scenario with a warmer climate due to an increased greenhouse effect.
- Sensitivity studies.

In order to avoid problems with the fact that the Earth's crust is initially in hydrostatic equilibrium in the GIA simulations, two consecutive glacial cycles were simulated in the two first cases above, whereby results were only used from the latter cycle. Furthermore, the shoreline displacement curve during the first 7,000–10,000 years in these two scenarios does not consist of data from the GIA model, but instead of extrapolated information from today's observed trends for the sites /21-17 and 21-18/, in line with regulatory stipulations. Variations in ice load over time are important input data to the GIA simulations. For this reason, information on ice thickness variations from the ice sheet simulations were used as input data for the local case (the Fennoscandian ice sheet), see Figure 21-2, while other information was used as input data for variations in ice load in faraway areas, for example North America. Variations in, for example, the North American ice sheet also affect isostatic conditions and shoreline displacement in Sweden. Background, methods and results from the GIA studies are presented in section 3.3 of /21.3/.

The results of the GIA simulations have been used in the compilation of the climate scenarios in SR–Can /21-3, sections 4.2 and 4.3, and 21-10, sections 9.4 and 9.6/. Despite the fact that the uncertainties in the GIA results are relatively large in some cases, the results for the main scenario show that land uplift at the two sites will continue for 40,000–50,000 years before the next period of glaciation occurs in the scenario. The remaining land uplift is on the order of 20–35 metres, with the higher values in Forsmark and the lower values in Oskarshamn.

The climate scenario with an increased greenhouse effect includes a total melting of the Greenland ice sheet, which is the most sensitive of today's ice sheets to temperature increases. The melting of the Greenland ice sheet corresponds to a global sea level rise of about seven metres. The results of the GIA simulations show that land uplift will continue on the two sites, as in the main scenario, despite the melting of the Greenland ice sheet. The rate of isostatic rebound is faster than the rate of sea level rise, so that the ground surface above the repository in this scenario is above sea level for more than 100,000 years on both sites. The scope of the land uplift is uncertain, however, due in part to uncertainties in the actual future sea level rise.

The scenario with a warmer climate due to an increased greenhouse effect, with its very long period of temperate conditions, is mainly positive for the performance of the repository /21-10, section 9.6/.

A concluding part of the GIA project studied the effect of including a 3D description of the Earth model, instead of a laterally homogeneous Earth model, which was used in the studies described above. Preliminary results show that the effect of including a laterally varying thickness of the Earth's crust greatly reduces the margins of error in the calculations of isostatic uplift and resulting shoreline displacement /21-19 and 21-20/.

Programme

SKB intends to supplement current knowledge with the refined predictions of sea level rises in conjunction with warmer climates /21-21/, and to include future scientific results and compilations regarding climate change, ice sheets and sea level variations in the climate scenario with increased greenhouse effect.

21.4 Permafrost growth

The permafrost climate domain prevail in areas where the temperature of the ground is at or below 0°C throughout the year. These are areas with a cold climate but no ice sheet. Usually the permafrost domain has a climate that is colder than the temperature domain but warmer than the glacial domain. The permafrost domain exists in Sweden today in parts of the mountains, where it is found discontinuously or sporadically.

Permafrost affects the groundwater's flow pattern and composition, the latter due to salt exclusion.

Conclusions in RD&D 2004 and its review

Kasam appreciated SKB's intentions to address questions concerning permafrost. SKI pointed out that SKB should have a more comprehensive description of permafrost, since it is important for the buffer's safety functions. SKI further noted that the uncertainties in calculated permafrost depth should be carefully evaluated, especially in a final repository Forsmark at a depth of about 400 metres.

Newfound knowledge since RD&D 2004

The current state of knowledge concerning theories of permafrost formation was described in section 3.4 of /21-3/.

Possible permafrost depths were studied for both Forsmark and Oskarshamn. The studies were carried out with an advanced numerical one-dimensional permafrost model developed at Helsinki University /21-22/. The study consisted of two main parts. In the first part, factors that can influence permafrost development such as soil layer, vegetation, snow cover, lakes and temperature were identified and investigated. In the light of the results achieved in the first part, permafrost on the two candidate sites was studied under a number of climate scenarios, among other things for a reconstruction of the last glacial cycle. Site-specific parameters of importance from the site investigations, for example the thermal conductivity and heat capacity of the rock, were used in these studies. Sensitivity studies for different climate evolutions and thermal properties of the rock were also performed. These sensitivity studies are judged to cover the variation that is needed to justify the adequacy of the chosen 1D approach, compared to if the studies had been done in 3D.

Site-specific analyses were also done of how the heat from the deposited fuel influences the development of permafrost on a given site with a site-adapted repository layout. Important input data in the permafrost analyses consisted of information from the ice sheet modelling (see section 21.2) and the modelling of shoreline displacement (see section 21.3). In the main scenario, the permafrost reaches a maximum depth of 250 metres in Forsmark and 160 metres in Laxemar. Examples of results from the permafrost study are given in Figure 21-5.

In addition to permafrost development in the main scenario (see Figure 21-5), permafrost development was analyzed in more extreme climates, also by modelling of permafrost depth. In this case, permafrost depth was calculated for a climate scenario that was exceptionally favourable for permafrost growth. Here it was assumed that the climate was as cold as during the last glacial, but much drier. No ice sheet could be formed to cover, and thereby insulate, the ground. It was further assumed that there was no insulating snow or vegetation cover during the year, and that the sites were never covered by the sea. The results of the calculation in this pessimistically chosen climate scenario show that the lowest temperature at repository depth is –0.7°C in Forsmark and +6.1°C in Laxemar. Together with the sensitivity studies of the dependence of the permafrost on the temperature, the results show that the temperature at repository depth is not so low that it can cause freezing of the buffer clay at repository depth on the sites in question /21-10, section 12.4/. This applies to both periglacial permafrost in front of the ice sheet and permafrost beneath the ice sheet.

Calculations were also carried out to study what freezing-induced pressure the copper canister can be subjected to if groundwater were, in the pessimistic climate case, to freeze in erosion cavities caused by buffer erosion. The results show that the maximum freezing-induced pressure is lower than the critical pressure for canister collapse /21-10, section 12.4.4/.

The results of the permafrost study are reported in sections 3.4 and 4.4.1 of /21-3/. The results have been used to compile the climate scenarios in SR-Can /21-3, section 4.2 and 21-10, section 12.4/. A smaller study of what freezing-inducted pressure would be obtained in connection with freezing of groundwater in erosion cavities in the buffer around the canister has also been carried out /21-3, section 4.4.1/. In addition to the model studies described above, a generic model study has been performed of salt exclusion (rejection) in conjunction with permafrost growth /21-23/.

Field studies of permafrost and its importance for hydrology and groundwater composition have been conducted at the Lupin Mine in Canada together with Posiva, the Nuclear Decommissioning Authority and Ontario Power Generation.

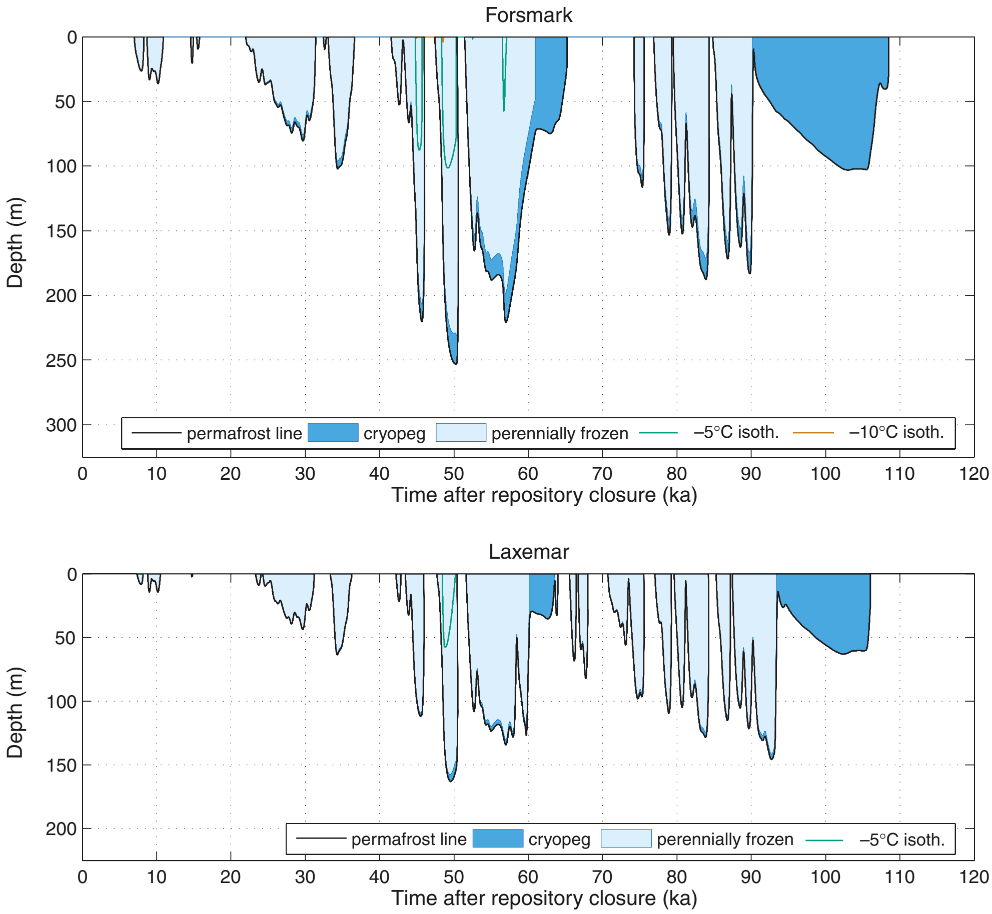


Figure 21-5. *Calculated permafrost depth for Forsmark and Laxemar for the latest glacial cycle. Cryopeg is ground that is not frozen, but remains at sub-zero temperatures.*

Programme

In similarity with the plans for further studies of groundwater flow and chemistry under glacial conditions, SKB intends to analyze the effects of the spatial extent of the permafrost for geohydrology and geochemistry. One possible approach is to conceptualize, by modelling or otherwise, the extent of the permafrost in the model domain for future simulations of the groundwater flow.

SKB also intends to study the effect of the fact that the backfill material freezes in deposition tunnels and ramp. To some extent this is expected to freeze both in the reference scenario and in climate scenarios that are more favourable for permafrost.

Furthermore, SKB plans to continue to support and follow the field studies of permafrost and its importance for hydrology and groundwater composition together with Posiva, the Nuclear Decommissioning Authority and Ontario Power Generation.

21.5 Climate and climate variations

Conclusions in RD&D 2004 and its review

SKI pointed out that SKB should more clearly describe how it will ensure that the selected climate evolutions shed light on the most important climate-related stresses on the engineered barriers in particular, for example hydrostatic pressure, groundwater chemistry and rock movements. Kasam expected SKB to discuss MIS 11 (the interglacial 400,000 years ago with a climate similar to today's) in future scenarios.

Newfound knowledge since RD&D 2004

SR-Can addresses the point made by SKI above by virtue of the fact that all climate-related processes are now handled by a systematic and complete analysis of the features, events and processes that are relevant to the climate-related issues /21-1/.

A compilation and synopsis of the climate variations within the current warm interglacial, but also for the Weichselian period, has been carried out and reported /21-24/. The study sheds light on climate variations during interglacials as well as possible climatic conditions southeast of an ice sheet that partially covers Sweden. The study provides data as a basis for setting bounds within which temperature and precipitation vary during the temperate domain.

A project aimed at quantifying, describing and understanding the causes of climate variations in Scandinavia during the past 1,000 years has been carried out /21-25/. Another purpose of the study was to evaluate how information from different types of climate archives can be used together with a regional climate model to describe the climate. Available information on climate variations in Sweden during the past millennium was analyzed in the project. The results of the project provide a basis for describing climate changes during the next 1,000 years. They also show the variability in the Forsmark and Oskarshamn areas during the past 1,000 years. The results contribute to the possibility of estimating the magnitude of future climate changes. Parts of the study are also published in /21-26/.

The interglacial during Marine Isotope Stage (MIS) 11, about 400,000 years ago, is often presented as an analogue to today's warm period (Holocene) due to similar orbital parameters for the Earth and thereby similar insolation conditions. SKB's climate programme contains no specific discussion and analysis of MIS 11. A similar situation was included in the two analyzed variants of the main scenario.

The evolution of climate-related parameters in a warmer climate affected by an increased greenhouse effect is presented in section 4.3 of /21-3/. SKB's assessment is that a prolonged period of ice-free warm conditions is for the most part advantageous for the safety function of the repository /21-10, section 9.6.4/.

Programme

SKB has initiated two projects concerned with qualitative descriptions of the climate in Scandinavia during extreme periods of the most recent glacial cycle. The first project is aimed at qualitatively studying extreme climate situations by climate modelling with a global climate model and a high-resolution regional climate model. The global climate simulations are being carried out at the Department of Meteorology, Stockholm University, and the regional climate simulations at the Rossby Centre, SMHI. The second project is aimed at quantitatively studying extreme climate situations during the most recent glacial cycle from paleodata by studies of lacustrine deposits. The project is under the leadership of the Department of Physical Geography and Quaternary Geology, Stockholm University.

The main purpose of the two projects is to obtain a more nuanced picture of what the climate in Scandinavia may be like during specific periods of a glacial cycle, for example periods with a cold but very dry climate that is favourable for permafrost growth. The studied time periods during the last glacial cycle are chosen so that the results of the modelling project and the paleodata project can be compared with each other in order to obtain a deeper understanding of the processes that control the climate during a glacial cycle.

Quantitative climate data are planned to be extracted for the climate periods in question for the Forsmark and Oskarshamn regions, for example for temperature, precipitation, runoff and evapotranspiration. The purpose is that these results can be used to better describe the climate during periods that are favourable for permafrost growth at the two sites, as well as for SKB's studies of biosphere evolution, see Chapter 27.

In addition to the selected periods during the last glaciation, the climate in Scandinavia will also be simulated for a future period with an increased concentration of greenhouse gases in the atmosphere in order to obtain comparable regional climate information for this climate scenario. Here as well, regional information will be extracted for Forsmark and Oskarshamn. Both climate projects are planned to be carried out during the current period.

In addition to the FEP processing of climate and climate-related processes, the results of these two studies will be used to ensure that the selected climate evolutions, above all the scenario that is favourable for permafrost growth and the scenario with increased greenhouse effect, are adequate and sufficiently pessimistic. In other words, the studies contribute to a better understanding of the more extreme climate scenarios that are analyzed in SKB's climate programme and to investigating the realism of these scenarios.

In view of the rapid advance of knowledge in the climate field – see for example /21-27, 21-28, 21-29 and 21-3/ and the references therein – SKB plans to continue to follow these issues and examine the consequences of the future climate for a final repository.

22 Fuel

The spent fuel that will be deposited in the repository comes from nuclear power plants. For an alternative with 50 years of reactor operation at Forsmark and Ringhals and 60 years at Oskarshamn, the total quantity of BWR and PWR fuel is estimated to be just under 12,000 tonnes /22-1/. In addition, 23 tonnes of mox fuel, 20 tonnes of fuel from the Ågesta reactor and some residues from fuel investigations at Studsvik will be deposited. The fuel's burnup can vary from approximately 15 to 60 MWd/kgU. Differences in radionuclide content between PWR and BWR fuel are marginal viewed from a safety assessment perspective. Mox fuel has a higher decay heat than uranium fuel, which means that less fuel can be deposited in each canister in order for the requirement of a maximum decay heat of 1,700 Watts per canister to be met. The differences between different fuel types are more important when it comes to assessing criticality. The assessments are therefore made based on the fuel types that are least favourable from a criticality viewpoint.

22.1 Initial state in fuel/cavity

22.1.1 Variables

In the safety assessment, the fuel is described by means of a set of variables which together characterize the fuel in a suitable manner for the assessment. The description applies not only to the fuel itself, but also the cavities in the canister, which water can enter if there is a defect in the copper canister. Processes such as fuel dissolution and corrosion of the cast iron insert will take place in the cavities. The cavities could thus be included in either the fuel or the canister subsystem, and have been included in the fuel here. The variables are defined in Table 22-1.

22.1.2 Geometry

The final repository will contain fuel of various types and geometries.

Conclusions in RD&D 2004 and its review

The field was judged not to require any further research, development or demonstration. New developments were to be monitored and would be acted on when appropriate. No direct viewpoints were offered on this by the authorities.

Table 22-1. Variables for the fuel.

Variable	Definition
Geometry	Geometric dimensions of all components of the fuel assembly, such as fuel pellets and Zircaloy cladding. Also includes the detailed geometry, including cracking, of the fuel pellets.
Radiation intensity	Intensity of alpha, beta, gamma and neutron radiation as a function of time and space in the fuel assembly.
Temperature	Temperature as a function of time and space in the fuel assembly.
Hydrovariables	Flows and pressures for water and gas as a function of time and space in the cavities in the fuel and the canister.
Mechanical stresses	Mechanical stresses as a function of time and space in the fuel assembly.
Total radionuclide inventory	Total occurrence of radionuclides as a function of time and space in the different parts of the fuel assembly.
Gap inventory	Occurrence of radionuclides as a function of time and space in the gap and grain boundaries.
Material composition	The materials of which the different components in the fuel assembly are composed, excluding radionuclides.
Water composition	Composition of water (including any radionuclides and dissolved gases) in the cavities in the fuel and canister.
Gas composition	Composition of gas (including any radionuclides) in the cavities in the fuel and canister.

Newfound knowledge since RD&D 2004

No new knowledge has been forthcoming.

Programme

The field is judged today not to require any further research, development or demonstration. New developments are being monitored and will be acted on when appropriate.

22.1.3 Radiation intensity

Radiation intensity is dependent on radioactivity, i.e. the inventory of radionuclides and the geometry of the fuel.

Conclusions in RD&D 2004 and its review

There was no research programme on this process in RD&D 2004, and no direct viewpoints on this were offered in the review.

Newfound knowledge since RD&D 2004

No new knowledge has been forthcoming.

Programme

Additional calculations may be required due to higher burnups.

22.1.4 Temperature

Conclusions in RD&D 2004 and its review

No research programme for this area was included in RD&D 2004, and no direct viewpoints were offered in the review.

Newfound knowledge since RD&D 2004

No new knowledge has been forthcoming.

Programme

The field is judged today not to require any further research, development or demonstration. New developments are being monitored and will be acted on when appropriate.

22.1.5 Hydrovariables

The hydrovariables – i.e. water pressures, water flows and gas flows – are not relevant to describe initially, since the canister is assumed to be intact.

22.1.6 Mechanical stresses

Conclusions in RD&D 2004 and its review

No research programme for this area was included in RD&D 2004, and no direct viewpoints were offered in the review.

Newfound knowledge since RD&D 2004

No new knowledge has been forthcoming.

Programme

The field is judged today not to require any further research, development or demonstration. New developments are being monitored and will be acted on when appropriate.

22.1.7 Total radionuclide inventory

Conclusions in RD&D 2004 and its review

SR-Can was based on the same inventory calculations as SR 97 /22-2/. The data report for SR-Can /22-3/ concludes that other factors than the inventory determine the release of radionuclides from a defective canister. The variations in inventory for a given decay heat in the canister are also relatively small for most nuclides.

Newfound knowledge since RD&D 2004

Calculations of the radionuclide inventory in a mox fuel have been performed in preparation for SR-Site.

Programme

New calculations of the inventories may be needed for fuel with a higher burnup.

22.1.8 Gap inventory

Conclusions in RD&D 2004 and its review

SKI points out that there is a lack of data for the rapid release of certain radionuclides from fuel. This could have a great effect on the consequence calculations, for example when it comes to the impact of iodine-129.

Newfound knowledge since RD&D 2004

An analysis of data for the fraction of the radionuclide inventory that has been segregated at the fuel-clad gap or in the grain boundaries was performed. A model for release of easily accessible nuclides for fuel with the burnup distribution analyzed for SR-Can was developed /22-4/.

Research on the evolution of the fission product distribution with time was done within the EU project SFS (Spent Fuel Stability Under Repository Conditions) and is reported in /22-5/. Several different attempts were made to model radiation-induced diffusion. With the conservative diffusivities /22-5/ that were recommended, the diffusion length for fission products can be estimated to be at most 0.1 to 0.2 micron in a million years for fuel with a burnup of 55 MWd/kgU. Thus, for fuel from the Swedish nuclear power programme there is no reason to assume that radiation-induced diffusion would lead to an increase of the gap inventory of radionuclides, even after a million years.

In an atomic-scale modelling of the material damage caused by alpha radiation /22-6/, the coefficient for radiation-induced diffusion was determined to be less than 10^{-26} metres per second in all calculation cases. This roughly corresponds to a diffusion length of less than 0.6 micron in a million years. Since the diffusion coefficient is dependent on the alpha activity, it will decline with time and the actual diffusion length will therefore be shorter.

Programme

It is proposed that the average burnup be increased to 60 MWd/kgU for both BWR and PWR fuel. The consequences of this will be examined into as a basis for SR-Site.

22.1.9 Material composition

Conclusions in RD&D 2004 and its review

SKB decided to conduct a study of the importance of non-radioactive fission products. No direct viewpoints on this were offered in the review.

Newfound knowledge since RD&D 2004

The quantities of barium in the spent nuclear fuel will be several orders of magnitude greater than the quantity of radium, see for example /22-7/. Co-precipitation of radium with barium could lead to reduced doses from radium.

Programme

Co-precipitation of radium with barium will be studied further prior to SR-Site, see also section 22.2.14.

22.1.10 Water composition

Under deposition conditions where water occurs in vapour form, see section 22.1.11 below.

22.1.11 Gas composition

Conclusions in RD&D 2004 and its review

The consequences of more water entering the canister must be studied. No direct viewpoints on this were offered in the review.

Newfound knowledge since RD&D 2004

The quantity of radiolytically produced nitric acid can be limited by replacing the air in the canister with argon. Since there are only very local areas with tensile stresses, the risk of stress corrosion cracking, which could reduce the strength of the canister, can be ruled out.

Programme

With 600 grams of water in the canister, the quantity of hydrogen gas that will be produced by corrosion is not negligible. The effects of the hydrogen gas build-up on the material properties of the canister components will be investigated.

22.2 Processes in fuel/cavity

A number of processes will with time alter the state in the fuel and in the canister's cavity. Some take place in any circumstances, while many others only occur if the isolation of the copper canister is breached and water enters the canister.

22.2.1 Overview of processes

The radionuclides in the fuel will eventually be transformed into non-radioactive substances by radioactive decay and nuclear fission. This process gives rise to alpha, beta, gamma and neutron radiation which, by interaction with the fuel itself and with surrounding materials, is attenuated and converted to thermal energy. Heat transport in the form of conduction and radiation changes the temperature in the fuel and heat is removed to the surroundings. The temperature change will lead to some thermal expansion of the fuel's constituents. This can, in combination with the helium formation caused by the alpha radiation, lead to rupture of the fuel's cladding tubes.

In an intact canister, radiolysis of residual gases in the cavities will lead to the formation of small quantities of corrosive gases, which could contribute to stress corrosion cracking of the cast iron insert.

If the copper canister is not intact, water may be enter the canister cavity, radically altering the chemical environment. Radiolysis of the water in the cavities will further alter the chemical environment. The water in the canister causes corrosion of cladding tubes and other metal parts in the fuel. If the cladding tubes' isolation should be breached initially or later by corrosion or mechanical stresses, the fuel will come into contact with water. This leads to dissolution of radionuclides that have collected on the surface of the fuel matrix, and to dissolution or transformation of the fuel matrix and release of radionuclides. The radionuclides may either be dissolved in the water, rendering them accessible for transport, or precipitate in solid phases in the canister's cavities. This is determined by the chemical conditions. On dissolution of the fuel, colloids with radionuclides may also form.

Radionuclides dissolved in water can be transported with mobile water in the canister (advection) or by diffusion in stagnant water. Colloids carrying radionuclides can be transported in the same way. Nuclides dissolved in water can be sorbed to the different materials in the canister. Certain nuclides can also be transported in the gas phase.

Finally, water can attenuate the energy of neutrons in the canister's cavities. Low-energy neutrons can subsequently cause fission of certain nuclides in the fuel, releasing more neutrons. If conditions are unfavourable, criticality may be achieved, i.e. the process becomes self-sustaining.

The research programme for the different processes in the fuel is discussed in the following sections.

22.2.2 Radioactive decay

Conclusions in RD&D 2004 and its review

A quality review of data on half-lives for all radionuclides of interest in the safety assessment was carried out for SR-Can. No direct viewpoints on this were offered in the review.

Newfound knowledge since RD&D 2004

Half-lives for all radionuclides analyzed in SR-Can are presented in /22-3/. There it is noted that a couple of the half-lives used in calculations of the radionuclide inventories have been replaced with updated values.

Programme

SKB has no programme of its own for studying half-lives, but keeps track of relevant research and updates the database when necessary.

22.2.3 Radiation attenuation/heat generation

Conclusions in RD&D 2004 and its review

No research programme for this area was included in RD&D 2004, and no direct viewpoints were offered in the review.

Newfound knowledge since RD&D 2004

New calculations of the thermal evolution in and around the canister were done in the SR-Can project.

Programme

The consequences of increased burnup for the thermal evolution need to be studied prior to SR-Site.

22.2.4 Induced fission – criticality

Conclusions in RD&D 2004 and its review

The field was judged not to require any further research, development or demonstration.

SSI pointed out that SKB should further study the consequences of what water penetration in the canister and the resultant changes (corrosion, degradation of fuel and insert and possible removal of material) can give rise to in view of the risk of criticality.

Newfound knowledge since RD&D 2004

No new knowledge has been forthcoming.

Programme

New calculations will be carried out to examine the consequences for criticality of casting defects in the canister insert. Criticality for mox fuel also needs to be studied. SSI's comments will also be taken into account in connection with the new criticality calculations.

22.2.5 Heat transport

Dealt with in section 22.1.4.

22.2.6 Water and gas transport in canister cavity, boiling/condensation

The process is strongly coupled to several other processes. The processes are dealt with collectively in section 23.2.

22.2.7 Thermal expansion/cladding failure

Conclusions in RD&D 2004 and its review

No research programme for this area was included in RD&D 2004, and no direct viewpoints were offered in the review.

Newfound knowledge since RD&D 2004

No new knowledge has been forthcoming.

Programme

The field is judged today not to require any further research, development or demonstration. New developments are being monitored and will be acted on when appropriate.

22.2.8 Advection and diffusion

Solutes in the interior of the canister can be transported by advection and diffusion. These processes are not discussed explicitly, but dealt with (often with pessimistic simplifications) integrated with other processes. Radionuclide transport in the near-field is dealt with in section 25.3.

22.2.9 Residual gas radiolysis/oxygen formation

Conclusions in RD&D 2004 and its review

Radiolysis calculations were to be carried out to determine whether the canister must be filled with an inert gas in order to prevent radiolytic formation of nitric acid. No direct viewpoints on this were offered in the review.

Newfound knowledge since RD&D 2004

Simple scoping calculations showed that an atmosphere with at least 90 percent argon would limit the quantity of nitric acid to acceptable levels. See also section 23.2.10

Programme

The field is judged today not to require any further research, development or demonstration. New developments are being monitored and will be acted on when appropriate.

22.2.10 Water radiolysis

Conclusions in RD&D 2004 and its review

The investigation of iron corrosion in initially oxygen-free water under gamma radiation was conducted during the period, see section 23.2.8.

No direct viewpoints were offered.

Newfound knowledge since RD&D 2004

The investigation has been concluded and reported /22-8/. The experiments were performed at two gamma dose rates: 300 Gy/h, corresponding to the dose rate on the inside of the cast iron insert, and 11 Gy/h, corresponding to the dose rate on the outside of the cast iron insert. The gamma radiation increased the corrosion rate by up to a factor of 30 in Allard water and at the highest dose rate. At 11 Gy/h, the corrosion rate declined with time and was after 7,000 hours comparable to the corrosion rate without gamma radiation. At 300 Gy/h the higher corrosion rate lasted longer and it was estimated that it might possibly be permanent.

With an intact canister the extent of the corrosion attack will be limited by the quantity of water inside the canister at closure, and the radiolysis will only affect the corrosion rate.

Programme

No further studies are planned.

22.2.11 Metal corrosion

This section concerns corrosion of cladding tubes and metal parts in the fuel.

Conclusions in RD&D 2004 and its review

The field was judged not to require any further research, development or demonstration. New developments are being monitored and will be acted on when appropriate. No direct viewpoints on this were offered in the review.

Newfound knowledge since RD&D 2004

No new knowledge has been forthcoming.

Programme

The field is judged today not to require any further research, development or demonstration. New developments are being monitored and will be acted on when appropriate.

22.2.12 Fuel dissolution

Conclusions in RD&D 2004 and its review

SKI noted that knowledge of the fuel's reaction in contact with groundwater has improved considerably in recent years. However, this knowledge needs to be better demonstrated in the form of quantitative model studies of mechanisms and processes. SKB also needs to give an account of the importance of fuel dissolution under reducing conditions but in the absence of high hydrogen gas pressure. SKB should continue to develop and use process models as well as to report the results in safety assessments, not to obtain a dissolution rate, but to demonstrate an understanding of processes for extrapolation using very long timescales and to provide a basis for sensitivity analyses and the characterization of uncertainties. SKI considered that one of the Chemlab probes should be used for fuel experiments rather than for actinide experiments.

Newfound knowledge since RD&D 2004

A compilation of data on fuel dissolution under reducing conditions was done during the period and a model that describes the dissolution of the fuel matrix was developed for the SR-Can safety assessment /22-4/.

Experiments with leaching of fuel samples taken from different segments in a fuel rod with burnup varying from 21 to 49 MWd/kgU /22-9/ showed a weak and almost linear increase of leaching (cumulative released fraction) up to 40–43 MWd/kgU, followed by a decrease. Fuel with a burnup of around 40-43 MWd/kgU has been used in most experiments conducted under reducing conditions in the past few years in SKB's programme due to the higher expected leaching. In view of the predicted increase in average burnup of fuel in the future, it is necessary to conduct experiments with fuel with a burnup of more than 50 MWd/kgU under different conditions in order to improve SKB's body of data.

The EU project SFS (Spent Fuel Stability Under Repository Conditions) was concluded and a compilation of the results regarding fuel matrix dissolution has been published /22-10/. Under final repository conditions during the first thousand years, radiolytic oxidants produced by the spent fuel are expected to be consumed by high concentrations of reductants in the form of divalent iron and hydrogen produced by anoxic iron corrosion. After very long times the remaining alpha activity in the fuel will be so small that not enough oxidants will be produced to cause a measurable oxidation of the fuel /22-11, 22-12 and 22-13/.

In SKB's programme, studies have been conducted with fairly fresh spent fuel in the presence of different and relatively high concentrations of dissolved hydrogen or divalent iron. Fresh spent fuel has the real material composition, but a very high radiation field compared with that expected in scenarios that include a possible contact with groundwater. At the same time, equivalent studies have been conducted with alpha-doped uranium dioxide in the presence of relatively low concentrations of reductants (divalent iron in the presence of hydrogen, produced by iron corrosion, or sulphide ions). Alpha-doped uranium dioxide better simulates the radiation field of several-thousand-year-old fuel.

The experimental studies of fuel leaching or of uranium dioxide doped with uranium-233 in the presence of 0.05 to 43 mM dissolved hydrogen are relatively new. The results of the EU project SFS and related studies have been compiled in /22-14/. In the fuel case, the real material composition and the presence of non-redox-sensitive fission products makes it possible to judge the dissolution rate via their release. A systematic reduction by more than two orders of magnitude of the released fraction of strontium or caesium during different time intervals was observed during more than one-year-long experiments at Studsvik. At longer leaching periods, the number of intervals where no releases of strontium or caesium could be measured increased. The concentrations of nearly all redox-sensitive nuclides from a pre-oxidized fuel layer decline with time to values equivalent to the solubility of their reduced oxides. In certain cases the concentrations of actinides, such as neptunium and plutonium, are much lower than the uranium concentrations. The ratio between actinide and uranium is fairly close to that in the fuel, even though the solubilities of their tetravalent oxides are relatively similar. This indicates a possible co-precipitation of neptunium and plutonium with uranium.

The first results from leaching of mox fuel exhibit similarities to experiments conducted with uranium dioxide fuel, see Figure 22-1. The same behaviour has been noticed during the more than three-year-long experiment, which continues to be analyzed in cooperation with the EU's Institute for Transuranium Elements (ITU) in Karlsruhe.

In order to study the first phase of the scenario with a damaged canister, fuel segments with holes made in the cladding have been studied – in cooperation with ITU – in the presence of water vapour under an argon or hydrogen atmosphere. Preliminary data show a pressure increase caused by radiolysis under argon, but no pressure increase is measured at 40 percent hydrogen.

Experiments have also been conducted with fresh fuel and lower concentrations of hydrogen (7, 10 and 30 percent hydrogen). Data obtained show that the concentration of non-redox-sensitive nuclides, such as strontium or caesium, increases under 10 percent hydrogen and that measurable concentrations of hydrogen peroxide and oxygen are produced. The same also occurs with 30 percent hydrogen in argon.

Mass balance experiments, where the time dependence of hydrogen and oxygen formation has been studied in a closed system with initially around two grams of fuel fragments and oxygen-free solutions, have been concluded and the results published /22-15/. For data from long-contact-time experiments in sealed glass ampoules that were analyzed after one, two and three years and in which fuel had been leached in the presence of 10 mM bicarbonate, geochemical modelling shows that the formation of secondary hexavalent uranium phases is not possible. A comparison of data from these ampoules with calculations shows that measured concentrations of radiolysis products such as hydrogen and oxygen are constant within the margins of error, despite the fact that radiolytic modelling of the entire system predicts an increase with time. The same applies to the concentrations of uranium and fission products such as strontium and caesium. The modelling work is continuing and new experiments are planned to improve the statistical basis and permit a radiolytic modelling of fuel dissolution.

Experiments have been conducted in cooperation with Posiva using the isotope dilution method with uranium dioxide doped with 0, 5 and 10 percent uranium-233 in the presence of metallic iron. This method permits an analysis of data even if uranium precipitation occurs /22-16/. The uranium concentrations that have been measured in the solution or by analysis of the iron surfaces at the end of the experiment are very low. Estimation of the matrix dissolution rate confirms previously measured low values /22-17/. The work is continuing within the framework of the EU project NF-PRO. A new study with the same materials but with solutions that only contain one ppm of sulphide – with or without the presence of metallic iron – show no measurable effect of either alpha doping level or experimental time on measured uranium concentrations.

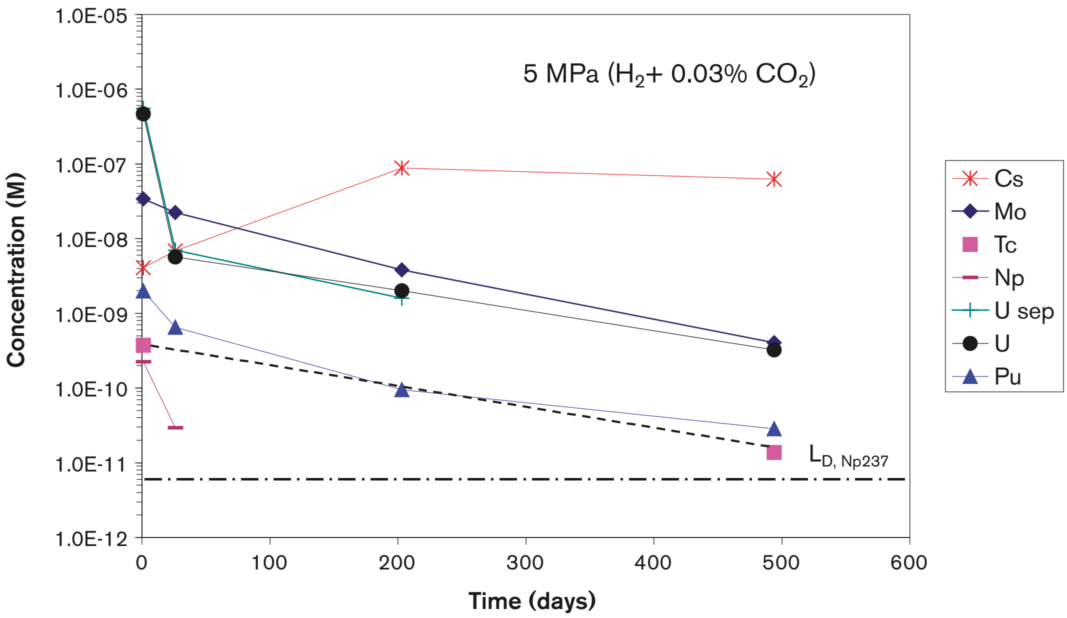


Figure 22-1. *Concentration of fission products and actinides in the mox leachate as a function of leaching time.*

The experiment with a uranium dioxide pellet doped with 10 percent uranium-233 /22-14/ was repeated later in cooperation with ITU without the presence of titanium particles, which could have influenced the result. Once again, very low concentrations of uranium in solution were measured. No increase in the concentrations could be detected during the experiment, which lasted more than one year. At the end of the experiment, the autoclave was opened in a glovebox filled with inert gas and the pellet was quickly transferred to a vacuum transporting vessel. Examination of the uranium dioxide surface by means of X-Ray Photoelectron Spectroscopy, XPS, revealed only stoichiometric uranium dioxide (UO_2), i.e. no oxidation of the surface could be observed. This result agrees with published data on XPS analyses in experiments with alpha radiolysis in hydrogen-saturated solutions and uranium dioxide surfaces /22-18/ and shows that the quantity of oxidized uranium at the surface decreases with time.

Electrochemical investigations have shown that the corrosion potential of uranium dioxide and Simfuel (uranium dioxide containing non-radioactive fission products and metal particles similar to those in spent fuel) decreases in the presence of hydrogen /22-19/. Under certain circumstances, the corrosion potential approaches the equilibrium potential between hydrogen and hydrogen ions. This may indicate a galvanic coupling between areas where this electrochemical process is catalyzed and the rest of the uranium dioxide surface. It is also possible that hydrogen radicals, which are formed by dissociation of hydrogen on metallic particles in fuel or on surface-active UO_{2+x}-sites under gamma irradiation, reduce oxidized pentavalent and hexavalent uranium on the surface to tetravalent uranium.

Our understanding of the kinetics and mechanisms of reactions between radiolytic oxidants and uranium dioxide has improved as a result of the studies performed at the Royal Institute of Technology (KTH) during the period. A study of the difference in oxidation exchange between one- and two-electron oxidants (such as hydrogen peroxide) showed a considerably lower oxidation exchange for one-electron oxidants (such as $IrCl_6^{2-}$), since they produce pentavalent uranium that does not go into solution /22-20/. The kinetics of the reaction between uranium dioxide and hydrogen peroxide (which, together with hydrogen, is the main product of alpha radiolysis) was studied as a function of the bicarbonate concentration, and rate constants and their dependence on ionic strength were determined /22-21/. Reduction of dissolved hexavalent uranium with hydrogen was studied as a function of temperature, and the reaction rate and the activation energy were determined. The addition of uranium dioxide could not catalyze the reaction /22-22/. The effect of irradiation on the reactivity of the uranium dioxide surface was studied, and a marginal increase in the reactivity of the surface with radiation dose was measured /22-23/. The effect of particle size on uranium dioxide oxidation and dissolution via reaction with permanganate ions was investigated by the use of aqueous powder suspensions with particles of different size. Rate constants and activation energies were determined for each size fraction, and the results showed that the rate constant only increased marginally with reduced particle size /22-24/. A study of the relative importance of different radiolysis products was carried out by comparing the uranium concentration in solution as a function of irradiation time (gamma radiation) by means of numerical simulation. The results show that molecular oxidants are of the greatest importance for oxidation of uranium dioxide at longer irradiation times, which greatly simplifies the simulation of fuel dissolution /22-25/. A model that describes the geometric alpha and beta dose distribution based on the radionuclide inventory in spent nuclear fuel has been developed at the Royal Institute of Technology (KTH) /22-26/. A model for radiation-induced dissolution of fuel when the surface concentration of hydrogen peroxide almost reaches a constant level due to equal rates of production and consumption has also been developed. The influence of other reactions in the solution is under study /22-27/.

Within the framework of the NF-PRO project, a study of the influence of dissolved hydrogen on the consumption of oxidants produced by alpha radiolysis in a homogeneous solution has been carried out at Chalmers University of Technology. Measurements of radiolytically produced oxygen in solutions of the plutonium isotope plutonium-238 under 10 bar of argon or hydrogen show that hydrogen does not affect the production of oxidants in a homogeneous solution, which in turn confirms literature data measured at lower hydrogen concentrations /22-28/.

Programme

In view of the predicted increase in average burnup in future fuel, new leaching tests are planned with fuels with burnups higher than 50 MWd/kgU under different conditions. The purpose is to improve SKB's statistical basis for calculating the dissolution of high-burnup fuel.

Experiments with alpha-doped material in the presence of reductants, which are expected to occur in deep groundwaters, will continue. Studies aimed at improving our understanding of the mechanisms for the processes that take place during fuel dissolution will continue during the period in cooperation with KTH, ITU and CTH. Actinide experiments in the Chemlab II probe at the Äspö HRL have been concluded and experiments with spent fuel or alpha-doped uranium dioxide are planned to start during the coming period in cooperation with KTH and CTH.

Research in the area of modelling of fuel dissolution and estimation of uncertainties in parameters and models is also being conducted within the framework of the recently started EU project Micado, in cooperation with KTH and Studsvik.

22.2.13 Dissolution of gap inventory

Conclusions in RD&D 2004 and its review

It is assumed in the safety assessment that the gap inventory dissolves immediately, since most of the segregated nuclides are highly soluble and mobile.

Newfound knowledge since RD&D 2004

No new knowledge has been forthcoming.

Programme

The field is judged today not to require any further research, development or demonstration.

22.2.14 Speciation of radionuclides, colloid formation

Conclusions in RD&D 2004 and its review

A new calculation of the solubility of radionuclides was performed in the SR-Can project in order to obtain a better estimate of uncertainties and sensitivities, particularly with respect to variations in the composition of the groundwater and the pore water in the bentonite /22-29/.

Newfound knowledge since RD&D 2004

Under the reducing conditions that are expected in a final repository, the uranium dioxide matrix is stable. Since there are relatively high concentrations of dissolved silicate, it has been suggested that the formation of a tetravalent uranium silicate phase (coffinite, $USiO_4 \cdot nH_2O$) is possible under reducing conditions. Coffinite has been observed in uranium deposits and existing thermodynamic data indicate that it may be more stable than uranium dioxide. Experimental studies were performed at Studsvik in cooperation with CEA in France to produce coffinite under conditions that would favour its formation. An investigation of natural coffinite materials showed that they contain relatively high concentrations of oxidized uranium. Analysis of all data shows that a transformation of the uranium dioxide matrix to coffinite under reducing conditions is unlikely even over long periods of time /22-30/.

In the scenario with a damaged canister, the redox conditions in the near-field are of very great importance. A research programme for studying the redox processes that are expected to occur in a damaged canister, especially their kinetics, has been under way for several years at SKB /22-31/.

Studies of the mechanism and the kinetics of the reduction of selenium, technetium and plutonium on iron corrosion products, including its characterization with XAS (X-Ray Absorption Spectroscopy) and RIXS (Resonant Inelastic X-ray Scattering), were conducted within the EU project NF-PRO.

At the end of the experiment, the surface of an iron pellet used during fuel leaching /22-32/ was examined by means of spectroscopic methods, and reduced fission products and actinides were characterized /22-33/.

A study with surface-sensitive spectroscopic methods (XPS) has shown that magnetite, which is the main corrosion product of iron under oxygen-free conditions, reduces hexavalent iron at the same time as divalent iron in the magnetite structure is oxidized to trivalent iron /22-34/.

SKB continues to participate actively in the OECD-NEA project TDB (Thermodynamic Data Bases) where quality issues related to the use of thermodynamic databases in safety assessments are discussed continuously.

Programme

A literature review of co-precipitation of radium with barium sulphate will be conducted in order to learn more about the process in preparation for SR-Site and possibly be complemented by experimental work.

Studies of redox kinetics for different oxidized forms of radionuclides (including Se(VI), Tc(VII) Np(V) and Pu(V), Pu(VI)) on fresh and corroded iron surfaces will continue in cooperation with Uppsala University, Studsvik, KTH, Nagra, ITU and the Paul Scherrer Institute.

22.2.15 Helium production

Alpha particles (helium nuclei) from alpha decay in the fuel form gaseous helium.

Conclusions in RD&D 2004 and its review

The field was judged not to require any further research, development or demonstration. New developments are being monitored and will be acted on when appropriate. No direct viewpoints on this were offered in the review.

Newfound knowledge since RD&D 2004

Several aspects of the evolution of the spent nuclear fuel over long periods of time, including the consequences of the helium build-up for the mechanical stability of the grain boundaries, have been studied within the framework of the French Precci project. It is thereby concluded that what happens with the helium that is produced by alpha decay is an open question /22-35/.

Programme

The issue is also relevant for the Swedish programme since the burnups of the future fuel will be higher than that those of the current inventory and since mox fuel will also be used in Swedish reactors. This will require research. Due to the long timespans for the helium build-up, experimental investigations are scarcely possible and SKB intends to investigate whether it is instead possible to use computer simulations.

23 The canister as a barrier

SKB's reference canister consists of an inner container of cast iron and an outer shell of copper. The insert provides mechanical stability while the copper shell protects against corrosion in the repository environment. Technical developments and equipment and methods for fabricating, sealing and testing the canister are described in Part III, Chapter 14.

The canister is an important barrier to the escape of radionuclides. This chapter describes the research being conducted by SKB to examine the long-term safety of the canister.

23.1 Initial state

By initial state of the copper canister and the nodular iron insert is meant the state of the canister at the time of deposition. This state is described in the safety assessment with the aid of a set of variables.

23.1.1 Variables

No changes have occurred with regard to the variables for the copper canister and the nodular iron insert. It is the same set of variables as that presented in RD&D-Programme 2004, see Table 23-1.

23.1.2 Geometry

Conclusions in RD&D 2004 and its review

SKI presented the viewpoint that the acceptance criteria must be based on what consequences a given defect can have for canister integrity.

Newfound knowledge since RD&D 2004

Various casting defects can occur in connection with the fabrication of the inserts. Possible defects that can occur are blisters (for example gas inclusions), shrinkage cavities (due to shrinkage of molten metal as it cools), defective graphite structure (for example "chunky graphite") and inclusions (such as slag and oxides).

Since RD&D-Programme 2004, a probabilistic analysis and a defect tolerance analysis have been carried out as a part of an effort to arrive at acceptance criteria for the nodular iron insert. Preliminary results from the defect tolerance analysis show that the insert is very defect-tolerant. The defect tolerance analysis will be reviewed and updated in certain respects.

Preliminary ultrasonic testing methods have been devised for the nodular iron insert and will be further developed.

Table 23-1. Variables for copper canister and nodular iron insert.

Variable	Definition
Geometry	Geometric dimensions of the canister components. This also includes a description of possible fabrication defects (e.g. in welding).
Radiation intensity	Intensity of alpha, beta, gamma and neutron radiation as a function of time and space in the canister components.
Temperature	Temperature as a function of time and space in the canister components.
Mechanical stresses	Mechanical stresses as a function of time and space in the canister components.
Material composition	Material composition of the canister components.

In the same way as in the casting of nodular iron, inclusions or cavities can also arise in the casting of copper. Casting defects have particularly been identified in large copper ingots, which are used as stock in the hot forming of copper tubes. They have been most pronounced in the ends of the ingot. These ends are cut off before further fabrication. Cavities in the inner parts of the ingot that are not oxidized may be squeezed together during the extrusion process so that they disappear, while cavities with oxidized surfaces end up as bands of oxide particles in the extruded tube.

Preliminary ultrasonic testing methods have been devised for copper components and will be further developed.

Both nondestructive and destructive testing have been carried out in order to fully evaluate the integrity of lid and bottom welds made by friction stir welding (FSW). Nondestructive testing (NDT) has been carried out using X-rays and ultrasound before and after fabrication. In addition, destructive testing has been carried out in the form of microscope studies and chemical analysis of the composition of the weld metal. As a whole the weld metal is very homogeneous. Only one type of recurrent discontinuity has been detected with nondestructive testing. Joint line hooking occurs when the tip of the probe penetrates too deeply and the material flow pulls the vertical joint line out towards the surface /23-1/. With the current welding procedure, joint line hooking can be minimized to less than two millimetres in the radial direction.

Programme

The defect tolerance analysis of the nodular iron insert will be updated. Ultrasonic testing of canister components is dealt with in Part III, sections 14.4.2 and 14.4.3. Further work will be done in the area of defects. Development of the probe design to minimize joint line hooking in friction stir welding is continuing.

23.1.3 Radiation intensity

SKB's criterion is that the surface dose rate on the canister may not exceed 1 Gy/h.

Conclusions in RD&D 2004 and its review

SSI finds that there is an uncertainty that entails a risk that the dose rate in water cavities near the surface will exceed 1 Gy/h in a small area closest to the canister.

Newfound knowledge since RD&D 2004

Alara Engineering /23-2/ has performed new calculations and used coupled photon and electron transport theory to determine the flow of electrons at the canister surface. The results showed that the importance of local conditions near the surface is rather small and that the dose rate to water at the outside of the copper surface is reasonably well determined by the gamma dose rate.

Programme

Further radiation shield calculations may be needed to cover higher burnups as well as future mox fuel.

23.1.4 Temperature

This refers to the initial temperature of the canister, i.e. the temperature immediately after deposition. This variable is formally included in the initial state, but occasions no research. The canister's temperature evolution is being estimated in an integrated temperature modelling of the repository's near-field.

23.1.5 Mechanical stresses

Conclusions in RD&D 2004 and its review

The field was judged not to require any further research, development or demonstration for canisters sealed by electron beam welding. The size and importance of any residual stresses in sealing welds made by friction stir welding should be investigated during the period.

SKI pointed out that the occurrence of any residual stresses in seal welds made by friction stir welding should be studied.

Newfound knowledge since RD&D 2004

Residual stress measurements have been performed on a lid weld made by friction stir welding /23-3 and 23-4/. The highest tensile residual stresses noted amount to 39 MPa, which is well below the yield strength of the weld metal.

Programme

Work to determine the residual stresses in seal welds made by friction stir welding will continue during the coming programme period.

23.1.6 Material composition

Conclusions in RD&D 2004 and its review

The field was judged not to require any further research, development or demonstration.

SKI pointed out that it remains to be shown whether, and if so how, the properties of the FSW welds differ from those of the parent metal, and what the effect is of any impurities in the weld.

Newfound knowledge since RD&D 2004

Chemical analyses of the weld metal have been performed on several lid welds /23-5/. Nickel particles from the tool probe and copper oxide particles were detected. The quantity of nickel in the weld was equivalent to up to 20 ppm and the oxide quantities were equivalent to 25 ppm. Ongoing activities show that the oxide quantities can be reduced by welding under shielding gas.

Programme

The consequences of foreign materials in the FSW weld will be further studied during the coming RD&D period. At the same time, development work will be pursued aimed at reducing the risks that foreign materials will get into the copper in the joint.

23.2 Canister processes

23.2.1 Overview of processes

Some of the radiation that penetrates out to the canister is converted to thermal energy by attenuation in the canister materials. Heat transport takes place by conduction within the insert and canister, and to a large extent by radiation between these two parts.

The insert and the canister can be deformed mechanically by external loads. Furthermore, thermal expansion occurs, causing changes in the cavity between insert and canister.

An important chemical process is external copper corrosion, but stress corrosion cracking (SCC) might also occur in both copper canister and nodular iron insert. The materials can be altered by radiation. If water enters, the cast iron insert will corrode, accompanied by the formation of hydrogen gas and galvanic corrosion.

Radionuclide transport in the canister cavity is dealt with in section 22.2.8. Radionuclide transport in the near-field is dealt with in section 25.3.

The research programme for the different processes in the canister is dealt with in the following sections.

23.2.2 Radiation attenuation/heat generation

The physical processes concerned here (radioactive decay and absorption of radiation) are well-known and sufficient data are available for the safety assessment.

Conclusions in RD&D 2004 and its review

No research programme was presented in RD&D 2004.

Newfound knowledge since RD&D 2004

No new knowledge has been forthcoming.

Programme

The field is judged not to require any further research, development or demonstration.

23.2.3 Heat transport

No new knowledge has been forthcoming. The process is deal with as in RD&D 2004, i.e. integrated with the temperature evolution of the fuel.

23.2.4 Deformation of cast iron insert

Conclusions in RD&D 2004 and its review

A large programme for probabilistic analysis of canister strength was started during 2003. In this programme we were supposed to gather material data from fabricated canisters. Compressive testing of canister sections was also supposed to be included.

SSI pointed out that it needs to be verified that the shortened canisters with screwed-on lids that have been pressure-tested do not have any advantages in strength compared with full-scale canisters with welded-on lids.

Newfound knowledge since RD&D 2004

Test bars for material characterization were taken out of three full-scale canister inserts according to a statistical test plan. Three different types of test bars were used to determine the statistical distribution of different material parameters and defects: bending test bars to determine fracture toughness, test bars for tensile testing and test bars for compression testing.

These data, together with results from finite element analysis of the stress-strain state in the canister insert, were then used in a probabilistic analysis to determine the probability of plastic collapse caused by high pressure or of fracture caused by crack growth in regions with tensile stresses /23-6/.

The most important conclusions from the probabilistic analysis were /23-7/:

- At an external pressure of 44 MPa, the probability of failure was insignificant (about $2 \cdot 10^{-9}$), even when several conservative assumptions were made.
- The stresses in the canister insert are mainly compressive under external pressure. The volume of the regions with tensile stresses is very small.
- The analysis for plastic collapse only considers the first local collapse event. Total collapse of the insert will occur at a much higher pressure.

Two large-scale pressure tests were carried out with short (1,050 millimetres) canister segments of full diameter /23-8/. In both cases the canister remained intact up to 130 MPa. The other canister was loaded to plastic collapse, which occurred at a load of 139 MPa. Calculations were performed in conjunction with the tests that showed that shortened canisters do not offer any advantages from a strength viewpoint.

The effect of earthquake-induced 10 and 20 centimetre long rock shears, with a shear rate of 1 metre per second, along a fracture through a deposition hole in a KBS-3V repository, was investigated for a number of different shear cases and for different properties of the buffer material /23-9/. The scenarios were modelled using the finite element method and calculations were done using the Abaqus code. A 3D element model was used to model the rock, the buffer and the canister. Contact elements that can simulate separation were used for the buffer-rock and buffer-canister interfaces.

The influence of mainly the following factors was investigated:

- The inclination of the intersecting fracture.
- The shear direction when the fracture is not horizontal (the inclination deviates from 90°).
- The location of the shear plane when the inclination is 90°.
- The magnitude of the shear displacement.
- Bentonite type.
- Bentonite density.
- The transformation of the buffer to illite or cemented bentonite.

Plastic strains larger than 1 percent occurred in the copper after only 10 centimetre shear in all cases with sodium and calcium bentonite. But for several shears in sodium bentonite and one shear in calcium bentonite, such plastic strains only occurred in the lid.

The plastic strain in the nodular iron was generally smaller than in the copper, mainly due to the higher yield stress of nodular iron. For all the cases with sodium bentonite except one and for about half of the cases with calcium bentonite, the plastic strain in the nodular iron was smaller than 1 percent after 10 centimetre shear. The plastic strain appears to increase with increasing shear displacement, although the influence of the shear displacement declines the softer the buffer material is. The maximum plastic strain in the copper tube and in the nodular iron insert was in all cases greater with calcium bentonite than with sodium bentonite.

When transformation to illite occurs, the effect of a rock shear on the canister is insignificant compared to when no transformation has taken place, since the stiffness and strength of illitic clay are only a tenth of the corresponding properties of MX-80. This is because almost the entire swelling pressure is lost in the illite.

As a result of cementation of bentonite with a thickness of 8.75 centimetres around the canister, the effect of a rock shear is more serious than for the original bentonite, since cementation increases the stiffness of the buffer. However, the properties of cemented bentonite are not known, so the calculation must be regarded as an example rather than as a prediction.

The calculations are associated with several uncertainties that should be considered when the consequences of a rock shear are analyzed.

Creep models were implemented in Abaqus to be used in the simulation of rock shear through a deposition hole /23-10/.

Programme

Work is under way on deterministic analyses of total collapse in intact canister inserts and inserts with casting defects and other defects that can reduce the strength of the insert. The results will also serve as a basis for acceptance criteria for nondestructive testing of canister inserts.

We also intend to augment the work with analyses of canister strength for shear displacement with probabilistic analyses. Work on the introduction of creep models will also continue. We will conduct whatever experiments are needed to verify the models.

23.2.5 Deformation of copper canister under external pressure

Deformation of copper canister under external pressure has been dealt with integrated with the cast iron insert in 23.2.4. We therefore mainly confine this discussion to research on the creep properties of copper.

Conclusions in RD&D 2004 and its review

The programme for creep testing was supposed to continue during the three-year period.

Kasam pointed out that further studies of creep of the copper material, and in particular the copper joints, were urgent.

SKI's viewpoint was that an integrated account was needed of experiments and modelling of creep in copper and how these results are to be used in the safety assessment.

Newfound knowledge since RD&D 2004

Specimens from lid welds made by FSW and EBW have been creep-tested at temperatures ranging from 75 to 175°C /23-11/. The results of the investigations of the FSW welds show that the material in the joint has similar creep ductility and creep life to that of the parent metal. Ductility at rupture was more than 40 percent.

Great attention has been given during the period to the mechanisms behind the effect of phosphorus on the creep ductility of oxygen-free copper /23-12 and 23-13/. It was discovered in around 1990 that pure copper (Cu-OF) has extra low creep ductility in the temperature interval 180 to 240°C. If 50 ppm phosphorus (Cu-OFP) is added to the material, the low creep ductility disappears. This has previously been explained by reference to the possibility that sulphur may have led to embrittlement of the material by formation of cavities around sulphide inclusions /23-14/. The metallography of the cavities in Cu-OF, and to some extent also in Cu-OFP, has now been re-evaluated. Based on this, nucleation and the growth of creep cavities has been modelled. In the model it is assumed that the cavities are formed when irregularities on opposite sides of a grain boundary meet during grain boundary sliding. The cavity growth can be diffusion-controlled or strain-controlled. Both processes are included in the modelling, and in the temperature range studied diffusion control has been found to be dominant. Phosphorus agglomerates at the grain boundaries in Cu-OFP block their sliding /23-12/.

In Cu-OFP the phosphorus is added to increase creep ductility, but it also greatly increases creep strength. The reason for this is that in the case of slow-moving dislocations, the interaction energy between the phosphorus atoms and the dislocations gives rise to an agglomeration and a blocking of the dislocations /23-13/.

A creep model has been developed for temperatures below 100°C and the loads to which the copper will be subjected in the final repository.

Programme

The investigations of the creep properties of copper will continue during the coming period as well. SKB will continue to analyze canister strength in connection with shear movements and perform the experiments needed to verify our models.

Calculations have shown that uneven swelling of the bentonite can lead to local tensile stresses of up to 59 MPa in the copper shell, see section A1.4.2 in Appendix A, i.e. a local plasticizing of the copper shell. A study of the effects of cold working on the creep properties of copper has therefore been initiated. The study will continue during 2008.

23.2.6 Thermal expansion

The difference in coefficient of thermal expansion between cast iron and copper can lead to strains in the copper canister. However, these are negligible from the strength viewpoint.

Conclusions in RD&D 2004 and its review

The field was judged not to require any further research, development or demonstration and no direct viewpoints offered in the review.

Newfound knowledge since RD&D 2004

No new knowledge has been forthcoming since RD&D-Programme 2004.

Programme

The field is judged today not to require any further research, development or demonstration. New developments are being monitored and will be acted on when appropriate.

23.2.7 Deformation from internal corrosion products

The build-up of corrosion products between the cast iron insert and the copper shell can lead to an internal pressure on the copper shell.

Conclusions in RD&D 2004 and its review

The ongoing experiments will be concluded during the period. Studies of analogues were to continue during the period, provided that good study objects could be found.

SKI pointed out that RD&D Programme 2004 does not state how SKB intends to handle the experimental results that show that pressure build-up from corrosion products does not occur to the extent previously assumed.

Newfound knowledge since RD&D 2004

The experimental studies on the consequences of the build-up of corrosion products in the gap between the copper shell and the cast iron insert were concluded during the period after having been conducted since SR 97 /23-16/. None of the experiments succeeded in showing any pressure build-up as a consequence of the build-up of corrosion products. The conclusion of the investigation was that if water enters the gap between the cast iron insert and the copper shell, corrosion products will be deformed and spread over the cast iron surface, rather than expanding and pressing out the copper shell from the insert. Eventually the gap will be filled with corrosion products that are gradually compacted. How corrosion then proceeds depends on whether water can penetrate into the corrosion products and reach the iron surface. The spread of the corrosion products was not restricted in an effective manner in the experiments. In further studies, SKB will therefore use miniature canisters with defective copper shells.

The absence of expansion caused by anaerobic corrosion in gaps is also supported by archaeological analogues. Archaeological copper-iron artefacts that have corroded for hundreds of years did not show any evidence of expanding corrosion products /23-17/.

Programme

The installation of miniature canisters (Minican project) in the Äspö HRL is finished and the canisters are being constantly monitored. It has not been decided how long the experiments will last, but some of the canisters will probably be examined towards the end of the period.

23.2.8 Corrosion of cast iron insert

If there is a penetrating breach in the copper shell, water can run into the gap between the canister insert and the copper shell and further into the insert, where it can cause anaerobic corrosion.

Conclusions in RD&D 2004 and its review

A study of corrosion of iron in contact with bentonite was conducted. The initial results showed a slightly higher corrosion rate than had been measured in the absence of bentonite. It was not clear what the cause of this was, and the investigation of corrosion of iron in contact with bentonite was to continue during the period.

The ongoing investigations of anaerobic corrosion of iron in a gamma radiation field were to be concluded during the period.

SKI pointed out that it had not been clarified what role a canister with a penetrating hole is given in the safety assessment and that it was therefore difficult to judge whether SKB is doing enough in the area of iron corrosion.

Newfound knowledge since RD&D 2004

SKB has studied the effect of bentonite on iron corrosion in an EU project (NF-PRO) as well as in cooperation with Posiva. The work is of relevance for both vertical (KBS-3V) and horizontal (KBS-3H) deposition according to the KBS-3 method. In the KBS-3V case, the cast iron can come into contact with bentonite in the buffer if the copper shell has been breached. In the KBS-3H case, the parcel with canister and bentonite is encased in a perforated steel cylinder, which will corrode away. The effect of the corrosion products on the bentonite is therefore of interest to study. The situation in the projects is reported in /23-18 and 23-19/.

The corrosion products formed in bentonite do not have as great a volume as those formed in the absence of bentonite, even though the corrosion rate was slightly higher in the presence of bentonite. Raman spectroscopy showed that the corrosion products consisted of an inhomogeneous mixture of magnetite, hematite and goethite, where magnetite was the dominant species. In the bentonite, the iron concentration declined with increasing distance from the interface between bentonite and iron, with local concentrations of up to 20 percent. The total iron content of the bentonite increased by several percentage points during the experiment, and its cation exchange capacity was reduced while its hydraulic conductivity increased considerably.

The effect of gamma radiation on iron corrosion is dealt with in section 22.2.10.

Programme

The experimental studies of iron corrosion in bentonite and the interaction between bentonite and iron will continue during the period. They will also be supplemented by geochemical modelling. It has not yet been fully clarified in what form the iron is present in the bentonite.

23.2.9 Galvanic corrosion

Metallic contact between cast iron and copper is a precondition for galvanic corrosion.

Conclusions in RD&D 2004 and its review

The field was judged not to require any further research, development or demonstration. New developments were to be monitored and would be acted on when appropriate.

No direct viewpoints were offered in the review.

Newfound knowledge since RD&D 2004

The results of an experimental investigation of the possible effects on the corrosion rate due to metallic coupling between copper and cast iron were reported in RD&D-Programme 2004. A final report was published on the project in 2005 /23-20/. The results showed that even though corrosion rates of up to 100 microns per year could be measured under oxygenated conditions, the rate was at least a factor of 100 lower under oxygen-poor conditions. The experiments were conducted in a glovebox in an atmosphere with 1–2 ppm oxygen. Typical corrosion rates were less than 0.1 micron per year at 30°C and less than 1 micron per year at 50°C. These rates are comparable to those measured without galvanic coupling between iron copper.

Programme

The field is judged today not to require any further research, development or demonstration. New developments are being monitored and will be acted on when appropriate.

23.2.10 Stress corrosion cracking of cast iron insert

Conclusions in RD&D 2004 and its review

The field was judged not to require any further research, development or demonstration.

Newfound knowledge since RD&D 2004

Calculations have shown that the canister insert has only very small regions with tensile stresses /23-7/. The risk that stress corrosion cracking could lead to canister failure can therefore be ruled out.

Programme

The field is judged today not to require any further research, development or demonstration.

23.2.11 Radiation effects

Conclusions in RD&D 2004 and its review

The field was judged not to require any further research, development or demonstration.

No direct viewpoints were offered in the review.

Newfound knowledge since RD&D 2004

Prior to RD&D-Programme 2001, SKB had calculations performed /23-21/ of the radiation dose to cast iron insert and copper shell and what consequences this could have for the mechanical properties of the canister. SKB concluded that the risks are negligible and that the damage in 100,000 years would not even be measurable.

New calculations carried out by CEA /23-22 and 23-23/ show that radiation-induced segregations of copper present as an impurity in steel give rise to significant embrittlement of low-alloyed steel used in disposal canisters for spent PWR fuel.

Programme

The effects of radiation on the canister insert must be further studied during the next few years.

23.2.12 Corrosion of copper canister

Under currently known conditions at the deep repository level, the canister is expected to remain intact for a very long time.

Conclusions in RD&D 2004 and its review

SKB's programme included investigations of the conditions for microbial corrosion, intergranular corrosion in welds, the effects of surface films on corrosion, and the mechanisms and kinetics of corrosion in oxygen-free sulphide environments.

SKI was pleased at SKB's further studies of copper corrosion and pointed out that an account was lacking of the importance of the oxide layer for corrosion of copper, particularly in chloride- and sulphide-containing waters, as well as of the ability of microbes to survive in the buffer and the possible occurrence and importance of a biofilm on the canister surface. SKI also thought it would be desirable for SKB to update its compilation on copper corrosion.

SSI pointed out that it needed to be verified that a weld made by friction stir welding has the same corrosion properties as the rest of the material. Kasam stated the same viewpoint and was also of the opinion that further studies were needed of corrosion induced by interaction with bentonite.

Newfound knowledge since RD&D 2004

Intergranular corrosion (grain boundary corrosion) of the welded joints was studied experimentally in an environment where it could occur. Copper samples were taken from welds on real canisters and exposed to ammonium hydroxide for 14 days at a pressure of 10 bar and a temperature of 80°C /23-24/. It was concluded that it was very unlikely that intergranular corrosion in the copper welds could have any harmful effect on the canisters under repository conditions.

The mechanisms and kinetics of copper corrosion in anaerobic chloride solutions containing sulphide (10^{-3} mol/l) were studied electrochemically under natural corrosion conditions /23-25/. Copper is not thermodynamically stable under these conditions, and anodic growth of a chalcocite-digenite film takes place by cathodic reduction of water. The film initially grows rapidly due to ion transport (or equivalent defect transport). If the film remains coherent, film growth ceases and corrosion proceeds very slowly. If tensions in the interface and the film are broken, film growth continues and a much thicker nodular corrosion product is formed. The goal of the study is to develop a corrosion model that could be used in the safety assessment.

Smith et al. /23-26/ studied the transformation of a Cu_2O film on copper to Cu_2S in a sulphide-containing aqueous solution with a combination of electrochemical methods and in situ Raman spectroscopy. The transformation to sulphide appears to take place at the oxide-liquid interface rather than by galvanic coupling of copper oxidation to Cu_2S and Cu_2O reduction to Cu.

Formation of copper sulphide on copper surfaces in bentonite with different swelling pressures has been studied under natural conditions and pressures at repository depth in model systems /23-27/. The quantity of copper sulphide formed decreased linearly with increasing density. The results of these experiments thus support the current model where microbial activity is not possible at full density. New follow-up experiments are being conducted where limit values of density for microbial activity in bentonite will be established to be used in the safety assessment. Quantitative data on sulphide formation and diffusion will also be obtained so that the safety assessments can include microbial activity instead of, as before, excluding microbial sulphide formation based on environmental factors.

Investigations of microbe occurrence will continue after experiments in the Lot series in the Äspö HRL are discontinued.

In addition to these investigations, a project is under way aimed at shedding light on the properties of copper oxide films. The project is employing surface-sensitive spectrometric methods to characterize sorbing and chemically bound sulphide and chloride species on clean copper surfaces and copper surfaces with different surface films.

Posiva is in the process of updating SKB's and Posiva's joint compilation about copper corrosion.

Programme

Further investigations of intergranular corrosion on copper are not deemed necessary. Work will continue during the period within the other projects described above.

23.2.13 Stress corrosion cracking of copper canister

Conclusions in RD&D 2004 and its review

A study of stress corrosion cracking (SCC) in acetate-containing water was to be conducted in cooperation with Posiva. Furthermore, the possibility of studying SCC by measurements of acoustic emission from crack growth was to be explored.

SKI said that the body of material for judging SCC is not complete. They also pointed out that SCC cannot immediately be excluded by reference to the fact that the canister is subjected to external pressure. Tensile stresses, potential and water environment must be judged in time and space if SCC is to be excluded.

Kasam was of the opinion that SKB should carry out accelerated long-term experiments to investigate the risks of SCC.

Newfound knowledge since RD&D 2004

The investigation of stress corrosion cracking in acetate-containing water has been concluded /23-28/. Copper and welds in copper were investigated at acetate concentrations from 1 to 100 milligrams per litre at a temperature of 100°C and a pressure of 14 MPa by slow strain rate testing. The elongation to fracture values in the tests were comparable to those in air. Fractography showed ductile fracture in both the parent metal and the weld metal. Thus, no susceptibility to SCC could be demonstrated in the environment in question.

The study of crack growth by means of acoustic emission measurements has also been concluded /23-29/. The tests, which were performed in 0.1 M $NaNO_2$, showed that the cracking had two kinetic stages: initiation and growth of microfractures at a lower stress intensity ($K_I = 10.5 \pm 0.6$ MPa·√m, $J_I = 114.6 \pm 11.7$ kJ/m²), and then a macrofracture stage at a higher stress intensity ($K_I = 29.3 \pm 1.2$ MPa·√m, $J_I = 578 \pm 8.1$ kJ/m²).

Programme

The likelihood of cracking due to stress corrosion will be further studied during the period.

23.2.14 Grain growth in copper

Conclusions in RD&D 2004 and its review

The field was judged not to require any further research, development or demonstration.

No direct viewpoints were offered in the review.

Newfound knowledge since RD&D 2004

No new knowledge has been forthcoming since RD&D-Programme 2004.

Programme

The field is judged today not to require any further research, development or demonstration. New developments are being monitored and will be acted on when appropriate.

23.2.15 Radionuclide transport

See further section 25.3, which deals with radionuclide transport in the near-field.

23.2.16 Integrated studies – evolution of damaged canister

This is dealt with in section 23.2.7.

24 Buffer

The main purpose of the buffer is to prevent flowing water from the rock from coming into contact with the canister and the spent fuel. To do this, the buffer must meet the following requirements:

- The buffer's hydraulic conductivity must be so low that any transport of corrodants and radionuclides takes place solely by diffusion.
- The buffer must retain its dimensions.
- The buffer must have a self-healing capacity, so that no permanent cracks form.
- The properties of the buffer must be physically and chemically stable on a long time scale.

To contribute to a favourable environment for the canister, the buffer must also prevent microbial activity on or near the surface of the canister.

Nor may the buffer have any properties that might have an adverse effect on the other barriers. To meet these requirements:

- The buffer's gas permeability must be sufficient to allow the large quantities of gas that may be formed in a damaged canister to pass through. This gas passage must not lead to the formation of permanent gas-permeable channels or cavities in the buffer.
- The buffer's swelling pressure must be high enough to provide good contact with the host rock and the canister, but not higher than what the canister and the host rock can withstand.
- The buffer's deformability must be great enough to absorb rock movements without the canisters being damaged, but small enough to hold the canisters in position.
- The buffer's heat conduction properties must be such that the heat from the canisters does not lead to unacceptable physical and chemical changes in the buffer.
- The buffer must not contain anything that has an adverse effect on the performance of the other barriers.

The buffer should also be able to filter out colloidal particles.

SKB has previously chosen a natural sodium bentonite of the Wyoming type as a reference material for the buffer. MX-80 is a trade name for a blend of different layers of natural clay from Wyoming or South Dakota in the USA. MX-80 specifies a given grade and grain size of the dried and ground bentonite. Starting with RD&D-Programme 2004, SKB abandoned MX-80 as a reference material, since studies in recent years of alternative buffer materials have shown that there are a number of sodium and calcium bentonites on the market that are very capable of meeting SKB's requirements, see further section 24.1.2.

Based on completed investigations, SKB has concluded that a bentonite buffer should have a density of 1,950–2,050 kg/m ^{3} after water saturation.

The chosen material has the following properties that relate to the above requirements:

Hydraulic conductivity and ion diffusion

The main function of the buffer is to guarantee that diffusion is the dominant transport mechanism around the canisters. With a bentonite buffer with a density of 2,000 kg/m^3 in the water-saturated state, the transport capacity for diffusion is at least 10,000 times higher than that for advection.

Bentonite limits the release of radionuclides from a defective canister. However, the effect is dependent on the properties of the individual nuclide (diffusivity, sorption coefficient and half-life) as well as the geometry of the near-field (the defect in the canister, transport pathways in the rock).

Swelling properties

The buffer must be able to swell to fill the space between canister and rock and to seal openings that may be caused by thermal and tectonic effects. The requisite expansion capacity of the buffer is estimated to correspond to a swelling pressure of at least approximately 1 MPa, which presumes a density of at least 1,900 kg/m^3 for MX-80 in the water-saturated state at a salinity of up to 10 percent.

Long-term stability

Commercial bentonites are natural materials that were often formed tens of millions of years ago. This does not automatically mean that bentonite is stable in the repository environment. However, the investigations of the long-term properties of bentonite that have been done within and outside of SKB's programme show that compacted bentonite can retain its favourable properties for long periods of time and under a variety of chemical and thermal conditions.

Microbial properties

It has been found that bacterial growth can occur in MX-80 buffer with a density of up to 1,700 kg/m^3 at water saturation, while 1,900 kg/m^3 does not allow any possibility of survival or reproduction of bacteria of the kinds investigated in SKB's research. This means that the latter density can be regarded as the minimum suitable.

Gas conductivity

The experiments that have been conducted under SKB's auspices indicate that MX-80 bentonite can open up and release large quantities of hydrogen gas, which may be formed by corrosion of the iron insert in a defective canister. Unacceptable pressures in the canister and against the buffer can thereby be avoided.

Deformation properties

The most important deformations in the buffer are upward expansion by displacement of the tunnel backfill and shear as a result of displacements in the rock. The upward-directed expansion can lift the tunnel floor, with fracture widening and greatly increased hydraulic conductivity as a consequence.

Displacements in the rock can take place in the form of tectonic or thermally induced shear of fractures that intersect the deposition holes. Practical tests with MX-80 with a density of up to approximately 2,050 kg/m^3 and application of a semi-empirical rheological model have shown that anticipated rock movements do not cause buffer deformations that give rise to canister damage.

Thermal properties

The buffer's capacity to transfer heat from canisters to rock is mainly important in that too low a thermal conductivity gives rise to high buffer temperature. This leads to altered solubilities of the buffer minerals and a vapour pressure that can cause expulsion of water vapour from the buffer through the overlying tunnel backfill.

Performance indicators

In order to evaluate the function of the buffer in the safety assessment, a number of so-called performance indicators (called "function indicators" in SR-Can) have been defined, along with criteria for them that the buffer must meet. These criteria are summarized in Table 24-1.

Fabrication of buffer blocks is described in Part III, section 13.3.1. Fabrication aspects are discussed in the following only insofar as they have a bearing on the presentation of the research programme for long-term function.

Table 24-1. Performance indicators for the buffer.

Performance indicator	Criterion	Background
Hydraulic conductivity	$k^{Buffer} > 10^{-12}$ m/s	Limit mass transport to a diffusion-dominated process.
Swelling pressure	$P_{swell} > 1$ MPa	Ensure sealing, self-healing capacity.
Maximum temperature	$T^{Buffer} < 100°C$	Ensure that the buffer retains its properties for long periods of time.
Minimum temperature	$T^{Buffer} > -5°C$	Prevent freezing.
Swelling pressure against the canister	*P swell > 0.2 MPa*	Prevent the canister from sinking.
Swelling pressure around the canister	*P swell > 2 MPa*	Prevent microbial activity.
Density around the canister	$\rho_{Bulk} > 1,650$ kg/m^3	Prevent transport of particles through the buffer.
Density around the canister	$\rho_{Bulk} < 2,100$ kg/m^3	Limit shear stresses on the canister due to rock movements.

Conclusions in RD&D 2004 and its review

SKI was of the opinion that SKB has a good programme for buffer issues, that a commendably clear account of these issues is given, and that significant progress has been achieved in recent years in terms of model studies, code development and experiments.

SKI pointed out that SKB needs to clarify and concretize the requirements specification for the buffer for future applications. SKB will make sure that material is available to justify requirements and associated criteria for buffer function. It should be possible to distinguish between requirements that must be shown to be satisfied during the disposal period and requirements that are more to be regarded as ideal conditions for the buffer.

24.1 Initial state of the buffer

24.1.1 Variables

The initial state of the buffer, i.e. the value these variables were assumed to have at the time of deposition, is described in the report on initial state that belongs to SR-Can /24-1/. The research programme for the initial state is described in the following section for the different variables in the buffer (the same variables are also used for the backfill).

The buffer is described in SR-Can and the associated buffer and backfill process report /24-2/ with the aid of a set of variables, see Table 24-2.

24.1.2 Geometry

The geometry of the buffer is determined by the dimensions of the canister and the thickness of the buffer material required to obtain the desired function. The previously specified dimensions of 35 centimetres on the sides of the canister, 50 centimetres underneath the canister and 150 centimetres above the canister still apply to KBS-3V. The dimensions are planned to be somewhat different for KBS-3H.

Conclusions in RD&D 2004 and its review

SKB intended to continue to consider other possible buffer materials among the bentonite clays in order to make it possible to optimize the procurement with respect to safety, availability and cost.

Table 24-2. Variables for buffer and backfill.

Variable	Definition
Geometry	Geometric dimensions of buffer and backfill. A description of e.g. interfaces on the inside towards the canister and on the outside towards the geosphere.
Pore geometry	Pore geometry as a function of time and space in buffer and backfill. The porosity, i.e. the fraction of the volume that is not occupied by solid material, is often given.
Radiation intensity	Intensity of alpha, beta, gamma and neutron radiation as a function of time and space in buffer and backfill.
Temperature	Temperature as a function of time and space in buffer and backfill.
Water content	Water content as a function of time and space in buffer and backfill.
Gas contents	Gas contents (including any radionuclides) as a function of time and space in buffer and backfill.
Hydrovariables	Flows and pressures for water and gas as a function of time and space in buffer and backfill.
Load situation	Pressure as a function of time and space in buffer and backfill.
Bentonite composition	Chemical composition of the bentonite (including any radionuclides) in time and space in the buffer. This also includes impurities and minerals other than montmorillonite.
Montmorillonite composition	Chemical composition of the montmorillonite (including any radionuclides) in time and space in buffer and backfill. This variable also includes material sorbed to the montmorillonite surface.
Pore water composition	Composition of the pore water (including any radionuclides and dissolved gases) in time and space in buffer and backfill.
Engineering materials	Composition of engineering materials in the deposition holes. This includes the bottom pad of cement.

Newfound knowledge since RD&D 2004

An extensive programme has been carried out to study alternative buffer materials /24-3/. The main purpose has been to correlate physical and chemical properties to fundamental mineralogical properties. The project includes the following material types:

- Products with a similar content of montmorillonite and a similar counterion distribution as in MX-80, since these materials can be assumed to have equivalent sealing properties.
- Materials that have a high content of montmorillonite and are dominated by divalent ions. The high densities of the buffer theoretically entail that such materials have sufficient swellability. Divalent counterions (such as calcium) are furthermore expected to provide advantages at low ionic strength in the groundwater.
- Materials that contain other swelling minerals.
- Materials that have a lower content of swelling minerals, principally for possible use as tunnel backfill.

A number of commercial bentonites from major producers have been investigated: MX-80 from Wyoming (American Colloid), four samples from India (Ashapura), and one sample from Greece (Silver & Baryte). Furthermore, six samples of lower quality from Denmark (NCC) and the Czech Republic (University of Prague) have been investigated. All samples have been analyzed with respect to swelling and mineralogical properties.

It can be concluded from these investigations that materials with a high montmorillonite content, similar charge distribution and sodium as a counterion exhibit negligible differences in physical properties, regardless of where they come from. Calcium as a counterion entails a lower swelling potential, but equivalent properties at the same buffer density. In terms of swelling properties, several of the investigated bentonites are suitable as buffer materials without necessitating any changes in the dimensions of the buffer. Other aspects, such as long-term stability and influence of accessory minerals, need to be further investigated, however.

Field tests of alternative buffer materials on the Lot scale have been installed in the Äspö HRL.

Programme

Greater knowledge of alternative buffer materials enables the procurement to be optimized with respect to safety, availability and cost. For this reason the field test "Alternative buffer materials" was started in 2006 in order to obtain a better understanding of the advantages and disadvantages that may be associated with different possible buffer materials. The test is being conducted on the same scale as the Lot test and consists of three parcels, each consisting of 13 different materials, see Figure 24-1. Each parcel has a heater with a target temperature of around 130°C. The shortest test will last for at least one year and the longest for at least five years. The parcels have been installed and the heaters activated. The test plan for analysis of the parcels is being determined. The majority of international partners are participating in and following the experiment.

24.1.3 Pore geometry

An initial condition given in SR-Can is that the buffer has a dry density of 2,000 ± 50 kg/m^3 in the saturated state. Providing that the mineral density is 2,750 kg/m^3 and the water density is 1,000 kg/m^3, we get a porosity of 43 percent and a dry density of 1,570 kg/m^3.

Conclusions in RD&D 2004 and its review

In RD&D-Programme 2004, it is pointed out that other clays than MX-80 could also satisfy the conductivity requirements that are made on the buffer. A choice of another clay might lead to the choice of another density and porosity. Because there is some uncertainty in the determination of mineral density, other combinations of saturation and dry density have been reported. This is of no practical importance, however.

Figure 24-1. *Installation of one of the parcels with 13 different materials in the "Alternative buffer materials" test in the Äspö HRL.*

Newfound knowledge since RD&D 2004

Calculations with the aid of theoretical swelling pressure models and laboratory experiments clearly show that the water in sodium-based bentonites is very well distributed between the mineral layers. The picture is not as clear for calcium-dominated systems.

Programme

The very low hydraulic conductivity of the buffer (despite the fact that its porosity is about 40 percent) suggests that the distribution of the pore volume is of crucial importance for the properties of the bentonite. Different qualitative and quantitative descriptions of pore structure – and how it affects properties such as diffusion, conductivity and swelling pressure – are found in the literature. SKB therefore intends to continue various investigations aimed at quantifying pore structures in potential bentonite materials under different physical and chemical conditions.

24.1.4 Radiation intensity

The initial dose rate on the canister surface was calculated in SR-Can to be a maximum of 500 mGy/h. The radiation is dominated by the nuclide caesium-137. The dose rate is used to assess radiolysis of pore water and radiation-induced changes of the montmorillonite. However, the analyses in SR-Can show that the importance of these two processes is negligible.

24.1.5 Temperature

The buffer and backfill are at ambient temperature at deposition. This varies with repository site and disposal depth and is approximately 10–15ºC. The temperature is dependent to some extent on the handling sequence, where the buffer blocks have been stored, heat from the deposition machine, etc. An uncertainty of around 5°C is reasonable.

Determination of the initial buffer temperature is of trivial importance, in contrast to the heat transport in the buffer after deposition, see section 24.2.11.

24.1.6 Water content

In SR-Can it is assumed that the compacted bentonite blocks have an initial water ratio of 17 percent, which gives a degree of saturation of between 65 and 70 percent. The pellets in the gaps between the buffer and the rock are assumed to have an initial water ratio of 10 percent, which gives a degree of saturation of 15 to 20 percent if the gap is not filled with water. The gaps between the blocks and the rock may be reduced to 2–3 centimetres, which means that pellets are not needed. The buffer-canister and buffer-rock gaps may be filled with water, but in SR-Can it is assumed that they are dry. In horizontal deposition according to the KBS-3H method, the initial water ratio is assumed to be 10 percent around the canister.

Conclusions in RD&D 2004 and its review

It was stated that the block compaction technology will be optimized.

Newfound knowledge since RD&D 2004

The effect of the water ratio on the durability of the bentonite blocks has been studied in KBS-3H. The investigations show that the blocks remain intact for different lengths of time if they are exposed to a rock surface with free water running down the rock surface 1–5 centimetres from the blocks. The blocks that had a low water ratio (10 percent) started to crack apart immediately, while the blocks with a high water ratio (24 percent) did not show any sign of cracking during a period of three months.

In horizontal deposition according to the KBS-3H method, the bentonite blocks that are placed between the perforated supercontainers may be manufactured with a gap to the rock surface of a centimetre or less, which means that the initial density must be lower. A higher water ratio is advantageous from a strength viewpoint for such blocks.

Programme

The tests of the water content of the blocks will continue.

Development of technology for the manufacture of blocks with a greater height is under way and will continue, see Part III, section 13.3.1.

24.1.7 Gas contents

The bentonite blocks have a degree of saturation that can vary between 65 and 70 percent. This means that 70 to 85 percent of the pore volume is filled with water and the remainder with air. The outer gap is left unfilled. The air in a deposition hole occupies approximately six percent of the volume. The uncertainties in gas contents are not important for long-term safety. The initial gas content follows from the water content and the porosity, see above.

24.1.8 Hydrovariables

The hydrovariables are water flow, water pressure, gas flow and gas pressure. Initially it is relevant to describe gas and water pressure. Flows do not occur initially in the buffer. At emplacement of canister and buffer, the deposition holes will be kept drained and the repository will be open to atmospheric pressure. This gives a gas pressure (air) of 1 atm (approx. 1 MPa) and a water pressure of 0.1–0 MPa in the surrounding host rock. There will, however, be an initial negative pore water pressure in the unsaturated bentonite blocks that drives the inward transport of water. This pressure is on the order of 40 MPa.

24.1.9 Load situation

The swelling pressure begins to build up when buffer and backfill come into contact with external water, see sections 25.2.5 and 25.2.6. Initially there is no swelling pressure.

24.1.10 Bentonite composition

Bentonite is the name of a naturally occurring clay that is rich in montmorillonite and varies in composition depending on how it is formed. Bentonite often occurs in several specific strata, which may vary in composition. In commercial products, such as MX-80, materials from different strata are often blended to meet specified quality requirements.

The commercial bentonites that are of interest as buffer materials have a relatively constant composition. The smectite content is normally about 80 percent. Bentonite materials for block manufacture will undergo extensive quality checks prior to compaction, including determination of the montmorillonite content.

All minerals beside montmorillonite are considered impurities in bentonite. Usually, the impurities consist of minerals that are of little importance for the performance of the repository (quartz and feldspar). Small amounts of e.g. amorphous silicon, calcite, pyrite, siderite and gypsum may, however, be of some importance for the chemical evolution in the repository's near-field, see section 24.2.17. This may be either an advantage or a disadvantage for the buffer properties. An example is calcite, which has a favourable pH-buffering effect, but which may also be enriched at the canister under the influence of a sharp temperature gradient. At present, however, there is no mineral that is considered to have a decisive adverse impact on repository performance at normally occurring concentrations. The composition of the impurities in a buffer material will therefore probably be allowed to vary within certain limits between different consignments of the material.

Conclusions in RD&D 2004 and its review

SKB planned to continue to develop methods for testing and analyzing swellable minerals in potential buffer materials.

Newfound knowledge since RD&D 2004

New methods for determining the mineral distribution in buffer materials have been used and developed. The important material parameter cation exchange capacity (CEC) has been determined by means of a relatively simple method /24-4/. The method has been compared with others to ensure it is reliable. Furthermore, a new analysis method (Rietveld technique) for quantification of minerals from X-ray diffractograms has been further developed by implementation of the software Siroquant 3.0. Detailed determinations of mineralogy have been performed for a large number of swelling clays /24-3/.

Programme

SKB intends to continue to develop testing and analysis methods, and to conduct investigations of swellable minerals in potential buffer materials, as described in section 24.1.2.

24.1.11 Montmorillonite composition

The ideal structural formula of montmorillonite can be written:

$(Al_{(4-x)}\ Mg_{x})\ (Si_{(8-y)}\ Al_{y})\ O_{20}(OH)_4\ k^{z}_{(x+y)/z}\ n(H_2O)$

where the sum of x and y can vary by definition between 0.4 and 1.2 units (charge per $O_{20}(OH)_4$), and $x > y$. A certain fraction of the aluminium (Al) can be regarded as exchanged for (Mg), and a smaller fraction of silicon (Si) is exchanged for aluminium (Al). The exchange of trivalent aluminium for divalent magnesium leads to a negative net charge in the mineral layers, which is balanced by exchangeable cations (k). Other substitutions also occur in natural systems, for example iron can replace aluminium to some extent.

Conclusions in RD&D 2004 and its review

A method for determining the structure of the montmorillonite was to be developed. Furthermore, studies of changes resulting from drying and exposure to air were announced.

Newfound knowledge since RD&D 2004

The method for determining the average structural formula of the montmorillonite has been further developed and has been used for a large number of swelling clays. The method entails that the montmorillonite is separated from other material and ion-exchanged to sodium form, after which the main elements are determined by means of a simple chemical analysis (ICP/AES). The average structural formula can then be calculated by various methods /24-5/.

Programme

The method for determining the structural formula of the swelling mineral will be further developed. An essential point is to determine the valence state of the iron content in the starting material, since this is decisive for the charge distribution in determining the structure. SKB intends to study any changes in the valence state of the iron as a consequence of e.g. exposure to atmospheric oxygen and drying, since this entails a change in the total layer charge. Mössbauer analysis will be tried to begin with. The statistical variation in the montmorillonite structure of a given buffer material is of interest and will be studied, for example with the aid of element analysis in a transmission electron microscope.

24.1.12 Pore water composition

Bentonite in nature contains water. After mining, the clay is dried and ground. At delivery the water content will be at most 12 percent, according to the current specification. Prior to compaction to blocks, water is added to achieve a water content of about 17 percent, which is equivalent to a degree of saturation of 65 to 70 percent in the finished blocks. The concentration of solutes in the pore water is thus dependent on the mineral composition of the buffer, as well as on the water content at different times. Direct measurement of pressed-out pore water is not suitable, due to the fact that a pressure-dependent ion equilibrium is developed, see section 24.2.15. When the buffer material is delivered, it will therefore be analyzed with respect to constituent minerals and ions in the supernatant of dispersed material (the aqueous solution on top of a slurried and centrifuged sample), which provides a good idea of the initial composition of the pore water.

Conclusions in RD&D 2004 and its review

Kasam thinks that SKB should propose limits for the concentrations of impurities in the bentonite buffer.

Newfound knowledge since RD&D 2004

The mineral composition of a number of different bentonites has been determined in a general study /24-3/, see section 24.1.2. In SKB's opinion, it is not possible at the present time to propose meaningful limits for the concentrations of impurities in the bentonite buffer.

Programme

See section 24.1.2.

24.1.13 Engineering materials

No foreign engineering materials are expected in the deposition holes.

24.2 Processes in buffer

24.2.1 Overview of processes

On emplacement, the buffer comes into contact with the hot canister surface. The thermal energy is spread through the buffer by heat transport and its temperature increases. The gamma and neutron radiation emitted by the canister decreases in intensity due to radiation attenuation in the buffer.

A negative capillary pressure exists initially in the pores in the buffer, causing water to be transported in from the surrounding rock. After the buffer has been saturated with water, this water inflow is very slow. Gas transport can occur during the saturation process, since water vapour can flow from the hotter parts of the buffer to condense in the outer, colder parts. Originally there is also air in the buffer, which can leave the buffer by dissolving in the pore water. This process is called gas dissolution. After water saturation, gas transport can occur if a canister is damaged, which causes corrosion of the insert in the canister, accompanied by hydrogen formation.

On absorbing water, the buffer and backfill swell, whereby a swelling pressure is built up. The swelling pressure is different in the buffer and backfill, which therefore interact mechanically. The swelling pressure is decisive for the mechanical interaction between canister and buffer, which can cause the canister to move in the buffer. On heating, the pore water in particular can expand due to thermal expansion.

The chemical evolution in buffer and backfill is determined by a number of transport and reaction processes. Solutes in the water can be transported by advection and diffusion. In the buffer, advection occurs almost exclusively during the water saturation process, after which diffusion dominates. By means of osmosis, the salinity of the groundwater in particular can affect the physical properties of the buffer. Ion exchange and sorption replace the buffer's original content of charge-compensating counterions with other ionic species. Chemical transformation of the buffer's swelling minerals can occur, leading to altered buffer properties. Other minerals undergo various dissolution and precipitation reactions in the buffer. On swelling, the buffer penetrates out into the fractures in the surrounding rock, where it can form colloids which can be carried away by the groundwater. This can lead to a gradual erosion of the buffer. The clay can be transformed by radiation effects and the pore water can be decomposed by radiolysis. Finally, microbial processes might possibly occur in the buffer.

After water saturation, radionuclide transport in the buffer is expected to take place exclusively by diffusion in the pores of the buffer, and possibly also on the surfaces of the clay particles. As long as there is enough bentonite left in the deposition hole, neither advection nor colloid transport is expected in a saturated buffer. Radionuclides can be sorbed to the surfaces of the clay particles. A crucial factor for this is the chemical form of the radionuclide, which is determined by the chemical environment in the buffer via the process of speciation. Together with the transport conditions, the rate of radioactive decay determines to what extent radionuclides from a breached canister will decay before reaching the outer boundary of the buffer.

The research programme for the various processes in the buffer is dealt with in the following sections. Many processes in the buffer are coupled and need to be studied integrated. Such studies are described in section 24.2.11, for example.

24.2.2 Radiation attenuation/heat generation

Gamma and neutron radiation from the canister are attenuated in the buffer. The magnitude of the attenuation is dependent above all on the density and water content of the buffer. The result is a radiation field in the buffer that can lead to radiolysis of water and have a marginal impact on the montmorillonite. The radiation that is not attenuated in the buffer penetrates out into the rock. Our understanding of this process is deemed to be good enough for the needs of the safety assessment.

24.2.3 Heat transport

In a buffer that is saturated with water and swollen, there is a direct thermal/mechanical contact between canister and buffer and between buffer and geosphere/backfill. Heat transport in the deposition hole is then a question of linear heat conduction under roughly constant conditions. The thermal conductivity of the water-saturated and homogenized buffer lies in the interval 1.1–1.3 W/m·K) /24-6/.

Conditions during the water saturation phase are more complicated. In the first place the properties of the bentonite buffer are dependent on water saturation to some extent, and in the second place there are gaps between canister and buffer and between the main part of the buffer (the bentonite blocks) and the geosphere. The gap between the canister and the unsaturated buffer is filled with air, while the gap between the bentonite blocks and the rock wall will be filled with bentonite pellets.

Since the temperature of the bentonite buffer cannot be allowed to exceed 100°C, the case with dry deposition holes will be crucial for the thermal design of the repository, i.e. for the choice of canister spacing and tunnel spacing under given heat transport conditions in the rock. The gaps contribute to raising the temperature at the canister surface and thereby also in certain parts of the bentonite buffer that will be in direct contact with the canister, i.e. the bentonite next to the end surfaces of the canister, see Figure 24-2.

Conclusions in RD&D 2004 and its review

RD&D-Programme 2004 stated that the temperature offset between canister surface and buffer can at most be around 17°C at the time of the temperature maximum, provided that the gap between canister and bentonite is 10 millimetres at deposition, that the deposition hole is dry and that the initial canister heat output is 1,700 W. This was based on observations from hole number 6 in the Prototype Repository in the Äspö HRL. It was further stated in RD&D-Programme 2004 that it should be possible to describe and set bounds on the total data and model uncertainty when it comes to calculated maximum canister and bentonite temperatures in a more schematic way than before, for example like in /24-7/.

Newfound knowledge since RD&D 2004

In the TBT test /24-8/ in the Äspö HRL we have been able to verify that the thermal conductivity properties of the buffer on a deposition hole scale agree well with the results of laboratory tests /24-6/. This is also preliminarily confirmed by thermal 3D simulations of the temperature evolution in the Prototype Repository /24-9/.

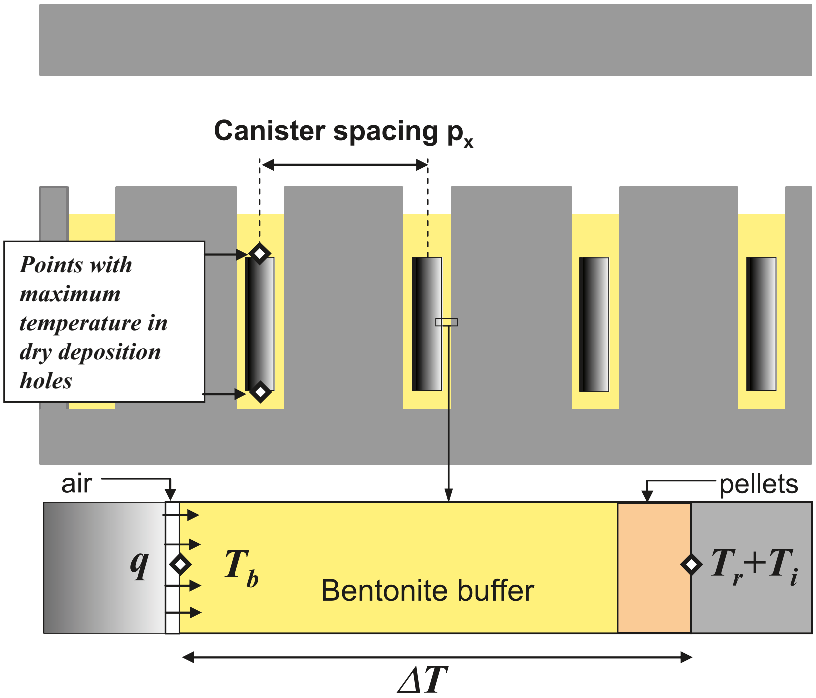


Figure 24-2. *Near-field with detail from barrier at canister mid-height. In dry deposition holes, the temperature of the bentonite will be higher at the end surface of the canister than at mid-height. T_b = bentonite temperature at mid-height, ΔT = temperature offset over buffer (blocks and pellets), q = heat flux from canister surface, T_r+T_i = temperature at rock wall.*

Additional evaluations of results from the Prototype Repository have shown that the heat transport across the pellet gap between the bentonite blocks and the rock wall is relatively efficient even during the initial period after deposition, before the pellet gap has absorbed water from the rock. The dry pellet gap appears to act like a material with a thermal conductivity of between 0.4 and 0.6 W/(m·K) /24-10/. The efficient thermal conductivity of the unsaturated buffer, i.e. the aggregate system of bentonite blocks and pellet gap, can be set at 1.0 W/(m·K). The open gap between canister and bentonite blocks can be assumed to have a conductivity of around 0.04 W/(m·K), of which about 0.03 W/(m·K) is due to conduction, while 0.01 W/(m·K) is due to radiation /24-10/.

Figure 24-3 shows the results of simulations of the temperature evolution around a KBS-3 canister carried out with Code Bright. Approximately 20 years after deposition, as a result of the open gap between canister and bentonite, the bentonite temperature at the base surfaces is about 13 degrees higher than at canister mid-height. The temperature difference is proportional to the canister's heat output, which after 20 years has declined from 1,700 W to about 1,300 W. If the temperature maximum occurs earlier the effect will thus be greater. The new model for calculating the maximum bentonite temperature /24-10/ includes the time dependence of the effect of the open gap, which means that we do not, as before, have to add a schematic gap margin in the thermal design of the repository /24-7/.

Programme

In the work of translating the calculation model to a design instruction for the sites, the work of developing design criteria for tunnel and canister spacing continues, see section 26.2.2.

The work of simulating the Thermo-Hydro-Mechanical processes in the Prototype Repository continues. In the big 3D models of the entire Prototype Repository that now exist, the wetting process is not taken into consideration. The results from the big 3D models will be used to define thermal boundary conditions for detailed models of some of the different deposition holes in the Prototype Repository. The results of the detailed THM models may, together with similar data from the Prototype Repository, provide a basis for a more exact determination of the buffer's heat transport properties, thereby reducing the uncertainties in the calculation models.

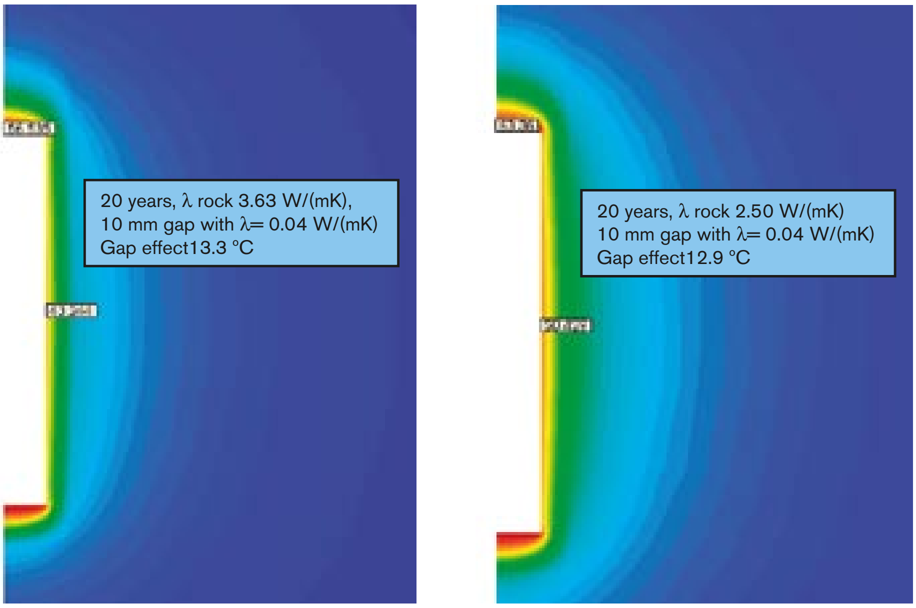


Figure 24-3. *Comparison between the temperature of the bentonite at canister mid-height and at the canister's base surfaces for two different assumptions concerning the thermal conductivity of the rock. At the base surfaces the bentonite and the canister are in direct contact so that bentonite and canister surface have the same temperature, which is not true at canister mid-height. The thermal conductivity of the host rock has a marginal impact on the effect of the air-filled gap.*

24.2.4 Freezing

Free water without salt freezes at temperatures below 0°C. When water undergoes the phase change to ice, latent heat is released and its volume increases (by about 9 percent). In a porous medium with water in the pores, this water freezes to ice at low enough temperatures. All the water doesn't freeze at the same temperature, however. A certain fraction of the water may remain in the unfrozen state even at temperatures below zero. The fraction of unfrozen water depends on different factors. Besides temperature, the mineral composition of the particles, the specific surface area of the particles, the water content, the presence of dissolved substances in the water and the water pressure are the most important factors. In buffer at repository depth, these factors reduce the freezing point. The water pressure and the salt content reduce the freezing point by 0.5–1.0 degree at a depth of 500 metres, and the specific surface area of the montmorillonite reduces the freezing point by more than 5 degrees in MX-80 in all water at the water ratios in question. Thus, freezing is not a problem in the buffer, see also section 21.4.

Conclusions in RD&D 2004 and its review

SKI recommended that SKB should consider experiments with freezing and thawing of the buffer.

Newfound knowledge since RD&D 2004

In conjunction with SR-Can, the conclusion was drawn that all water in the buffer is unfrozen at temperatures above –5°C. Temperature modelling of glaciation scenarios shows that the probability that the temperature in the buffer will fall below –5°C, and thus that freezing of the water in the buffer will occur, is very small. A new model based on thermomechanics is under development.

Programme

Continued theoretical studies supplemented by laboratory experiments to verify the theories and the conclusion that no water freezes at temperatures above –5°C. Most of the research on freezing is being done for the backfill, which freezes at higher temperatures and is exposed to lower temperatures in tunnels and other backfilled openings.

24.2.5 Water transport under unsaturated conditions

When the repository has been sealed, the buffer will absorb water from the surrounding rock. During the saturation phase, the buffer will build up a swelling pressure that mechanically affects the rock, the canister and the backfill. Water transport in the unsaturated buffer is a complicated process that is dependent on, among other things, the temperature and the smectite and water content of the different parts of the buffer. The most important driving force for achieving water saturation is a negative capillary pressure in the buffer pores, which leads to water uptake from the rock.

The hydraulic conditions in the rock surrounding the deposition hole are thus crucial for the course of the saturation process. With an unlimited supply of water, full water saturation will be achieved between canister and rock within a few years. A number of conditions in the rock are of importance for the water supply.

Conclusions in RD&D 2004 and its review

The existing body of knowledge is incomplete, and a rather extensive programme of laboratory, field and theoretical studies was outlined.

SKI expressed the following opinions:

- Resaturation and the early evolution of the buffer should be dealt with in greater detail in future safety assessments.
- The drier conditions in the Forsmark lens need to be taken into account.
- SKB should strengthen its thesis that slow resaturation does not have any negative impact. What, for example, are the consequences of dryout near the canister, slower homogenization of the swelling pressure, delayed closure of fractures, accumulation near the canister surface, faster water saturation in the backfill than in the buffer, etc?
- Can the rock matrix contribute to resaturation?
- Positive that SKB uses Code Bright.
- On what timescales is the buffer homogenized?

Newfound knowledge since RD&D 2004

The conclusion is drawn in SR-Can that the time to full water saturation of the buffer is largely dependent on the properties and frequency of water-conducting fractures. In the absence of fractures, it is dependent on the hydraulic conductivity of the rock mass. If the latter is greater than 10^{-12} metres per second, the time is dependent on the properties of the buffer, which means that the buffer between canister and rock is saturated in a few years. The buffer above and below the canister needs about ten years to full water saturation. Under very dry conditions the time to full saturation may be hundreds of years, but this does not adversely affect the buffer.

Our knowledge of the water uptake and transport properties of the buffer is sufficient for the safety assessment, but certain parameters and properties are associated with uncertainties, which means that further study is required. So far the calculations have been performed with the assumption that homogeneous conditions prevail in the buffer from the start (no consideration given to pellets and gaps). Better understanding and tools for taking these conditions into consideration are under development.

A great deal of work has been devoted to studying the water uptake process in the buffer. Studies have been conducted both in the field and in the laboratory, as well as theoretically in the form of model calculations and model development. Here are a few examples:

The largest driving forces for water in unsaturated buffer are the negative pore pressure and the temperature gradient. Factors that affect the negative pore pressure are therefore important for water transport. The way in which the negative pore pressure varies with initial state, water ratio and swelling pressure was studied in a doctoral project /24-11/ and subsequent supplementary studies. These results have since been used both in model development and to determine input parameters to the calculations. The experiments show how temperature, hysteresis, external pressure and degree of saturation affect the negative pore pressure.

The water saturation process is also being studied in joint international projects such as the Äspö Task Force on Engineered Barrier Systems (TF EBS) and Decovalex. In the former project, controlled laboratory experiments are modelled, after which modelling and calculation results are compared and the suitability of the models is evaluated. Modelling groups from eight different countries are participating.

A number of model calculations of the water saturation process in the KBS-3V concept have been carried out to study the influence of the rock and the backfill. The influence of the backfill on the time to full water saturation of the buffer has in particular been studied /24-12/. The results show that this influence is only significant if the rock around the deposition hole is very dry in comparison with the rock in the tunnel. The time to water saturation of the buffer is reduced by a factor of two if water is freely available in the backfill compared to if there is no water in the backfill at a hydraulic conductivity of 10^{-13} metre per second in the rock around the deposition hole. In some calculations the interaction between buffer, backfill, rock and fractures has been studied in a three-dimensional geometry that simulates a final repository of infinite extent. Figure 24-4 shows an example of such a calculation where two water-conducting fractures have been simulated.

Studies of the water saturation process were also made in a number of full-scale experiments in the Äspö HRL. In the Canister Retrieval Test, the TBT test and the Prototype Repository, the wetting of the buffer was followed with RH sensors, which measure relative humidity (RH) /24-13, 24-14 and 24-15/. After more than five years of wetting via filters on the inside of the deposition hole wall, the Canister Retrieval Test was mined. The buffer in the upper half of the deposition hole was sampled, after which water ratio and density were determined on a large number of samples. Both predictive modelling with Abaqus and the measurements of relative humidity in the buffer showed that full water saturation could be expected to have occurred between the rock and the canister, but not above and beneath the canister. The sampling confirmed this, as shown in an example in Figure 24-5.

Similar measurements in the Prototype Repository, where wetting of the buffer takes place from the natural rock, shows that the wetting rate varies between different deposition holes, as expected. For example, wetting has come far after five years in the wet deposition hole 1, while certain parts of the dry deposition hole 2 show no or very slow wetting.

These field tests were accompanied by coupled THM model calculations, where the water saturation process was the most important process studied. Certain calculations were done with Abaqus for the Canister Retrieval Test. The Canister Retrieval Test is included as a modelling object in TF EBS, where detailed coupled THM calculations will be done by several calculation groups to simulate the course of events. In the case of the Prototype Repository, modelling was included in the EU project that also included installation of the experiment. Furthermore, THM modelling of the experiment is being done with Code Bright as a part of the follow-up.

The TBT test was preceded by both design modelling and prediction /24-16/. In parallel with the follow-up of measurement data, modelling of certain phenomena was done /24-17/. This modelling was mainly done with Code Bright.

Programme

The laboratory and model development work is continuing in order to gain an even better understanding of, and improve the models for, the wetting process. The model calculations of the various field tests in the Äspö HRL are continuing, and comparisons are being made with both measurement data from installed sensors and actual conditions measured during excavation and sampling (so far only the Canister Retrieval Test). The modelling work in the international projects Decovalex and TF EBS is continuing. This programme will be dealt with in greater detail in section 24.2.11.

Since the hydraulic interaction between the buffer and the rock is crucial for the wetting process, a field test in the Äspö HRL is also planned. The two international modelling projects (Task Forces) for engineered barriers (TF EBS) and groundwater flow (TF GWFTS) will study and model this in a joint project.

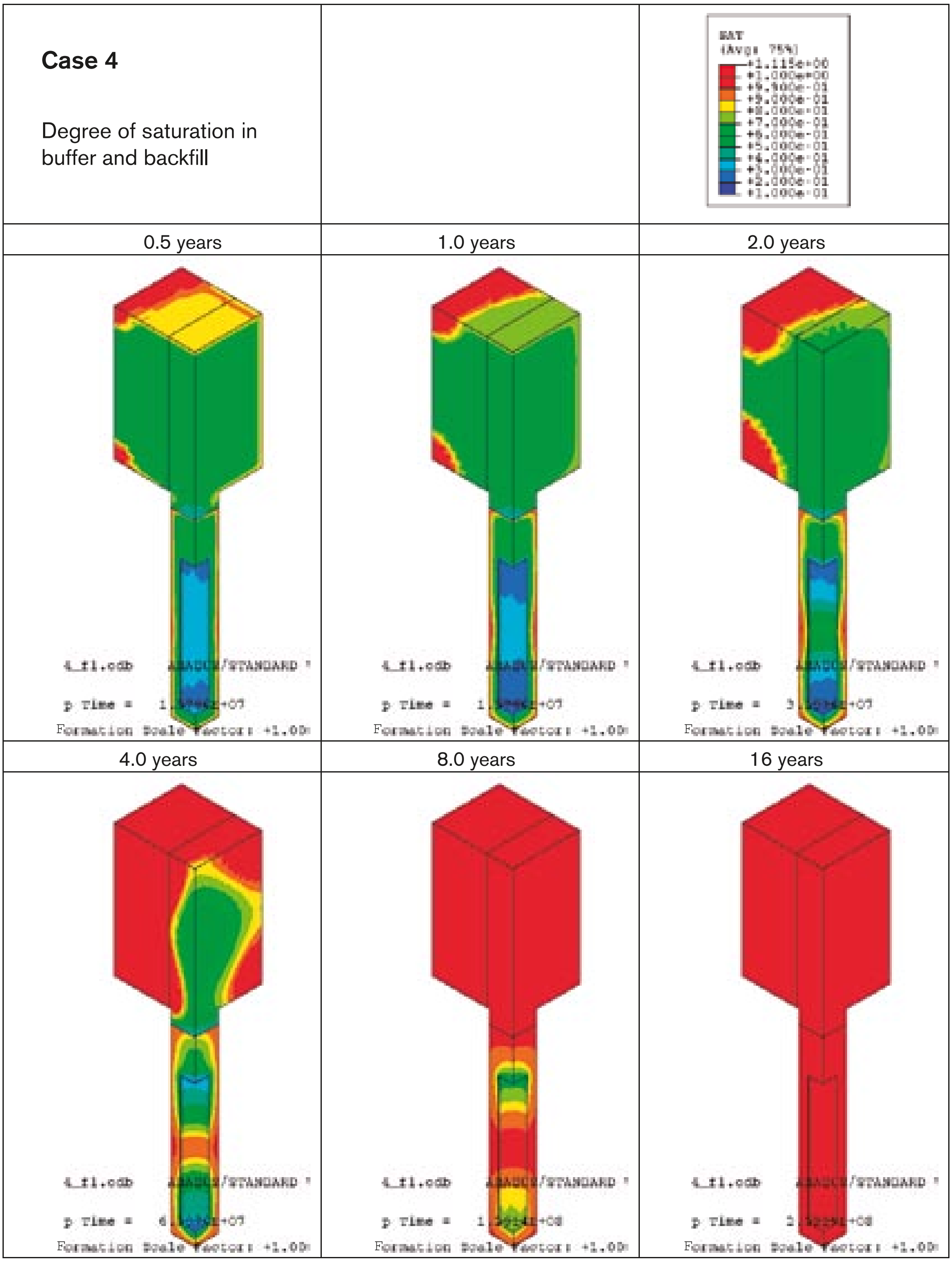


Figure 24-4. Sample calculation of the wetting process in buffer and backfill. Vertical fractures that intersect the tunnel midway between the deposition holes and a horizontal fracture that intersects the deposition hole in the middle of the canister. The degree of saturation at different times is shown.

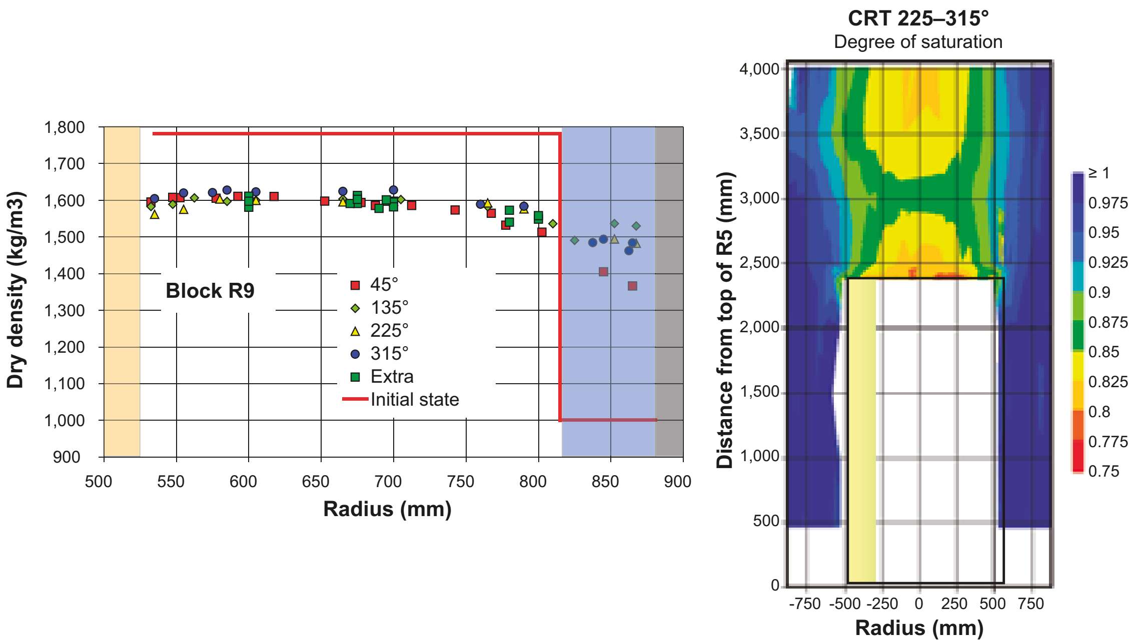


Figure 24-5. *Example of results of sampling in Canister Retrieval Test. The left-hand figure shows measured dry density as a function of the radius between the canister (525 millimetres) and the rock (875 millimetres) in ring 9, while the right-hand figure shows the degree of saturation as level lines in a vertical section.*

24.2.6 Water transport under saturated conditions

The interaction between water and montmorillonite in the bentonite is the basis for the sealing properties of the bentonite. When all pore space in the buffer is filled with water, the interaction leads to an effective distribution of most of the water to an approximately one-nanometre-thick water layer between the clay particles. This distribution, but above all the direct force interaction between the water and the montmorillonite, is an effective barrier to water movements. Normally the flow resistance for water is given in the form of hydraulic conductivity. The reference bentonites in SR-Can have a hydraulic conductivity of about 10^{-13} metre per second, which is of the same order of magnitude as fracture-free granite.

Conclusions in RD&D 2004 and its review

Laboratory tests with different salinities and ionic species were supposed to be done with several other bentonite materials as well. Conductivity measurements were supposed to be carried out at elevated temperatures. Further development of the THM models for water-saturated buffer were to continue.

SKI noted that the impact of high salinities should be studied further, and that SKB needs to show that initial cementation does not adversely affect buffer properties. Bentonite from Milos needs to be tested further with respect to its sealing properties.

No doubts prevailed about the buffer's ability to limit the water flow in the deposition holes in accordance with its safety function, provided that no extensive transformation or loss of buffer takes place. The process is critical, however, since it is dependent on other processes, above all colloid formation with an accompanying loss of buffer material. There is still much uncertainty in this area.

Newfound knowledge since RD&D 2004

A comprehensive laboratory programme /24-3/ has been carried out with respect to properties such as hydraulic conductivity for some fifteen different bentonite and swelling clay materials (buffer and backfill candidates). The programme included both bulk materials and materials from the clay fraction that had been ion-exchanged to sodium form. The sealing properties were determined as a function of material density and salinity. Further, a detailed mineralogical analysis was performed of the constituent clay materials, which makes it possible to relate the hydraulic conductivity to the type and quantity of swelling minerals.

Test A2 in the series Long Term Tests of Buffer Materials (Lot) was concluded at the beginning of 2006. The test had then been in progress for nearly six years with exposure to groundwater from the Äspö HRL and a maximum temperature of 130°C. The entire test parcel, including 15 centimetres of host rock, was overcored and lifted up in one piece. The bentonite was then divided under controlled conditions. An extensive analysis programme has since been carried out on the test material with respect to physical and mineralogical properties. Independent laboratories in Finland, France, Switzerland and Germany have performed analyses as a complement to those performed in Swedish laboratories.

Hydraulic conductivity has been determined for reference material and for material from the A2 test that had been exposed to elevated temperatures (30 to 130°C).). Preliminary results show that the exposed material has a slightly lower hydraulic conductivity than the reference material.

Programme

Laboratory determinations of hydraulic conductivity for samples taken from the Canister Retrieval Test at the Äspö HRL will be carried out using the same method as was used for the material in Lot A2.

Hydraulic conductivity will be determined for the reference material and for the exposed material for all test materials in the "Alternative buffer materials" test at the Äspö HRL.

A specific laboratory study will be conducted for the purpose of determining in detail the relationship between hydraulic conductivity and swelling pressure for both sodium- and calcium-dominated bentonites.

24.2.7 Gas transport/dissolution

In the case when a copper canister is damaged and water can come into contact with the insert, hydrogen gas will be formed inside the canister. Dissolved gas is transported slowly through the bentonite buffer. It is highly likely that a gas phase and a gas pressure will be built up inside the canister. It is important to be able to show that this pressure will not lead to any negative consequences for the performance of the repository. This means that the gas must be able to escape without damaging buffer or rock.

Conclusions in RD&D 2004 and its review

Kasam was of the opinion that SKB's research on large-scale gas transport through the bentonite buffer is important.

Newfound knowledge since RD&D 2004

SKB's research on gas transport has been focused on Lasgit in the Äspö HRL. Lasgit is a full-scale experiment with KBS-3V geometry for studying the effect of gas transport in the buffer. Figure 24-6 shows the structure of Lasgit with instrumentation.

Lasgit was installed in February 2005. Despite the fact that Lasgit has been equipped with buffer blocks with a very high initial degree of saturation and that the deposition hole is relatively conductive, the buffer is still not homogenized. Figure 24-7 shows the pressure situation in Lasgit after 680 days.

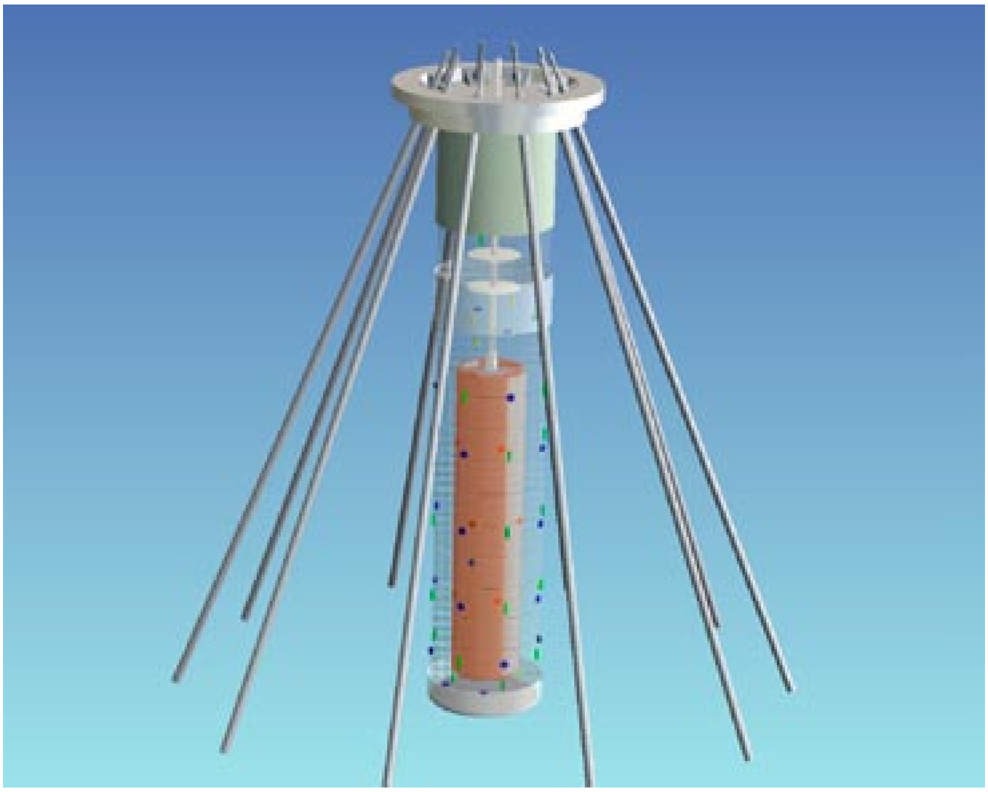


Figure 24-6. *Lasgit with plug, anchor, injection system and instrumentation.*

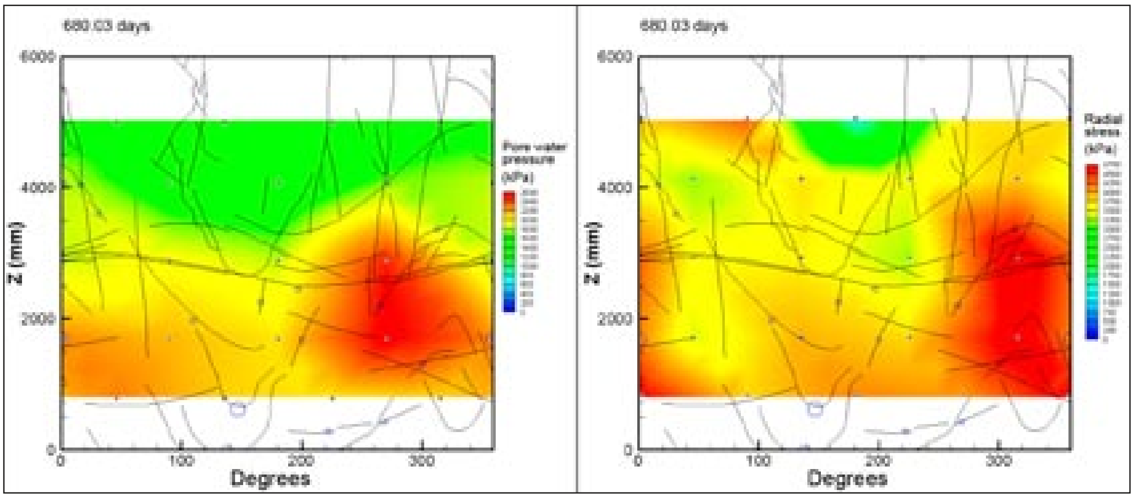


Figure 24-7. *Figures (a) and (b) show the distribution of pore water pressure and radial stress (swelling pressure) measured in the boundary area between buffer and rock in the deposition hole in Lasgit after 680 days. A zone with elevated radial stress can clearly be seen in Figure (b).*

Programme

Gas began to be injected in Lasgit in the spring of 2007. This could provide preliminary results regarding how the gas build-up and transport processes take place. However, since the buffer has not achieved its equilibrium state, the results from the first test series must be treated with some caution.

A programme for complete tests will be prepared based on the results and experience gained from the preliminary gas injection series.

24.2.8 Piping/erosion

Water inflow in the deposition holes and tunnels in a final repository mainly takes place through fractures in the rock, leading to wetting and homogenization of buffer and backfill. But in general the buffer and the backfill cannot absorb all water that runs through a fracture, resulting in the build-up of a positive water pressure when the flow of water is obstructed. If the support pressure and the strength of the buffer and the backfill are not great enough, piping may occur with accompanying erosion.

The processes and consequences associated with piping and erosion have been studied in some projects, involving a number of laboratory test series on different scales. Knowledge is insufficient today and more studies need to be, and are being, conducted. The piping and erosion referred to here mainly occur before full water saturation has been achieved.

Conclusions in RD&D 2004 and its review

In RD&D-Programme 2004, the problem was mainly addressed in relation to KBS-3H, where it is extra-critical since piping and erosion that occur far inside the deposition tunnel can be propagated through the entire tunnel past all intervening canisters. It was concluded there that a gap on the order of several centimetres is not capable of stopping the water inflow in the base scenario (0.1 litre per minute inflow per canister section), but that an engineering solution is required /24-18/. Experiments will be performed to obtain a better understanding of how piping occurs. Erosion will also be studied if it is concluded that piping cannot be avoided.

Viewpoints and questions from the review:

- Can erosion or chemical transformations create heterogeneity in the buffer?
- SKI was of the opinion that SKB should primarily investigate whether buffer erosion and piping is a problem for the reference concept KBS-3V.
- SKI called for modelling of processes that could affect the buffer's homogeneity and swelling properties, for example possible mass losses of bentonite near the buffer's interface against the rock.
- A number of critical uncertainties remain to be studied, for example the risk of erosion during deposition.

Newfound knowledge since RD&D 2004

Valuable conclusions were drawn in connection with SR-Can. A typical inflow in a deposition hole in Forsmark is 0.01 litre per minute. At this value, piping accompanied by erosion will presumably not occur. By a prudent choice of deposition hole location and by excluding certain holes, it should be possible to prevent piping entirely in the deposition holes.

At Laxemar the inflows are considerably higher. About 20 percent of the holes are expected to have an inflow in excess of 0.1 litre per minute. By a prudent choice of deposition hole location, grouting and exclusion of certain holes, it should be possible to prevent piping in Laxemar as well.

SR-Can's process report for buffer and backfill also concludes that present-day knowledge is insufficient for being able to establish exact limits for when piping and harmful erosion will occur.

A number of test series, mainly within the projects KBS-3H and Baclo, have enhanced our understanding of these processes, but a great deal still remains to be done. Today's knowledge level is summarized in a report /24-19/.

Since a support pressure in the form of swelling pressure or some type of confinement is needed from a force equilibrium point of view in order to stop piping, it is clear that either the gap has to be very small so that a matching swelling pressure can build up quickly, or the geometry has to be such that piping is stopped by valve or constraint effects. The latter phenomenon is probably responsible for the fact that piping appears to be stopped in gaps smaller than 0.5 centimetre in the most difficult reference cases (see below) if pre-wetting is done.

The erosion measurements show that erosion is sensitive to salinity and appears to decline with time. It can be measured as the fraction of material in the water and declines rapidly with time to between 1 and 10 grams per litre.

The processes have been observed in the field, especially in Lasgit where an inflow of 0.2 litre per minute resulted in an erosion that did not stop, but continued at a rate of about 1 gram per litre until the inflow source was short-circuited.

Programme

The piping tests in the KBS-3H project are continuing. There the conditions under which piping can be prevented are being studied, as well as how the risk can be minimized with engineering solutions. Inflows of 0.1–1.0 litre per minute and pressure increase rates of between 100 and 1,000 kPa/h in connection with obstructed flow are being studied. For KBS-3V, tests with the right geometry and buffer probably need to be done in order to determine where the limits go. An engineering solution may be needed at high inflows.

Erosion is mainly being studied in the Baclo project, where different materials are exposed to different flow rates and the eroding quantity is measured. Additional tests need to be done where the influence of flow length and time is studied.

The results can be studied in the field in connection with the mining of hole 1 in the Prototype Repository, where the inflow at installation was 0.08 litre per minute. If the erosion has continued for five years, it should be possible to see the consequences when the repository is mined. If no bentonite losses are found, this provides strong support for setting the limit at 0.1 litre per minute.

24.2.9 Swelling

The swelling process has been lumped together with other stress- and strain-related processes that can cause mass redistribution in the buffer such as thermal expansion, creep movements and a number of interactions with canister, near-field rock and backfill.

Water uptake after deposition in the buffer and the backfill, which are inhomogeneous at emplacement, will lead to swelling. This causes all gaps in the buffer, between rock and buffer and between canister and buffer to disappear, and the buffer to be homogenized. However, some inhomogeneity will remain due to friction in the bentonite. In the buffer, heating will furthermore lead to thermal expansion of the pore water. If swelling is prevented, a swelling pressure will instead develop.

In the interface between the buffer and the backfill, an interaction arises due to the fact that the buffer exerts a swelling pressure against the backfill, and vice versa. Since there is a difference in swelling pressure, a net pressure arises against the backfill, whereby the buffer and the backfill are compressed. The size of the upswelling depends on the original densities of the buffer and backfill, as well as the expansion and compression properties of the materials and the friction against the rock. Calculation models, both analytical and numerical, exist for analysis of this interaction.

A mechanical interaction between buffer and canister arises due to the fact that the buffer generates both compressive and shear stresses. The interaction also arises through the pore water, which only generates compressive stresses, and through gas in the buffer, which also only generates compressive stresses. These three variables change during the water saturation process. The weight of the canister acts on the buffer, while the weight of the buffer on the canister only has a negligible effect. Rock movements that arise in the fault plane, for example after earthquakes, give rise to stresses on the canister, which are transmitted from the rock through the buffer. The processes associated with the mechanical interaction between buffer and canister after water saturation are relatively well understood. The uncertainty mainly concerns the evenness of the wetting and the pressure build-up caused by possible gas formation. Another uncertainty stems from creep movements of the canister caused by the weight of the canister.

The mechanical interaction between buffer and near-field rock is caused by, among other things, swelling pressure from the buffer, convergence of deposition holes and shear movements in the rock. Convergence is dealt with in section 26.2.9. In KBS-3H the bentonite will first penetrate through the outer perforated supercontainer and further into the space between the rock and the container. In the long term the container will corrode. The transformation from iron to magnetite entails a volume increase and an increased pressure against the rock and the canister.

The swelling causes clay to penetrate into the fractures in the rock. Due to the swelling properties of the bentonite, any damage that arises in the buffer – for example due to piping and erosion, gas penetration or rock movements – will swell shut and self-heal.

In the long run, chemical changes in the buffer can lead to changes in its swelling and deformation properties, see section 24.2.17. A model for swelling under water-saturated conditions has previously been developed for the finite element code Abaqus. Swelling occurs during the water saturation phase as well, see section 24.2.11.

Conclusions in RD&D 2004 and its review

The following was established in the programme:

- Laboratory tests and model development for further study of the swelling properties of buffer and backfill materials will continue.
- Investigations of the influence of pore water chemistry and density on the swelling properties of other buffer candidates will be performed.
- Studies in KBS-3H of the interaction with the perforated supercontainer will continue, for example in Big Bertha (large-scale test set-up).
- The consequences of the interaction between the buffer and different types of backfills will be examined.
- Additional modelling of rock shear will be done and the need to conduct further experiments will be considered.

The following questions and viewpoints were offered in the review:

- On what timescales is the buffer homogenized?
- Can erosion or chemical transformations create heterogeneity in the buffer?
- SKB would need to study at what density canister sinking can occur in order to be able to set the safety margin at 2,000 kg/m^3.
- Large-scale shear tests could provide valuable data for future safety assessments.
- SKI called for modelling of processes that could affect the homogeneity and swelling properties of the buffer.
- How important is it that homogeneity is achieved within a given time?
- A number of critical uncertainties remain to be studied, for example around the mechanical interaction between buffer and backfill.
- It should be possible to study the early upswelling of the buffer by inactive demonstration deposition.

Newfound knowledge since RD&D 2004

A couple of performance indicators that are formulated in SR-Can concern these processes:

- The swelling pressure should exceed 1 MPa everywhere in the buffer in order to ensure good contact with the rock.
- The swelling pressure should exceed 2 MPa everywhere in the buffer to prevent bacterial activity. This limit applies directly after water saturation and homogenization, however. In the event of loss of bentonite at a later stage, the minimum pressure is 1 MPa.
- The density after full water saturation may not exceed 2,050 kg/m^3 in order to prevent canister damage due to rock movements.

In SR-Can it was concluded that the swelling pressure from the buffer does not have a detrimental effect on the canister and that upswelling against the backfill does not affect the density of the buffer around the canister /24-20/. A local loss of 100 kg of bentonite in a deposition hole can be homogenized sufficiently in order to maintain sufficient swelling pressure. Not even the loss of a whole bentonite ring is expected to lead to advective conditions. Calculations have also shown that the margin until canister sinking becomes critical is very great. A swelling pressure of 200 kPa causes only two centimetres of sinking.

It is also concluded in SR-Can that the canister can withstand a rock shear of 10 centimetres through a deposition hole, even after transformation of the buffer to calcium bentonite in the most unfavourable shear direction. However, some uncertainties remain regarding the effect on the copper lid and the consequences of partial cementation of the buffer.

Several series of swelling pressure measurements have been carried out. The influence of the pore water chemistry and the montmorillonite content of the buffer have been investigated. The swelling pressure of alternative buffer materials, as well as of material from the Lot test, has also been measured. The latter had been exposed to a maximum temperature of 130°C for five years. No effect on the swelling pressure was found.

When the above Lot parcel was mined, however, it was found that the stress-strain properties had changed in the warm part of the material. The fracture in uniaxial compression tests was more brittle than expected. If this is a sign of incipient cementation, it may mean that the parameters for e.g. the rock shear calculations should be changed. The cause must be investigated.

When the Canister Retrieval Test in the Äspö HRL was mined, a large number of samples were taken in the upper half of the deposition hole. Measurement of density and water ratio showed how far the homogenization had gone, see for example Figure 24-5 in section 24.2.5.

A number of calculations have been carried out of effects of swelling and homogenization of buffer in different scenarios. The mechanical properties of the buffer, which control the swelling and consolidation phase, are based on models and properties derived for MX-80. Effects of bentonite loss have been modelled with Abaqus. Bentonite losses on three different scales have been studied:

- If erosion due to colloid transport is equivalent to the loss of one or more bentonite blocks, the empty space will swell shut again with a permanent sharp reduction in density, especially near the canister. Figure 24-8 shows an example of a calculation. When large quantities of bentonite are lost, or the bentonite is missing from the start, the bentonite swells and fills the empty spaces. The resulting density and swelling pressure are fairly low, due to the friction in the buffer and against the rock surface. For an opening of 50 centimetres, the swelling pressure is on average 0.5–1.0 MPa in almost the entire former hole. If the rock surface is smooth and the friction against the rock is halved, the swelling pressure will be more than 1 MPa in most of the former space.
- The worst possible case for erosion during installation is a flow of 0.1 litre per minute in a deposition hole. This flow erodes 10 grams dry weight of bentonite per litre of water. During a period of twelve weeks, this yields a total water flow of 12,100 litres and a total dry mass of eroded bentonite of 121 kg. The calculations of the swelling and homogenization of the buffer after a local bentonite loss of this order of magnitude have been done assuming two different geometries of the empty space. In one of the geometries, half a ring located at the rock surface reaching all around the periphery of the deposition hole was simulated. The results show a permanent reduction in density and swelling pressure due to the friction in the bentonite. However, the swelling pressure after completed homogenization is not below 1 MPa in any of the cases with a ring thickness varying from 3.4 cm to 13.4 cm.
- Piping and erosion results in a small pipe that leads the water and bentonite solution out through the buffer into the backfill. Such a pipe will ultimately swell up and seal when the water flow has stopped. FEM modelling of the process of self-sealing of long open pipes in compacted bentonite has yielded some interesting results. A long open pipe does not seal completely – a reduced density with an infinitely small hole will remain.

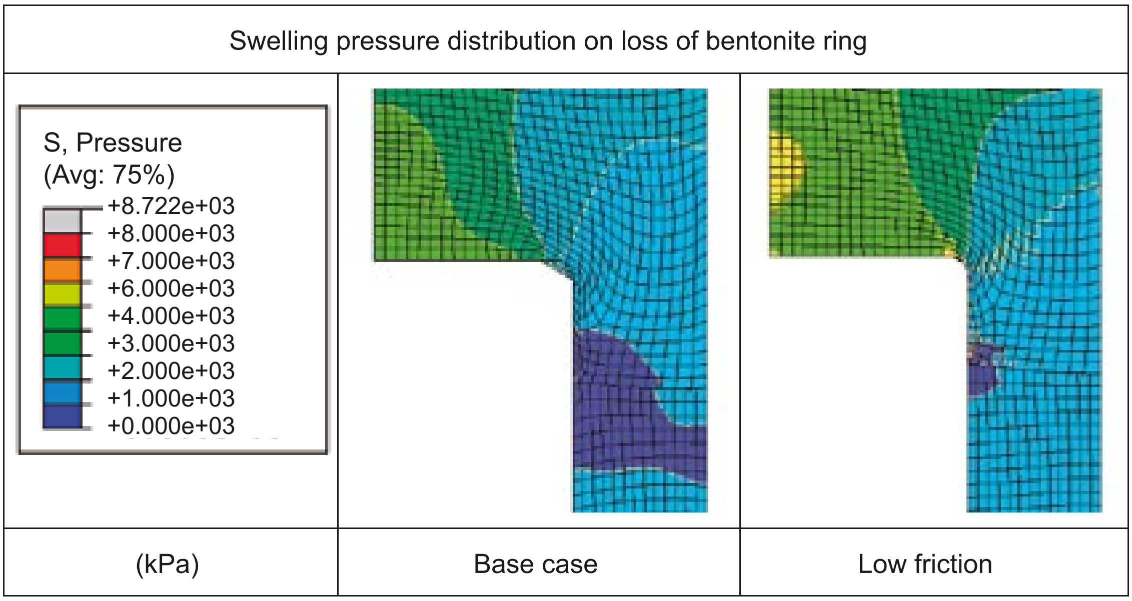


Figure 24-8. *Calculated swelling pressure distribution after swelling shut of a space corresponding to the loss of a 0.5 metre high bentonite ring: the base case with a friction angle of 8.7 degrees against the rock wall and another case with halved friction due to a smooth wall.*

The uncertainties regarding the material model in the case of strongly swelling bentonite make these results somewhat uncertain, especially at high void ratios (the ratio between the pore volume and the volume of the solid material). Certain results should therefore be checked by swelling tests in the laboratory.

Calculations of the upswelling of the buffer against the backfill have been done for a large number of backfill materials /24-21 and 24-22/. Besides the base case with a 30/70 mixture, calculations were done for Friedland clay and Asha 239 bentonite. A simplified calculation was also done of the upswelling against blocks of Friedland clay with pellets in the gaps under the assumption that the backfill remains unwetted throughout the wetting of the buffer. The calculations yielded an estimated upswelling of approximately 8 centimetres. However, the results must be considered preliminary due to uncertainties in assumptions and supplementary tests and calculations need to be done.

The influence of rock shear with a shear rate of 1 metre per second along a fracture through a deposition hole in a KBS-3V repository was investigated for a number of different shear cases and for different properties of the buffer material /24-23, 24-24, 24-25/. The scenarios were modelled using the finite element method and the calculations were done using the Abaqus code. A 3D element model was used to model the rock, the buffer and the canister. Contact elements that can model separation were used for the interfaces between the buffer and the rock and between the buffer and the canister.

The influence of the inclination of the intersecting fracture, the shear direction, the location of the shear plane, the magnitude of the shear displacement, the bentonite type (Ca or Na) and the bentonite density were studied. Furthermore, the consequences of transformation of the buffer to illite or cemented bentonite were investigated.

The influence on the canister is always greatest for calcium bentonite due to higher swelling pressure and greater stiffness of the bentonite. The greatest damage occurred after 20 centimetres of shear in calcium bentonite with a density of 2,050 kg/m^3. The greatest plastic strain was 19 percent in the copper tube and 13 percent in the iron insert (but for different shear cases). The corresponding strains after 10 centimetres of shear were 10 percent and 5.4 percent. For sodium bentonite the greatest plastic strain was 8 percent (5.5 percent) in the copper tube and 3.6 percent (1.3 percent) in the iron insert, where the values in parentheses are after 10 centimetres of shear.

The consequences of conversion to illite are advantageous for the canister (due to greatly reduced swelling pressure). As a result of cementation of bentonite with a thickness of 8.75 cm around the canister, the effect of a rock shear is more severe than for the original bentonite, since cementation increases the stiffness of the buffer. However, the properties of cemented bentonite are not known, so the calculation must be regarded as an example rather than as a prediction.

The vertical displacement of the canister in the KBS-3H concept has been studied in a number of consolidation and creep calculations using the FEM programme Abaqus. The creep model used in the calculations is based on Singh-Mitchell's creep theory. The model creep was adapted to and verified for the buffer material in earlier tests. A porous elastic model with Drucker-Prager plasticity was used for the consolidation calculations. For simplicity the buffer was assumed to be fully water-saturated from start.

Two types of simulations were done. The two cases represent two extreme cases, one with a backfill that has a low stiffness and the lowest allowable swelling pressure and the other with a backfill in the tunnel that has the highest possible swelling pressure and stiffness.

The calculations include two stages, where the first stage models the swelling and consolidation that takes place in order for the buffer to reach force equilibrium. This stage takes place during the saturation phase and the subsequent consolidation/swelling phase. The second stage models the deviatoric creep in the buffer during 100,000 years.

The calculations show that the canister settlement is very small, even at low swelling pressure and density. The base case, corresponding to the expected final buffer swelling pressure of 7,000 kPa, yields a total settlement of the canister of only 0.35 mm for the fixed boundary case. There is a heave of the canister of about 4.5 mm at the other case with 30/70 backfill due to the upward expansion of the buffer. At reduced swelling pressure the settlement increases, but is not more than about 23 millimetres at the very low swelling pressure of 80 kPa in both cases. Figure 24-9 shows consolidation and creep settlement as a function of the swelling pressure for the two calculations.

Programme

Swelling and mass redistribution are important processes for the performance of the final repository. Both understanding and models need to be improved.

The work with laboratory tests and model development to study the build-up of the swelling pressure during the wetting phase and its influence and dependence on the negative pore pressure will continue, see sections 24.2.1a and 24.2.14.

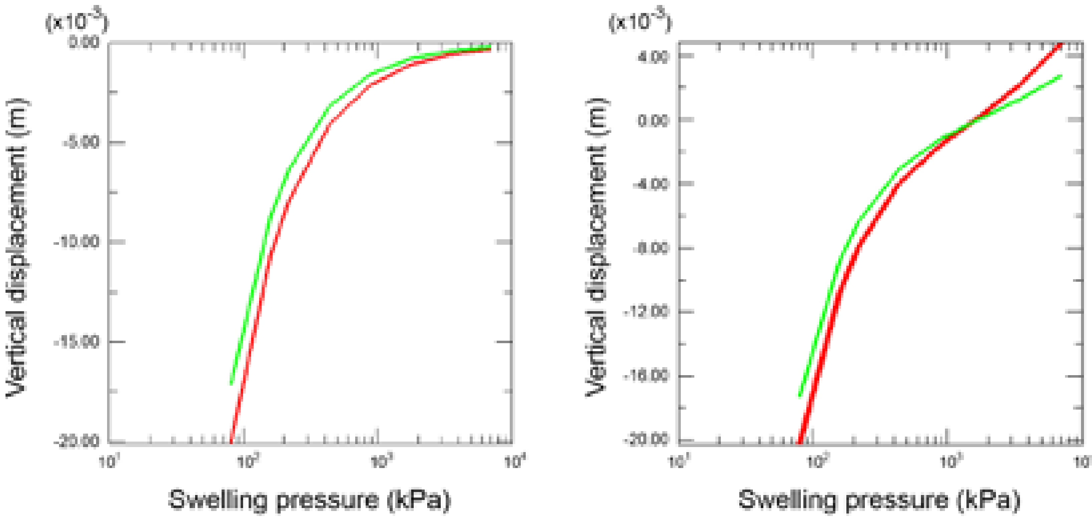


Figure 24-9. *Vertical displacement of the canister as a function of the swelling pressure for the two cases with fixed boundary buffer/backfill (left) and free boundary with 30/70 backfill (right). Negative displacement means sinking. Red line: Only consolidation/swelling. Green line: Consolidation/swelling plus creep.*

Swelling-out of bentonite through the holes in the perforated supercontainer in KBS-3H will be studied in a test where hole geometry and gap width are simulated on a full scale (Big Bertha).

Evaluation and further investigations of samples from the mined Canister Retrieval Test in the Äspö HRL will be done together with modelling.

The swelling and homogenization process will be studied in a number of laboratory experiments and model calculations. This work is intended to result in either a verification of existing models or an improved model. The following tests are planned or being considered (and modelled):

- Uniaxial swelling tests in an oedometer with a constant radius and either a raw or friction-free boundary (oedometer ring).
- Radial swelling tests in an oedometer where a tubular opening is allowed to swell shut.
- Scale tests (1:10) of a deposition hole with lost bentonite rings according to the modelling described above.
- Same as above but on a full scale in the Äspö HRL (being considered).

Canister shear by an earthquake will be further investigated both in the laboratory and by modelling:

- Modelling of and comparison with the three scale tests done in the early 1990s with water-saturated MX-80 as the buffer and pure solid copper as the canister. Three tests on a scale of 1:10 with different shear rates were carried out. Large quantities of data and information are available from these tests. By using today's material models and calculating with Abaqus in the way shown above and comparing the results, the models can be verified or improved.
- Laboratory tests with calcium bentonite to verify or improve the material model. The model for calcium bentonite has been determined by modifying the model for sodium bentonite based on knowledge of the difference between these materials.
- Renewed model calculations may be done with a realistic geometry of the lid.
- Other shear tests may be done if needed to verify the models.

The cause and consequence of the brittle behaviour of the buffer that was discovered in the Lot test will be investigated and evaluated.

Additional laboratory experiments, where effective pressure is measured during and after high water pressures have been applied, will be done to investigate whether cycles of high water pressures can affect the swelling pressure.

24.2.10 Thermal expansion

When the temperature changes in the buffer, the volume of the pore water will change more than the volume of the mineral phase. The pore water pressure rises when the temperature increases. Temperature differences between different parts of the buffer thereby lead to pressure differences, which in turn lead to movement of the pore water to equalize the differences. This process could bring about high pressures against rock and canister if water saturation occurs before the temperature maximum. The process is well understood in water-saturated bentonite. For unsaturated bentonite the thermomechanical theory is not complete, but the consequences of this process are deemed in this case to be unimportant for safety. Thermal expansion is included in the coupled THM model, see section 24.2.11.

24.2.11 Integrated studies – THM evolution in unsaturated buffer

When the repository has been sealed, the buffer will absorb water from the surrounding rock. The water uptake affects and is affected by a number of coupled thermal, hydraulic and mechanical processes. Extensive experimentation and model development are being conducted in this area within SKB's programme.

Conclusions in RD&D 2004 and its review

A comprehensive programme of modelling and model development, follow-up of the field tests in the Äspö HRL and laboratory experiments was set up in RD&D-Programme 2004.

SKI was of the opinion that significant progress has been achieved in recent years in terms of model studies, code development and experiments. SKI also said that SKB needs to show, in preparation for coming applications, by practical experiments that their knowledge of and models for the functions of the buffer are adequate.

SKI thought that the early evolution of the buffer should be dealt with in greater detail in future safety assessments and that the drier conditions in Forsmark need to be particularly taken into consideration, wondered if the rock matrix can contribute to wetting, and wanted SKB to show that one consequence of dry conditions in the form of slow resaturation does not have any negative impact. SKI thought that it is positive that SKB uses Code Bright.

SKI said that in general, SKB is conducting a good set of experiments at the Äspö HRL.

SSI felt that SKB is doing ambitious work with model development and extensive laboratory studies on the properties and functions of the bentonite buffer, but also that SKB must conduct a renewed analysis of the need and adequacy of long-term tests in the Äspö HRL concerning the functions of the buffer and the backfill.

Newfound knowledge since RD&D 2004

Integrated studies are not dealt with in SR-Can as a special process, but are divided in the Process Report into thermal, hydraulic and mechanical processes. The coupling of the THM processes during the saturation phase is not crucial for the safety of the final repository, but important for an understanding of how the buffer is wetted, swells and is homogenized under the influence of temperature changes. It is also important for the understanding and evaluation of the field tests in the Äspö HRL.

Coupled THM processes during the water saturation phase and their interaction with the rock, the canister and the backfill have been studied by development of material models and modelling of different experiments and scenarios, by measurement of the THM processes in large-scale tests in the field and by small-scale laboratory tests. See also sections 24.2.3 and 24.2.5.

Model studies

In the past three years, Code Bright has been used for coupled THM simulations of a number of experiments. This applies to the tests that have been analyzed within Task Force EBS and the TBT project (TBT 2 and TBT 3) /24-16 and 24-17/. This work has yielded new insights regarding moisture redistribution under thermal gradients, mechanical processes and the dynamics of gas breakthrough. Large-scale TH models have also been made of the TBT and Prototype tests in the Äspö HRL. It has, however, been found that more work is needed to be able to execute large-scale fully coupled models with sufficient numerical stability. The need for an alternative to BBM (Barcelona Basic model), which serves as a basis for the mechanical constitutive laws in Code Bright, has also been recognized. BBM is an elastoplastic model with two independent variables (net stress and pore pressure potential) that was developed for unsaturated soils.

The description of the mechanical processes in unsaturated MX-80 bentonite has therefore been developed. Great emphasis has been placed on clarifying the dynamics and relevance of BBM in order to arrive at the best strategy and relevant parameter values for simulating blocks and pellets in KBS-3 with the current implementation of Code Bright. In this work, the accepted pressure and water retention properties of the material have also been related to the mechanical deformation relationships, which in turn has led to a framework for a new elastoplastic model. An important aspect of this work has been being able to evaluate parameter values from different types of laboratory experiments in a manner consistent for BBM.

Model calculations have also been done with existing models for unsaturated processes in Abaqus. These have included studies of the saturation process in KBS-3V deposition holes with fully coupled THM calculations of the interaction with backfill, rock and canister /24-1/. Similar model calculations are being done for a repository with horizontal deposition in the Decovalex project.

The Task Force on Engineered Barrier Systems (TF EBS), with participants from eight organizations representing different countries, is a natural prerequisite for the modelling work in the Prototype Repository. The work began at the end of 2004 and will during the first four-year period include two benchmark studies where coupled THM processes in unsaturated bentonite are studied, namely small-scale laboratory experiments and large-scale field tests. Benchmark 1 has been carried out during the first two years. The study includes modelling of a number of laboratory tests with MX-80 and Febex bentonite that have been exposed to different temperature and water situations. The work within TF EBS has so far led to a deeper understanding of the ability of the codes to model different states in the saturation process.

Modelling of the THM processes in the buffer in the Prototype Repository is under way and is coupled to the aforementioned development of the mechanical processes with determination of parameter values etc. The model takes into consideration differences in density between the buffer blocks and the pellet-filled gap.

Field studies

Experimental studies of the coupled THM processes under unsaturated conditions have been conducted both in the field and in the laboratory. A number of field tests are under way in the Äspö HRL where these processes are being measured under realistic conditions. The Prototype Repository, the Canister Retrieval Test and TBT are the foremost examples. These tests cover both wet and dry conditions and are being conducted for various lengths of time. This means that the measurement results from installed sensors, as well as measurements on samples taken from excavations, will be able to be used for many different wetting cases in the evaluation of the coupled THM processes by comparisons with model calculations. The Canister Retrieval Test was discontinued in the spring of 2006 and has yielded valuable information on the coupled processes, see also section 24.2.5.

Laboratory experiments

Our knowledge of the coupled hydromechanical processes in unsaturated bentonite has increased as a result of laboratory studies that have led to a PhD thesis /24-11/ and continued with new experiments aimed at defining the parameter values in Code Bright. The overall objective of the PhD thesis was to develop a conceptual model of the hydromechanical behaviour of bentonite. The influence of the experimental technique was also investigated to permit a correct evaluation of the experimental results.

The main goal of the laboratory programme was to investigate how the water retention properties of bentonite were affected by constrained swelling, the development of swelling pressure at reduced negative pore pressure, and the impact of external pressure and swelling pressure on the negative pore pressure. The experimental types that were chosen for most of the experiments were gradual increase of the relative humidity together with free swelling, or constrained swelling with simul–taneous measurement of swelling pressure. Experiments were also conducted with constant water content and an externally applied pressure. Relative humidity was measured in these experiments. The results of the laboratory experiments were used to find a relationship between water ratio, void ratio, swelling pressure and negative pore pressure. It was assumed in the analysis of the experimental results that equilibrium was achieved in the samples.

The measured axial swelling pressure P_a, which arose in samples during water uptake with constrained swelling, was normalized with a pressure of P_{ret}, equivalent to the swelling pressure at saturation. This normalization was done so that P_a would be independent of the void ratio. The normalized axial swelling pressures from samples of one type are shown in Figure 24-10.

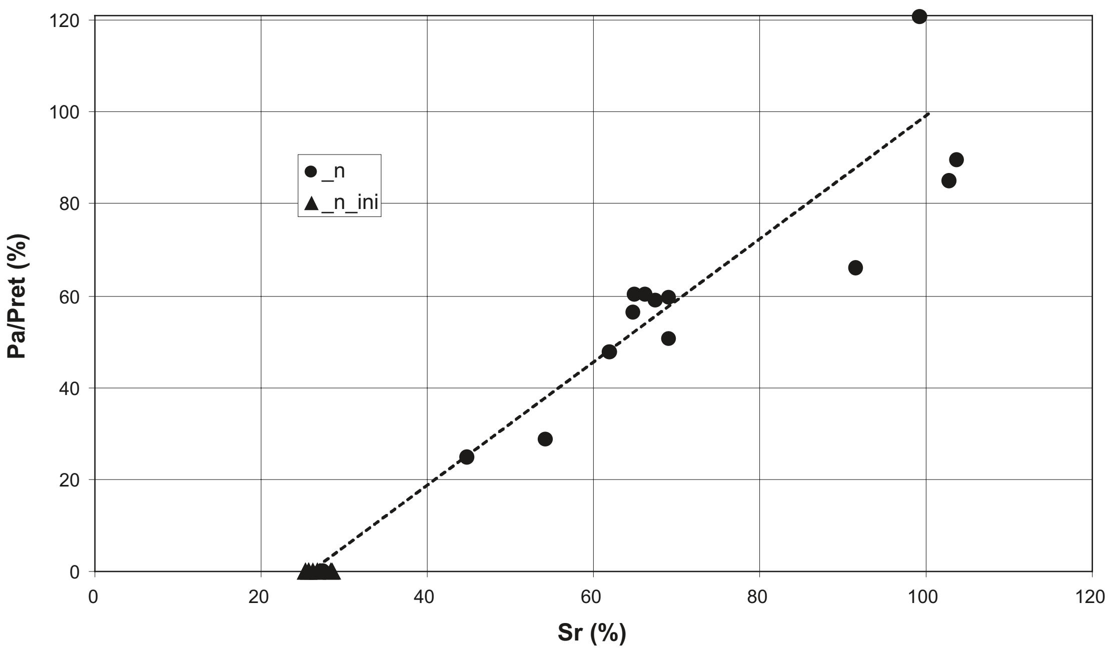


Figure 24-10. *Normalized axial swelling pressure (Pa/Pret) from samples of one type with different degrees of saturation (Sr). A dotted line connects the starting ratio with the ratio at saturation.*

A relationship is proposed between the normalized swelling pressure and the degree of saturation S_r according to equation 24-1. In this equation, $P(S_r,e)$ is the swelling pressure, $P_{ret}(e)$ is the swelling pressure at saturation, $S_{r,ini}$ is the degree of saturation at the start and e is the void ratio.

$$P(S_r,e) = \frac{S_r - S_{r,ini}}{1 - S_{r,ini}} \cdot P_{ret}(e) \qquad (24\text{-}1)$$

Equation 6-2 below is based on a thermodynamic ratio for water saturation, which has also been compared with the laboratory results in the study. The equation relates the swelling pressure $P(RF,w)$ to the actual relative humidity in bentonite RF and the relative humidity according to the water retention curve $RF_{ret}(w)$ for the actual water ratio w. R is the general gas constant, T temperature, ρ_w the density of the water and ω_v the molecular weight of the water vapour.

$$P(RF,w) = -\frac{R \cdot T \cdot \rho_w}{\omega_v} \cdot \ln\left(\frac{RF_{ret}(w)}{RF}\right) \qquad (24\text{-}2)$$

Examples of measured swelling pressures and calculated swelling pressures from equation 24-2 are shown in Figure 24-11. The agreement turned out to be good. The symbols represent different ways of determining RF_{ret}.

A model consisting of equations 24-1 and 24-2 is proposed. The model can be used when two of the four parameters (water ratio, void ratio, swelling pressure and negative pore pressure) are known. It can be used, for example, to evaluate field measurements and to model the latter stage of a wetting process. The equation is primarily based on results from experiments performed with an increased degree of saturation and with a constant void ratio, but they are also recommended to be used for an increasing void ratio.

An experimental programme is currently under way that is a continuation of the work described above aimed at obtaining an even better understanding and improving the models of THM processes in unsaturated bentonite buffer. An important purpose of the experimental programme is to determine the compression module and the swelling-shrinking module and other parameters that are needed to model with Code Bright but also to study alternative models.

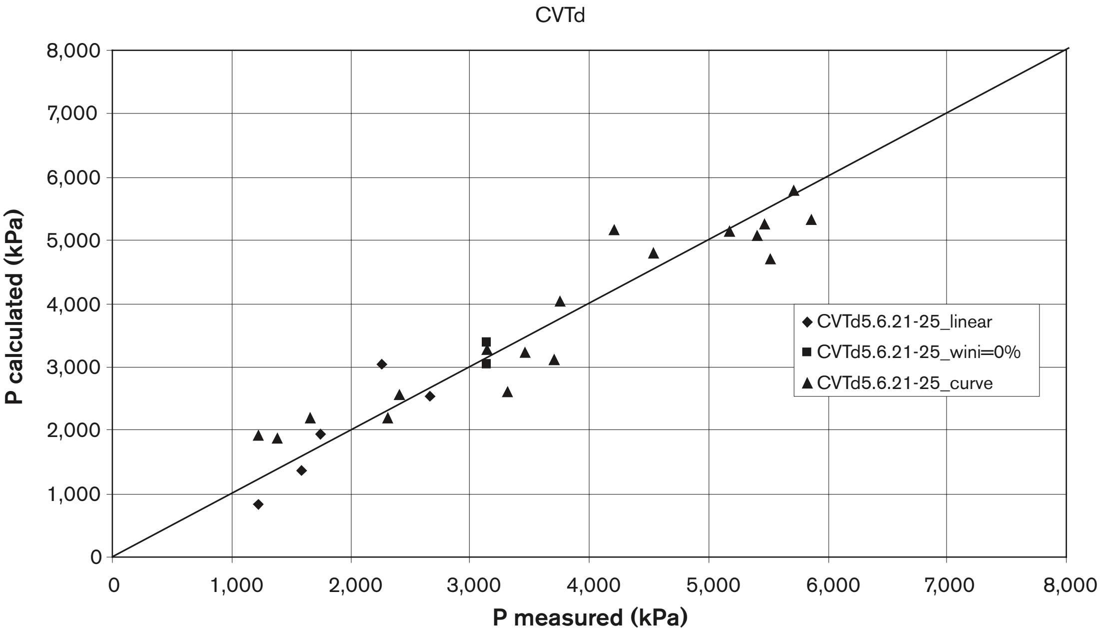


Figure 24-11. *Measured swelling pressure and calculated swelling pressure according to equation 24-2. The line shows equal pressures.*

A number of integrated studies have been conducted of KBS-3H. One interesting example is a study of how water diffuses from a wet rock surface over an air-filled gap to a free surface on a bentonite block. By measuring the increase in weight and volume of the bentonite as a function of time at different gap widths and different original water ratios in the bentonite, it is possible to check a model for this coupled process. Both a small laboratory scale and a scale of 1:5 have been studied. The study also dealt with cracking in the bentonite.

Programme

Model studies

The FEM codes Abaqus and Code Bright are the main ones used to model coupled THM processes in unsaturated buffer and backfill. Since Abaqus has shortcomings that cannot be remedied, Code Bright has become the instrument that will be used in the future for more advanced studies of processes and consequences of different wetting scenarios. There is a need to develop Code Bright, both with regard to the code's choice of mechanical and hydrodynamic constitutive relationships, and with regard to its selection of element types.

In order to be able to make relevant predictions of stress build-up and displacements, a new elastoplastic model is needed that implicitly takes into account the customary swelling pressure properties. Such a mechanical model should use the water ratio as a state variable instead of the pore pressure potential.

In order to be able to make correct simulations of moisture transport, new expressions are needed for the description of the transport coefficients. This applies both to advective fluid flow and diffusive vapour transport. General development of the handling of the gas phase is also needed, in particular to be able to describe gas breakthrough. In the code's current implementation, the water retention properties are defined as a relationship between the pore pressure potential and the degree of saturation. Instead it is desirable to have a more physically relevant representation that relates the pore pressure potential to a water ratio and a stress state. It is also an ambition to be able to handle hysteresis effects.

Finally, there is a need to increase the selection of element types in the code. At present only standard elements are implemented. Contact elements and friction elements are needed in order to be able to correctly simulate gaps and axial movements in the deposition holes.

In order to be able to develop the material models and the usability of Code Bright, the source code has been procured. Improvements of, for example, the material models and new subroutines will be implemented in the code and tested.

The international projects are continuing. In TF EBS, field tests will be modelled and the results compared with measurement results. First the two field tests in the URL Buffer/Container Experiment and the Isothermal Test will be modelled, where the interaction between dry rock and buffer will particularly be studied. Then the Canister Retrieval Test in the Äspö HRL will be used as a benchmark test, see section 24.2.5.

The model calculations in the Decovalex project will continue with a focus on the interaction between buffer and rock. The modelling of the Prototype Repository is continuing and is coupled to the development of the hydromechanical models.

Field studies

The results of measurements and samplings in the Canister Retrieval Test will be used in e.g. TF EBS for comparisons with modelling results.

The ongoing field tests in the Äspö HRL (for example the Prototype Repository and TBT) will continue with measurement of THM processes. In the event of a future mining of the repository, careful samplings and determinations will be done in a manner similar to the Canister Retrieval Test. Comparisons between measured data and modelled expected results will provide valuable information on the rock-buffer interaction during the wetting process, especially for the Prototype Repository, where natural wetting from the rock takes place in deposition holes with highly varying hydrological conditions.

New field tests will be considered. The tests in question are a full-scale simulation of a section of a KBS-3H repository and a new Prototype Repository for KBS-3V.

24.2.12 Advection

Solutes can be transported in stagnant pore water by pressure-induced flow. The process is of importance in the buffer during the unsaturated period when a net flow of water takes place into the buffer. The most important requirement on the buffer material is that it should prevent flow around the canister under saturated conditions. Solute transport in the pore water is then dominated by diffusion, see section 24.2.13. Water flow in the buffer under unsaturated and saturated conditions is dealt with in sections 24.2.5 and 24.2.6.

It was stated in SR-Can that advection could be a dominant transport process in cases where a large quantity of buffer has been lost through erosion, see section 24.2.18.

24.2.13 Diffusion

Solutes can be transported in stagnant pore water by diffusion. In this way the substances move from areas of higher concentration to areas of lower concentration. The process leads to redistribution of solutes in the pore water and thus affects the pore water composition.

The diffusion process is strongly coupled to nearly all chemical processes in the buffer, since it accounts for transport of reactants to and reaction products from the processes. Diffusion is thereby a central process for the entire chemical evolution in the buffer. The process is included in 24.2.3 about radionuclide transport.

24.2.14 Osmosis

The sealing properties of the buffer, principally high swelling pressure and low hydraulic conductivity, are intimately linked to the bentonite's ability to absorb and bind water. The binding force of bentonite is mainly dependent on the proportion of montmorillonite and on the details in the mineral structure of the montmorillonite. The binding force for a given bentonite material declines as the quantity of absorbed water increases. The relationship can be measured and is usually described with a so-called water saturation curve. Other components in a repository system – such as host rock, salt in the groundwater and bacteria – can also bind water to varying degrees, leading to competition for the water. The bentonite's swelling pressure is thereby affected, which can be described quantitatively as osmotic pressure changes.

The conditions in a deposition hole with bentonite and groundwater are typical for systems that can be described with Donnan equilibrium, which is characterized by the fact that an ion cannot diffuse freely in the system, usually due to its size. In highly compacted bentonite, the charged individual montmorillonite layers have very limited mobility due to their size and the large number of layers. The prerequisite for equilibrium in such a system is that the product of the chemical activities of the diffusible ions is equal in the groundwater and in the pore water between the bentonite layers, and that electrical neutrality prevails in both compartments. The natural and relatively high negative charge of the mineral layers is compensated by counterions. In compacted bentonite, the distribution between bentonite and water entails a counterion concentration of several moles per litre. The ion concentration in the pore water will therefore be dominated by the montmorillonite's counterions, even at relatively high groundwater salinities. An increase in the groundwater's ion concentration therefore leads to a much smaller increase in the ion concentration in the pore water. The difference in concentration increase gives rise to a new osmotic equilibrium, which leads to a reduction in the bentonite's swelling pressure. The pressure changes can be calculated, since the activity of counterions and ions in the groundwater can be determined.

Conclusions in RD&D 2004 and its review

SKB said that bentonite exposed to various sodium chloride concentrations, both in laboratory experiments and in natural conditions, reacts as can be calculated based on ion equilibrium.

SKB intended to study the effects on swelling pressure and hydraulic conductivity of other ionic species than sodium and for different types of bentonites.

SKI believes that the impact of brines should be further studied in order to provide ample statistical support for the criterion of maximum salinity and to study the effect of gradual variations between fresh and saline waters.

Newfound knowledge since RD&D 2004

SKB does not believe that the sealing properties of the buffer are affected very much by the pressure effect at high salinities under KBS-3 conditions. The sealing requirements on the tunnel backfill are lower than in the buffer. At low groundwater salinity, these requirements can be met by sodium bentonite with relatively low density. However, such a material is not suitable, since its sealing properties deteriorate at high salinities. Instead, SKB intends to use material with high density, either a mixture of crushed rock and bentonite or a natural clay material with an equivalent content of swelling minerals.

An extensive laboratory programme has been carried out covering the effects of different concentrations of sodium, calcium, magnesium, potassium and copper chloride on different bentonites and other swelling clays /24-3/. In Swedish groundwaters, calcium is the only positive ion – besides sodium – that occurs in concentrations that are of importance for osmotic effects. Most of the study was therefore concentrated on conditions with sodium and calcium chloride.

Test A2 in the Lot series at the Äspö HRL has been mined and analyzed, see section 24.2.6. The groundwater in the Äspö HRL has a total salinity of around 1.2 percent by weight and the positive ions are dominated by roughly equal mass fractions of calcium (40×0.6 gram per litre) and sodium (23×0.1 gram per litre). The swelling pressure of the exposed bentonite has been studied in subsequent laboratory experiments. The results show expected small changes as a consequence of groundwater salinity (24.2.6).

The conceptual model for ion equilibrium has been improved and the effects of swelling pressure can be calculated taking into account the chemical activity of constituent ions. Pressure calculation based on ion equilibrium agrees very well with the results of laboratory experiments for all investigated sodium chloride solutions (0.1 to 3.0 M) and bentonite densities. The laboratory experiments also show that the negative effects of high salt concentrations are much less in calcium-dominated systems than in sodium-dominated ones. Calculation of ion equilibrium shows the same effect qualitatively, but agreement is less good than for sodium-dominated systems.

Programme

SKB considers that the process has been well illuminated with respect to sodium-dominated systems and that further research is not warranted. The osmotic effects are less for calcium-dominated systems than for sodium-dominated systems, according to both laboratory experiments and theoretical calculations. The current calculation model does not, however, show equally good agreement with laboratory experiments as far as calcium-dominated systems are concerned. The model for ion equilibrium is based on an analytical calculation of the distribution of the charge-compensating ions between the mineral layers (Poisson-Boltzmann distribution). The calculation method is considered to generally underestimate ion condensation at the mineral surfaces for divalent ions, which in turn leads to an overestimation of the pressure reduction.

SKB believes that it is important to ensure a correct conceptual picture and therefore intends to continue with more advanced modelling tools in order to describe calcium-dominated systems. In-depth analytical models for calculation of the distribution of the charge-compensating ions exist within surface chemistry. The usability of these models will be studied. The charge distribution will also be studied with the aid of molecular dynamics.

24.2.15 Ion exchange/sorption

Electrical neutrality is maintained in smectite by the fact that positively charged counterions in the pore water compensate the individual negatively charged mineral layers, see also 24.2.14 and 24.2.17. The counterions are relatively weakly bound to the mineral surfaces and have some mobility, as a result of which the system strives for equilibrium with an external solution, see 24.2.14. Thus, the ions that are present in the pore water at equilibrium and the extent of their occurrence will be dependent on the groundwater chemistry and what other minerals are present in the bentonite. Redistribution of counterions is called ion exchange and is an example of a sorption process. Different types of counterions bind to the surfaces with different strengths and are hydrated to different extents depending on size and charge. This means that bentonites with different counterion distributions will have different physical properties, for example swelling pressure and swellability.

Conclusions in RD&D 2004 and its review

SKB stated that ion exchange from sodium to calcium, or vice versa, does not affect the buffer's sealing properties for the natural sodium- and calcium-dominated bentonites investigated. However, swelling potential is much lower for calcium-dominated bentonites, which leads to lower swelling pressure and higher hydraulic conductivity at low densities.

SKI pointed out that the sealing properties of Milos bentonite need to be further investigated.

Newfound knowledge since RD&D 2004

Laboratory investigations have been performed on a number of bentonites that have been ion-exchanged completely to sodium, magnesium and potassium /24-3/. Differences were found in this study in the density dependence of the swelling pressure for different counterions. The difference is particularly pronounced between mono- and divalent ions at lower densities (below buffer density).

Lot parcel A2, which was concluded and analyzed during 2006 (see section 24.2.6), has yielded a large body of material for both isothermal conditions and sharp temperature gradients. Among other things, a certain uptake of copper(II) ions in exchange position is noted. This copper stems from instrumentation tubes and from the simulated fuel canister. A comparison with previously mined Lot parcels (one-year test) shows, however, that the quantity of ion-exchanged copper does not increase with time. The released copper thus derives from initial anaerobic corrosion processes.

A general geochemical modelling of a KBS-3 deposition hole /24-26/ has taken into account the ion exchange processes and their coupling to mass transport in the buffer and in surrounding groundwater. The effect of groundwaters with different ion contents has been quantified.

Programme

The effect of divalent ions (calcium) on swelling needs to be studied in detail both for buffer density and for dispersed systems. Laboratory tests and direct measurements (for example with SAXS), analytical solutions and molecular dynamics are possible methods.

Quantification of the processes needs to be handled in a way that agrees conceptually with the picture of montmorillonite from a surface chemistry perspective. Such a treatment has also begun. Additional research, including both laboratory investigations and modelling, should be conducted.

24.2.16 Montmorillonite transformation

The desirable physical properties of the buffer, mainly swelling pressure and low hydraulic conductivity, are due to interaction between water and the montmorillonite in the bentonite. This interaction is affected by changes in the ion concentration in the groundwater and by changes in the mineral structure of the montmorillonite, see section 24.2.15. The mineralogical stability of the montmorillonite is therefore of crucial importance for the performance of the buffer.

Montmorillonite can be stable for hundreds of millions of years in its formation environment, but changes in the geochemical environment can lead to a relatively rapid change of the mineral structure, see section 24.1.11.

Minerals occur in nature with a similar structure but with great differences in layer charge. If the charge is close to zero (for example pyrophyllite), the interaction with water is insignificant, which results in radically different properties compared with montmorillonite. A slightly greater layer charge, and thereby more charge-balancing cations, leads to greater interaction with water. If the layer charge is great enough, however, more ions will be fixed to the mineral layers, resulting in less interaction with water. The end mineral in such a series is mica. The typical properties of the montmorillonite are thus a consequence of a medium-high layer charge.

The fixing of charge-balancing ions depends to a high degree to the properties of the ion. Potassium ions, for example, are bound at a lower layer charge than sodium ions, which are in turn bound at a lower charge than calcium ions. Illite is a material with a layer charge between those of montmorillonite and mica. Potassium ions are fixed to some extent in an illite clay, but not sodium or calcium ions. Fixing of multivalent ions, usually iron or magnesium, can also take place via a bridge of hydroxide, which gives a chlorite mineral.

In order for a montmorillonite to be transformed towards illite or chlorite, there must be an increase in the layer charge, which can be brought about by release of silicon, exchange of aluminium or change of valence in the structure (iron).

In the event of a transformation, secondary processes may be of importance for the performance of the buffer. Release of silicon would probably lead to precipitations of different silicon minerals, which can affect the rheological properties of the buffer (cementation), see section 24.2.9.

Conclusions in RD&D 2004 and its review

The pH conditions that are characteristic for Portland cement (pH between 13 and 14) lead to a rapid dissolution of the montmorillonite in bentonite, whereby silicon in particular is released.

Laboratory tests should be performed with natural materials of lower quality than commercial bentonites.

SKB planned to study changes in buffer properties as a consequence of reactions with iron.

The following viewpoints were offered in connection with the review:

- SKI wanted answers to the question of whether chemical alterations can cause heterogeneities in the buffer and considers it important to show that initial cementation and/or transformation to non-swelling clay mineral does not lead to a tangible deterioration in buffer properties.
- SKB needed to decide whether cement has to be avoided or limited in the near-field around buffer and canister.
- SKI feared a partial transformation of the buffer that could lead to a deterioration in properties.
- It would be valuable if SKB provided more detailed information on the expected results of ongoing long-term tests.
- SKI considered that an account is lacking of how chemical processes are to be integrated into the work with coupled processes.
- SKI called for modelling of processes that could affect the buffer's homogeneity and swelling properties, for example possible changes in the mechanical and hydraulic properties of the buffer near the canister and in the interface with the rock due to chemical alterations.
- Kasam wanted the consequences of a limited illitization to be investigated.

Newfound knowledge since RD&D 2004

SKB has carried out a laboratory study /24-27/ where bentonite was exposed to pH conditions equivalent to those in Portland cement. the study shows a relatively rapid incongruent dissolution of the bentonite.

Literature data on montmorillonite stability have been compiled with respect to processes and quantitative models. Comparative calculations have been carried out for existing models /24-28/.

Several independent laboratory analyses have been carried out on material from Lot test A2, see section 24.2.6, with respect to mineralogical alterations in the montmorillonite.

Studies of metallic iron in contact with water-saturated bentonite under anaerobic conditions have indicated a corrosion process where iron is to a certain extent absorbed into the clay matrix and alters it instead of forming stable corrosion products on the surface of the metal /24-29/. In some cases a direct transformation of the smectite to non-swelling iron-rich phases has been found /24-30/.

Programme

A laboratory study will be carried out in cooperation with Nagra. The main purpose is to verify the models and parameter values that SKB is using for montmorillonite transformation.

Test parcel S2 in the Lot series at the Äspö HRL will be concluded and analyzed in accordance with the analysis programme for the A2 test, see section 24.2.6. The already analyzed A2 test was performed under accelerating conditions, i.e. at elevated temperature and with local additives. The S2 test, on the other hand, was performed under as buffer-like conditions as possible.

Geochemical modelling is planned in the Lot project, where the stability of montmorillonite is specifically taken into account.

Continued analyses of the Lot parcel are being carried out. Geochemical modelling is planned in the Lot project, within Äspö TF EBS.

When it comes to iron coupled to montmorillonite transformation, it is relevant to study both the influence of iron in its various forms (metallic or ionic) and how structural iron in the montmorillonite affects its properties. Metallic iron can act as a reducing agent and structural iron is redox-active, which makes it likely that these factors can interact. An example of ongoing work within SKB that sheds light on both of these aspects is the field test "Alternative buffer materials". In this test, 13 different buffer materials with varying contents of structural iron are exposed to an approximately 130°C hot iron canister.

24.2.17 Dissolution/precipitation of impurities

The fraction of the buffer material that is not montmorillonite consists of other common minerals such as quartz, feldspars, gypsum, calcite and small amounts of organic material. The secondary minerals are included here among the impurities in the material, since they do not contribute to the sealing properties of the buffer. In the repository environment, these minerals can be dissolved and sometimes re-precipitated depending on the prevailing conditions. This redistribution of minerals can alter the sealing properties of the buffer, as well as the rheological properties so that the material becomes stronger and more brittle (cementation). Dissolution and precipitation of impurities also affects the ion exchange and sorption processes, see section 24.2.15, by affecting the local pore water chemistry.

Conclusions in RD&D 2004 and its review

The ongoing laboratory tests within the Lot project are expected to provide an answer to the question of whether the precipitations are due to vaporization of incoming water during the water saturation phase, or whether the process continues even after full water saturation.

The following viewpoints were offered in connection with the review:

- More work is required to investigate impurities and accessory minerals. A qualitative account of the way in which they can affect long-term safety is needed for all components.
- SKI wanted answers to the question of whether chemical alterations can cause heterogeneities in the buffer and considers it important to show that initial cementation and/or transformation to non-swelling clay mineral does not lead to a tangible deterioration in buffer properties.
- SKB may need to use bentonite models that take into account thermodynamic properties for more complex clay minerals.
- SKI considered that an account is lacking of how chemical processes are to be integrated into the work with coupled processes.
- SKI called for a description of the modelling tools that handle chemical processes, for example precipitation reactions driven by the temperature gradient.

  SKI called for modelling of processes that could affect the buffer's homogeneity and swelling properties, for example possible changes in the mechanical and hydraulic properties of the buffer near the canister and in the interface with the rock due to chemical alterations.
- SSI pointed out that analogues can be a way to study cementation.
- Kasam thought that SKB should propose limits for the concentration of impurities in the bentonite buffer.
- Kasam also thought that the function of the buffer as a consequence of combinations of impurities should be studied.

Newfound knowledge since RD&D 2004

Test parcel A2 (see section 24.2.6) in the Lot project was mined and analyzed in 2006. The bentonite was fully water-saturated, and a minor redistribution of sulphate minerals in particular (gypsum, anhydrite) was observed. The fractions of the buffer material that had been exposed to high temperatures (130–80°C) exhibited a small but significant cementation.

SKB has carried out a general modelling of the geochemical evolution in a deposition hole according to KBS-3V /24-1/. The results show a redistribution of both silicon and sulphate minerals under the influence of the thermal gradient. Silicon is precipitated in the outer, cooler parts of the buffer, while anhydrite is enriched nearest the canister surface.

Programme

Test parcel S2 in the Lot series in the Äspö HRL will be concluded and analyzed in a manner similar to the analysis programme for the A2 test, see section 24.2.6. In the S2 test, the buffer material has been exposed to KBS-3 conditions, in other words without elevated temperatures or added chemicals.

Most of the solution/precipitation processes are well known and can be modelled for less complex systems. Certain transport and reaction mechanisms that are specific for the bentonite material have not yet been fully elucidated, however. In connection with the Lot project, a programme has therefore been initiated for the purpose of carrying out geochemical modelling of the field tests with new simulation tools. Another goal of the programme is to achieve a better conceptual understanding of the processes in bentonite pore water.

24.2.18 Colloid release/erosion

The buffer and the backfill in a KBS-3 repository consists for the most part of microscopic smectite particles. During water saturation the particles in the highly compacted blocks will be subjected to very strong repulsive forces. This causes the buffer to swell and the empty spaces in the deposition holes to be filled up. The buffer can also swell short distances into the fractures in the walls of the deposition hole. Water that flows into the fractures could shear off the outermost particles and expose new particles to the flowing water. This problem is exacerbated if the water has very low ionic strength.

Conclusions in RD&D 2004 and its review

SKI thought that SKB should first of all investigate whether buffer erosion and piping is a problem in the reference concept KBS-3V, especially the effect of glacial groundwater.

Newfound knowledge since RD&D 2004

The possibility cannot be ruled out today that the groundwaters in Forsmark and Laxemar will have very low salinities after a glaciation. This may cause the bentonite to form colloids and be eroded away.

The very rough model that was used in SR-Can showed that very large quantities of buffer could disappear. It is clearly imperative to acquire a better knowledge and understanding of the erosion process in preparation for SR-Site.

Up to December 2006, three different types of tests had been conducted in the bentonite erosion project.

A number of experiments have been performed to study how ionic strength and gravitation affect bentonite solution stability, see Figure 24-12.

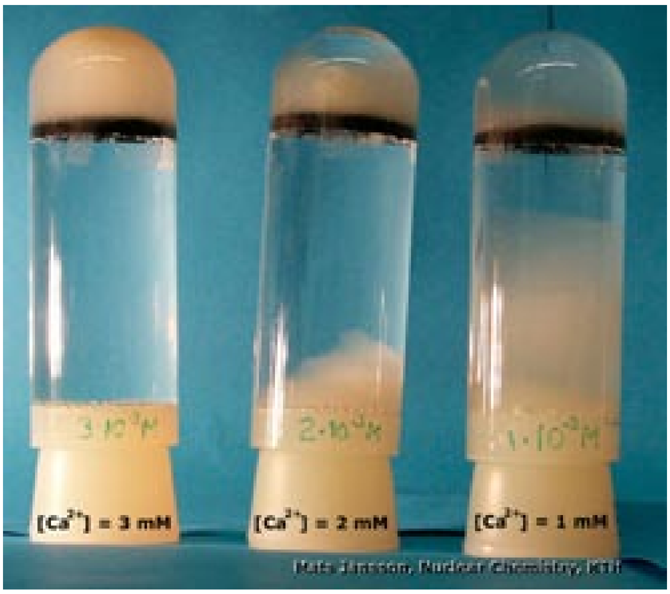


Figure 24-12. *0.1 gram of sodium montmorillonite was dissolved in 10 millilitres of distilled water. A screen was placed on top of the montmorillonite solution with an O-ring as support. Solutions with varying* Ca^{2+} *concentration were added before the test tube was turned upside down.*

In another experiment, changes in the concentration profile during bentonite swelling were studied. When the experiment was interrupted, samples were taken in the bottle and a concentration profile was obtained, see Figure 24-13.

A long-term test where bentonite swelling/dissolution was studied in an artificial water-conducting fracture was started in July 2006. Figure 24-14 shows a schematic illustration of the experimental set-up. Figure 24-15 shows how the bentonite has expanded out of the container and starts to disperse into the fracture. A number of similar experiments are planned where pure sodium and calcium bentonite will be used.

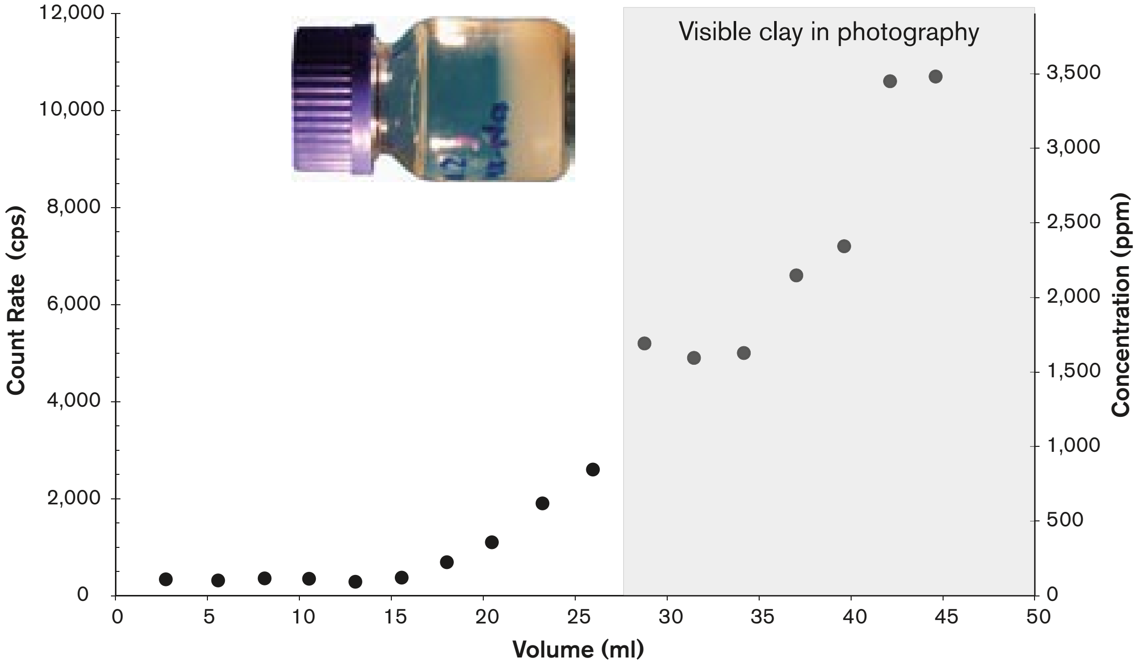


Figure 24-13. *Concentration profile in the bottle when the experiment was interrupted.*

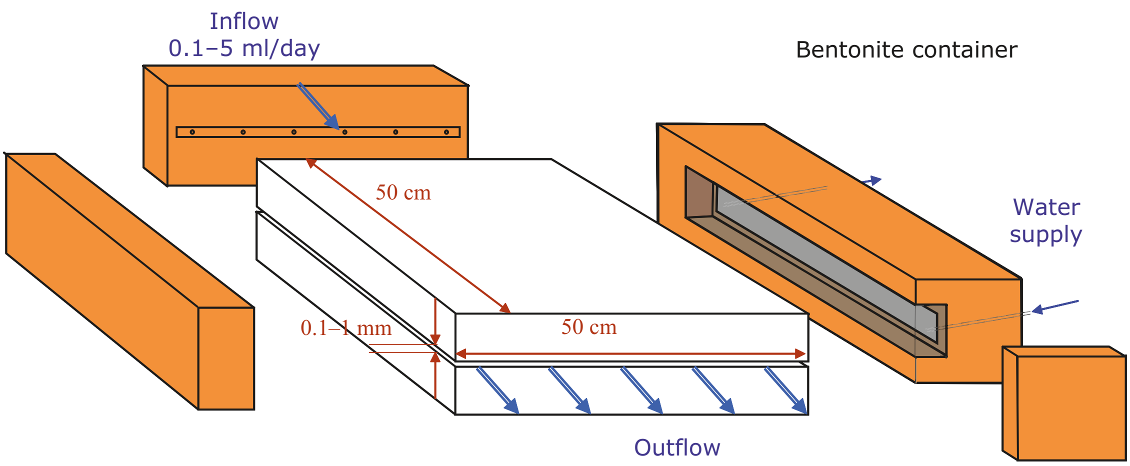


Figure 24-14. *Schematic illustration of experimental set-up. To simulate a fracture, two sheets of plexiglas were placed close to each other (1 mm). A bentonite container was placed at one end. The bentonite was saturated with water via a channel on the rear of the container before distilled water began to be pumped through the fracture in a direction perpendicular to the bentonite container.*

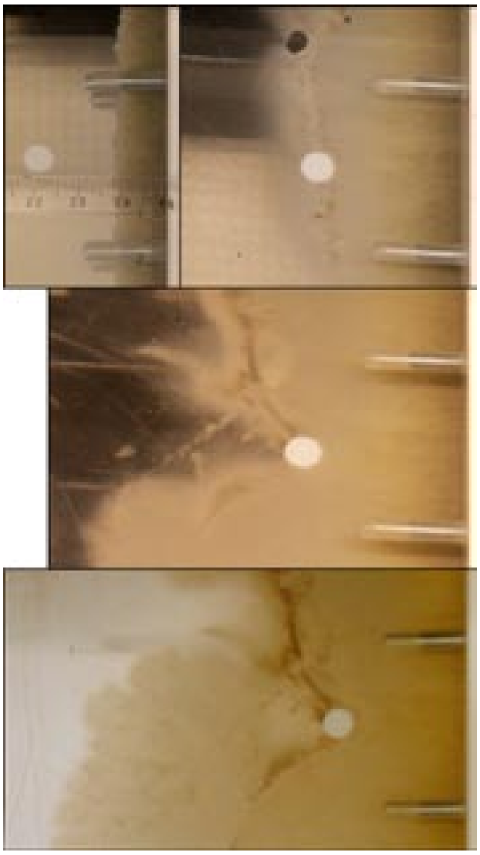


Figure 24-15. Changes in a bentonite profile in a part of the artificial fracture. The photograph at the upper left was taken when the bentonite was fully saturated, before water had begun to be pumped through the fracture. At the upper right, water had been pumped through the fracture for four weeks. The middle picture was taken after 18 weeks of pumping, and in the lower picture water had been pumped through the fracture for 27 weeks.

Programme

SKB has started a project (Bentonite Erosion) to study erosion of bentonite in dilute waters. The purpose of the project is to develop a quantitative model to judge the extent of the erosion process in the safety assessment SR-Site. The project is planned to have a duration of two years.

The different phases in the project are:

1. Literature studies and information gathering.
2. Modelling:
   - Gel/sol behaviour and release of particles to groundwater.
   - Importance of fracture apertures and flow fields.
   - Molecular dynamic modelling.
   - Reactive transport – especially Na/Ca exchange.
3. Experiments:
   - Permeability in dilute systems.
   - Rheological properties in dilute systems.
   - Swelling pressure in dilute systems.
   - Critical Coagulation Concentration (CCC).
   - Cation exchange and ion exchange processes.
   - Colloid filtration in impurities.
   - Importance of impurities.
   - Flow in fractures.
4. Workshops.

24.2.19 Radiation-induced montmorillonite transformation

Conclusions in RD&D 2004 and its review

Montmorillonite in the buffer can be broken down by gamma radiation. The result of this is a decrease in the montmorillonite concentration. However, experiments have shown that the accumulated radiation dose to which the bentonite will be exposed in a final repository does not cause any measurable changes in the montmorillonite concentration.

Newfound knowledge since RD&D 2004

It is shown in /24-31/ that a dose of $4 \cdot 10^{18}$ alpha particles per gram of bentonite completely destroys the material. According to the radionuclide transport calculations in SR 97 /24-32/, the total alpha decay of $4 \cdot 10^{18}$ disintegrations per gram is only reached after a million years, and only in the buffer nearest a damaged canister. The conclusion in SR-Can was that the process is unimportant for the repository's safety. This conclusion still holds, but the original reference for the effect of alpha radiation on bentonite cannot be said to have the quality that is required for SR-Site.

Programme

The existing literature will therefore be reviewed to see if better data can be found. It is also possible that experiments will be necessary.

24.2.20 Radiolysis of pore water

Gamma radiation that penetrates through the canister can decompose pore water by radiolysis, forming OH radicals, hydrogen, oxygen and several other components. The oxygen is consumed rapidly by oxidation processes that affect the redox potential, while the hydrogen is transported away. The canister's wall thickness is, however, sufficient so that the effect of gamma radiolysis on the outside is negligible, see section 23.1.3.

24.2.21 Microbial processes

Microbial processes can give rise to the formation of gases and sulphide under certain conditions. Gas formation could result in mechanical stresses in the repository, while sulphide could corrode the copper canister. In order for microbial formation of sulphide to be of any importance for the life of the canister it must take place very close to the canister's surface.

Conclusions in RD&D 2004 and its review

SKB described studies of copper corrosion in alkaline water in RD&D-Programme 2004.
A programme to investigate the bacterial corrosion of copper has been under way for several years now. The results showed that introduced sulphate-reducing bacteria could not survive in bentonite with a density of 2,000 kg/cm^3 /24-33 to 24-36/.

SKI drew SKB's attention to the inadequacy of the available material concerning the ability of microbes to survive in the bentonite, especially sulphate-reducing bacteria. SKI noted that certain buffer properties (such as the occurrence of microbial activity) had been formulated as preferences rather than requirements and wondered whether this means that such properties will be given greater weight in the safety assessment. This applies, for example, to the analysis of the importance of microbial activity in the buffer for copper corrosion. As knowledge of the survival capabilities of microbes increases, SKI thought that it is becoming increasingly difficult to exclude microbial activity through environmental factors. SKI therefore considered it necessary to show to effects of microbial activity in the safety assessment. In the case of copper corrosion, it is not sufficient to study the processes in the bulk of the bentonite; the interface processes must also be analyzed, such as the possibility of the occurrence of a biofilm on the canister surface.

Newfound knowledge since RD&D 2004

In the background material for RD&D-programme 2004 /24-33 to 24-36/, strains of bacteria from the laboratory had been used for the most part, which has been criticized since naturally occurring bacteria are generally considered to be more viable than laboratory strains. The research since RD&D-Programme 2004 has therefore concentrated on studying naturally occurring bacteria. It was long ago demonstrated, but is not generally known, that clays are excellent preservatives for bacteria. Before freeze drying became standard, scientists stored bacteria in dried clay. New results show that commercial bentonite, in this case MX-80, contains sulphate-reducing bacteria. An example is *Desulfovibrio africanus*, which has high temperature and salt tolerance /24-37/. A more thorough investigation of the DNA content of this buffer material has shown that a large number of different DNA signatures occur with a clear dominance of Gram-positive bacteria /24-38/. Thus, it has been established that buffer and backfill of MX-80 will contain a large number of different bacteria (including sulphate-reducing bacteria) that are activated when the bentonite absorbs water.

Research on microbial life in deep groundwaters has been going on since 1987 and has led to a hypothesis where hydrogen gas is of central importance as an energy source and electron donator /24-39/. New experiments at the Äspö HRL have shown that hydrogen increases the microbial formation rate of acetate and sulphide. These processes are coupled, but are carried out by different groups of bacteria. The maximum sulphide formation rate with a supply of hydrogen under natural conditions at a depth of 450 metres was 0.14 milligram of sulphide per day. The systems reached just over 7 milligrams of sulphide per litre after 100 days. Clearly, sulphide can be formed rapidly by bacteria at repository depth and a high concentration can be reached under optimal conditions, especially with a high hydrogen concentration, for example from iron corrosion. These results were new when the full-scale Lot test and the Canister Retrieval Test were mined in 2006. The investigations of these buffer materials showed that acetate- and sulphide-forming bacteria were generally present in the buffer at a density bordering on 1,900 kg/cm^3. Unsaturated buffer in the Canister Retrieval Test with a density of just over 2,000 kg/cm^3 also contained living acetate- and sulphide-forming bacteria. At a combination of high temperature, a density of 2,000 kg/cm^3, full swelling pressure and full saturation, however, bacteria could not be detected (with a few exceptions).

Programme

Formation of copper sulphide on copper surfaces in bentonite with different swelling pressures has been studied under natural conditions and pressures at repository depth in model systems /24-37/. The quantity of copper sulphide formed decreased linearly with increasing density. The results of these experiments thus support the current model where microbial activity is not possible at full density. New follow-up experiments are being conducted where limit values of density for microbial activity in bentonite will be established to be used in the safety assessments. Quantitative data on sulphide formation and diffusion will also be obtained so that the safety assessments can include microbial activity instead of, as before, excluding microbial sulphide formation based on environmental factors.

Investigations of microbe occurrence will continue after experiments in the Lot series in the Äspö HRL are discontinued.

24.2.22 Radionuclide transport – advection

The main function of the buffer is to guarantee that diffusion is the dominant transport mechanism around the canisters. With an MX-80 buffer with a water-saturated density of 2,000 kg/m^3, the transport capacity for diffusion is at least 10,000 times higher than that for advection.

In SR-Can, radionuclide transport is also calculated for a case where the buffer has been lost and mass transport is dominated by advection.

24.2.23 Radionuclide transport – diffusion

The transport of radionuclides through the buffer is mediated by different diffusion mechanisms. It has been established that certain cations can have high diffusivities (be transported more efficiently).

When bentonite has such a high density that the electrical double layers between two planes overlap, a phenomenon known as anion exclusion occurs. Anions cannot penetrate into the interlamellar pores due to the electrostatic forces between the negatively charged surfaces and the anion. Anion exclusion significantly reduces the porosity available for diffusion of anions. The effect of anion exclusion becomes less at high salinities, and in crushed rock/bentonite mixtures it is negligible.

Conclusions in RD&D 2004 and its review

In SKI's opinion, SKB has a good programme for studying radionuclide migration in the buffer, and further enhancing their understanding of surface diffusion, anion exclusion and complex formation with organic substances seems to be a correct priority.

Kasam was of the opinion that an overall thermodynamic model should be established for the transport (diffusion) of the most important radionuclides (for example radionuclides of caesium and iodine) through the bentonite.

Newfound knowledge since RD&D 2004

As a part of SR-Can, a report has been published /24-40/ describing diffusion and sorption of radionuclides in bentonite. It deals with the derivation and selection of migration parameters for radionuclides in a buffer of MX-80 bentonite. Recommended values for the following parameters, together with associated uncertainties, were derived and documented for 38 elements and oxidation states:

- diffusion-available porosity (ε),
- effective diffusivity (D_e),
- distribution coefficient (K_d).

Because of the conditional nature of these parameters, particularly of K_d, they were derived specifically for the conditions expected to be relevant for consequence calculations in the safety assessment. K_d values were generally evaluated for specific pore water compositions and solid/water phase ratios representative of MX-80 compacted to a dry density of 1,590 kg/m^3. For K_d, this was done for several pore water compositions to reflect variations in geochemical boundary conditions. D_e and ε were derived as a function of density. Parameter derivation was based on systematic datasets available in the literature and/or on thermodynamic models. The uncertainties in the parameters were assessed for a given set of conditions from the safety assessment and as a function of variability in these conditions.

Finally, apparent diffusivity (D_a) values were calculated from the derived parameters and compared with independent experimental results to arrive at self-consistent sets of migration parameters.

Programme

At present it looks as though data for sorption and diffusion from /24-40/ will be sufficient for SR-Site. It is, however, possible that some data will be updated if new knowledge is forthcoming.

SKB has started a project to verify the model for mass transport between the buffer and the flowing water in a fracture in the rock. The purpose is to study the transport of radioactive tracers between bentonite and flowing water in an artificial fracture on a laboratory scale.

24.2.24 Radionuclide transport – sorption

The surface of smectitic clays has a permanent negative charge. The charge imbalance is neutralized by an exchange of cations between the layers. When the clay is water-saturated, the exchangeable cations are hydrated and an electrical double layer is formed in the water/clay interface. The charge-compensating cations can easily be exchanged for other cations from the solution that is in contact with the clay surface. Sorption of cations in smectite minerals can be described as ion exchange reactions and modelled with thermodynamic equilibrium constants or selectivity coefficients. Ion exchange is the typical sorption mechanism for alkali and alkaline-earth metals. Many transition metals are also sorbed via ion exchange.

Radionuclides can also be sorbed via reactions with the surface and form surface complexes. Most actinides and lanthanides form surface complexes. Nuclides sorbed as surface complexes cannot be transported by surface diffusion.

SKB does not consider sorption in bentonite to be a prioritized research area. However, existing data will be updated with new information prior to each new safety report.

24.2.25 Speciation of radionuclides

The speciation of radionuclides is of importance for sorption and diffusion in the buffer. It is influenced by what speciation the nuclide had at the boundary to the buffer, i.e. inside the canister, but also by the chemical conditions in the buffer. The speciation process is discussed in section 22.2.14.

24.2.26 Radionuclide transport – Colloid transport through bentonite

The buffer is supposed to prevent colloids and radionuclides from escaping from a damaged canister.

Conclusions in RD&D 2004 and its review

It was reported in RD&D-Programme 2004 that organic colloids can diffuse through bentonite. In SR-Can, however, it was assumed that inorganic colloids are filtered by the buffer if its saturated density exceeds 1,650 kg/m^3. This value was based on Japanese studies with gold colloids.

Newfound knowledge since RD&D 2004

To verify these conclusions, SKB has conducted a project on transport of inorganic colloids through bentonite. Colloid filtration in compacted bentonite is being studied to determine whether colloids are effectively filtered by bentonite compacted to dry densities relevant for the final repository, and to study which factors limit colloid diffusion. Another underlying purpose is to study whether inorganic and organic colloids have different diffusion properties. Previous experimental studies have show that small organic humic colloids can diffuse through compacted bentonite, and that they increase the transport of radionuclides that are strong sorbed to bentonite. Gold colloids are effective filtered by compacted bentonite. Some transport of gold colloids takes place in bentonite of lower density (1,0 g/cm^3), but very slowly, see Figure 24-16. The conclusion is that the premises used in SR-Can are valid.

Programme

In order to determine whether there is a specific filtration limit for colloids, diffusion of gold colloids with a diameter of 5 nanometres is currently being studied. It is possible to carry out similar diffusion experiments with gold colloids with a diameter of 2 nanometres, as well as with other biological or inorganic particles with smaller diameters.

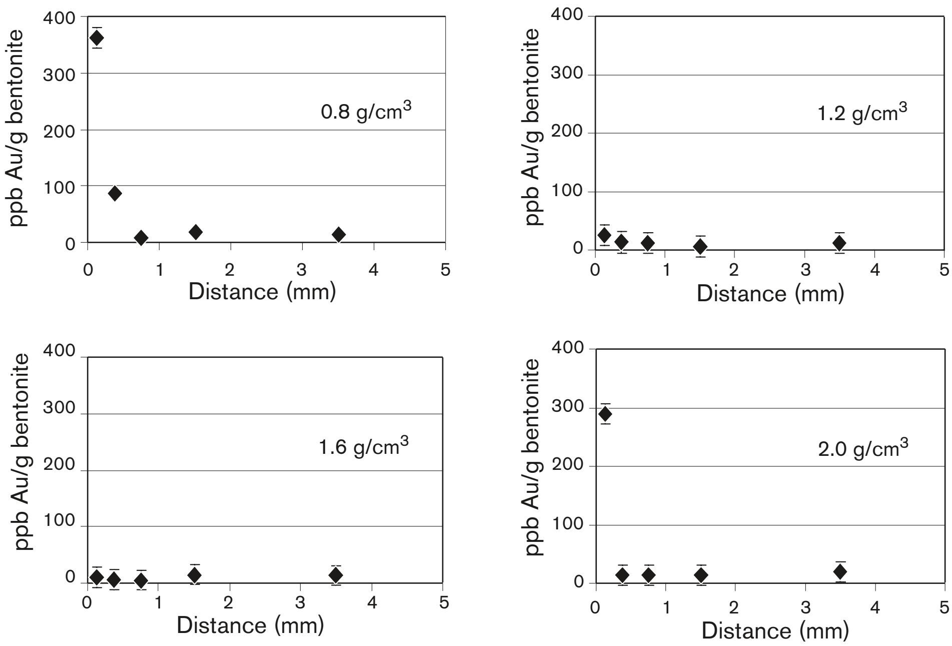


Figure 24-16. Concentration profiles of gold in the compacted bentonite pellets that were used in the diffusion experiment. The high value in the first data point in the graph, 2.0 g/cm³, is presumably the result of contamination, since the swelling pressure at the high dry density caused deformation of the metal filter.

25 Backfill

The backfill in the tunnels is not in itself a barrier in the KBS-3 concept. It is, however, necessary in order for the buffer and the rock to have the desired function. The requirements made on the backfill are:

- The backfill must have a stiffness that minimizes the upward expansion of the buffer. The density of the buffer is thereby maintained.
- The backfill must have a hydraulic conductivity that is comparable to that of the surrounding rock. Otherwise the deposition tunnels may act as conductive pathways that influence the water flux in the repository.
- The backfill must exert a given swelling pressure against the roof to maintain a swelling capacity that can seal possible effects of piping and creep movements in the backfill.

The backfill may not have any adverse effect on the barriers in the repository, which imposes some requirements on its chemical composition.

25.1 Initial state of the backfill

25.1.1 Variables

More or less the same set of variables is used to describe the backfill as for the buffer, see Table 24-1.

25.1.2 Geometry

The dimensions of the backfill are given by the dimensions of the tunnels.

25.1.3 Pore geometry

The initial pore geometry (porosity) of the backfill follows trivially from its material specifications.

25.1.4 Radiation intensity

The initial radiation intensity in the backfill is negligible.

25.1.5 Temperature

A determination of the initial temperature in the backfill is trivial. It will be close to the initial temperature of the rock.

25.1.6 Water content

The initial water content in the backfill follows trivially from its material specifications. It is a parameter that can be checked when the material is mixed.

25.1.7 Gas contents

The initial gas content in the backfill follows trivially from its specifications.

25.1.8 Hydrovariables

The hydrovariables are water flow, water pressure, gas flow and gas pressure. Initially it is relevant to describe gas and water pressure. Flows do not occur initially in the backfill. At emplacement, the repository will be open to atmospheric pressure. This gives a gas pressure (air) of 1 atmosphere (approx. 0.1 MPa) and a water pressure of 0–0.1 MPa in the surrounding host rock. On the other hand, as in the buffer there will be an initial negative pore water pressure in the unsaturated backfill, which drives the inward transport of water along with the positive pressure from the water in the rock. This negative pore pressure is dependent on which concept is chosen.

25.1.9 Load situation

The swelling pressure begins to build up when buffer and backfill come into contact with external water. Initially there is no swelling pressure.

25.1.10 Backfill composition

The quantity and composition of impurities is mainly dependent on which backfill concept is chosen. The consequences of these impurities must be evaluated for each concept. See section 25.2.2.

25.1.11 Montmorillonite composition

See section 25.2.2.

25.1.12 Pore water composition

The water in the backfill is a blend of the bentonite's original water and water added at deposition. Its composition is mainly dependent on which water is added.

25.1.13 Engineering materials

See section 24.2.16 (iron and cement).

25.2 Processes in the backfill

25.2.1 Overview of processes

Basically the same processes take place in the backfill as in the buffer, although sometimes on a different scale. Moreover, the crushed rock, if any (defined as an impurity in the backfill), plays a somewhat different role than the impurities in the buffer, for example by contributing to sorption. The research programme for the various processes in the backfill is dealt with in the following sections.

25.2.2 Integrated studies – composition and function

The properties of the backfill are determined not only by its composition, but also by its density and the salinity of the groundwater. Together with Posiva, SKB is conducting a development project where different backfilling concepts are being developed and compared with stipulated requirements. A backfilling concept is defined by the composition of the backfill material and the installation method, which determines what density can be achieved. The exact composition of the backfill, and requirements on density, will be chosen when the necessary data are available from the site in question.

Conclusions in RD&D 2004 and its review

The goal of the project "Backfilling and Closure of Tunnels and Rock Caverns" is to develop materials and technologies for backfilling and closure of a deep repository for spent nuclear fuel of the

KBS-3 type. The conclusion from Phase 1 of the project was that the backfilling concept where material is compacted in situ in the tunnel and the concept where pre-compacted blocks and pellets are placed in the tunnel will be further studied.

Like SKB, SKI drew the conclusion that pure crushed rock is ruled out as backfill in deposition tunnels, while the alternative involving the 30/70 mixture of bentonite and crushed rock needs to be further investigated. SKI also supported SKB's plans to investigate the Friedland clay and compacted block alternatives. SSI also commented that it is good that SKB has intensified its research, development and demonstration programme in order to arrive at a working concept to backfill the tunnels.

SKI pointed out in its review that SKB should, prior to future applications, present a concept for backfilling of tunnels that meets the requirements made on repository function.

Newfound knowledge since RD&D 2004

In the Baclo project, different combinations of materials and installation methods have been studied and compared with the performance indicators expressed in SR-Can. The conclusion of this work is that the installation of pre-compacted blocks and pellets of bentonite-like materials and bentonite with a low smectite content give the greatest margin to the performance indicators. This work is further described in Part III, Chapter 15.

The flow tests performed in the Backfill and Plug Test indicate that the hydraulic conductivity in the backfill is higher than the performance indicator 10^{-10} metres per second.

Programme

The Baclo project will be focused on piping and erosion during the backfilling operation, see further Part III, Chapter 15. The processes involved in the healing of any pipes and water saturation and homogenization of the backfill will also be investigated.

The deformation properties of the backfill will also be tested in situ in the Backfill and Plug Test project.

25.2.3 Radiation attenuation/heat generation

The process can be neglected in the backfill.

25.2.4 Heat transport

Conclusions in RD&D 2004 and its review

The heat transport properties of the backfill were found to be of little importance for the temperature evolution in the near-field.

Newfound knowledge since RD&D 2004

New calculations /25-1/ confirm that the heat transport properties of the backfill (within previously assumed intervals) are of negligible importance for canister temperature. This is also true of the variable that determines the dimensions of the repository, namely the maximum temperature of the bentonite at the canister's base surfaces in dry deposition holes (cf. Figure 24-2 in Chapter 24).

Programme

The heat conduction properties of all new backfill materials are determined and/or estimated. The conclusion that heat transport properties are of no importance for canister temperature is being verified by calculations.

25.2.5 Freezing

See section 24.2.4 about freezing in the buffer. This is basically the same process as takes place in the backfill when the material freezes. The difference is that the specific surface area of the proposed backfill materials is less (and the temperature is thus higher) when all water begins to freeze. The temperatures can also be lower in tunnels and shafts above the repository level. Freezing of the water in the backfill can thus not be ruled out.

Freezing of backfill is not addressed in RD&D-Programme 2004. Nor has any specific research been conducted in this area, except for related geotechnical applications. The process is, however, included in SR-Can. There it is noted that the question of whether freezing can occur in the backfill at repository level is important and that separate studies of when freezing occurs and its consequences will be carried out for both buffer and backfill.

Both theoretical and laboratory studies of freezing will be conducted and the long-term consequences for these materials will be investigated. The following is planned:

- Theoretical studies of the freezing mechanism and its consequences in the form of elevated pressures against the surroundings.
- Laboratory studies of the freezing mechanism as support for the theories.
- Long-term consequences in the form of ice lens formation, water transport with growth of the ice lenses, accompanying expansion pressure against the rock and healing of the inhomogeneities after thawing will be investigated both theoretically and in the laboratory.

25.2.6 Water transport under unsaturated conditions

The differences in the properties (e.g. permeability, negative pore pressure) of in situ-compacted 30/70 mixture, pellets and blocks of for example Friedland clay are very great and result in a great difference in the wetting rate. See also section 25.2.2.

Conclusions in RD&D 2004 and its review

The wetting of the buffer through the backfill can be significant if the rock around the deposition hole is very dry. Theoretical studies of this were planned.

SKI considered that, just as for the buffer, SKB needs to systematically analyze the features, events and processes (FEPs) that can cause a deterioration in long-term function of the backfill. Such long-term effects do not affect the unsaturated processes, however.

Newfound knowledge since RD&D 2004

Investigations of the wetting of the backfill have been conducted mainly via model calculations and measurements in the field tests at the Äspö HRL.

Model calculations of the water saturation process in the backfill tunnels and its effect on the wetting of the buffer have been carried out for SR-Can /25-2/. In situ-compacted 30/70 mixture and in situ-compacted Friedland clay were used as backfill materials. The most important conclusions from the calculations were as follows:

- The time to complete saturation varies from 0.5 year for the 30/70 backfill with one metre between the fractures to more than 150 years for Friedland Clay with 25 metres between the fractures.
- The influence of the backfill material on the wetting rate is strong due to the difference in hydraulic conductivity between the different types of backfill material, which seems to be the property that controls the wetting rate. The difference in time to achieve full saturation of Friedland Clay is about ten times longer than for 30/70 backfill if the fracture transmissivity is sufficiently high (greater than 10^{-10} m^2/s).

- The influence of fracture frequency is strong since very little water is transported in the rock matrix at a hydraulic conductivity of 10^{-13} metres per second. The time to full saturation is almost proportional to the fracture distance.
- The influence of transmissivity is insignificant except for the combination of the lowest transmissivity (10^{-11} m^2/s) and 30/70 backfill, since the transmissivity is high enough compared to the hydraulic conductivity of the backfill to yield a high water pressure in the fracture/backfill interface and since the water inflow is thus hindered by the backfill and not the fracture.
- The influence of high matrix permeability (10^{-12} m/s instead of 10^{-13} m/s) is not very strong for the 30/70 and Friedland Clay (a factor of 1–2 faster), since the average hydraulic conductivity (including the fractures) is not affected very much and the hydraulic conductivity in the backfill is still much higher than in the rock matrix.
- If there are no escape routes for the air in the initially unsaturated backfill other than through the host rock, the trapped air will influence the saturation process. The trapped air then forms a "bubble", which holds back the inflowing water and delays the saturation. This effect is more important the more permeable the rock is. When the water inflow from the rock is high, the gas diffusion rate will control the water saturation process.

In situ-compacted Friedland clay with low density has been assumed. If pre-compacted blocks are used instead, the density will be higher, the hydraulic conductivity lower and the time to full saturation considerably longer. Renewed calculations are needed to study this.

The measurements of the water saturation process in the Prototype Repository suggest that the wetting of the 30/70 mixture has gone faster than expected, which may indicate the occurrence of piping in the backfill.

Programme

The measurements in the Prototype Repository will continue. When the repository is mined, sampling and water ratio determination will show whether the water saturation process for the entire backfill has gone as rapidly as the measurements suggest.

Present-day knowledge of the wetting processes in blocks of e.g. Friedland clay and in pellet fill is insufficient to permit a good prediction of the wetting rate. Laboratory tests will therefore be performed with these materials. The problem is reminiscent of that for the buffer, with similar swelling of blocks and compression of pellet fill. The advanced coupled hydromechanical models that have been developed for the buffer should therefore also be applied to the backfill.

The wetting process in a backfill with blocks of Friedland clay and with bentonite pellets in the rock-block gap will be studied, both on a small scale in the laboratory for the separate phases and in test in the Äspö HRL with the composite concept. Both high and low inflows from the rock will be studied.

Parts of the model calculations described above will be re-done with backfill of blocks and pellets of Friedland clay.

25.2.7 Water transport under saturated conditions

The process is identical to the equivalent process for the buffer, right down to a few important differences in the properties, especially for the concept with the 30/70 mixture. Water permeability after saturation is determined by the backfill's content of montmorillonite and other clay minerals and the composition and density of the pore water, but also by its homogeneity. In contrast to buffer, backfill of crushed rock mixed with bentonite cannot be made highly homogeneous. This is partly because the mixing procedure does not produce a uniform distribution of bentonite and crushed rock, and partly because application and compaction cannot be done as effectively over the whole cross-section and length of the backfill.

Due to problems in obtaining sufficiently high density and homogeneity for 30/70 mixture that is compacted in situ, in combination with the great influence of saline groundwater and thereby problems obtaining sufficiently low hydraulic conductivity, the alternative concept with blocks of e.g. Friedland clay (or 30/70 mixture) and bentonite pellets has been put forward as a main concept.

Conclusions in RD&D 2004 and its review

The conclusion was that investigation of hydraulic conductivity in mixtures would continue, mainly in the Backfill and Plug Test project, while investigations of other concepts would be done in a separate project (Baclo).

In its review, SKI commented in more general terms that SKB should analyze the features, events and processes (FEPs) that cause a deterioration in long-term function for the backfill as well. Specifically, they said that the Milos bentonite should be further tested, since the density achieved in the Prototype Repository is not sufficient. The interpretation of this statement was that they drew the same conclusion as SKB regarding the difficulties of achieving sufficient density for mixtures compacted in situ.

Newfound knowledge since RD&D 2004

It is stated in SR-Can that blocks of either Friedland clay or 30/70 mixture are required to achieve sufficient density in the backfill. In such cases, both materials meet the requirements on hydraulic conductivity. But Friedland clay has much lower hydraulic conductivity and thereby greater margins than the 30/70 mixture. Due to problems with healing of erosion pipes in the 30/70 mixture, Friedland clay has been designated the main candidate.

In situ measurement of hydraulic conductivity in the backfill after full water saturation in the Backfill and Plug Test has been carried out after RD&D-Programme 2004. The measurements have been made on the compacted material of 30/70 mixture. Two types of measurements have been performed:

- The average permeability over a large cross-section has been evaluated by applying a constant hydraulic gradient between the filter mats and measuring the flow.
- Local permeability has been evaluated around filter tips installed in the backfill by applying a constant water pressure in the filter and measuring the flow.

The results are summarized in Figure 25-1 together with results from laboratory measurements. The results clearly show that the dry density 1,700 kg/m^3, which was reached in central parts of the backfill in the field tests, results in a hydraulic conductivity greater than 10^{-10} for water with a salinity of 1.2 percent.

Laboratory measurements of the hydraulic conductivity of different clays and clay mixtures that are candidate materials for backfill have been performed in the Baclo project /25-3/. A summary of these results for water with 3.5 percent salinity is shown in Figures 25-2 and 25-3. The results show that the requirements on dry density to achieve a hydraulic conductivity of less than 10^{-10} metres per second are very different. For the natural clays, the dry density needs to lie between 1,100 kg/m^3 and 1,500 kg/m^3, depending on grade. In general, this is much lower than what is achieved during block compaction and what is required from a compressibility viewpoint. A dry density greater than 1,700 kg/m^3 is required for all mixtures except 50/50.

Programme

No more field measurements of hydraulic conductivity are planned in the Backfill and Plug Test project. However, the densities will be verified on excavation and supplementary tests may be performed on the excavated material.

The Baclo project will continue and supplementary measurements of hydraulic conductivity will be made on the candidate materials at the densities expected to occur in the field.

The need for a new field test with backfill of blocks and pellets and similar measurements as in the Backfill and Plug Test project will be considered.

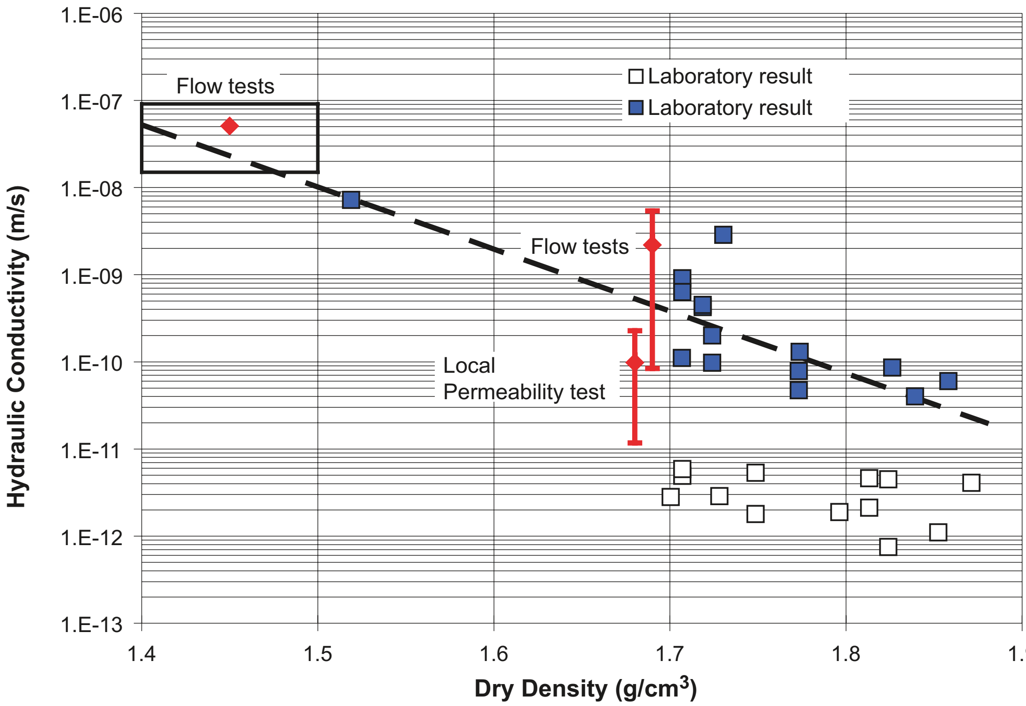


Figure 25-1. *Compilation of results of measurement of hydraulic conductivity in backfill consisting of a mixture of 30 percent bentonite and 70 percent crushed rock. The blue squares are results of laboratory tests with the same water as in the field test (1.2 percent salinity), while the red markings are results from tests in the field.*

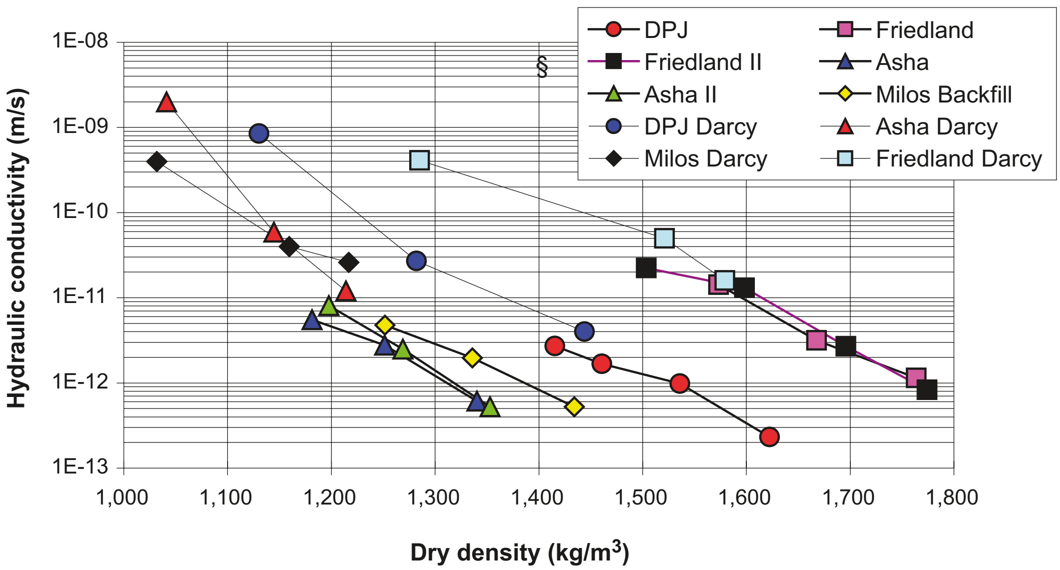


Figure 25-2. *Hydraulic conductivity of the natural clays evaluated from the oedometer tests and flow tests (Darcy) with water of 3.5 percent salinity.*

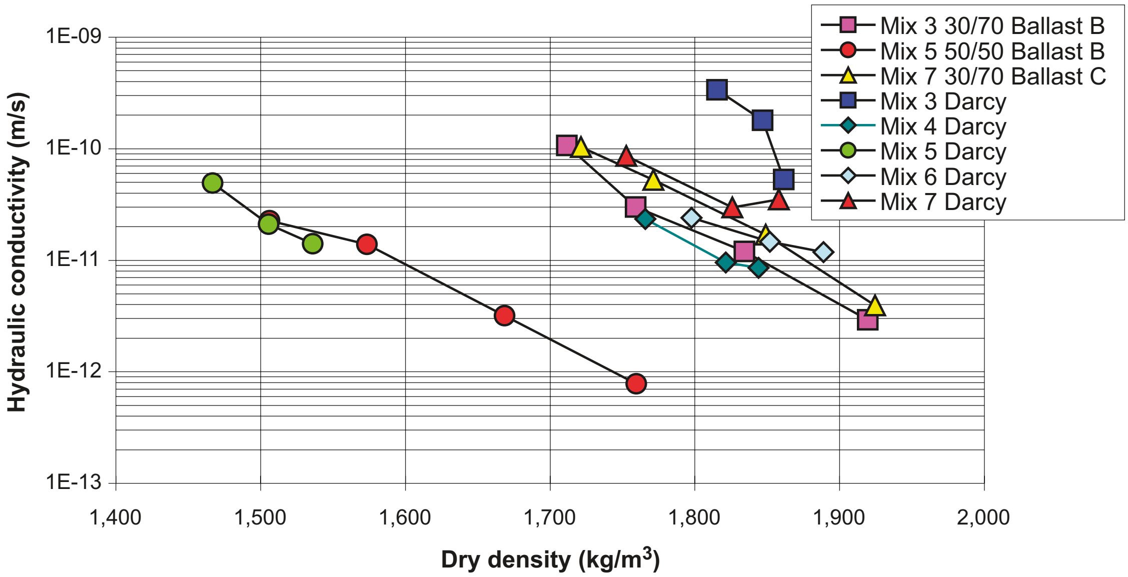


Figure 25-3. *Hydraulic conductivity of mixtures of Deponit-Ca bentonite and different aggregate materials evaluated from oedometer tests and flow tests (Darcy) with water of 3.5 percent salinity. Mix 4 and Mix 5 contain 40 and 50 percent bentonite, respectively, while other mixtures contain 30 percent bentonite.*

25.2.8 Gas transport/dissolution

Gas transport in the backfill is not judged to be an important process. If gas can find its way through the buffer, the transport capacity of the rock is sufficient for the pathway through the backfill to be uninteresting.

25.2.9 Piping/erosion

The process is the same as for the buffer, but the effect may be more serious, since most of the candidate materials have poorer healing capacity. On the other hand, the safety consequences are mitigated due to the distance to the canister.

The process was not addressed in RD&D-Programme 2004, but SKI thought that SKB should investigate the effects of piping and erosion for the backfill as well, which can lead to loss of material after closure of a deposition tunnel. It is stated in SR-Can that the process can lead to loss or redistribution of the swelling clay component, which leads to increased hydraulic conductivity and reduced swelling pressure. The uncertainties regarding the consequences are great today, and experiments are needed to study them. A tight end plug in the deposition tunnel will presumably be needed to prevent large quantities from disappearing.

In the Baclo project, a number of test series have been carried out /25-4/ and additional series are under way to investigate the erosion and sealing properties of several backfill candidates:

- Erosion in blocks of Friedland clay when water is allowed to flow in a channel of blocks is being investigated by measuring the quantity of eroded clay in the water. The density of the blocks, the flow rate, the salinity of the water and the flow time are varied.
- Erosion in pellet fill is being investigated in a similar manner. Pellet size, bentonite type, flow rate and salinity of the water are varied.
- Ability of bentonite pellets to seal fractures where eroding material runs.

Preliminary results show that the salinity of the water and how much water has run through the channel have a great influence on the erosion rate, expressed as mass of eroded material divided by mass of water. The erosion rate is generally between 1 and 10 grams per litre of water. The lower the salinity and the greater the amount of water (the longer the time), the lower the erosion rate. Bentonite pellets also seem to be able to seal fractures smaller than 0.15 millimetres.

The tests will continue and be supplemented with similar tests of other materials. The goal is to bound the quantity of backfill that can erode away both before complete sealing with the end plug has been achieved and by internal redistribution of eroded material.

25.2.10 Swelling

The swelling and compression properties of the backfill are important for the performance of the final repository, see the introduction of the next chapter.

Conclusions in RD&D 2004 and its review

It was stated in RD&D-Programme 2004 that the compression and swelling properties of the backfill are important and will be investigated. The influence of the backfill on tunnel convergence was studied.

Newfound knowledge since RD&D 2004

SR-Can concludes that the compression and swelling properties of blocks of both Friedland clay and 30/70 mixtures are good enough to provide sufficient swelling pressure against the rock and to prevent excessive upswelling of the buffer in the deposition hole. However, the healing capacity of mixtures after piping and erosion is doubtful, so Friedland clay is recommended.

Swelling pressure and swelling and compression properties have been investigated in the Baclo project for several backfill candidates. The following investigations have been or are being conducted:

Measurement of swelling pressure has been carried out with four different natural clays and several mixtures of 30–50 percent bentonite with 50–70 percent aggregate, which have been saturated with water containing 3.5 and 7 percent salt, respectively. Sample results are summarized in Figures 25-4 and 25-5, where swelling pressure is plotted as a function of clay void ratio. The tests were done to investigate where the boundary goes to obtain a swelling pressure of 100 kPa, which is why the

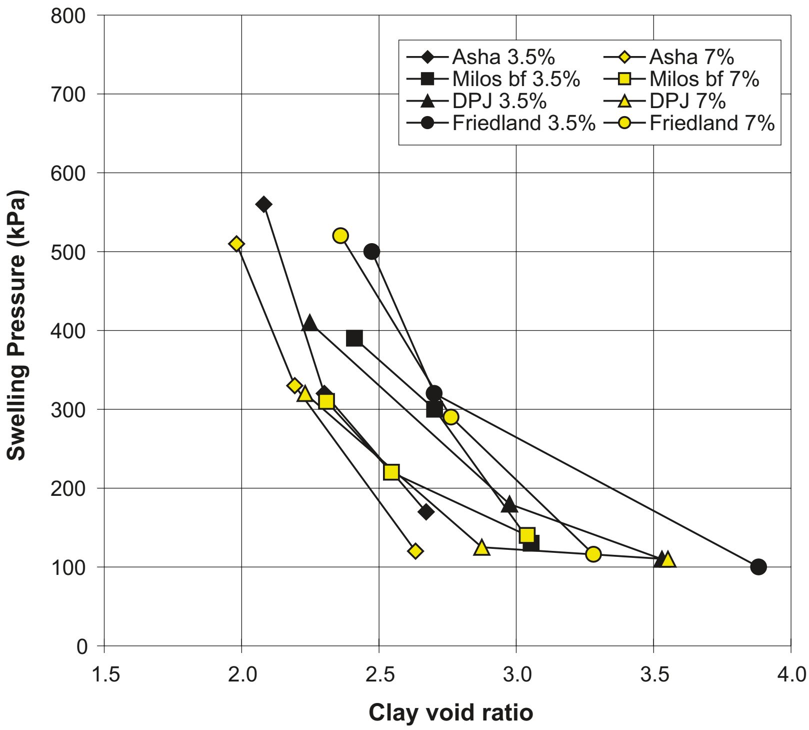


Figure 25-4. *Measured swelling pressures as a function of the clay void ratio of four different natural clays. The symbol key describes the name of the clay and the salinity of the added water.*

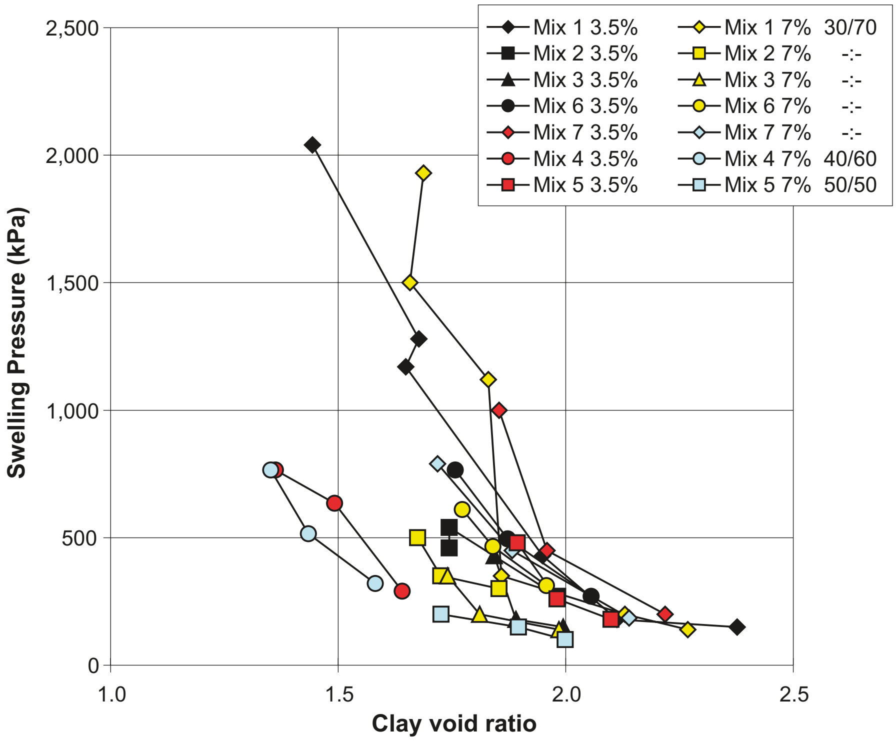


Figure 25-5. *Measured swelling pressures of mixtures of bentonite and aggregate. The symbol key describes the number of the mixture, the salinity of the added water and the mixing ratio bentonite/aggregate.*

void ratios are relatively high. This boundary goes at a clay void ratio of 2.0 or higher for all the materials, which is equivalent to a dry density (of the clay phase) of about 0.9. The results show that there will be large margins to the minimum swelling pressure for the natural clays, since the final density of the swollen blocks gives a much lower clay void ratio. The margins are not as great for the mixtures.

The compressibility of equivalent backfill candidates has also been measured by means of oedometer tests. The materials have been gradually loaded and the deformations measured. The relationships between density and applied load have then been used to calculate how different combinations of buffer densities, backfill materials and backfilling densities affect the upswelling of the buffer in the deposition holes.

Table 25-1 shows what dry densities the different backfill materials need to have to meet the following three requirements:

1. Swelling pressure greater than 200 kPa (greater margin than performance indicator).
2. Hydraulic conductivity less than 10^{-10} m/s.
3. Compressibility must not be so great that upswelling of the buffer results in a saturation density at the top of the canister that is lower than 1,950 kg/m^3.

Table 25-1. Required dry density of the different buffer candidates to meet the three requirements on swelling pressure, hydraulic conductivity and compressibility.

Material types	Required dry density (kg/m³) based on: Hydraulic conductivity	Swelling pressure	Deformation properties
Asha 230	1,120	1,050	1,160
Milos bf	1,090	1,060	1,240
DJP	1,220	1,240	1,400
Friedland	1,400	1,350	1,510
30/70 mixture	1,700–1,890	1,730–1,800	1,690
50/50-mixture	1,280	1,450	1,560

Tests are being conducted of the self-healing capacity of the backfill materials. The tests are being conducted in the following way: Samples with a diameter of 50 millimetres and a height of 50 millimetres are saturated with water in oedometers, after which hydraulic conductivity is determined on the untouched sample. Then a hole with a diameter of 5 or 10 millimetres is drilled in the sample, which is then allowed to self-heal with a free supply of water for about three weeks. Then hydraulic conductivity is measured again. Salinities of 1 or 3.5 percent are used in the supplied water. Figure 25-6 shows the results of the tests performed to date. Asha and Friedland clay of high density do not suffer permanent damage. Friedland clay of a lower density has elevated hydraulic conductivity. Self-healing was poor in the mixtures and a permanent hole was observed. The pellets exhibited similarly poor healing at the high salinity, due to the low density. In a backfill of blocks with pellets in the gap, the density and healing capacity of the pellet fill will increase significantly due to the swelling of the blocks.

Programme

Studies of the swelling and compression properties of different backfill candidates are continuing in the Baclo project. The same applies to the investigations of the mechanical interaction of the materials with buffer and rock. The interaction between the emplaced backfill blocks and the pellet-filled gap will also be studied so that the initial state after full homogenization is known. The compression and strength properties of the composite system of blocks, gaps and pellets before wetting will be investigated in the laboratory so that the consequences of the special case with a dry tunnel and a wet deposition hole can be calculated, since the upswelling of the buffer before the backfill is wetted may not be too great.

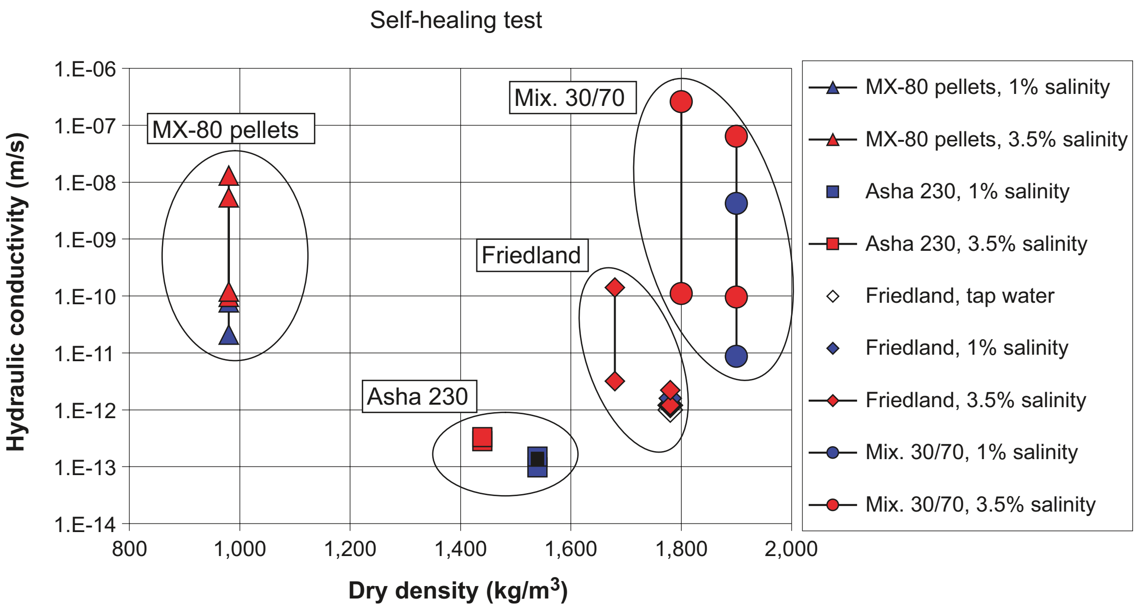


Figure 25-6. *Comparison of hydraulic conductivity of different backfill materials measured in untouched condition and after a five millimetre hole has been drilled through the sample and allowed to heal for three weeks. The lower value corresponds to the untouched state.*

25.2.11 Thermal expansion

The process can be neglected in the backfill.

25.2.12 Advection

Studies of transport of colloids in glacial water have started (actually in the rock). Erosion of material during the installation phase has also been studied, mainly in the Baclo project. For other studies, see sections 25.2.6 and 25.2.7.

25.2.13 Diffusion

If the backfill material has a low hydraulic conductivity, diffusion will be the dominant transport mechanism for dissolved species.

25.2.14 Osmosis

See section 24.2.14.

25.2.15 Ion exchange/sorption

See section 24.2.15.

25.2.16 Montmorillonite transformation

See section 24.2.16.

25.2.17 Dissolution/precipitation of impurities

See section 24.2.17.

25.2.18 Colloid release/erosion

See section 24.2.18.

25.2.19 Radiation-induced montmorillonite transformation

The process is judged to be negligible in the buffer and therefore also in the backfill.

25.2.20 Radiolysis of pore water

The process is judged to be negligible in the buffer and therefore also in the backfill.

25.2.21 Microbial processes

The potential for bacterial activity increases in the backfill material with decreasing density and increasing water content. Many bacteria consume oxygen as they metabloize organic material, methane, iron and sulphur, see section 24.2.21.

25.2.22 Radionuclide transport – advection

It is assumed that radionuclides can be transported both advectively and diffusively through the deposition tunnels. Diffusive transport is normally assumed to be dominant and advective transport negligible /25-5/. But if the conductivity of the backfill should for some reason be higher, advective material transport may be of importance for the safety assessment of a KBS-3 repository. As a part of the work with SR-Can, the importance of this was investigated by assuming 100 times higher conductivity in the deposition tunnels compared with the base case that had been selected. The time and distance a particle must migrate in the deposition tunnel before it enters a fracture zone in the rock and leaves the near-field model was then compared for the different simulation cases.

Based on this, an advective transport rate was then calculated and used as input for the transport modelling that was done with the simulation programme Compulink /25-6/. The simulations in SR-Can showed that the effect of this increased advective transport in the deposition tunnels was of limited importance for the KBS-3 repositories studied in SR-Can /25-7/.

25.2.23 Radionuclide transport – diffusion

Diffusion of radionuclides in the backfill is of subordinate importance for repository safety. Other transport pathways dominate the spread of radionuclides from a damaged canister.

25.2.24 Radionuclide transport – sorption

Conclusions in RD&D 2004 and its review

A conclusion based on e.g. experience from SR 97 was that sorption of radionuclides in the backfill is of very limited importance for repository performance.

Newfound knowledge since RD&D 2004

Radionuclide transport (migration) parameters for a backfill consisting of blocks of highly compacted Friedland clay were discussed in /25-8 and 25-9/. Recommended values for the following parameters, together with associated uncertainties, were derived and documented for all relevant elements and oxidation states:

- Diffusion-available porosity (ε).
- Effective diffusivity (D_e).
- Distribution coefficient (K_d).

In principle, data and uncertainties were derived based on a similar project recently done for sorption in MX-80 /25-8/. Since K_d is dependent on prevailing conditions, values were derived for the premises that are relevant for the analysis. If possible, K_d values were evaluated for specific pore water chemistries and solid/water phase ratios that are representative for Friedland clay compacted to a dry density of 1,780 kg/m^3. In cases where experimental data or sorption models with sufficient quality are lacking, the reference values chosen in /25-9/ were rescaled to the sorption capacity for Friedland clay. The recommended values for diffusivity D_e and porosity ε are based on the relationships given in /25-9/, which make it possible to calculate these parameters as a function of density. The associated uncertainties were qualified for a given set of conditions and have been further estimated for the variability under these conditions.

Programme

SKB does not consider sorption in the backfill to be a prioritized research area. The data given in /25-8/ should be good enough to be used in SR-Site.

25.2.25 Radionuclide transport – speciation of radionuclides

The speciation of radionuclides is of importance for sorption and diffusion in the buffer. It is influenced by what speciation the nuclide had at the boundary to the backfill, i.e. inside the buffer, but also by the chemical conditions in the backfill.

The speciation process is discussed in section 22.2.14.

25.3 Integrated modelling – radionuclide transport in the near-field

Conclusions in RD&D 2004 and its review

The direct conclusions reported in connection with the review of RD&D-Programme 2004 were related to the model description. It has now been improved.

Newfound knowledge since RD&D 2004

Based on experience from the safety assessment SR-Can – and in particular the positive results reported from the attempts to join canister and lid – the requirements on the program code for radionuclide transport in the near-field have been partially reformulated. The scenarios for radionuclide transport in the near-field that were analyzed were mainly a case with partially eroded buffer around the deposition hole (called the advection case in the SR-Can's Main Report) and a case where the canister has been sheared due to an earthquake (called the shear case). The case with a canister defect that gradually expands (called the pinhole case), which has traditionally been used in radionuclide transport calculations, has been reduced to an illustrative case.

Programme

Due to the partially changed requirements, the work of developing program codes for the near-field must be pursued in even closer cooperation with the methodology and research work being carried out as a part of SR-Site. The changes in the code concept that were made prior to RD&D-Programme 2004, when the programming environment was changed from the previous Fortran-based COMP23 to Compulink, which is based on Matlab and Simulink, are considered to simplify this work.

26 Geosphere

26.1 Initial state of the geosphere

The final repository will be built in widely occurring crystalline rock of granitic composition. The analysis of long-term safety is based on the state that exists when the repository has just been closed and sealed. This in turn requires knowledge of the state that existed before the repository was built and how it was then affected. The results of the site investigations are the primary basis for determining the post-closure state of the repository. The site investigations are dealt with in Part II.

Groundwater flow and pressure are above all affected by the drainage of the facility during construction and during deposition of the canisters during the operating phase. If water of a different composition flows towards the repository, the chemistry of the groundwater may also be affected by the groundwater flow. The chemical conditions are also influenced by the fact that the repository is kept open and various materials are introduced. The initial state of the repository is affected by the stress redistributions that can take place in conjunction with repository construction. The magnitude of this influence depends on several factors, for example how the repository is built and how long it is drained.

The repository is designed primarily with aim of achieving as good performance and safety as possible. Canister and tunnel spacing is determined by the temperature in and around the repository, and major fracture zones are avoided. In general, conditions in the rock that are favourable for long-term safety are also conductive to good constructability and good occupational safety. Good constructability and a stable hard rock facility are also advantageous for safety during the operation of the facility.

26.2 Processes in the geosphere

26.2.1 Overview of processes

Heat that is generated in the fuel is conducted out via the canister and the buffer and heats the host rock. The groundwater is redistributed in the geosphere's fracture system by groundwater flow. Gas flow may also occur. A mechanical state exists initially in the geosphere which is determined by the natural rock stresses and the fracture systems on the repository site and by the changes caused by construction of the repository.

The mechanical evolution is determined by how the geosphere responds to the different mechanical loads to which it is subjected. The loads may consist of the thermal expansion caused by the heating of the repository, the pressure from swelling buffer and backfill, effects of earthquakes and the large-scale tectonic evolution. Changes in the geosphere may include fracturing, reactivation (sudden movements in existing fractures) or rock creep (slow redistributions in the rock). Movements in intact rock, i.e. compression or expansion of otherwise intact rock blocks, also occur, along with erosion, i.e. weathering of the surface rock, particularly in conjunction with glaciations.

The post-closure chemical evolution is determined by a number of transport processes and reactions. The predominant transport process over long distances is advection, while diffusion plays a great role over short distances and in rock blocks where the water is immobile.

In advection, solutes accompany the flowing water. The process leads to mixing of different types of water from different parts of the geosphere. Reactions occur between the groundwater and fracture surfaces and these give rise to dissolution and precipitation of fracture-filling minerals. Moreover, very slow reactions occur between the groundwater and the minerals in the rock matrix. Microbial processes, degradation of inorganic materials from repository construction, colloid formation and gas formation take place in the groundwater. During a glaciation, methane ice formation and salt exclusion can also occur.

Diffusion can be important if the water is immobile or moves very slowly. An important aspect of this is matrix diffusion, where radionuclides diffuse into the stagnant water in the microfractures in the rock and are thereby retained and transported more slowly than the flowing water. Sorption, where radionuclides adhere (sorb) to the surfaces of the fracture system and the rock matrix, is also crucial for radionuclide transport. Matrix diffusion and sorption are the two most important retention processes for radionuclides in the geosphere. Another factor that can be of importance for retention is sorption on colloidal particles and transport with them.

The chemical environment in the water determines which speciation (chemical form) the radionuclides will have, which is particularly crucial for sorption phenomena. Certain nuclides can be transported in the gas phase. Radioactive decay influences the groundwater's content of radionuclides and must therefore be included in the description of transport phenomena.

The research programme regarding different processes in the geosphere that can influence long-term safety is discussed in the following sections.

26.2.2 Heat transport

Conclusions in RD&D 2004 and its review

Results were reported in RD&D-Programme 2004 from studies regarding how to calculate the maximum temperature of the canister and how it is related to the heat transport properties of the rock, the heat output of the canisters at deposition, the deposition geometry and the conditions in the buffer. The calculations, which can be carried out with different combinations of analytical and numerical methods, also took into account the problem of heat conduction on different scales /26-1/. Different laboratory-based methods for predicting the thermal conductivity in the rock nearest a borehole were compared with a large-scale method for measuring direction in the borehole, called the thermal response test /26-2/. Thermal conductivity was overestimated in these field tests by about 25 percent compared with the effective thermal conductivity obtained from laboratory measurements. It was concluded that the full-scale model needs to be developed so that compensation can be made for the effects of water movements in the boreholes during measurement.

The results of a systematic evaluation of some methods for determining thermal conductivity and heat capacity in the laboratory were also reported in RD&D-Programme 2004 /26-3/. A preliminary strategy for a thermal site descriptive model had been devised during the site investigation phase /26-4/. The scale dependence of effects of rock type distribution had been analyzed /26-5/. Furthermore, thermal conductivities, measured or calculated from mineralogical composition, had been analyzed statistically. In addition, preliminary relationships between the density and thermal conductivity of the rock types were presented.

The regulatory authorities observed that SKB had modified its research efforts in relation to previous RD&D programmes and considered that with the additional research that had now been conducted, SKB has a better level of ambition in its programme to resolve important remaining issues in the heat transport area. They pointed out the importance of SKB studying the impact of anisotropy and actively continuing to develop a field instrument which can determine the thermal properties of the rock mass in boreholes. SKI also emphasized the importance of continuing the temperature measurements in the Prototype Repository at the Äspö HRL in order to permit calibration of the thermal model calculations being used and to enable the thermal parameter values obtained from the laboratory tests at the Swedish National Testing and Research Institute (SP) to be used.

The regulatory authorities make a general comment that it is important to give attention to the disturbances that occur as a result of the blasting of the repository. The underground excavation work can affect both the thermal and the rock mechanical initial states.

Newfound knowledge since RD&D 2004

The current temperature criterion applies to the maximum bentonite temperature, while the previous criterion applied to the temperature of the canister surface. In dry deposition holes, where the vertical canister-bentonite gap remains for decades after deposition, the maximum bentonite temperature will exist at the canister's base surfaces, where buffer and canister are in direct thermal contact. A thermal analysis of the canister-buffer system has been carried out where this has been taken into account /26-6/. Data on the thermal properties of the different components (gap, bentonite blocks, pellet fill) have been obtained from measurements in the dry and well instrumented hole number 6 in the Prototype Repository at the Äspö HRL /26-7/. Figure 24-3 in section 24.2.3 shows the temperature in buffer and rock around a KBS-3 canister with a 10 millimetre gap between the vertical canister surface and surrounding bentonite blocks for two different assumptions concerning the thermal conductivity of the rock. After 20 years the calculated difference in bentonite temperature is about 13 degrees, which is a measure of the total effect of the air-filled inner gap if the gap is uniform along the entire height of the canister and around its entire periphery. The gap effect is directly proportional to the canister's heat output and decreases with time. The results of the analysis /26-6/ can be used directly for calculating the maximum bentonite temperature for arbitrary deposition geometries using an analytical method similar to the one used previously /26-1/. The gap effect is included as a time-dependent temperature increment. Figure 26-1 shows as examples 90°C isolines in a nomogram of canister spacing vs. tunnel spacing, in other words the canister and tunnel spacing that would be needed assuming that the total model and data uncertainty is 10°C.

With the above-mentioned analytical solution, it is easy to investigate the effects of different disturbances in the layout, for example the temperature increase that would result if a canister position has to be moved slightly (for example to avoid what may be a long fracture). The analysis shows that the bentonite temperature of a canister may increase by around one degree if the distance to a neighbouring canister is reduced by one metre and the deposition geometry is otherwise unchanged /26-8/.

A method has been developed for upscaling of laboratory determinations of the thermal conductivity of different rock types to scales that are relevant for calculating the temperature evolution of individual canisters in typical deposition geometries /26-9/. The upscaling method takes into account variability within rock types and between rock types.

Characterization of the thermal conductivity and spatial variability of the bedrock is costly and time-consuming if it is done by means of laboratory determinations. There is a need to develop more efficient and inexpensive methods. Within the framework of the site investigations, development work has been pursued on other ways to determine the thermal conductivity of the rock. It is logical to assume that the thermal conductivity of a crystalline rock is generally dependent on the composition, density and thermal conductivity of the minerals in the rock. Based on idealized

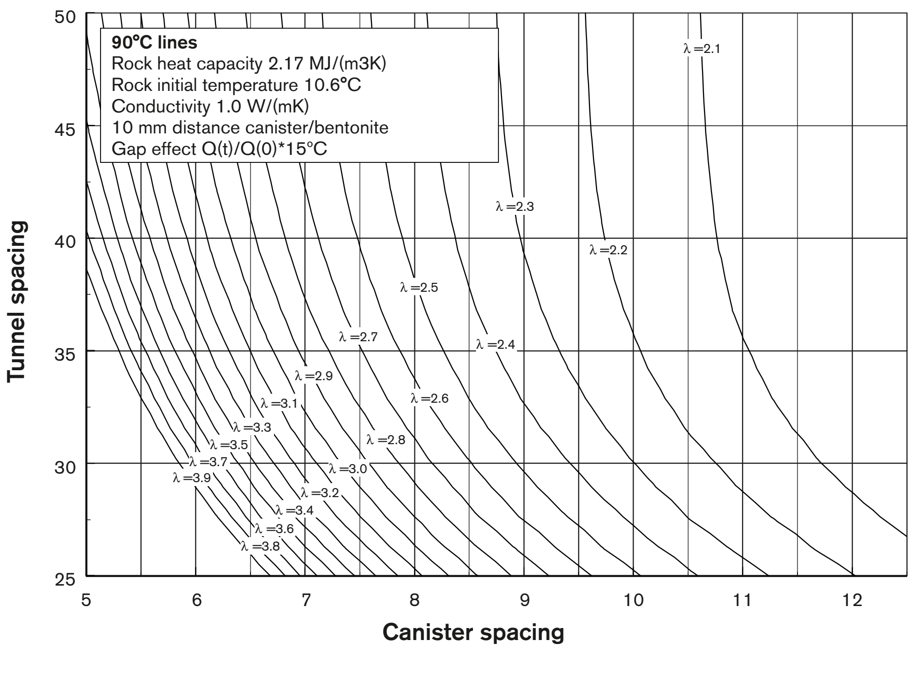


Figure 26-1. Isolines for 90°C maximum bentonite temperature.

mineral compositions for igneous rock types, such a general correlation has been demonstrated between density and thermal conductivity. Furthermore, this correlation has been verified by means of investigations in the laboratory of rock cores from the site investigation areas. It has then been possible by means of geophysical borehole logging that measures density variations (gamma probes) to determine both thermal conductivity and spatial variability for above all felsic and intermediate igneous rocks /26-10, 26-11/.

Kristensson and Hökmark /26-12/ analyzed the temperature evolution in the Prototype Repository in the Äspö HRL. One of the purposes was to investigate how well the calculated rock temperature in the area nearest the different canisters can be matched with corresponding measured temperatures if it is assumed that the heat transport can be described as linear, isotropic and homogeneous heat conduction. This means that a globally applicable thermal conductivity is used – despite the fact that predictions based on laboratory determinations indicate a standard deviation of 0.28 W/(m·K). Figure 26-2 (upper left) shows calculated rock temperatures 1,117 days after heating started in the inner section, while the upper right shows the positions of measurement points used for comparison between model and experiment. The three lower graphs show the comparison for points outside canisters 1, 4 and 6. Equivalent comparisons for the points outside canisters 2, 3 and 5 showed similar agreement, i.e. with differences of less than 2°C.

The temperature evolution in the Prototype Repository's rock mass is important not only for an understanding of heat transport in the rock and the connection between measurement data on the laboratory scale and the outcome on the tunnel scale, but also for defining the boundary conditions for THM models of the evolution of the buffer towards water saturation.

A joint project with Posiva regarding a logging device (Tero) for in situ determination of thermal properties has been completed /26-13/. Furthermore, we have carried out an initial rough inventory of other borehole methods.

Scale and anisotropy effects have been studied in the field and evaluated prior to the concluding site modelling /26-14, 26-15, 26-16/.

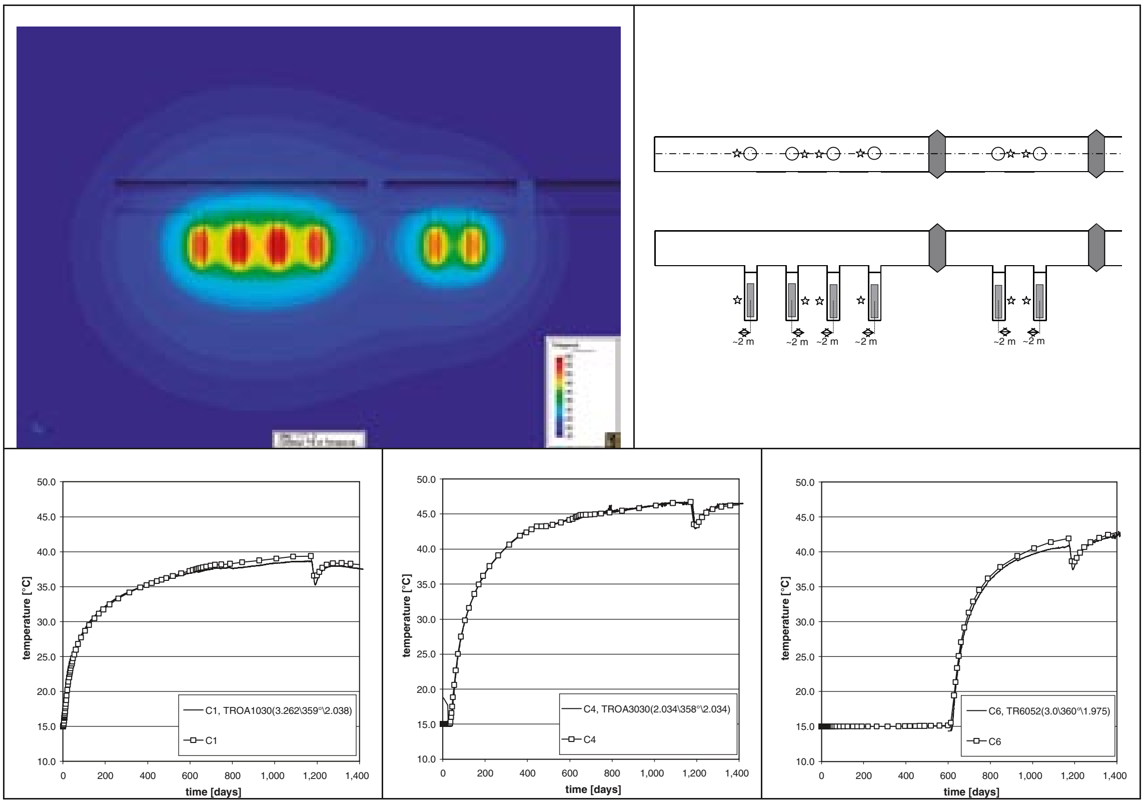


Figure 26-2. Upper left: rock temperatures after 1,117 days of heating. Upper right: instrument positions for comparison. Lower: comparison for the points outside canisters 1, 4 and 6.

Programme

The work of quantifying and limiting the uncertainties in the temperature calculations will continue. Similarly, the development of both field and laboratory methods for determining thermal properties will continue. Special attention is being devoted to methods for determining the spacing between the canisters in the deposition tunnels, which is dependent on e.g. thermal conditions.

Work is continuing on the principles for thermal modelling of the sites. Spatial variation and upscaling to a relevant scale will be linked to the geological site models and analyzed by means of geostatistical methods.

Temperature measurements in boreholes have been used to determine the temperature at repository depth and to confirm measurements of water flow with hydraulic methods. However, the temperature distribution contains more information that can be used to:

- Investigate the spatial variation of thermal conductivity on a larger scale (it is largely proportional to the temperature gradient).
- Determine historical climate changes.
- Determine the size of the heat flow.

SKB intends to evaluate whether a programme that sheds light on the above questions should be carried out or not. If such a programme is implemented, it will be coordinated with efforts in climate-oriented project areas, see section 21.4.

26.2.3 Groundwater flow

Conclusions in RD&D 2004 and its review

It was stated in RD&D-Programme 2004 that the two model tools ConnectFlow and DarcyTools would be further developed in several projects. This has been done and is described below. It was further stated that efforts would be made to develop and apply near-surface hydrogeological modelling. This is also described below.

SKI observed in its assessment that the programme provides a good summary and status report of the modelling tools that are used to describe groundwater flow. Furthermore, SKI thought that the programme for the development of ConnectFlow and DarcyTools was well thought out and ambitious, and it was an advantage that these codes are being used and tested in site modelling and safety assessment. At the same time it was pointed out that it is vital that the codes be evaluated and documented before they are applied in SR-Can and SR-Site.

SKI further offered the opinion that simplified assumptions concerning, for example, boundary conditions on the surface and lake bottoms as well as the heterogeneity structures of the rock and the Quaternary deposits have not yet been justified and confirmed. The programme lacked a plan for how SKB will obtain data to test and verify these models. However, SKB would like to state that the models can handle virtually any boundary conditions and heterogeneity structures whatsoever, but that these are site-specific issues that hare handled in connection with site investigations and site modelling.

SSI observed in its review that research on the interface zone between geosphere and biosphere is important, but that a clear plan was lacking for how SKB intends to conduct this research.

SSI further pointed out that the results of the completed modelling of surface water hydrology should be interpreted with caution, since the assumptions were much too simplified. Furthermore, SKB should make sure that the necessary data are collected in the site investigations. SKB would like to clarify that data collection is a question that is handled within the site investigations.

Kasam observed in its review that it is very important that the programme for groundwater flow should be carried out. Furthermore, they emphasized that information on geological structures and boundaries, as well as detailed information on stratigraphies and water levels in the assessed discharge areas, should be used in the regional flow calculations. These questions are discussed below in connection with the supraregional study that has been conducted of eastern Småland.

Kasam also stated that the natural groundwater recharge at repository depth should be determined by different independent methods.

Newfound knowledge since RD&D 2004

Groundwater flow modelling has been carried out within site modelling, in the safety assessments and in various independent projects. The results obtained under these three categories are dealt with below.

A strategy for hydrogeological modelling has been gradually developed under the site model versions 1.1 to 2.1. Specifically, a regional-scale hydrogeological groundwater model is being developed, along with a repository-scale HydroDFN (Discrete Fracture Network) model. The purpose of the regional description is to describe the current hydrogeological situation, including its historical evolution. The integration of geological and hydrogeochemical data, as well as the properties of the surface system, are important components here. The explicit description of water-conducting fractures in the HydroDFN model provides important input to design and safety assessment, but is also integrated in the regional hydrogeological description. Site models for the two sites are described in /26-17, 26-18/. The primary knowledge these models have generated is a description of the site-specific conditions, but the methodology for how to develop these types of models and integrate data of different types is also an important advance.

Within site modelling, progress has also been made regarding near-surface hydrogeological modelling and the coupling of geosphere and biosphere. The modelling tool MIKE SHE /26-19/ has been used to build models for simulation of water flows and solute transport in both Forsmark and Simpevarp/Laxemar. MIKE SHE can be used for simulation of the entire "land part" of the hydrological cycle and its couplings to processes in the atmosphere (precipitation and evaporation). The modelling thus includes both saturated and unsaturated flow in soil and rock as well as surface water flow on the ground surface and in watercourses. Transport modelling can also be done, whereby processes such as pure advective transport (particle tracking) and complex reactive transport can be taken into account.

In the first versions of the site descriptive models /26-20, 26-21/, the surface hydrological modelling was based on weather data from SMHI stations outside of SKB's investigation areas. These models have since been further developed by being based to an increasing extent on site data in the form of both weather data and site-specific data on hydrogeological and other properties /26-22, 26-23/. The main components of the water balance (precipitation, evapotranspiration and runoff) have hereby changed a great deal, particularly in Forsmark. Further modelling, based on updated models and the longer time series that will be available at the end of the site modelling, needs to be done before representative mean values and variation measures can be established.

Within SR-Can, methodology has been developed for analyzing both an open repository and the long-term hydrogeological evolution of a closed and resaturated repository. Specifically, methodology has been developed for direct use of the derived site models in combination with site-adapted layouts of the planned repository. For the open repository simulations, questions such as impact area with drawdown of the groundwater table, size and spatial distribution of inflows in the repository, and upconing of saline water to repository level are of interest. The code DarcyTools has been further developed to handle these questions. An unstructured grid is used, permitting high resolution at tunnels and deposition holes. A coarser resolution is used on the regional scale. The methodology has been used for both Forsmark and Laxemar /26-24, 26-25, 26-26/. An initial attempt to model the resaturation phase for the entire repository volume has also been made in these studies.

The MIKE SHE code has also been used to simulate open repositories /26-23, 26-27/. In general, this modelling provides answers similar to those provided by the simulations with DarcyTools above, but the focus is on the near-surface system. Specifically, seasonal variations in the hydrological cycle can be analyzed, as well as the effect of the open repository on near-surface hydrological processes, such as unsaturated flow and runoff in watercourses.

For long-term safety under resaturated conditions, questions of interest are the groundwater flow in the near-field around the deposition holes and the transport pathways for the radionuclides from the repository to the biosphere. The ConnectFlow code has been developed to explicitly incorporate tunnels and deposition holes so that a quantification of groundwater flow can be done for near-field modelling. Furthermore, transport pathways and properties along these flow paths (F-factor, travel time etc) for different release pathways from the canister are calculated (for example a fracture that intersects the deposition hole, a fracture that intersects the tunnel, etc). This methodology has been used for hydrogeological modelling in SR-Can /26-28, 26-29/. Other functionality that has been developed is density-driven flow in fracture networks, matrix diffusion of salt (which affects the density-driven flow), but only in continuum models, and transport including matrix diffusion of different water types and/or individual solutes, which permits comparison with chemistry data. This process modelling has also been used in the site modelling described above.

Methodology for simulating groundwater flow under glacial conditions has also been developed /26-30, 26-31/. A model describing flows during the build-up and retreat of a glacier has been developed. The boundary conditions are obtained from an ice model /26-32/, while the regional-scale hydrogeological model is based directly on the site descriptive model.

Among other major studies that have been conducted are theoretical studies of open repositories /26-33, 26-34/. The former study tested the ConnectFlow code for open repository studies and studied which surface boundary conditions should be used in this type of simulation. The latter study analyzed which process complexity was needed to simulate an open repository. Full two-phase flow, unsaturated flow and saturated flow with a free groundwater surface were compared. The results indicate that for most practical applications, linked to issues at repository depth, the approach with saturated flow with a free groundwater surface is sufficient. This is also the approach that is used in the SR-Can studies that are discussed above. For questions linked to the near-surface system, however, a higher process complexity (for example unsaturated flow) should be used, as in the MIKE SHE code. This code, or a similar tool, is also needed in cases where the possible effects on e.g. specific surface water bodies that cannot be represented explicitly in pure groundwater models are to be investigated.

In simulating an open repository, it is often observed that the simulated flow in the tunnels is higher than indicated by field data. The reason for this may be two-phase flow or a mechanical impact, which results in a hydraulic alteration of the rock nearest the tunnel. Another explanation model has been presented in /26-35/. It is based on the concept of hyperconvergence in channel networks. The effect arises in fractured rock where the water flow takes place in channels that converge in towards a tunnel. The extra convergence, called hyperconvergence, to which the channels give rise explains the reduced water inflow.

Supraregional groundwater modelling has been done of the flow conditions in eastern Småland /26-36/. This study has been done in response to the regulatory authorities' questions regarding previous supra-regional studies conducted by SKB. The purpose was to evaluate conceptual simplifications and model uncertainties in supraregional groundwater modelling and to carry out an in-depth and open-minded analysis of the flow conditions in eastern Småland. The results indicate that the topography is the most important factor for the regional flow pattern from repository depth. The topographical undulation is of greater importance than the properties of the conductivity field. Regarding the properties of the conductivity field, it is noted that depth-decreasing horizontal anisotropy dominates over the influence of lithological units, deformation zones, dolerite dykes and Quaternary deposits on the flow pattern.

A new hydrogeological model of Äspö has been constructed with the modelling tool DarcyTools. The model includes all new site data up until 2005. One purpose has been to incorporate or cross-check against chemical data as well. The model will be used as a practical tool in planning experiments and activities in the Äspö HRL.

The transport resistance (the F-factor) along a flow path in a groundwater flow model affects the final modelled retention of solutes. The F-factor is determined by the geometric properties of the fractures and the flow in the fractures along the flow path. Local aperture variability thus also affects the F-factor due to the formation of channels in the individual fracture. However, this variability is routinely neglected in models containing thousands of fractures or more. The importance of intra- and intervariability in fractures is analyzed in /26-37/. The study indicates that variability between fractures dominates the resulting F-factor distribution for typical assumed values of aperture variability within and between fractures. The study further shows that the reduction in F-factor that is typically used in the safety assessment to account for channelling is conservatively set.

The two codes ConnectFlow and DarcyTools are being further developed and documented continuously. The development work for ConnectFlow is being pursued via collaboration in iConnectClub, which includes, besides SKB, Posiva (Finland), Nagra (Switzerland) and Obayashi (Japan). SKB is also carrying out a doctoral project where ConnectFlow is used, see further under "Programme" below. DarcyTools has been updated to version 3.0 and is documented in /26-38/. Evaluation of both codes is taking place within both site modelling and the Äspö Task Force GWFTS applications.

Programme

The development work that is being pursued is strongly linked to the codes ConnectFlow, DarcyTools and MIKE SHE. The needs of SR-Site are judged to be well provided for, but certain pieces remain to be put in place, see below.

A new routine for particle tracking will be developed in ConnectFlow. This routine, which does not have the numerical problems that previous versions have had, is important for use of the code in SR-Site. In addition, the methodology for incorporating hydrogeochemical data and the coupling with the surface water description are being developed. Work is also under way to find a complete solution for density-driven flow in DFN models. The current solution (see e.g. /26-39/) is approximative. Finally, some development of ConnectFlow is taking place within Äspö Task Force GWFTS, where the current Task 7 is aimed at quantitatively using flow data from Posiva Flow Log measurements.

Development of a simplified method for describing how backfilled tunnels are resaturated is being pursued in DarcyTools. A first application of the proposed methodology is presented in /26-25, 26-26/. The method needs to be further verified to be considered fully usable for SR-Site. DarcyTools will also be used to study how an open repository influences upconing of saline water and the flow that is caused by the thermal load from the repository. Finally, development of DarcyTools is underway where the Navier-Stokes equations for fluid flow are used. Possible areas of application for this modified code are grouting problems and simulation of transport in fractures with variable aperture.

An important part of the surface hydrological modelling is to determine the main components of the water balance and their variations in time (from year to year and during single years) and space (between different parts of the model area). Measurement results from runoff stations on the sites are now beginning to become available and will probably be significant for further improving the surface hydrological models in this respect.

Identifications of recharge and discharge areas, plus calculations of the water exchange between soil and rock, are other important types of results for which advances have been made and where further improvements are predicted when more detailed cross-checks against site data are possible. Methodology for calibration and other forms of comparison with measurement data will be further studied in a modelling project.

Some code development may also be pursued in MIKE SHE. This includes, for example, the possibility of using particle transport to study how substances are transported through the coupled groundwater-surface-water system.

A method for simulating groundwater over one or more glaciation cycles will be developed. The need of degree of complexity should be evaluated, and conceptual issues illuminated. Regarding conceptual issues, one that can be specifically mentioned is how the subglacial layer works from a hydraulic viewpoint. How much meltwater reaches the rock beneath a glacier? What spatial extent does the permafrost attain at different points in time during the glacial cycle?

A site-specific application of the hyperconvergence concept has begun for the purpose of judging the relevance of the method for further use in site modelling and safety assessment.

26.2.4 Gas flow/dissolution

Conclusions in RD&D 2004 and its review

RD&D-Programme 2004 noted that the question of two-phase flow during resaturation of a repository should be studied more closely. SKI supported this viewpoint in its review and noted that it is good that SKB intended to take into account two-phase flow in the analysis of repository resaturation, since this phase occurs during the time when a relatively detailed analysis of the repository evolution is required. In its review, SKI also pointed out that SKB would be well served by a tool for scoping calculations of gas transport in the geosphere.

Furthermore, SKI thought that SKB should also investigate whether there may be a link between gas flow and colloid transport, since colloids can accumulate in the interface between two phases. This question is discussed in section 26.2.21.

Newfound knowledge since RD&D 2004

The need for two-phase flow in open repository simulations has been examined in /26-34/ and is described in section 26.2.3. The resaturation process has been analyzed with DarcyTools in SR-Can. This is also described in section 26.2.3.

Simplified calculations of gas flow in the geosphere have been carried out in SR-Can for both Forsmark and Laxemar /26-28, 26-29/. The simplified types of models which the regulatory authorities have called for can thus be said to be available.

Programme

For resaturation of tunnels see section 26.2.3. As noted there, the issue has not yet been fully investigated, and some development is continuing. Specifically, the methodology will be further developed and applied more site-specifically in SR-Site.

26.2.5 Movements in intact rock

Conclusions in RD&D 2004 and its review

RD&D-Programme 2004 described the development and application of the strategy for site descriptive models /26-40 to 26-44/ where the fundamental questions have to do with characterizing the mechanical properties of the rock. The strategy includes selection of relevant scales for describing the stress state. A thorough overview of methods for stress measurements and their evaluation was presented in RD&D-Programme 2004 /26-45 to 26-49/. Furthermore, a systematic overview study /26-46/ was presented in which the importance of the stress paths for loading and movements in the intact rock was described. Criteria for different modes of failure that can occur around openings in the repository were compared. The report particularly shows that light support, for example from the tunnel backfill, can be of importance in preventing the occurrence and growth of brittle failure. Preliminary results were reported for the Apse experiment (Äspö Pillar Stability Experiment) in the Äspö HRL /26-51, 26-52/. Stresses and deformations due to blasting and thermomechanical loading have been studied in the experiment. Based on a detailed characterization, stresses and deformations have been modelled and then compared with measurement data.

The regulatory authorities believe that the evaluation and analysis of the Apse experiment should be very useful, but that the account given in RD&D-Programme 2004 is a bit brief. They emphasize that the Apse experiment is important for assessing possible rock breakout around deposition holes and the effects of the bentonite as rock support to prevent rock breakout with time. Further, the regulatory authorities consider that the site-specific aspects of rock stress and strength need to be further analyzed.

Newfound knowledge since RD&D 2004

SKB has further developed the technique for characterizing the mechanical properties of the rock and applied this technique to the investigation areas in Forsmark and Laxemar in order to derive site descriptive rock mechanical models.

SKB has tested site model data for Forsmark and Laxemar in numerical near-field calculations /26-53/ based on preliminary site-specific design proposals and on the general so-called Layout E /26-54/. It was found that for given in situ stresses and thermomechanical properties in the most important rock domains, there is a great risk of thermally induced spalling a few years after deposition in dry deposition holes where buffer and pellet fill do not absorb water and develop a stabilizing pressure on the deposition hole wall fast enough. Provided that the deposition tunnels are oriented parallel to the largest main stress, however, there is little risk of spalling in these tunnels during the construction phase.

The Apse experiment in the Äspö HRL has been concluded and reported, both as a technical report /26-8/ and in the form of a doctoral thesis /26-55/. The experiment has involved subjecting an already stressed pillar between two deposition holes to gradually increasing load by means of heating so that the tangential stresses gradually approached and exceeded the yield strength of the intact rock. A rubber bladder was installed in the first hole, in which a small stabilizing pressure was maintained against the hole wall during the excavation of the second hole and during the heating phase. Figure 26-3 (upper left) shows the general experimental layout with the two closely situated holes in the arched floor of a tunnel.

Spalling occurred during excavation in a limited horizontal section in the open hole. The yielding gradually propagated downward along the hole wall as the tangential stresses increased during subsequent heating, see Figure 26-3, right. Figure 26-3 (lower left) shows the nature of the yielding with tensile fractures parallel to the periphery of the hole and chips that were detached in the sector of the hole periphery where the tangential stresses were greatest.

No spalling was observed in the deposition hole, which was stabilized by the pressurized bladder. After the yielding in the open hole had developed as shown in Figure 26-3 (left), the stabilizing water pressure was gradually reduced from about 700 down to 0 kPa. When the pressure had reached about 200 kPa, an increase of the microseismic activity in the pillar could be observed. Figure 26-4 (left) shows how the frequency of acoustic emissions (AEs) varied at the end of the heating phase. The maximum at day 62 (15 July) coincides with the pressure reduction in the stabilized hole. Figure 26-4 (right) shows the AE frequency in detail during the pressure reduction. The following was observed:

- Spalling is initiated as small tensile fractures parallel to the periphery in the sector of the periphery where the tangential stresses are greatest and propagates inward until the yielding has taken on a notch-shaped self-stabilizing geometry. This agrees with observations made in AECL's Underground Research Laboratory (URL) in Canada.
- The depth of the yielding did not increase appreciably as the tangential stress increased, see Figure 26-5. The maximum depth was about 15 centimetres.
- The yield strength was about 57 percent of the uniaxial compressive strength of the rock.
- The slight pressure from the bladder (several hundred kPa) was sufficient to suppress spalling in the stabilized hole.

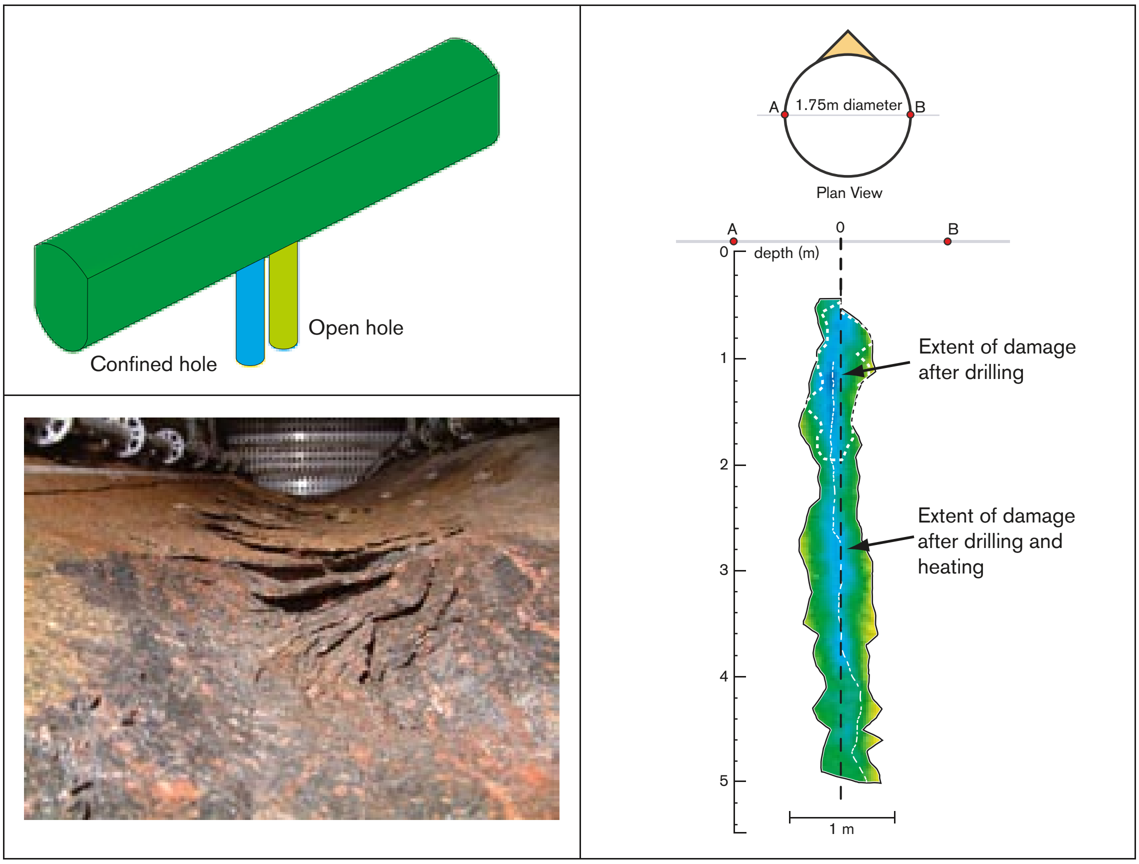


Figure 26-3. Upper left: general layout of the experiment. Right: geometry and development of yielding. Lower left: spalling after drilling.

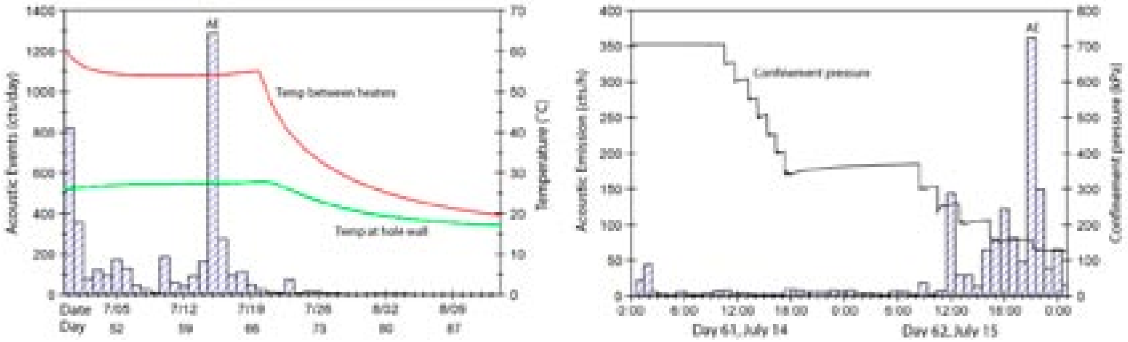


Figure 26-4. AE frequency (d^{-1}) in relation to the temperature in two points at a depth of 3.5 metres (left) and in relation to the pressure in the stabilized hole (h^{-1}, right).

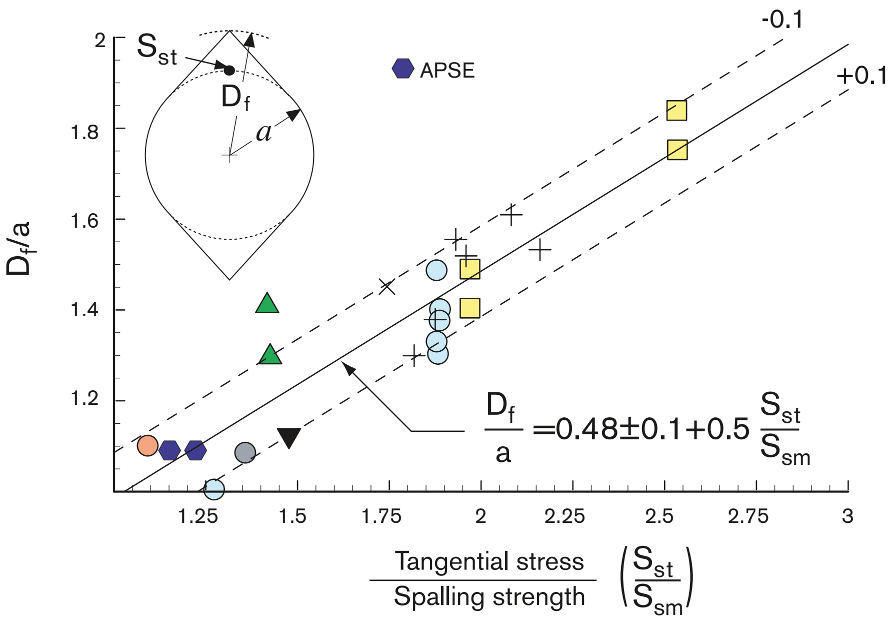


Figure 26-5. The depth of the damaged zone as a function of the maximum tangential stress normalized to the yield strength. The gradual load increase in the Apse experiment caused only a small increase in the notch depth compared with cases where the load is established directly as a result of excavation. From /26-8/ (based on /26-56/).

In the site investigations, extensive field work has been done on rock stress measurements. Overcoring and hydraulic methods have been applied on both sites. Both methods have their limitations at great depth, especially in Forsmark (where the rock stress level is higher) compared with the Oskarshamn area /26-59/. However, the methods appear to provide a similar picture of the stress situation down to levels around or slightly above the depths studied for a final repository, even though the failure rate for both methods increases with depth. The overcoring method, which assumes that the rock reacts elastically when a core is drilled free, may have some problems with microfracturing, for example. Furthermore, fractures may occur straight across the core at great depths due to the special measurement geometry that is required with a thin-walled, hollow core. Measurement is thereby overestimated or prevented. Hydraulic methods in an anisotropic stress field at great depth (elevated stress magnitudes) tend merely to cause gently-dipping fractures, due to the fact that a fracture is normally induced at the minimum main stress or due to the fact that the fracture cannot be induced at great depth. Studies of indirect observations, such as core discing and borehole breakouts, or rather the absence of these phenomena at depth, help in bounding the stress level /26-58, 26-59/.

Studies of the degree of microfracturing in drill cores, which is probably caused by destressing when the core is drilled free, have been conducted continuously during the site investigations. Analyses of results from Forsmark indicate a possible connection between the reduced P-wave velocity in drill cores with increasing depth and the ratio for the formation factor measured in the laboratory and in situ, respectively. This was judged to be due to fracturing in connection with destressing.

Programme

The Apse experiment has shown the importance of light support in stabilizing the walls of the deposition holes, where the thermally induced increase of the tangential stresses could lead to spalling. A project that is aimed at investigating this support effect will be carried out in the form of a field experiment and in the form of a modelling programme in cooperation with the University of Alberta in Canada. The field experiment will have a design similar to Apse, but on a smaller scale and without the extensive instrumentation that Apse had. The effect of the support provided by a non-water-saturated pellet fill next to the wall of the deposition hole will particularly be investigated. The purpose of the modelling programme is to develop the modelling technique and obtain a better understanding of the fundamental mechanisms. This will make it possible to better model observed and documented stress-induced fractures, for example those observed in Apse and AECL's URL in Canada.

A programme is being carried out within the framework of the site investigations to quantify the degree of stress-induced microfracturing in drill cores from several depths in Forsmark and Laxemar by means of triaxial loading and microscope studies.

In order to reduce uncertainty in rock stress measurements at great depths, but above all to obtain efficient methods as a basis for the geotechnical design of rock support, SKB is intending to try other methods. They are aimed at calculating the stress state by means of deformation measurements in connection with tunnelling. The development work is a part of the effort to obtain efficient tools in the application of the Observational Method in underground construction (see Part II, section 6.3.3).

26.2.6 Thermal movement

Conclusions in RD&D 2004 and its review

RD&D-Programme 2004 described risk assessment for canister damage due to thermomechanical loading. This risk is negligible, provided no deposition holes will be intersected by fractures with a length greater than 700 metres in the dip direction /26-60/. It was further noted that evaluation and reporting of the SKB work with simulation of the Febex experiment (within the Decovalex initiative) was under way.

The regulatory authorities were of the opinion that it has not yet been shown that deposition holes will not be intersected by fractures with a length greater than 700 metres in the dip direction. Nor did the regulatory authorities think that SKB had demonstrated that fractures of a shorter length do not need to be taken into consideration in the analysis of thermomechanical loading. Furthermore, they thought that thermal movements that occur in the rock mass in the Prototype Repository in the Äspö HRL should be should be taken advantage of for calibration. A general comment is that ongoing experiments need to be concluded and analyzed before definite conclusions can be drawn concerning thermally-induced movements in the rock mass.

Newfound knowledge since RD&D 2004

The temperature evolution in the Apse experiment has been back-calculated with measured temperatures, after which the evolution of thermal stresses in the pillar between the two deposition holes has been calculated /26-61/. The results have then been utilized to determine the spalling strength of the rock by comparison with the observed evolution of the spalling in the wall of one of the deposition holes. See also section 26.2.5, which comments on the evaluation of the Apse experiment /26-8/ and near-field models.

Regarding geological-structural characterization and questions linked to thermomechanical loads, see section 26.2.7.

Programme

The analytical thermomechanical solution developed by Claesson and Probert /26-62/ will be further developed so that cases with several different deposition areas can be analyzed. The original equations will be coded to easy-to-use mathematical calculation sheets. The purpose is to permit quick and easy analysis of the effects of varying the deposition geometry, the effects of time differences between different deposition campaigns, etc.

The thermomechanical evolution in the Prototype Repository will be analyzed using a method similar to that previously employed for the Apse experiment /26-61/. The analysis will be based on the verified thermal analysis now available, in other words by careful description of how the effect has varied in the different canisters.

The possible pressure dependence of the coefficient of thermal expansion of typical repository rock types will be determined, mainly by means of a literature study. The purpose is to assess the risk that the thermal stresses in the repository are underestimated due to the fact that the parameter values are determined by tests on unloaded specimens.

A study of characterization of microfractures caused by thermal expansion is being coordinated with other efforts when it comes to time-dependent deformations and fracture dynamics, see section 26.2.9.

26.2.7 Reactivation – movements along existing fractures

Conclusions in RD&D 2004 and its review

In RD&D-Programme 2004, SKB referred to various studies of the role of the fracture system for deformations in the near-field in connection with tunnel excavation and boring of deposition holes /26-63/. The main conclusion is that fracture systems of the type assumed in the model do not play any decisive role purely mechanically, at least not when it comes to the occurrence of failure in intact rock blocks or the general deformation pattern. When it comes to the risk of spalling, the stresses and the direction of the stresses in relation to tunnels and cavities are more important than details in the fracture geometry, see also /26-52, 26-64/.

RD&D-Programme 2004 also gave an account of shear movements due to earthquakes. Previously (for example in SR 97), seismically induced shear movements in fractures have been analyzed using a statistical (non-dynamic) calculation method with statistically generated earthquakes that induce movements in statistically generated site-specific fracture populations containing fractures of different lengths and orientations. This issue has now also been analyzed dynamically with the codes Wave and Flac3D /26-65/. The dynamic results indicate that the statistical contribution to the induced fracture movement is dominant, at least at the short distances that will be important for the final repository. For a fracture at a distance of a few hundred metres, however, it is not the seismic moment but the local, and presumably magnitude-independent, stress change that is crucial. A compilation of documented earthquake-induced damage to underground structures shows that the effects, in the form of documented permanent deformations, are limited to the area nearest the earthquake, even in cases where road or rail tunnels intersect the active zone /26-66/.

The regulatory authorities proposed that the maximum displacements due to earthquakes should be reported in the form of a diagram, where the magnitude of the earthquake, the distance from the epicentre and the displacement are presented graphically. This would make it easier to judge how these parameters vary and how they are dependent on each other. The magnitude and direction of probable stress states should thereby be taken into account. They further observed that SKB's conclusions concerning fracture movements in connection with earthquakes with a magnitude of six or more are still associated with uncertainties. This requires further work before the results can be translated into a feasible concept and be used in the safety assessment. Furthermore, the regulatory authorities commented on the lack of studies shedding light on and determining the strength and deformation characteristics of the major fractures and fracture zones.

Kasam believed that seismic measurements and measurement of in situ deformation take place for a long time and that GPS measurements should be resumed in Oskarshamn and established in Forsmark. Kasam also wanted a definition of the overall objective of determining the respect distance to fracture zones.

Newfound knowledge since RD&D 2004

A round of calculations with the two-dimensional distinct element code UDEC has been carried out to determine whether the repository can behave like a plane of weakness. The results show that the tunnels would have to be more closely spaced than 20 metres in order for the effect of the tunnels not to be negligible.

Regarding the effects of earthquakes, dynamic analyses have been performed using the distinct element code 3DEC /26-62/. Two different earthquake geometries were analyzed: one where the fault reaches one kilometre below ground (Case A) and one where the fault breaches the ground surface (Case B). In both cases the earthquake was a magnitude six. The hypocentre of the earthquake was about three kilometres below the ground surface, so that the rupture propagated in the fault plane with 70 percent of the shear wave velocity in the surrounding elastic rock, see Figure 26-6.

The purpose of the study was to determine the magnitude of the secondary shear movements that can be induced in fractures at different distances from an earthquake. A large number of circular fractures, called target fractures – all 300 metres in diameter with a friction angle of 34 degrees and a constant pore pressure of 5 MPa – were defined at different distances from the quake zone. The possible shear movement of target fractures in conjunction with seismic activity in nearby zones is one of the reasons the canisters should not be deposited in holes intersected by major fractures /26-65/. Figure 26-7 shows that the maximum calculated shear movement of fractures at a distance of 200, 600 and 1,000 metres from the fault was well under a decimetre, i.e. considerably less than the current canister damage limit. At a given load the shear movement is proportional to the diameter of the fracture, which means the results can be translated directly into equivalent results for smaller fractures, for example those with a diameter of 150 metres. As is evident from the figure, the study shows that canisters can be deposited in deposition holes that are intersected by fractures with a diameter of 300 metres or less if the distance from the deposition hole to a possible magnitude six earthquake is 200 metres or more. At smaller distances, the diameter of intersecting fractures may not be greater than 150 metres. No canisters are deposited within a respect distance of 100 metres, regardless of the calculation results. The shear movements in Figure 26-7 are the greatest given by the 3DEC simulations at the different distances. The average movements were much smaller. Figure 26-8 shows the maximum slip (displacement) in all fractures at distances of 200 and 600 metres in the two 3DEC models.

The results – that is the distance limitations and fracture size rules – were judged to be valid for larger earthquakes as well, for example magnitude seven earthquakes /26-62/. From several aspects, for example when it comes to the average displacement sum and the maximum shear rate, the simulated quake was actually equivalent to a magnitude seven earthquake. At small distances the intensity is decisive, not the extent of the active zone or the released strain energy. Furthermore, there is a considerable margin in the calculation results to the canister damage limit, see Figure 26-8.

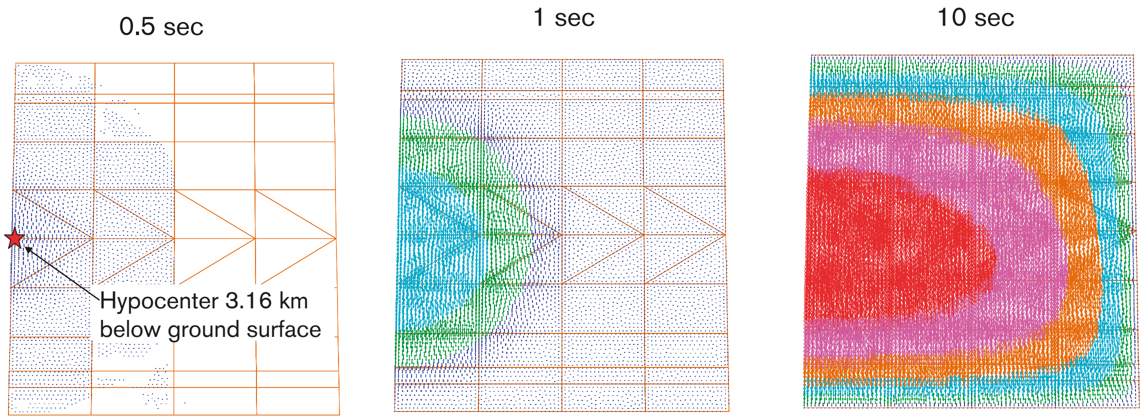


Figure 26-6. *Initiation and propagation of rupture in dynamic 3Dec model of earthquake with symmetry plane in hypocentre. The total rupture area is about 20 km² /26-62/.*

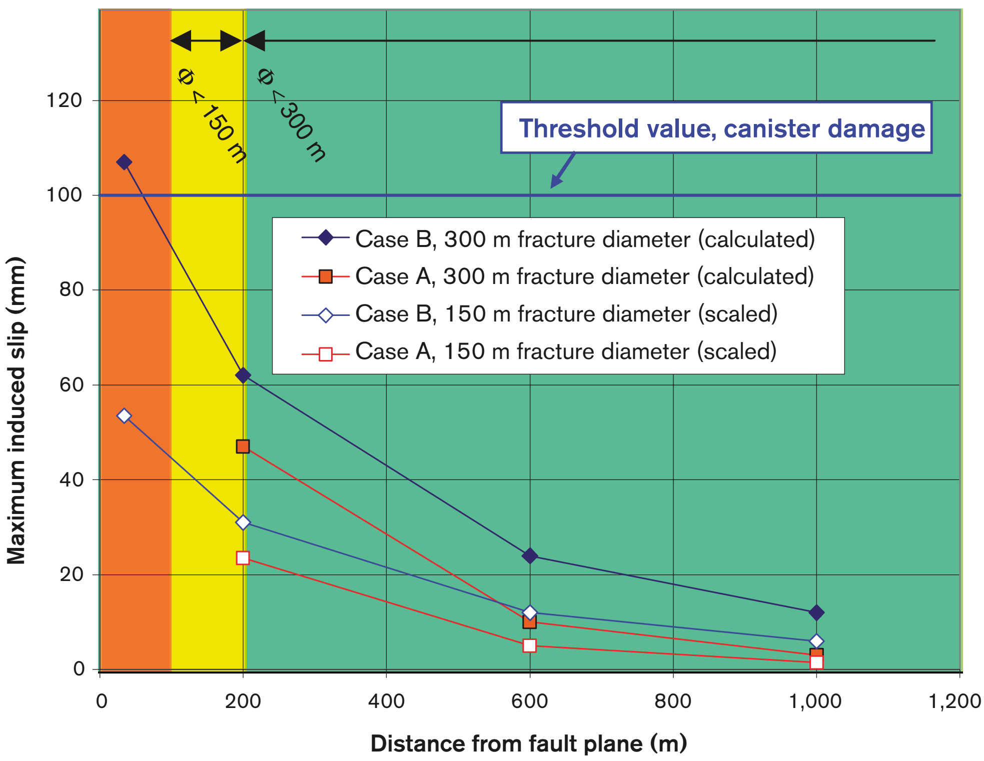


Figure 26-7. *Filled symbols: calculated maximum induced shear movement (slip) in fractures with a diameter of 300 metres at different distances from magnitude six earthquakes. Empty symbols: equivalent results scaled to fractures with a diameter of 150 metres. The figure indicates that canisters can be deposited in holes intersected by fractures with a diameter of less than 300 metres at a distance of 200 metres from potential quake zones. At distances of less than 200 metres, the diameter of the intersecting fractures may not be greater than 150 metres. Canisters should not be deposited within a distance of 100 metres from the potential quake zone, regardless of the calculation result.*

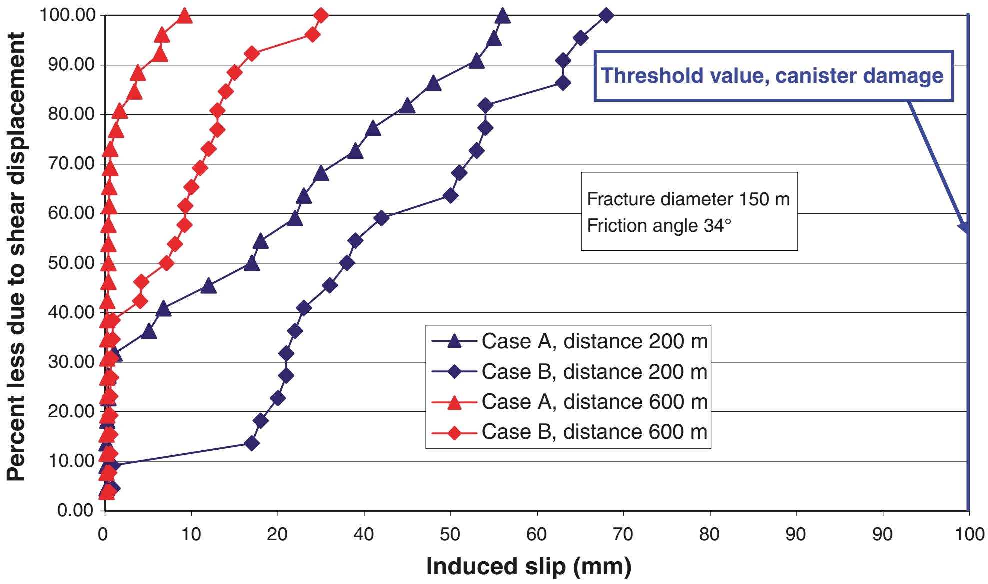


Figure 26-8. *Distribution of shear displacement (slip) in all modelled fractures at distances of 200 and 600 metres from a magnitude six earthquake.*

Uppsala University has conducted two studies describing different mechanical effects in the Earth's crust of a glaciation similar to the Weichselian glaciation /26-67, 26-68/. Both studies were based on numerical two-dimensional modelling with the finite element code Abaqus. The first study /26-67/ concerned the stability of the crust and the potential for earthquakes during the deglaciation period, as the ice sheet retreated. The elastic crust was approximated by average properties and was furthermore assumed to be incompressible. The other study concerned the stress evolution at a depth of 500 metres in Forsmark and Laxemar and was carried out with more developed crustal models and for two assumptions regarding the temporal evolution of the Weichselian glaciation. The results are above all relevant for defining mechanical boundary conditions for near-field models, for example of the type analyzed in /26-53/.

The international programme Decovalex III was a continuation of the multidisciplinary collaboration aimed at developing modelling tools for Thermo-Hydro-Mechanical (THM) processes in fractured rock and buffer material. Decovalex III was carried out during the period 1999–2003. Fourteen funding organizations, both government agencies and industrial organizations, participated. A large number of calculation activities were carried out, including a Bench Mark test (BMT3/WP4) focused on THM effects of glaciation and deglaciation. BMT3/WP4 was a generic exercise based on geological and hydrogeological data from a site in the northern hemisphere (Whiteshell, Canada), which is assumed to be subjected to a climate-driven environmental impact at the ground surface. The modelling mainly concerned the hydromechanical impact of a glaciation cycle (up to a hundred thousand years) on a hypothetical repository. A number of different scenarios and model sets were dealt with, for example permafrost, 2D versus 3D conceptualization, inland versus near-coastal repositories and sea level changes. SKB's involvement in BMT3/WP4 mainly concerned site-specific hydromechanical modelling with a focus on groundwater pressure heads, flows, rock stresses and fracture zone displacements /26-69 to 26-71/. Even though the highly simplified conceptual assumptions affect the results, the conclusions are:

- Subglacial groundwater is partially driven by consolidation of the bedrock under the ice load, which means that long-range glaciation scenarios should take hydromechanical process couplings into account.
- The altered behaviour of the near-surface boundary condition over a long time entails a need for transient simulations in order to assess the effects of large hydraulic pressure pulses that affect low-permeability bedrock formations.
- 3D modelling should be performed, since 2D modelling overestimates the possibilities of hydraulic fracturing in closed fractures without connectivity with other fractures.

Differential SAR Interferometry (DinSAR) is a technique that compares phase shifts in multiple images from a radar satellite above an area. The purpose is to determine changes in the ground surface. The method has the potential to detect millimetre-scale displacements (mainly vertical) within the radar sensor's visual field. The co-interpreted resulting image is called an interferogram and contains information that is related to the topography and/or to the deformation of superficial objects. New calculation algorithms can use many images acquired over a long time period over the same area to determine the movement history of individual objects (permanent scatterers). A study using this new technique has been conducted for the Forsmark region. The overall purpose is to measure any postglacial movements in existing fracture zones. A number of 40 ERS-1 and ERS-2 satellite scenes from the period 1992–1999 were treated. The total area studied was 1,500 km^2, and 20,000 permanent scatterers (outcrops and man-made structures) were identified for the analysis. There was some dominance of permanent scatterers in near-coastal locations, where the bedrock is exposed. The main result is that no movements could be observed during the studied period in any regional lineament or in any fracture zone in the Forsmark area. Several cases of local subsidence in loose sediments were identified, however. The most pronounced subsidence (about 25 millimetres maximum during the period) can be noted in the fill materials in the extended piers outside the nuclear power plants. It should be pointed out that no subsidence was detected for the power plant buildings /26-72/.

The mechanical properties of a major deformation zone, the Singö Zone in Forsmark, were estimated on the basis of numerical simulations and deformation measurements carried out during the construction of the SFR access tunnels /26-73/.

An overall geological-structural characterization project has been carried out. The focus was on quantifying the occurrence and extent of fractures and minor deformation zones on the order of 100–500 metres /26-74/. The report on the project discusses different methods for determining the location, orientation and length of such structures during different investigation stages and the various stages in the construction of the repository. A methodology for mapping potentially discriminating fractures was also developed within the project. This methodology is based on fracture mapping in tunnels and application of DFN modelling /26-75, 26-76/.

Programme

The work of developing and analyzing models of stability conditions and stress evolution in the Earth's crust during a glaciation cycle is continuing. The models that have previously been analyzed have been two-dimensional and based on simplified assumptions regarding how the properties of the crust and mantle (compressibility, density, viscosity, etc) vary with depth. The next step is to study a three-dimensional situation.

The work of studying the premises for hydraulic fracturing will continue with modelling using the simulation code 3Dec.

The dynamic simulations that have so far been done with 3Dec have pertained to magnitude six earthquakes. The modelling technique, to control rupture propagation with the aid of 3DEC's built-in programming language so that the rupture propagates radially from an assumed hypocentre, will be modified. We have been able to analyze, or at least bound, the effects of major quakes as well. A magnitude seven earthquake requires a model that must be between one and two orders of magnitude larger than the models analyzed to date, counted in number of elements and grid points. This lies beyond what is practically feasible with today's computation capacity. The modelling technique will therefore be modified so that the earthquake zone is represented to full depth, but so that the zone is truncated vertically at a distance of several kilometres from the hypocentre. The influence of the length of the zone in the strike direction, i.e. effects of movements in remote parts of the zone, will thereby not be represented completely correctly.

The thermomechanical near-field models (Forsmark and Laxemar) analyzed previously /26-53/ to determine what transmissivity changes can be expected in the fractures in the near-field during construction, thermal load and a glaciation cycle will be developed to agree with layout and rock properties according to the description in the updated layout and site descriptions.

The deformation zones in and around the deposition areas will affect the thermal volume expansion of the near-field and thereby the thermal stresses around deposition holes and tunnels. To bound this influence, large-scale 3DEC models of the sites are being analyzed. The large-scale 3DEC models will then be used to derive relevant mechanical boundary conditions for the near-field models.

The deformation measurements using GPS (Global Positioning System) technology that were initiated for the Forsmark area in 2005 will continue up until 2008. The goal of the study is to obtain additional experience of the technique with fixed GPS stations and measure any ongoing bedrock movements (mainly horizontal) along the most pronounced regional deformation zones: the Singö Zone and the Forsmark Zone.

26.2.8 Fracturing

Conclusions in RD&D 2004 and its review

RD&D-Programme 2004 states that general aspects of the problem of spalling and stability of the deposition hole walls have been dealt with in an overview study /26-50/. In particular, the importance of a light support pressure from the buffer to prevent initiation and propagation of failure that can lead to spalling is discussed. A separate compilation of geological, mechanical and thermomechanical parameter values for the rock mass around the Apse experiment was published as a basis for prediction of the occurrence of spalling under thermomechanical loading of the Apse pillar /26-77/. Furthermore, various development projects for calculation codes, for example Fracod and Particle Flow Code, aimed at fracturing processes, were described, but also calculations for thermomechanical simulations with Flac3D and JobFem. Results were presented for the calculation code Examine3D (elastic premises) and can serve as a basis for determining which areas may enter a failure state. It was concluded that calculations with Examine3D can be regarded as a platform for the development of models for failure and fracture propagation.

The regulatory authorities thought that the section in RD&D Programme 2004 that deals with fracturing is important and awaited the modelling results from continued applications of the calculation codes Fracod and PFC. They noted that SKB's account includes rock creep but says nothing about subcritical fracturing, namely, fracturing occurring over long periods of time and at loads that are far below the normal rupture limit, see also section 26.2.9 concerning time-dependent deformations. It was further commented that the importance of the EDZ (Excavation Damage Zone) is still an open question which needs to be taken into account in future analyses. The regulatory authorities thought that SKB should provide a coherent account of its view of the EDZ, its effects and its importance for safety.

Newfound knowledge since RD&D 2004

The Apse experiment has been evaluated in its essential respects. Development of techniques for modelling of brittle failure and fracture propagation has continued; see previous section 26.2.5 concerning intact rock.

Safety assessment aspects of the excavation-disturbed zone (EDZ) have been addressed within the framework of SR-Can, see for example section 13.6.6 of /26-78/. According to SR-Can, an EDZ with up to one and a half orders of magnitude higher conductivity than the surrounding rock would not entail any major safety problem. A fundamental prerequisite is, however, that tunnelling is carried out according to quality-assured practices.

Programme

For planned work, see the programme description for intact rock in section 26.2.5, as well as sections 12.5 and 12.7 in Part III.

26.2.9 Time-dependent deformations

Conclusions in RD&D 2004 and its review

It was claimed in RD&D-Programme 2004 that the tunnel backfill cannot contribute to limiting convergence that is due to slow creep movements that take place in the rock within a distance of several tunnel diameters from the tunnel. It may, however, be sufficient to limit the scope of block breakout and the initiation and development of progressive failures in the rock nearest the tunnel walls /26-79/.

The regulatory authorities were of the opinion that SKB's proposed programme is reasonable and that calculations of time-dependent are of the utmost importance. They commented that SKB has so far conducted a literature survey of normal creep in rock masses (only a preliminary report was then available), but that another issue, subcritical fracturing, requires different types of analyses. The regulatory authorities believed that SKB should analyze the influence of creep for both fractures and intact rock, and give an account of the importance of subcritical fracturing and its creation of new microfractures as a function of time /26-80, 26-81/. The creation of new microfractures over long periods of time is important for assessing how permeability around deposition holes and tunnels changes.

The regulatory authorities further believed that the impact of subcritical fracturing is probably greatest on sites with high rock stresses, as is the case in Forsmark. They commented that the high stress magnitudes at the proposed deposition levels in Forsmark indicate that subcritical fracturing could occur. Subcritical fracturing is related to the rate at which fracturing occurs and is often presented in graphic form as the fracture rate as a function of the fracture mechanics parameter of fracture toughness (propensity to break). In the case of rock material, the fracture toughness declines as the deformation rate decreases. The slower the deformation, the greater the probability of rupture. As far as the regulatory authorities knew, these relationships had not yet been studied and tested by SKB.

Newfound knowledge since RD&D 2004

A literature survey /26-82/ of time-dependent deformations in rock masses, particularly along fractures of different types (filled, unfilled), has been conducted and reported. One of the conclusions is that the ratio between stress and strength must exceed certain threshold values in order for any creep at all to occur.

Programme

Time-dependent deformations are generally linked to fracture dynamics. A coordinated study is being initiated. It will investigate and gain a better understanding of the occurrence of microfractures, subcritical fracturing and creep. The study will also cover all aspects of thermally induced microfractures.

26.2.10 Erosion

Conclusions in RD&D 2004 and its review

Long-term erosion of the geosphere has been judged by SKB to be of subordinate importance for the long-term performance and safety of the final repository. Some estimates of the scope of glacial erosion are given in the literature, see for example /26-83/.

The regulatory authorities commented that SKB refers to its climate programme, which handles issues relating to erosion. However, SKI finds that specific studies concerning this process are lacking in SKB's climate programme. Therefore, the need still exists for SKB to study and report the possible importance of the process for the performance of a final repository. The regulatory authorities also reminded SKB about the comments made in their review of RD&D Programme 2001.

Newfound knowledge since RD&D 2004

An estimation of the erosion depth during the Quaternary Period has been carried out on behalf of SKB /26-84/. The study estimates an upper bound for the average erosion of bedrock during a glacial cycle or a single glaciation. The study is based on the assumption that the clastic sediments formed by ice sheet erosion during the Quaternary period still exist within the formerly glaciated area. The average depth of the glacial erosion of the bedrock was estimated to be between 0.2 and 4 metres during a full glacial cycle. If the extremes in the assumptions made are excluded, the average erosion during a glacial cycle can be estimated to be about one metre.

The erosion process has also been studied within the framework of SR-Can (Process Report), where current literature in the field is reviewed and conclusions are drawn regarding the impact on the repository. The issue has also been addressed in the above-cited SKB report /26-84/. During ice-free periods, fluvial erosion is judged to be the most important denudation process. The most extensive erosion is assumed to occur in conjunction with glaciations, and then only during periods with warm-based conditions in the ice sheet. The glacial erosion then occurs above all in low-lying parts of the terrain, such as along valleys. The scope of the erosion is much less above gently-dipping zones of bedrock. The results of the studies show that erosion of the geosphere has an insignificant impact on the long-term performance and safety of the final repository.

Programme

SKB will continue to monitor the literature in this field. SKB will also cooperate with Posiva to compile the results of other completed studies, which is meaningful owing to the similar geological and climatological conditions in the areas of interest around the Bothnian Bay. But this is not expected to alter the picture that erosion of the geosphere is negligible in an assessment of the repository's performance.

26.2.11 Advection/mixing – groundwater chemistry

This section deals with the effect of the mixing that occurs due to the fact that the water moves at varying velocity in the fracture system in the rock and how the process affects the chemistry of the groundwater. Section 26.2.12 deals with the importance of advection and dispersion for radionuclide transport.

Conclusions in RD&D 2004 and its review

Mixing calculations for both Äspö and the investigated sites have been carried out with the aid of the statistical computer programme M3 /26-85/ and the groundwater flow model DarcyTools. To some extent it has been possible to utilize both hydrological and chemical data for models of advection/mixing on a large scale. SKI pointed out the risk of statistical interpretations of data and the difficulties of alternative interpretations of the groundwater flow situation. SKI encouraged SKB to collect and use more data, which should result in better models and in turn promote paleohydrological interpretations that could be used for scenario selection and safety assessment.

Newfound knowledge since RD&D 2004

The new data that have been collected within the site investigation programme have been analyzed and site models have been created /26-86, 26-87/. These models have utilized both hydrogeochemical and hydrogeological data, as well as our knowledge of the paleohistory of the sites. The models have been used in the SR-Can safety assessment in order to model in detail the groundwater chemistry during the temperate period following the closure of the final repository /26-88/.

The computer model DarcyTools has been updated and verified by modelling the groundwater flow at Äspö, see section 26.2.3. The computer code M3, which is used for statistical processing by multivariate analysis, has been developed with support from SKB. The programme has been updated /26-89/ and is in the process of being verified.

Programme

The development of models for groundwater flow is described in section 26.2.3. Verification of the updated M3 will be concluded within the next few years.

Within the site investigations, site-specific mixing calculations will continue to be important for obtaining a deeper understanding of the evolution of the water on the site. Calculations of the evolution of salinity in connection with extensive climate changes over long time intervals will be carried out within the framework of SR-Site.

26.2.12 Advection/mixing – radionuclide transport

Conclusions in RD&D 2004 and its review

It was stated in RD&D-Programme 2004 that no specific programme for advection/mixing would be initiated. But it was mentioned that the question of advective transport with matrix diffusion along transient flow paths would be studied. It was also mentioned that a project for upscaling of the F-factor was planned.

The regulatory authorities did not comment on this process in their review.

Newfound knowledge since RD&D 2004

No project has been specifically devoted to advection/mixing. It can, however, be noted that the report /26-37/ that was discussed in section 26.2.3 also indirectly concerns advection since channelling in variable-aperture fractures was analyzed.

The projects concerning upscaling of the F-factor and transport in transient flow fields are dealt with in section 26.2.26.

Programme

The planned version of DarcyTools that solves the Navier-Stokes equations for groundwater flow (see section 26.2.3) also makes it possible to perform detailed studies of advection in individual variable-aperture fractures. Questions that can be elucidated include, for example, dispersion/mixing in individual fractures nearest the canister. Mixing in a network of Fracture Intersection Zones (FIZs) can also be studied. The need for these types of simulations will be evaluated before detailed studies are commenced.

In reactive transport models (see section 26.2.26), it is often necessary to obtain information on mixing conditions. Such information can be obtained from a groundwater flow model. The problem is that flow models are often based on dispersion rather than mixing. There is thus a need to evaluate the difference between mixing and dispersion in groundwater flow models. This activity may be undertaken if reactive transport models are to be used to a greater extent.

26.2.13 Diffusion – groundwater chemistry

This section deals with the effects of molecular diffusion of groundwater components globally in a very long time perspective and how the process affects hydrochemical conditions. Molecular diffusion and matrix diffusion and their importance for nuclide transport are dealt with in section 26.2.14.

Conclusions in RD&D 2004 and its review

Site investigations in Finland and Sweden have shown that the hydrogeochemical conditions on the sites are very similar. Meteoric water, old seawater and glacial water occur in varying proportions in the rock down to a depth of approximately 500 metres. The salinity increases linearly with the depth. At depths greater than 500 metres the salinity increase accelerates and the water is estimated to have a residence time far in excess of 10,000 years. This indicates that a dynamic process controlled by inflow of water from higher-lying areas and outflow in lower-lying areas is going on down to a depth of 500 metres. At greater depths, the groundwater system is unaffected by this dynamic. If the dynamic water has a measured residence time of 1,000 to 10,000 years, the corresponding value for the stagnant water is much longer. The conclusion is that the deep brine (saline water), which is mobile in a geological time perspective, can be regarded as stagnant in a 10,000–100,000 year perspective. It is possible that diffusion process affect the salt distribution in the groundwater in the deepest rock volumes.

Newfound knowledge since RD&D 2004

As far as SKB knows, no new knowledge in the area has been forthcoming.

Programme

This field is not judged to require any extensive research, development or demonstration today. New developments are being monitored and will be acted on when appropriate. For example, SKB will investigate whether it is possible to utilize data from Greenland, with its thick ice sheet, to check the models for groundwater flow and salt distribution under such conditions. A preliminary inquiry has not uncovered any such data.

26.2.14 Diffusion – radionuclide transport

Conclusions in RD&D 2004 and its review

It was noted in RD&D-Programme 2004 that the Long Term Diffusion Experiment (LTDE) in the Äspö HRL would start during the current period, and that the doctoral project concerning the use of electrical measurement methods for estimating the rock's formation factor in situ would be finished. Both of these goals have been achieved. Specifically regarding in situ measurements of the formation factor, it is noted that this method is now routinely used in the site investigation programme.

The regulatory authorities did not offer any comments on this section of RD&D-Programme 2004.

Newfound knowledge since RD&D 2004

The focus on LTDE has shifted slightly during the most recent period. The experiment has been focused more on sorption than diffusion. In situ values of sorption coefficients (K_d values) are now sought after rather than diffusion coefficients. The experiment has consequently been renamed LTDE-SD, where SD stands for sorption-diffusion. The reason for this new orientation is the knowledge that emerged in the data compilations for diffusion and sorption values for SR-Can /26-90, 26-91/, where it is noted that the greatest uncertainties were found to exist for the sorption values. LTDE-SD is therefore discussed in section 26.2.17.

The electrical resistivity method has been used in the site investigations to estimate the formation factor in situ along boreholes. Furthermore, different experiments are being conducted in the laboratory to measure diffusion or properties of importance for diffusion on site-specific material. Results from measurements of the formation factor have been reported /26-92, 26-93/. Results from measurements with diffusion cells are not available yet, however. The in situ measurements provide an opportunity to study the natural variability in the formation factor within a given rock type, as well as to study whether systematic differences exist between different rock types and between the two investigated sites. The results are summarized for the two sites in version 1.2 of the site models in /26-92, 26-93/.

Data on matrix diffusivities (diffusion coefficients) have been compiled for use in SR-Can /26-90/. It is observed in the report that the site-specific values obtained by means of the electrical resistivity method in situ are more reliable than the corresponding laboratory values. This is mainly due to the destressing of the samples that takes place in the laboratory and thereby results in higher values. A much larger body of data is also obtained from the in situ measurements. In general, it is concluded that data indicate that there is an interconnected pore system for matrix diffusion, and that this pore system in the investigated cases exceeds one metre at least.

The composition of the matrix pore water has also been analyzed in the site investigations /26-94/. By comparing the composition of this stagnant water with the composition of the flowing water in the fractures, matrix diffusion can be estimated. If the two water types are in equilibrium, this is an indication that matrix diffusion is effective. The method has been developed at the Äspö HRL within the project for matrix fluid chemistry /26-95/, see also section 26.2.15.

Programme

During the current period, LTDE-SD analyses will be done in the laboratory, and a final report will be published. Even though the focus is on sorption, diffusion coefficients will hopefully also be obtained. The field experiment is, however, abbreviated compared with the previous plan so it only lasts about six months. Furthermore, diffusion experiments will be performed in the laboratory to permit in situ values and laboratory data from LTDE-SD to be compared with data from the site investigations.

Measurements of the composition of the matrix pore water will also proceed during the final phase of the site investigations. The goal is to be able to study a diffusion profile from a flowing fracture into the stagnant water in the matrix. The primary challenge is to identify, during drilling, a fracture with suitable properties and orientation so that pieces can then be taken from the drill core for further leaching experiments.

26.2.15 Reactions with the rock – groundwater and rock matrix

Conclusions in RD&D 2004 and its review

The interaction between the matrix pore water/fluid and the groundwater takes place mainly by diffusion. Chemical reactions will mainly take place with fracture-filling minerals. In the long term, however, reactions with the rock's primary minerals are of greater importance for the chemistry of the groundwater. This effect is most pronounced in aquifers in sedimentary rocks, while rock-water reactions in crystalline rock proceed more slowly.

The composition of the groundwater in fractures is often affected by both mixing and reactions. Matrix pore water in crystalline rock has, on the other hand, only been studied at a few places

/26-96, 26-97/. A conclusion from these studies is that the matrix pore water can have a much higher salinity that the groundwater in surrounding fractures and can thereby possibly have a negative impact on the engineered barriers. For this reason, studies of matrix pore water/fluid were started in the Äspö HRL (Matrix Fluid Chemistry Experiment).

In the Matrix Fluid Chemistry Experiment /26-95/ we sampled and analyzed water/fluid present in the pores in the rock. The results of the experiment show that contact between matrix fluid and groundwater in the fractures takes place through slow migration in a network of microfractures with small dimensions and low hydraulic conductivities. Solutes are transported within the rock matrix by diffusion. The matrix pore water has preserved brackish waters of unknown age. Based on measurements of the parameter $\delta^{18}O$, these waters could be postglacial or from a previous glaciation. The experiment has shown that most of the sampling sections have achieved approximate equilibrium between the matrix pore water and the water present in the permeable fractures. But there are also indications that certain rock volumes have a more closed pore system that has preserved water of lower salinity. The conclusion from the Matrix Fluid Chemistry Experiment is that in most sections there is only a small component in the matrix fluid that is the result of long-term reactions between rock and water. The results show that there is no reason to suspect that there is any highly saline matrix fluid at repository depth in an environment similar to that in the Äspö HRL.

Newfound knowledge since RD&D 2004

Experience from the Matrix Fluid Chemistry Experiment has been applied to the site investigations. Sampling and analysis of the matrix pore water has been and is being developed considerably. The existing results have been presented within the framework of the site modelling /26-94, 26-99/.

Programme

Within the site investigation programme, samplings of the matrix pore water will continue. The evaluation of these results will be of importance for SR-Site and for assessing the possible future need for further research, development or demonstration.

26.2.16 Reactions with the rock – dissolution/precipitation of fracture-filling minerals

Conclusions in RD&D 2004 and its review

Dissolution and precipitation of fracture-filling minerals is a constantly ongoing process. Most of these minerals have been formed under hydrothermal conditions, but low-temperature minerals are also present. They can be utilized to understand the evolution of the groundwater chemistry, for example with respect to redox conditions.

Oxidizing conditions at repository depth can be broken down into two sub-problems:

- The repository will be oxygenated during construction and operation. Some oxygen will probably remain in and near the repository at closure.
- Fears have been expressed that oxygenated water might penetrate down to repository depth during periods of greatly changed hydrogeological conditions, for example in conjunction with a glaciation.

To be able to evaluate the risk that glacial meltwater reaches repository depth, a re-examination was conducted of existing data from both the Äspö HRL and Klipperås (occurrence of redox-sensitive minerals etc) and other places /26-99/.

The evaluations of both water chemistry /26-85/ and fracture mineralogy /26-100/ show that there are clear indications that components of a glacial meltwater have reached great depths (deeper than 500 metres). But there are no traces to indicate that this water might have been oxygenated below a depth of about 50 metres. There are, on the other hand, strong indications that reducing conditions have existed at depths below 100 metres for a long time /26-100, 26-101/. It would therefore be misleading to associate the presence of glacial meltwater with oxidizing conditions.

In the Rex Project (Redox Experiment on Detailed Scale) in the Äspö HRL, studies were made of how oxygen remaining after closure of a repository can react with minerals and groundwater in the rock around the tunnel and the deposition holes or along the conductive fractures /26-102/. The results from the in situ experiment were confirmed by replica experiments in the laboratory. Both investigations showed that the oxygen had been completely consumed after a few days.

Besides the oxygen consumption rate, the available buffering capacity is of great importance. The buffering capacity for inorganic reactions between oxygen dissolved in water and reducing substances (divalent iron and sulphide) in solution and in fracture-filling and matrix minerals can be estimated. Experiments have been conducted with weathering of the fracture-filling mineral chlorite /26-103/. Chlorite is a common mineral in fractures and also occurs in alteration minerals in the surrounding rock matrix. The mineral usually contains significant quantities of divalent iron and therefore contributes to the rock's buffer capacity against intrusion of oxygen-containing groundwaters. As far as the capacity of microbes is concerned, some fundamental research remains to be done, see section 26.2.18.

Equip was an EU project conducted during 1997–2000 aimed at using fracture-filling minerals, mainly calcite, as indicators of current and former groundwater chemistry /268-100/. Generally speaking, calcite is the most useful mineral, since it can be formed under very different conditions and furthermore provides information on which type of groundwater the calcite has been formed from. The composition of isotopes and trace elements is of help in this. Sulphide minerals and iron oxides or iron oxyhydroxides can also be useful in interpreting redox conditions. Uranium series analyses from clay- and hematite-rich fracture fillings from the Äspö HRL have been evaluated. The results support the interpretation that the current redox front (transition from oxidizing to reducing conditions) does not reach a greater depth than about 30 metres on Äspö /26-104/.

SKI pointed out in its review of RD&D-Programme 2004 that even if a scenario with changed redox conditions at repository depth can be considered to be of very low probability, new modelling studies could be of benefit for SKB's safety assessments.

Newfound knowledge since RD&D 2004

The properties of fracture-filling minerals may be useful for determining previous redox conditions. Studies of calcites within the EU project Padamot have been concluded /26-105/. The results of the project, which is aimed at studying iron(III) oxides at the Äspö HRL /26-106, 26-107/, are in the process of being reported.

The experience gained from Padamot has been transferred to the site investigations, and the results of the fracture-filling mineral studies are available as P reports, for example /26-108, 26-109/.

Several studies of weathering rates of ferrous fracture-filling minerals have recently been published, for example /26-110, 26-111/.

In SR-Can, model calculations have been carried out to show how deep a glacial water can percolate. Renewed models have also been used to investigate how deep oxygenated glacial water can reach before the oxygen is consumed /26-112, 26-113/.

Programme

Further experiments with weathering of ferrous fracture-filling minerals are planned within the coming six-year period. One question to explore is the occurrence of microbial processes in laboratory experiments.

The problem of dating different water/mineral processes has still not been solved. Continued measurements of iron(III) oxides and uranium series analyses are therefore planned for the upcoming period. Measurements of traces of organic molecules, called biomarkers, will be evaluated as indicators of previous groundwater chemistry.

26.2.17 Reactions with the rock – sorption of radionuclides

Conclusions in RD&D 2004 and its review

It was mentioned in RD&D-Programme 2004 that another experiment in the Äspö HRL with uranium and technetium would be conducted within the actinide project that is utilizing the Chemlab II probe.

It was stated in RD&D-Programme 2004 that there may be a need to develop process-based models of sorption. It was further mentioned that a licenciate project concerning the use of electrical methods to determine K_d values on intact pieces of rock would be conducted.

The regulatory authorities did not make any specific comments.

Newfound knowledge since RD&D 2004

The experiments with uranium and technetium in the Chemlab II probe have been conducted and reported in /26-114, 26-115/. Approximately one percent of the injected technetium was found in the eluate. The breakthrough curve for this fraction followed the curve for tritiated water (HTO). Uranium exhibited some retention, where approximately 40 percent of the uranium made it through, all in hexavalent form. The remaining technetium and uranium was found bound to the same (often ferrous) minerals in the fracture.

Electrical methods are used to estimate K_d values for sorption. In brief, the method involves increasing the penetration of a tracer in a piece of rock by means of electromigration (electrical potential gradient). It is estimated that an increase of two to three orders of magnitude can be achieved for sorbing substances. Preliminary results indicate that it is possible to use the method for sorbing tracers. The estimated K_d values are considerably lower than the equivalent K_d values measured in batch experiments /26-116/. The results thus confirm the theory that K_d values measured in batch experiments on crushed material overestimate sorption.

Two different studies are being conducted in the area of process-oriented sorption modelling. One has to do with prediction of the batch sorption measurements being performed within the site investigation programme. Here a surface complexation model is being used to predict the sorption coefficients for nickel that have been measured for a sample of Ävrö granite from Laxemar. By assuming mineralogy and that nickel is the only sorbing substances, K_d values for both saline and fresh groundwater have been calculated. The predicted values agree relatively well with the experimentally measured values for both water types, given different assumptions regarding magnetite's share of the sorption surface area (BET surface area) for the predicted values. In another project, the surface complexation model for nickel from the first project is being used in a first test of reactive transport modelling. This transport model should be able to predict transport of nickel in connection with changes in hydrogeochemical condition, for example pH. At present, the model only includes sorption on surfaces. Matrix diffusion with sorption on inner surfaces is not included.

As described in section 26.2.14, LTDE has now mainly become a sorption experiment, LTDE-SD. The experiment has been started in the Äspö HRL. Results will be available during 2007–2008, see below.

Both batch-sorption measurements and through-diffusion measurements are being performed in the site investigations, providing K_d values for site-specific materials. Furthermore, K_d values are being measured on some whole pieces, as well as both CEC (cation exchange capacity) and BET area (a measure of surface area available for sorption) on a number of samples. Some of the results have been reported in /26-92, 26-93/.

A compilation of sorption data for use in SR-Can has been done in /26-91/. It is stated in the report that it is generally difficult to use generic data, since different experiments have been done in different ways and the documentation is often insufficient. It is further stated that the use of K_d values from batch sorption measurements is associated with great uncertainties and probably overestimates sorption since new surface areas are created in batch measurements. Finally, the evaluation of batch sorption measurements is not trivial either. Given these difficulties, it is desirable to be able to perform measurements on intact pieces of rock, for example with the electrical method described above, and to perform in situ measurements. The LTDE-SD set-up can, in simplified form, be used to measure K_d values in a more production-like way in situ in a detailed characterization phase in a tunnel.

The effect of bacteria on sorption processes has been investigated and reported in /26-117/. The study shows that a biofilm can reduce the rock's sorption capacity. But this does not apply to trivalent substances. A broader discussion of these effects and other knowledge regarding microbial processes is presented in section 26.2.18.

Programme

The doctoral project concerning electrical methods for measuring K_d values will be finished during 2008. Given the results achieved, an assessment will be made of whether this method, or a developed version of it, can be used under production conditions during the detailed characterization phase.

Process-oriented sorption modelling and reactive transport modelling will continue during the current period. Specifically, the studies described above will be concluded and the results reported. After this an assessment will be made regarding continued development and use of this type of modelling.

During the current period, the analysis phase of LTDE-SD will be carried out in the field, analyses will take place in the laboratory and the results will be reported. K_d data will be obtained from measurements both in situ and in the laboratory. This will permit comparison. The relationship between laboratory and field data is important for correct interpretation of, for example, laboratory data obtained in connection with the site investigations.

26.2.18 Microbial processes

Conclusions in RD&D 2004 and its review

Microbes affect the groundwater chemistry by speeding up reactions which otherwise proceed very slowly. Redox reactions are above all affected, but weathering reactions can also be catalyzed.

Research in the Äspö HRL and elsewhere has shown that different types of microbes live in the fractures in the crystalline bedrock. Some live on organic carbon compounds that accompany infiltrated meteoric water from the earth's surface, while others can live on methane and hydrogen from the Earth's mantle /26-118/.

Microbes under ground can live without oxygen. In fact, some are so sensitive to oxygen that they die if oxygen is present in their environment. However, many of the underground microbes are capable of consuming oxygen, as the Rex experiments in the Äspö HRL have shown /26-119/.When oxygen is not present as an oxidant, different microbes can instead make use of other compounds, such as hexavalent sulphur in sulphate ions with formation of sulphide(-II), or trivalent iron in various minerals, which then dissolves in the groundwater (in the form of Fe^{2+}). Tetravalent manganese in brownstone can also be used by microbes, and then dissolves in the groundwater (in the form of Mn^{2+}). Numerous microbes in groundwater break down organic carbon compounds to carbon dioxide to obtain energy, while others use methane gas as an energy source. All of these groups have been found to be widely present in deep groundwaters /26-120 to 26-122/. Together, the lives of these microbes in the groundwater influence the geochemical environment in the water-filled fractures in the rock.

Bacteriogenic iron oxides are formed by bacteria when anaerobic iron-bearing groundwater reaches environments with oxygen. It has long been known that iron(III) oxides sorb trace metals. Experiments conducted in the Äspö HRL show that the retardation of trace metals in bacteriogenic iron oxides greatly exceeds their retardation in inorganic iron oxides /26-123/.

Microbial oxygen consumption in a fracture has been modelled /26-112/. The calculations also included inorganic processes, for example pyrite oxidation. They evaluated a case where an infinite quantity of oxygenated water flows through a fracture. The modelling results show that microbial processes should have a great effect in the short term, but that inorganic reactions take over in a long-term perspective.

SKI pointed out that SKB should primarily evaluate processes that have a negative impact on the safety of the repository, such as sulphate reduction near deposition holes, the impact of complexing agents from microbial activity, and the limitation of matrix diffusion due to biofilms. SKI also observes that the use of microbial processes that have a positive impact on repository safety (oxygen consumption) in safety assessments is highly dependent on the availability of mathematical models and data.

Newfound knowledge since RD&D 2004

A laboratory at a depth of 420 metres in the Äspö HRL permits continued work on microbes and their importance in the final repository in a project called Microbe /26-124/. Boreholes have been instrumented and the chemistry and microbiology of the groundwater have been characterized and reported. The composition and microbial content of the groundwater are fairly typical of groundwaters at this depth. In the laboratory it is possible to work anaerobically in a box. Several systems use circulating groundwater taken from a fracture inside the rock. This makes it possible to study microbial processes under repository conditions with regard to pressure, chemistry and temperature. A gas chromatograph and equipment for gas extraction are installed in the laboratory. Measurements of gas can take place directly after sampling in the laboratory's culturing system or after sampling along the tunnel. A series of different experiments is planned at this site. The effect of microbial biofilms on sorption of radionuclides has been investigated with this system /26-125/. The effect is not unambiguous. Most of the radionuclides investigated (cobalt, promethium, americium, thorium, neptunyl(V) and molybdate) were sorbed in lower quantities on rock surfaces with biofilms than on clean rock surfaces. Promethium was sorbed in higher concentrations on a biofilm than on a clean rock surface /26-117, 26-126/. Thus, microbial biofilms can have a negative impact on matrix diffusion /26-127/.

Methane-oxidizing bacteria have been found to occur widely near the ground surface in Olkiluoto, Finland, at a depth of between 3 and 20 metres. They are particularly common at great depths, where methane from under ground meets oxygen from the atmosphere. Similar results have been obtained at the Prototype Repository in the Äspö HRL. Methane oxidizers are widely present in the backfill material, but have only rarely been detected in the surrounding groundwater. The oxygen concentration in the gaseous environment in the Prototype Repository is much lower than in air. The results of these research projects are being published during 2007 and provide qualitative evidence for the fact that microbes reduce oxygen with methane in groundwater.

Microbial mobilization of radionuclides with complexing agents has been investigated in a laboratory environment. Clear mobilization effects have been found, particularly in an anaerobic environment, but also under aerobic conditions /26-128/.

The site investigations in Sweden, the Äspö HRL and Posiva's investigations in Olkiluoto have yielded valuable additional knowledge regarding the occurrence of different microorganisms in deep groundwaters. Of special interest are microbial processes that result in sulphide, since this has a negative impact if it reaches the canister. At the same time, microbial sulphide formation generally contributes to a low redox potential in groundwater. Sulphide can only be formed by microbial processes in the depth interval in question. Acetogenic bacteria form acetate from hydrogen and carbon dioxide. Sulphate-reducing bacteria form sulphide from lactate, or acetate and hydrogen. Both of these groups of microbes occur widely in the investigated groundwaters. Acetogens were found in 91 of a total of 99 investigated samples and sulphate-reducers were found in 78 of a total of 100 investigated samples. These results indicate that sulphide production from hydrogen via acetate can be an important process in deep groundwaters. The process has been studied /26-129/ at a depth of 450 metres in the Äspö HRL in closed systems to which hydrogen is added. The results show clearly that sulphide can be formed rapidly by bacteria at repository depth. The concentration can be high under optimal conditions, particularly in groundwater with a high hydrogen content, for example from corrosion of iron, or at places where hydrogen transport from mantle processes is high. The results will be used to calculate sulphate reduction and formation near deposition holes.

Programme

Research is continuing on microbial processes that lead to sulphide formation and on the ability of microbes to reduce oxygen and buffer the redox potential at a low level that is favourable for the repository. The work is mainly being carried out at repository depth in the Äspö HRL under in situ conditions with naturally occurring microbes. Experiments under controlled conditions in the laboratory will also be carried out and followed up in the Äspö HRL. The impact of bacteriophages (viruses that attack bacteria) is being studied.

Microbial mobilization and immobilization of radionuclides are being quantified under different conditions. The work is mainly being carried out at repository depth in the Äspö HRL under in situ conditions with naturally occurring microbes. The impact of bacteriophages is being studied.

We will start new projects for the purpose of modelling microbial processes that make use of results obtained to date from the site investigations, Olkiluoto and the Äspö HRL. As the research in the programme generates new results, they will be included in the modelling work. The modelling is especially being focused on microbial processes that can have a negative impact on some barrier function, for example sulphate reduction. The effects of microbes that have a positive impact on repository safety, for example by consumption of oxygen and biosorption of metals, may also be modelled.

26.2.19 Decomposition of inorganic engineering material

Conclusions in RD&D 2004 and its review

The process is of importance for the geosphere in an initial phase and close to the repository, when conditions are affected by the construction work and by steel and cement in the repository.

An in situ experiment was carried out in Grimsel, Switzerland, for the purpose of studying how concrete pore water reacts with rock minerals.

Newfound knowledge since RD&D 2004

A project has been started in cooperation with Posiva to develop and test low-pH grouting materials, i.e. grouting materials that should have pore water with a pH lower than 11. This is described in Part III, Chapter 12. Preliminary leaching tests have been performed on these low-pH cement materials.

Programme

Leaching of low-pH cement will be carried out for the purpose of investigating whether organic cement additives can be leached out and whether these additives can affect radionuclide sorption on rock. We will also model the degradation of these cement materials over long periods of time.

The other principal inorganic engineering material is steel. This field is not judged to require any extensive research, development or demonstration today.

26.2.20 Colloid formation – colloids in groundwater

Conclusions in RD&D 2004 and its review

Colloids are tiny particles that can remain in solution for very long times. This means that they can accompany the groundwater and even act as carriers of radionuclides. SKB has been conducting studies and measurements of colloids for more than ten years. The conclusion from these studies, both nationally and internationally, is that the colloid content of the groundwater in Swedish granitic bedrock mainly consists of clay, silicon and iron hydroxide particles. The mean concentration is 20 to 45 ppb, which is low. The concentration is limited by the fact that the colloids adhere to the fracture surfaces, which reduces their stability and transport capacity. In Nevada in the USA, where hundreds of underground nuclear bomb tests have been performed, measurements have shown that plutonium, cobalt and europium in the groundwater could be detected 1.3 kilometres from the detonation site. These measurements indicate a rapid colloidal transport of plutonium, cobalt and europium, since filtrations of samples showed that all elements occurred in the form of colloids. It is probable that cobalt and europium were associated with natural clay colloids and plutonium was colloidal itself.

A project was carried out in the Äspö HRL for the purpose of determining the occurrence and stability of colloids and their potential for transporting nuclides, as well as the potential of the bentonite for generating colloids. The role of bentonite clay as a colloid source was investigated at varying groundwater salinities (NaCl/CaCl) in laboratory experiments. Chemical changes, size distributions and the effects of sodium- and calcium-rich bentonite were studied.

In its review of RD&D-Programme 2004, SKI commented on the importance of studies of groundwater with lower ionic strength. Further, SKI pointed out that the field tests should be designed so that colloid transport models can be tested /26-130, 26-131/. Studies of the interaction between radionuclides and colloids were recommended.

Newfound knowledge since RD&D 2004

The stability of bentonite colloids in various salt solutions and temperatures has been studied in a laboratory setting, see section 24.2.18. One study was conducted to investigate how the stability of the bentonite colloids is affected by the heating of the buffer. The study shows that the bentonite colloids are slightly more stable at higher temperatures at an ionic strength of 0.001 M, which is supported by theoretical calculations /26-132/. Furthermore, critical coagulation constants (CCCs) were determined for Na-bentonite in contact with sodium and calcium by studying the sedimentation rate. The effect of mineral surfaces (crushed granite and quartz) on the stability of the bentonite colloids was studied and indicates that the mineral surfaces do not affect the stability of the bentonite colloids at an ionic strength of 0.001 M.

How radionuclides interact with colloids and fracture-filling materials in groundwater from the Äspö HRL and the stability of the colloids were studied at INE-FZK in Karlsruhe, Germany. Bentonite colloids aggregate instantaneously when they are introduced into groundwater from the Äspö HRL. The effect of the presence of bentonite colloids, fracture-filling material and fulvic acid on the radionuclides strontium-90, caesium-137, americium-241, neptunium-237, uranium-233 and plutonium-244 was studied in groundwater from the Äspö HRL for three months. Strontium(II) and uranium(VI) remain unaffected and do not sorb to fracture-filling mineral, which caesium(I) does. Americium(III) and plutonium(IV) form unstable colloidal species in both the presence and absence of bentonite colloids. Experimental data indicate that natural organic matter can act as a carrier of radionuclides, although not at the high salinities present in the groundwater from the Äspö HRL today.

Colloidal transport of latex colloids and bentonite colloids under different conditions has been studied in a well-defined fracture in a 1×1×0.7 metre large granite block in Canada. The advantages of investigating colloidal transport in this granite block are that both high and low flow rates can be investigated, the fracture is well-defined, and after the tests the location of colloids that have not emerged can be studied. Transport tests with 100 nanometre latex colloids and bentonite colloids in distilled water show that at high flow rates (450 millilitres per hour), the latex and bentonite colloids show similar behaviour. The transport rate is rapid and most get through. At 45 millilitres per hour differences start to arise, and at 6.2 millilitres per hour the transport capacities diverge. The bentonite colloids slow down, but small quantities are transported even in these dilute waters. The tests confirm that latex colloids can be used as model colloids for bentonite colloids in transport tests in saline waters at high, but not at low, flow rates. Transport tests with bentonite colloids have also been carried out in groundwater in the Äspö HRL. The bentonite colloids precipitate rapidly and no transport takes place. After the test, the fracture was flushed with distilled water, but no mobilization of colloids was obtained.

Dipole tests with 50 and 100 nanometre latex colloids have been performed on the True-1 experimental site in the Äspö HRL with pump flow rates of 300 and 780 millilitres per minute. According to the tests performed in the granite block, the latex colloids can represent bentonite colloids at these high flow rates, since the bentonite colloids are not themselves stable in these saline waters. Even though the data uncertainty is high, the results show that the transport rate was rapid and recovery was great. Due to the high uncertainty, filtration constants cannot be calculated from these data.

Studies of colloids under natural conditions in the groundwater in Forsmark and Laxemar have continued. The measurements show that the colloid concentrations and composition are similar to those found in the Äspö HRL.

Programme

Additional studies will be conducted in a laboratory setting to see in which types of groundwater and at what temperatures bentonite colloids are stable. The stability of bentonite colloids at high temperatures will also be investigated at varying ionic strengths as a complement to the above-mentioned study at an ionic strength of 0.001 M.

Sedimentation tests in comparison with tests to generate bentonite colloids will be carried out at the Paul Scherrer Institute (PSI) in Switzerland in cooperation with the Royal Institute of Technology in Stockholm. The purpose is to see if the same equilibrium concentration of bentonite colloids is also obtained if different types of tests are performed.

Radionuclide transport in the presence of bentonite colloids was also carried out in the spring of 2007 at INE-FZK in Karlsruhe, Germany, in a drill core from Äspö. We also plan to investigate the possibility of performing a similar test in the Äspö HRL with a well characterized drill core in a glovebox connected to borehole KA2512A.

Tests in Canada with the granite block are planned. Transport of bentonite colloids at low flow rates in water with low salinity is being studied. The bentonite colloids are fractionated to investigate whether filtration on the basis of size can be seen and to see whether monodispersive bentonite colloids are altered during transport due to flocculation or dispersion processes. Bentonite erosion experiments may also be carried out in the granite block, but these experiments should be coordinated with other well defined laboratory experiments so that data can be properly evaluated. All experiments performed in the granite block will be modelled to obtain transport and filtration constants for colloids.

We are also investigating the possibility of participating in the Colloid Formation and Migration project (CFM) in Grimsel, Switzerland, where the transport of bentonite colloids in dilute waters is being studied.

26.2.21 Colloid formation – radionuclide transport with colloids

Conclusions in RD&D 2004 and its review

RD&D-Programme 2004 stated that if tracer tests with colloids were conducted, the tests would also be modelled. It was further stated that the new numerical version of FARF31 could be used to study radionuclide transport with colloids.

SKI said in its review that SKB has a more comprehensive and well-developed understanding of colloids compared with the situation a few years ago. However, SKI also recommended that SKB study how colloids and radionuclides react.

Newfound knowledge since RD&D 2004

The stability of bentonite colloids, interactions between bentonite colloids and natural colloids, and sorption between actinides and bentonite colloids are being studied in the Colloid Project in the Äspö HRL, see section 26.2.20.

The new numerical version of FARF31 that can handle colloids, FARF33, has been published /26-131/. The code has been verified by comparison with both FARF31 and a code that can handle colloids, Collage II.

SKB is participating in the EU project Funmig, where colloid transport and radionuclide transport with colloids are being studied.

Programme

The Colloid Project will continue as described above in section 26.2.20. The sub-project Colloid Actinide can be mentioned specifically with regard to radionuclide transport. The question is whether retention of actinides decreases in the presence of colloids, in other words do actinides prefer to sorb to bentonite (colloids) or to fracture-filling mineral? Another question is whether actinide-colloid complexes are stable. The experiments will be carried out in situ in a drill core.

26.2.22 Gas formation/dissolution

Conclusions in RD&D 2004 and its review

Gases that occur dissolved in the groundwater are of varying composition. The main components are usually the following, in order of decreasing concentration: nitrogen, methane, argon, helium, carbon dioxide, hydrogen and carbon monoxide. Traces of ethane, ethylene, acetylene, propane and propylene also occur. The total quantity of dissolved gas per litre of analyzed Swedish groundwater varies from about 30 millilitres to about 100 millilitres, at depths down to a kilometre beneath the surface. These quantities lie well below the solubility limits for the encountered gases at the pressure prevailing at the depth in question. Larger quantities of gas have been encountered in groundwaters sampled in Olkiluoto, Finland: up to 300–400 millilitres of gas per litre of groundwater /26-120/. Here the gas also has a different composition.

Newfound knowledge since RD&D 2004

The database of dissolved gases in groundwater is being added to continuously /26-118/, both with data from groundwater around the Äspö HRL and with data from groundwater at the site investigations.

Equipment for gas analysis in groundwater has been installed under ground in the Äspö HRL and in a laboratory at Göteborg University, where research on dissolved gases is being conducted. New methods have been developed for extraction and analysis of all occurring gases. Research is being conducted on the impact of the gases on the occurrence and activity of microorganisms, and on the impact of the microorganisms on the content and composition of the gases. The results of these investigations are reported in section 26.2.18.

Programme

Equipment for gas sampling and analysis will continue to be developed, as will sampling on the sites. Studies aimed at understanding the origin and transport of methane and hydrogen are of importance for safety assessments of the final repository. Discussions are being held on the possibility of analyzing inert gases from the site investigations. This is being done to obtain information on the infiltration temperatures of the different types of water.

26.2.23 Methane ice formation

Conclusions in RD&D 2004 and its review

At low temperature and high pressure, water and methane form a solid phase called methane ice. Methane ice can form under permafrost, for example, and has been studied in different geological environments: in crystalline rock, for example in Canada /26-133, 26-134/, in sedimentary rocks in Russia /26-135, 26-136/ as well as in sea sediments, for example in Canada /26-137/. A review of existing knowledge was done in /26-138/.

Together with researchers from Finland and Canada, SKB started studies of a gold mine in a permafrost area in Canada (the Lupin Mine).

SKI is of the opinion that knowledge of methane ice formation and salt exclusion needs to be improved and that it is difficult to judge whether investigations of gold mines in permafrost areas can contribute the necessary knowledge.

Newfound knowledge since RD&D 2004

The studies started by SKB in the Lupin Mine were completed /26-133, 26-134/. No methane ice was found.

Programme

In order to understand methane ice formation, knowledge is needed concerning the origin of the methane and transport possibilities. Studies in permafrost areas will continue in other mines in Canada (High Lake, Nunavut Territory). The investigations of pore water and groundwater chemistry in the site investigations can also contribute to tracing the depth of previous permafrost and methane ice formation.

26.2.24 Salt exclusion

Conclusions in RD&D 2004 and its review

When saline water freezes slowly, the solutes (salts) present in the water are forced out into solution. This process can be of importance in a cold climate, for example during a period with permafrost.

One of the main indicators for tracing salt exclusion is the occurrence of sulphate-rich water, formed by the dissolution of mirabellite. Other indicators are very low values of the parameters $\delta^{18}O$ and $\delta^{2}H$ that have arisen in connection with salt exclusion /26-134/, fractionation of boron isotopes (high $\delta^{11}B$ values /26-139/) and the formation of calcites with high $\delta^{13}C$ values /26-140/. The dynamic groundwater situation in conjunction with deglaciation and the subsequent variations in sea level along the Baltic Sea coast have led to a mixing of different groundwaters, which makes it very difficult to distinguish any water that may have been formed as a result of salt exclusion. Investigations in the Lupin Mine in the permafrost area in Canada have not been able to demonstrate the effect of salt exclusion.

Newfound knowledge since RD&D 2004

If salt exclusion occurs, the saline waters will move towards greater depth due to their greater density and be added to the saline groundwaters that already exist at these levels. It is therefore not likely that accumulations of saline groundwater will be found beneath layers of permafrost. Generic model studies have been conducted in the SR-Can safety assessment aimed at determining whether excluded salts beneath a permafrost layer could affect the swelling capacity of the backfill. The calculations show that the saline groundwater moves rapidly downward in transmissive fracture zones due to its higher density. The saline groundwater is relatively immobile in rock volumes with low hydraulic conductivity.

Programme

Investigations in mines in permafrost areas will continue. See also section 19.2.23 above. Further modelling studies are planned within SR-Site.

26.2.25 Integrated modelling – hydrogeochemical evolution

In combination with groundwater flow, groundwater composition is of great importance for the performance of the final repository, in both the short and long term. The interaction between the engineered barriers and the groundwater determines how long the spent nuclear fuel will remain isolated. Even in a situation when this isolation has been breached, the groundwater is of crucial importance for dissolution and transport of radionuclides in the fuel. The SR-Can safety report is a good example where the importance of the groundwater for the safety of the final repository is emphasized.

The hydrogeochemistry programme in the site investigations aims at describing the chemistry of the groundwater in the final repository volume and its environs from a safety assessment perspective and producing the body of chemical data required to design the final repository. In general, SKB's geochemistry programme contributes to a general understanding of how the groundwater system works at repository depth. Hydrogeochemical and hydrogeological data together provide a description of the water flux within the repository area and its influence on groundwater composition, as well as how this composition varies in the projected repository volume.

The simplest hydrochemical model is a spatial distribution of the concentrations of the most important solutes in the rock volume. Normally the distribution of the main components sodium, potassium, calcium, manganese, chlorine, sulphate and hydrogen carbonate, including pH, is investigated, but it is also of great value to include the stable and radioactive isotopes deuterium, oxygen-18, sulphur-34, carbon-14, carbon-13, tritium and strontium-87. The distributions of the concentrations of the individual solutes are in some cases indicative of specific ongoing chemical processes.

More knowledge is obtained by a statistical processing using multivariate analysis, which results in a subdivision into different classes. The different classes represent water which has undergone a certain evolution. By comparing the different classes, their different evolutionary pathways can be identified, regardless of where in the volume they occur. A typical water is defined within each class and is then allowed to represent that class. Typical waters then comprise the basis for further calculations of reactions and mixing ratios. Measurement data for e.g. the ten most important components can be included in these calculations /26-85/. The calculated mixing proportions and the actual measured composition comprise the basis for calculating the scope of chemical reactions. It is then assumed that a discrepancy in the concentration of any of the components is the result of a chemical reaction that occurs after the water has been mixed. It may be a question of dissolution or precipitation of different minerals or microbial processes which generate e.g. sulphide, carbonate, divalent iron etc. The code M3 (Mixing and Mass balance Modelling), which has been developed with Matlab as a base, is used for this hydrochemical modelling, see section 26.2.11. The reasonableness of the results is checked by alternative modelling, for example geochemical simulations with the code PhreeqC.

A constantly recurring question is whether the groundwater samples really represent the groundwater at the depth where they have been taken. Studies of fracture-filling minerals can contribute to evaluating the stability and representativeness of the hydrogeochemical system. The main task of the EU projects Equip and Padamot /26-100, 26-105/ has been to propose suitable methods for gathering paleohydrological information, i.e. information from fracture-filling minerals concerning current and historical water chemistry. The investigations of fracture-filling minerals that have been done in the Äspö HRL indicate a division into three zones, where the zone beneath a depth of 800 metres appears to be relatively isolated.

Knowledge of the microbial processes has increased in recent years /26-86, 26-87/. They have been found to have a great influence on the hydrogeochemical evolution and thereby on the hydrogeochemical interpretation.

Conclusions in RD&D 2004 and its review

Data gathered in SKB's previous study site programme and in the Äspö HRL (between 1980 and 2001) has been modelled. The mixing pattern has provided a picture of what changes can be expected in the composition of the groundwater in the future /26-141/. The present-day situation is expected to prevail during the coming 1,000-year period. In a 10,000-year perspective, land uplift and possible climate changes will result in changes that can be calculated with available hydrogeological and hydrochemical models. In a 100,000-year perspective, assumptions concerning then-prevailing climatic conditions completely determine what situation can be expected. In this time perspective, it is meaningful to identify which climate situations may cause the greatest changes and analyze their effects.

SKI pointed out in its review of RD&D-Programme 2004 that SKB needs other models than M3 to understand processes involving reactive components in the groundwater. SKI also pointed out that geochemical data should be used to draw conclusions concerning recharge and discharge areas and flow directions on a local and regional scale.

Newfound knowledge since RD&D 2004

Hydrochemical models have been constructed for both sites. The models include both mixing proportions and equilibrium reactions with fracture-filling minerals /26-86, 26-87/. The original M3 program has been further developed /26-89/. Hydrogeological models of the sites have used chemical data as a part of their calibration /26-17, 26-18/. These models have then been used together with a model for mineral reactions in SR-Can to provide a detailed picture of the groundwater chemistry during the temperate period following the closure of the final repository.

Programme

There are no plans for method development in the field. The methodology is being applied in the site investigation programme and the safety assessments.

26.2.26 Integrated modelling – radionuclide transport

Conclusions in RD&D 2004 and its review

It was mentioned in RD&D-Programme 2004 that Task 6 within Äspö Task Force MGFTS was in progress and that certain model development for radionuclide transport in the safety assessment was also taking place. The True Block Scale Continuation and True-1 Continuation field experiments were also mentioned.

SKI mentioned in its review that SKB's programme for radionuclide transport models is appropriate and that SKB has an ambitious programme for field studies. They also pointed out that SKB's activities in the area of geosphere transport agree with the results from the EU project Retrock.

Specifically, SKI noted that it is positive that SKB is developing models to take into account heterogeneity along the transport pathways in the rock. SKB should, however, investigate the extent to which data can be obtained in the site investigations to enable the heterogeneity and variability of the retention parameters to be included. In the cases where site-specific data cannot be obtained, SKB should describe the uncertainties that this will result in and how these uncertainties will be handled in the safety assessment.

Finally, SKI also considered the work being done within the framework of the Äspö Task Force (Task 6) to be a valuable contribution to providing greater knowledge within the area.

In its review, SSI said that it is good that SKB is further developing its models for radionuclide transport. This will make it easier to take into account varying properties along the transport pathways in the rock. However, SKB should clarify the need for site-specific information such as diffusion coefficients, matrix porosity and effective diffusivity. SKB should also specify what the uncertainties are and how they will be dealt with in the safety assessment.

SSI also noted that it is important that SKB verify and document new models before they are used for future permit and licence applications. They further pointed out that SKB should examine the importance of the simplifications associated with the safety assessment models, for example with regard to sorption kinetics, one-dimensional description of multi-path transport and colloidal transport. Finally, SSI stated that they take a positive view of the fact that SKB has begun to study transport processes in the interface between geosphere and biosphere and how this will be included in future safety assessments.

Newfound knowledge since RD&D 2004

The Tracer Retention Understanding Experiments (True) have proceeded during the entire preceding period. The following activities have been pursued within the True-1 Continuation project:

- Fault Rock Zones Characterization.
- Complementary laboratory sorption experiments.
- True-1 Scientific papers.
- True-1 Completion.

In the activity Fault Rock Zones Characterization, scientists are studying not only mineralogy and hydraulic properties, but also pore structure and in situ porosity of breccia and gouge material (different fracture-filling materials). Injection of epoxy, with subsequent overcoring and image analysis of the pore structure, are also included. The supplementary sorption experiments in the laboratory are aimed at experimentally verifying previously used, calculated sorption coefficients (K_d values). This activity is related to the activities described above in section 26.2.17. The sorption measurements are being made on different types of fracture-filling materials. Feature A is the fracture in which all tracer experiments within the True-1 project have been carried out. True-1 Completion is aimed at characterizing the internal structure and the sorption sites in Feature A. This characterization includes supplementary tracer tests, epoxy injection and overcoring, including analysis. The tracer tests consist of Swiw (Single Hole Injection Withdrawal) tests, flow tests (according to the reciprocal cross-hole method) and CEC tests. Since Feature A is penetrated by several boreholes, tracers can be monitored in other boreholes when Swiw tests are performed in a single hole. This, as well as information from the flow tests, is intended to provide information on, among other things, channelling in Feature A. The purpose of the CEC tracer tests is to estimate the cation exchange capacity of a natural fracture and to study the reversibility of caesium sorption. After this characterization round, the microstructural model will be updated. Finally, the True-1 Continuation project includes publishing scientific articles that summarize SKB's efforts in this area.

Phase BS2 has been under way in the True Block Scale Continuation project. The specific retention properties of a background fracture and of a major structure (zone) have been investigated in this phase. Both non-sorbing and sorbing tracers have been injected into the background fracture and directly into the zone during pumping in the zone. The evaluation indicates that the retention properties are significantly different for the two flow paths. Specifically, the retention properties (for matrix diffusion and sorption in different fracture-filling materials) are more favourable in the flow path in the zone compared with the flow path that includes the background fracture. However, total retention (retardation) is greater in this latter flow path thanks to the smaller groundwater flow in the background fracture. The evaluation demonstrates how important small fractures nearest a potentially leaking canister can be for radionuclide retention. Phase BS2 has been reported in a final report /26-142/ and in background reports /26-143 to 26-146/, see also /26-147, 26-148/.

Within Äspö Task Force MGFTS, Task 6, which is aimed at building a bridge between site modelling and safety assessment modelling, was recently concluded. Evaluation reports /26-149, 26-150/ have been published for the initial modelling exercises (which dealt with transport in an individual fracture) and for the construction of the semi-synthetic block-scale model (hydrostructural model and microstructural model) used for subsequent modelling exercises. The evaluation reports make references to the individual modelling reports. An evaluation report for the later modelling exercises in the fracture network in the block-scale model has been finished /26-151/, see also /26-152/.

A final report has been published on the EU project Retrock /26-153/. The project is about how retention and transport processes for radionuclide transport are to be treated and modelled in safety assessments. In terms of content, however, the Retrock project has already been reported in previous RD&D-programmes.

Based on SKB's accumulated experience from tracer tests (with a specific focus on the True experiments in the Äspö HRL), Task 6 and Retrock, a report has been compiled that discusses how and when information from tracer tests can be used in safety assessment applications /26-154/. The limitation with tracer tests is the short time scale in relation to the time scale of interest for the safety assessment. Tests in the field thus provide quantitative information on parts of the system that are not necessarily of interest in longer time perspectives. An example is retention properties of fracture-filling materials. They strongly influence and can completely dominate a tracer test, but are of little interest over longer periods since this material can be saturated.

There are, however, other good reasons for conducting tracer tests, such as to test connectivity in fracture networks, to demonstrate general process understanding and predictive capability with regard to retention processes, and to study how different laboratory-measured values are upscaled to field scale. A general conclusion is that it is seldom possible to use parameter values obtained from tracer tests directly in the safety assessment, but that the understanding that is obtained on the different experimental scales can be used to derive effective values for use in the safety assessment.

A number of tracer tests have been performed with the Swiw method in the site investigations. They have been analyzed both with a simplified evaluation method /26-155/ and with the modelling tool DarcyTools /26-156/. The evaluation shows that retention of sorbing tracers took place, but that it is difficult to obtain quantitative values of individual parameters.

Within radionuclide transport for the safety assessment, some minor updates of FARF31 have been done. These updates do not apply to the code itself but rather the handling of input and output data. In SR-Can /26-39/, FARF31 has been integrated more clearly with the groundwater flow model ConnectFlow and the near-field model COMP23. The near-field model describes the outflow from three separate sources: a fracture that intersects the deposition hole, the excavation-disturbed zone in the floor of the deposition tunnel, and a fracture that intersects the deposition tunnel. ConnectFlow describes in detail the groundwater flows for these three separate sources, while COMP23 delivers nuclide flows to FARF31 for the same sources. FARF31 then calculates nuclide transport along three separate flow paths for each canister. These flow paths have been calculated in ConnectFlow. ConnectFlow also calculates how large a fraction of each transport pathway goes through rock, the excavation-disturbed zone and tunnels.

A new method for simulating radionuclide transport is being developed. Instead of using semi-analytical expressions such as FARF31, a particle method is used: Particles on Random Streamline Segments (PORSS). The advantage of this methodology is that it can handle general variability in properties along and across flow paths, transient flow, and even decay chains (variability in both retention properties and hydrodynamic quantities) /26-157 to 26-160/. The methodology also contains an upscaling algorithm for transport from discrete networks to continuum applications /26-161/. How the different parts of the method are implemented in a new code is described below under “Programme”.

In radionuclide transport, the hydrodynamic situation controls matrix diffusion. This is usually expressed as the ratio of the flow-wetted surface to the flow rate. In connection with channelling in a fracture plane caused by aperture variability, the flow-wetted surface, and thereby matrix diffusion, decreases. In connection with strong channelling, however, stagnant water occurs between the channels. Radionuclides can therefore diffuse into this stagnant water from the flowing channels and then from the stagnant water into the matrix. A solution for handling this type of problem has been presented in /26-162/. In principle, the solution presented can be incorporated into existing codes for radionuclide transport. But the most important thing is to be able to show that matrix diffusion takes place even in cases with channelling in fractures.

Modelling of advective transport in the coupled groundwater-surface water system has been done with MIKE SHE and is reported in /26-23/. The modelling shows that this is a workable approach for shedding light on relevant questions linked to transport in the interface zone between geosphere and biosphere.

Programme

What mainly remains to be done in the True-1 Continuation project is to report results and produce scientific articles. Certain laboratory work on the sorption studies also remains to be done, and evaluation and reporting of the tracer tests remains to be done in True-1 Completion. The modelling of the Swiw tests carried out in the True-1 Completion project is also expected to yield knowledge that can be used to evaluate the Swiw tests that were done in connection with the site investigations. Since Feature A is well characterized compared with the fractures used in the site investigations and several monitoring boreholes are located in Feature A, it is in principle easier to evaluate the Swiw tests in the Äspö HRL.

Phase BS3, aimed at a final integration of the entire True BS project, remains to be done within the True Block Scale project. The results of Phase BS3 will be reported in scientific publications.

During the coming period, the PORSS method will be implemented in a program code that can be used alongside FARF31 in the safety assessment. The code is called Marfa (Migration analysis of radionuclides in the far-field). Input data from ConnectFlow are used in the same way as FARF31 does today, but instead of using integrated parameters for travel time and transport resistance (F-factor), Marfa reads information from each segment along a flow path. In an initial phase, Marfa will handle time-dependent flow, while the subsequent version will be fully transient. Marfa is being developed together with Posiva in Finland.

The first test of Marfa will take place when some of the results in SR-Can are to be recalculated. This also requires some development of ConnectFlow to be able to deliver segment-based data. After this first test, calculations are planned where different parts of the functionality in ConnectFlow-Marfa will be tested, for example different retardation models for radionuclide transport in different parts of the system (rock, deformation zones, tunnels, surface layers), estimation of effective retention parameters along flow paths with different types of variability, and simulation of transport under the transient flow conditions entailed by a glaciation cycle. The interest in an international modelling exercise where ConnectFlow-Marfa could be used and compared with other modelling concepts will be looked into. An exercise of this kind would enhance the credibility of the new concept and the new code.

Codes for reactive transport modelling are also being developed. This is described above in 26.2.17. But further mention can be made here of a planned project in the Äspö HRL where the developed methodology will be used to construct a site-specific transport model for fractures in the Äspö HRL. In terms of purpose, this model can be compared with the models devised for other disciplines in the Äspö HRL, for example hydrogeology and hydrogeochemistry. A separate project is also planned where this type of model will be tested for safety assessment applications. Questions such as how sorption is affected when geochemical conditions change can then be studied.

Transport modelling with MIKE SHE will continue in order to gain a better understanding of transport in the near-surface soil layers and in the interface zone between geosphere and biosphere.

27 Biosphere

Several major steps have been taken in SKB's biosphere programme since RD&D-Programme 2004. The biggest advances have been made in the work with the SR-Can safety assessment. A new methodology has been used for the biosphere, where a landscape dose is calculated. The analyses of the future evolution and the dose calculations are done using coherently logical and scientifically defensible methodology. Site data can be utilized to a great extent and the whole landscape is analyzed. A new calculation tool has been launched for this work, which permits complex calculations to be carried out faster than previous tools and is at the same time user-friendly.

The knowledge obtained from the biosphere programme on the sites has provided a more concrete picture of the biosphere. The site investigations have also generated data to a database that permits more realistic dose models.

To disseminate knowledge of the work that has been done, publication in scientific journals has tripled since RD&D-Programme 2004, with 30 articles published during the period. A special issue with eleven articles in the journal Ambio has been one way to disseminate information on SKB's biosphere programme. In addition, some 80 reports have been published.

The coming period will be characterized by extensive efforts when it comes to analysis of site-specific data, as well as a safety assessment. The long-term biosphere research is well designed to contribute methodology and data for these tasks, but there is also a preparedness to conduct targeted research to solve any new problems that may emerge.

27.1 State of the biosphere

The surface ecosystems or the biosphere are the part of the earth in which most living organisms – animals, plants and humans – live. The consequences of a release of radioactivity from the repository in the form of a dose to humans and other organisms will appear in the biosphere. Calculations of the flux of radionuclides in the biosphere and the dose consequences this leads to are therefore an important part of a safety assessment. The calculated consequences are used to show whether the regulatory requirements on safety and limit values that are expressed in doses are met, and as a yardstick for comparing different facilities, technical solutions or sitings. Credible calculations require a realistic description of events and processes in the biosphere with reasons why certain processes are important and why others can be ruled out. The states of the surface ecosystems also comprise chemical (salinity, oxygen content), hydrological (water balance) and geological (shoreline displacement) boundary conditions for processes in the geosphere.

The overall goal of the biosphere programme is to describe, based on modern scientific knowledge, the most important processes in the biosphere from a radiological point of view and to provide sufficient scientific support for assessing the environmental consequences of constructing and operating a repository.

The methodology for biosphere calculations has taken a giant step forward in SR-Can in that site data are used to a great extent for the first time. A whole new way of calculating the dose to humans and to the affected population has been presented, along with a new type of dose conversion factor (LDF = Landscape Dose Factor) based on existing knowledge of the sites.

In the review of RD&D-Programme 2004, the regulatory authorities took a positive view of the fact that SKB has increased its level of ambition in the biosphere area in recent years. SSI welcomes the fact that SKB's research in the biosphere area in recent years has been conducted more methodically and with a higher level of ambition that has previously been the case, but says that RD&D-Programme 2004 does not provide a good description of the biosphere research that is being done. Kasam considers RD&D-Programme 2004 to be clearer than previous programmes with respect to further studies of the biosphere and supports the goals of the programme to describe, with a modern knowledge base, the most important processes in the biosphere from a radiological standpoint and to provide support for environmental impact assessment. Kasam is also of the opinion that the models should be applied to both radionuclides and other substances that can affect the environment. In the following sections we try to shed further light on results obtained and our goals. We also hope that we can inspire other actors to use our methods to study other substances than radionuclides in the environment.

27.2 Understanding and conceptual models

Government regulations require that future safety assessments provide a more realistic description of the biosphere and an estimation of the consequences of a release for surrounding fauna and flora /27-1, 27-2/. The site investigations make the biosphere concrete, which means that simplifications in how the biosphere is conceptualized must reflect the site in question.

The development of process-based models is deemed to be an appropriate way to demonstrate understanding, at the same time as these models provide numerical results that can be used in the safety assessment. A systems ecology approach is taken, where both biotic and abiotic processes in the ecosystems are taken into account. Knowledge of the processes is found within many areas, for example in conceptual and numerical models for forestry, and in studies of the cycling of nutrients in lakes and seas or of the cycling of toxic pollutants. On the other hand, this information has seldom been used for studies of radionuclide cycling. Generalizations are also required for the long time horizons and varying environments that are considered in a safety assessment for a final repository.

Process studies at the investigation areas comprises a valuable complement to models, both to gain and demonstrate understanding and to generate results that can be used in the safety assessment.

In order to create a credible description of the evolution of the biosphere over time, and of the effects of a possible leakage of radionuclides from a future repository, the conceptual models used need to reflect current scientific thinking in radioecology, ecology, ecotoxicology, hydrology and environmental protection. Figure 27-1 shows a conceptual model of interconnected surface ecosystems.

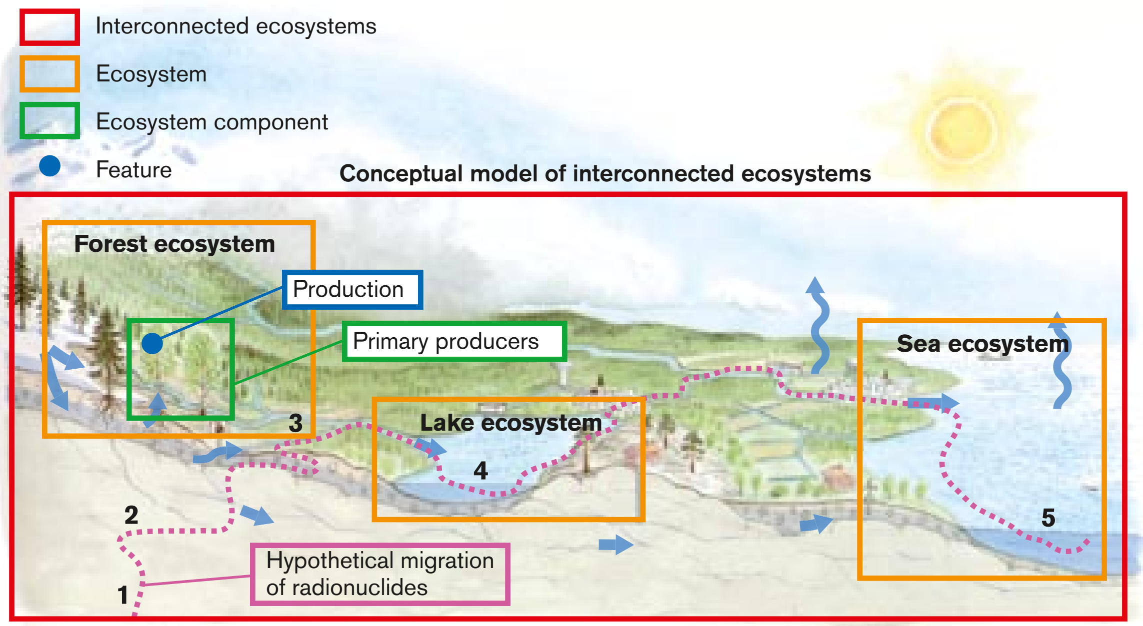


Figure 27-1. Conceptual model of a site where bedrock, regolith, soil cover, biota and hydrology are illustrated. The red dotted line illustrates the hypothetical transport pathway for a radionuclide. (1) The nuclide enters the hydrological flow model. (2) The water flow in the fractured part of the bedrock and in the rock/soil boundary is modelled. (3) A hydrological model describes the surface flow path. (4 and 5) Release to the ecosystems can take place via wetlands, streams, lakes or lakes or farmland to the final destination: the sea.

Conclusions in RD&D 2004 and its review

RD&D-Programme 2004 stated that the long-term support for competence building was continuing and that the documentation for the biosphere matrix would be supplemented. The compilation of important processes would continue, particularly the international cooperation. It was moreover said that newfound knowledge from several sub-programmes would be assimilated, for example with regard to model development and transport processes as well as quantification of important processes in forest ecosystems, mireland and sediments.

In its review of RD&D-Programme 2004, SKI and SSI said that comprehensive documentation must provided of the processes included in the models used. SSI further considered that a comprehensive description of all models to be used in the safety assessment is needed, along with an account of how well they represent the relevant ecosystems.

Newfound knowledge since RD&D 2004

In the analysis of the site investigations, site-specific information has been processed /27-3 to 27-5/ and has made it possible to concretize the change in the landscape /27-6, 27-7/, which has been essential in order to be able to calculate the landscape dose factor in SR-Can /27-8/. The systems ecology approach /27-9/ has been valuable in systematizing the knowledge and using comparable measures of mass flows, where water and organic carbon represent the measurement variables for the flows /27-3, 27-5/. The normalization to organic carbon has simplified the description of the mass flows, but also made it possible to calculate the most exposed group in the event of a radioactive release from the repository /27-8/. Human food ingestion can be converted to organic carbon. Since the total quantity of organic carbon within an area is limited by plant production, the sustainable food supply for future humans can be calculated on the investigated sites /27-10/. Since transfer factors have been converted to measures based on organic carbon instead of being given per unit wet weight as is customary, the variations in the transfer factors have been greatly reduced /27-11/.

With the new landscape models /27-6 to 27-8/ we have gained a thorough understanding of the properties at the sites in time and space.

The SurfaceNet network for surface ecosystems has been created for more effective communication of newfound knowledge and understanding between those who perform site investigations, site analysis, research and safety assessment. This group includes representatives of disciplines such as hydrology, geohydrology, chemistry, terrestrial and marine ecology, limnology, Quaternary geology, cultural geography and safety assessment. The discussions in SurfaceNet have contributed to new scientific insights when it comes to modelling of landscapes and ecosystems, and the dynamics of ecosystems. Interactions with contractors at universities have been particularly important in SurfaceNet's work in order to achieve good quality in the programme. In addition to the studies described below, the publication of a special issue of Ambio (volume 35, issue 8, 2006) has been important in disseminating the knowledge, see section 27.8.

The collaboration with universities for long-term competence development has continued. During the period SKB has supported two doctoral theses, one in limnology at Uppsala University /27-12/, see section 27.6, and one in Quaternary geology at Stockholm University /27-13/, see section 27.7. Furthermore, SKB has supported and partially supervised a degree project at Uppsala University about a radionuclide profile in a mire /27-14/, which has resulted in a doctoral project at Umeå University, see section 27.4. At Lund University a degree project about forest soil has been supported /27-15/, and at Stockholm University a project about distribution of elements in marine organisms has been carried out with support from SKB /27-16/.

At present, SKB is supporting a doctoral student in oceanography at Stockholm University in calculating particle transport in the sea, see further section 27.6, and a doctoral student in hydrology at Stockholm University /27-17/. In cooperation with Bioprota, SKB is supporting a doctoral student at Université Henri Poincaré in Nancy, France, who is studying the movements of iodine in a bog in Canada. Bioprota is an international project concerning biosphere aspects of the assessment of the long-term safety of the final repository.

Programme

SKB will continue its collaboration with universities to sustain a dialogue at the cutting edge of research and to secure long-term competence development. The systems ecology approach will continue to be an important methodology for obtaining a coherent overall picture of the biosphere in time and space. Much of our understanding of the sites will be developed in the different programmes described below and will be reported prior to SR-Site. The most important processes and interactions will be documented in the work for each individual ecosystem.

27.3 Model development

In recent years a far-reaching modernization of SKB's tools for dose calculations in the biosphere has been carried out with the development of Pandora (Tensit), which is based on Simulink and Matlab /27-18, 27-19/. SR-Can was the first safety assessment where the tool was applied.

SKB's modelling of radionuclide transport in the biosphere in previous safety assessments has been carried out with the tools Biopath and Prism. These tools have been developed by Studsvik with support from SKB since the 1970s. The tools have been utilized for the KBS studies of the final repository, for the first safety assessments of SFR, and subsequently for SKB 91, SR 97 and Safe. Biopath and Prism have gradually been further developed /27-20 to 27-22/. The models represent a holistic viewpoint which was pioneering in the environmental field in the 1970s. At that time they were also regarded as advanced numerical tools. The model concept has largely been taken over in most models that handle radionuclide transport in the biosphere in other countries. The concept is based to a large extent on the use of generic transfer factors (or transfer and bioaccumulation factors), which presumes that the system being modelled is in equilibrium. Furthermore, the transfer factors are based in many cases on empirical data and lack a mechanistic explanation. The models describe the pathways that affect man and human food, while other parts of the biosphere are seldom dealt with.

With the newly developed tool Pandora, process-based models can be used, which was considered necessary in RD&D-Programme 2004 to be able to make use of site-specific information on processes and states in the ecosystems. Furthermore, a more realistic description of the biosphere is needed to satisfy the requirements made by the authorities on an analysis of the possible consequences of a future release of radionuclides from a final repository. To estimate the consequences for surrounding fauna and flora in accordance with the regulations, models are needed that are based on the radionuclide flow in the entire ecosystem and not just for specific pathways that are critical for man, such as well or cow's milk.

The use of process-based models solves some of these problems. Except for via water flows, the transfer between compartments is then based on natural processes such as photosynthesis, decomposition, food ingestion, metabolism and nutritional needs. These processes are coupled and the flows are driven for the most part by the mass balance between the fixation and decomposition of organic material. The mass balance induces other flows of organic and inorganic materials (e.g. oxygen, carbon dioxide, water and nutrients). Proportional flows of radioactive substances are associated with these flows. The models are general and can be used for all radionuclides. Even if data are lacking for transfer factors, good estimates can be made of the concentration in different compartments and organisms. Another advantage is that the models are scalable to different site and climatic conditions. Many of the variables that control radionuclide uptake are measurable in the field and are not nuclide-specific, for example the geometry of the catchment areas, insolation, water balance, and the composition of the ecosystem.

Conclusions in RD&D 2004 and its review

The goal of RD&D-Programme 2004 was to have a fully functioning simulation environment in Tensit for use in SR-Can. This goal was fulfilled with the use of Tensit (later renamed Pandora) in SR-Can, see below.

In the review of RD&D-Programme 2004, SKI considered that the development of models in the biosphere area must be prioritized and site data integrated into this work to verify the models in time for a licence application. SSI was of the opinion that the development of a systems ecology model was a good complement to the compartment models that had been used previously.

Newfound knowledge since RD&D 2004

The tool Pandora /27-19/ was used for the calculation of LDFs (landscape dose factors) in SR-Can /27-8/. Some revisions of the tools were made during SR-Can in order to be able to optimize calculation times and handle landscape evolution more effectively. Furthermore, Pandora and the probabilistic tool Eikos were modified for simple execution of probabilistic calculations /27-23/. Pandora is being developed in cooperation with Posiva and is at this point a very flexible model platform.

In conjunction with SR-Can, version control and automatic documentation were also implemented with the version control tool Subversion /27-24/, with traceability for handling the numerous models and input data that are regularly updated /27-6, 27-7/.

Another tool that has been evaluated is Ecopath. It is a general ecological model package. The analyses show that Ecopath can simplify or replace more complex models in aquatic ecosystems /27-25/, which makes it interesting for general applications where site data are lacking. This tool is therefore more interesting for other organizations that do not have access to site data to the same extent as SKB. The results of the evaluation have been published in a scientific article /27-26/.

GIS has been used to a great extent to build up the landscape model and compile data from the ecosystems /27-6, 27-7/, see Figure 27-2. GIS has also been used to calculate runoff based directly on topography and to compile input data for the process-based MIKE SHE models, see section 27.4.

A forest model has been constructed for the safety assessment /27-27/, see further section 27.5.

Programme

Pandora will be used to build process-based models for the different ecosystems. The tool will be updated when relevant during the course of the work. Version control and report generation will also be modified, as will routines for verification. The ecosystems that are needed are described in the following sections.

27.4 Transport processes

The transport processes determine which ecosystems and organisms will be exposed to radionuclides and how great the dilution will be. In the safety assessment, the transport processes comprise an important part of the calculations. The most important transport-related variable is water flux. It plays an important role in all biosphere objects and is mainly dependent on the components of the surface water system (runoff, streams, lakes and sea). The surface water movements also affect how different biosphere objects are coupled together, see for example Figure 27-2.

For radionuclide transport, the vertical transport in the interface zone from the rock to the recipient is essential. It affects where any releases can take place, and thereby which ecosystems can be affected. Studies in this interface zone are made with tools that describe both the deep-lying and the superficial groundwater flows. The work is therefore described both in this paragraph and in section 26.2.3 for the geosphere. Other potentially important transport processes are those that take place from the groundwater table to plants and deposits in the unsaturated zone.

A certain fraction of the radionuclides in the environment will be bound to particles, humus complexes and organisms. The transport of radionuclides in the biosphere is therefore dependent to a great extent on particle transport. Particle transport can be passive, as in the case of sedimentation and resuspension, or active, as in the case of transport via swimming organisms, food ingestion, trade, etc.

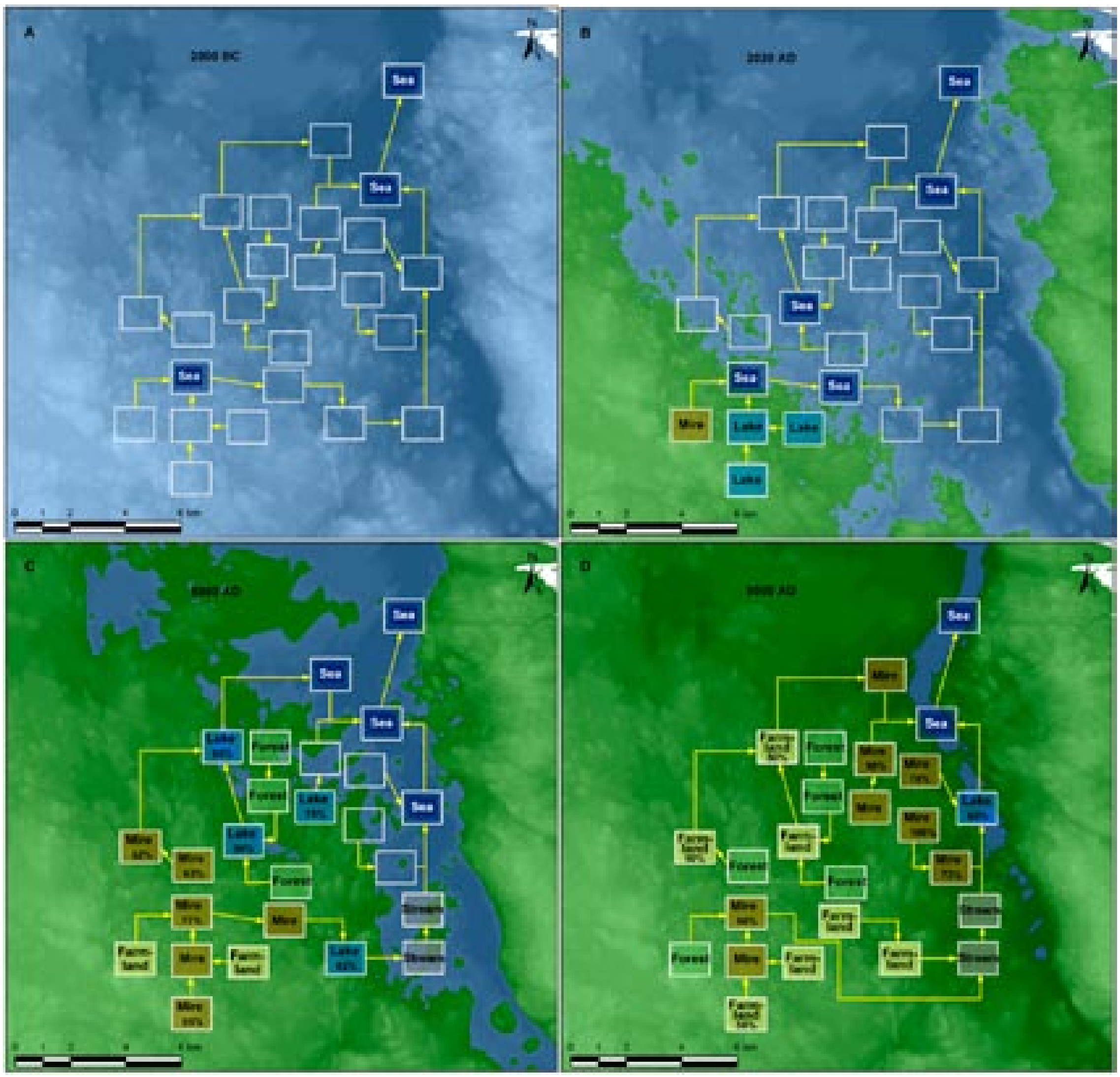


Figure 27-2. *The landscape model in Forsmark. The boxes represent different ecosystems that are interlinked by surface hydrology as indicated by the arrows. The maps show the landscape at different times: A) marine stage from 8,000 BC to 1,000 AD, B) coastal stage (today), C) coastal stage (5,000 AD) and D) terrestrial stage after 7,000 AD /27-6/.*

Conclusions in RD&D 2004 and its review

RD&D-Programme 2004 proposed studies in surface hydrology with an evaluation of surface hydrological models and simplified GIS tools, as well as model studies of nuclide transport at discharge points from the rock, particularly how nuclides move near lake and sea basins. RD&D-Programme 2004 also proposed model and literature studies of particle transport as described above, supplemented with field data from the site investigations. In addition, a model and literature study of human transport activities under various conditions was proposed in order to define how large a population can be affected by a contaminated area. Such a study would facilitate a judgement of the representativity of the most exposed group, in accordance with SSI's regulations. The results of the proposed studies are presented below.

In its review of RD&D-Programme 2004, SSI wrote that research on the interface zone between geosphere and biosphere is important and that they took a positive view of the fact that SKB had begun to study transport processes in the interface zone between geosphere and biosphere and how this is will be included in future safety assessments. However, SSI noted that SKB lacked a clear plan for research on this interface zone. Furthermore, SSI thought that the results of the modelling of surface water hydrology should be interpreted with caution, since they are much too simplified. In addition, SSI felt that SKB should make sure that the necessary data for this is collected in the site investigations.

Newfound knowledge since RD&D 2004

In the landscape models in SR-Can, the hydrology of the whole landscape is used to a greater extent than in previous safety assessments. Different biosphere objects that are situated along the path of the water in the catchment areas are interconnected, which means that radionuclides from several release points can be added together in, for example, lakes downstream. In this way it is possible to detect a possible accumulation of radionuclides in areas downstream of the discharge points /27-8/. The preliminary sensitivity analyses of the landscape dose factors (LDFs) /27-8/ show that the topography is of great importance. This is because the topography controls the size of the sub-catchments, i.e. the total runoff, as well as the volumes or areas of the different objects, which in turn affects the water flux in the different objects. It is positive from a modelling viewpoint that the doses are affected by relatively easily predictable properties such as topography. Furthermore, the landscape models provide completely new ways to link discharge points with the properties of the objects and to take advantage of and utilize site-specific properties.

Surface hydrology has been described with simple GIS models that calculate the area of the sub-catchment upstream of the discharge point and multiply the area by the specific runoff /27-6, 27-7/. The topographic wetness index (TWI) is an example of another simplified model that has been used, and other GIS-based methods can provide guidance on where discharge can take place, where wetlands are located and where streams originate /27-28/. These "simplified" models have been compared with different types of more advanced hydrological models in GIS /27-17, 27-29/ or in special tools such as MIKE SHE /27-30/ and Shetran /27-31/. Identification of recharge and discharge areas for groundwater are an important part of the hydrological modelling. Recharge and discharge areas for near-surface groundwaters in Forsmark have been identified by topographical as well as hydrological and chemical methods. A compilation and comparison of the results is presented in /27-32/.

The MIKE SHE tool is process-based and simulates the entire hydrological cycle within the studied area. This means that the modelling includes both groundwater flow and unsaturated flow above the groundwater table, as well as surface water flows on the ground surface and in watercourses, see Figure 27-3. This makes the tool suitable for studying interactions with deeper groundwaters, see section 26.2.3, but also for comparing the properties of simplified models. The "simplified" GIS models are used in the safety assessment to predict future surface hydrology and calculate the water flux in future ecosystems.

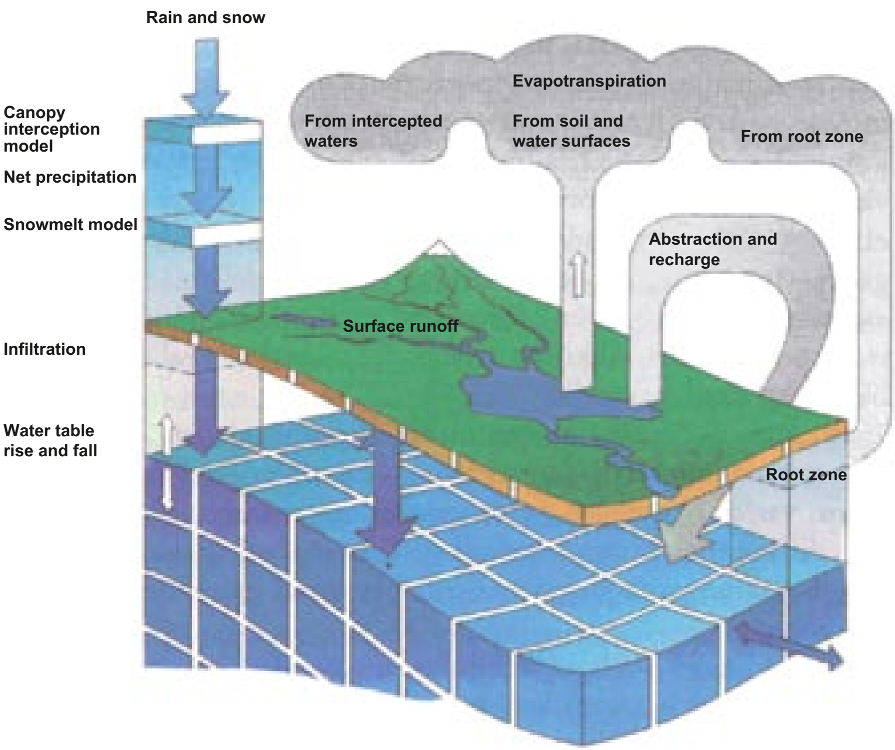


Figure 27-3. *Overview of model structure and component processes in the tool MIKE SHE /27-30/.*

The MIKE SHE tool has been used to describe the present-day near-surface hydrology on the sites /27-33 to 27-35/, see Figure 27-4. This modelling work has also been presented in scientific journals /27-36/. Furthermore, comparative flow modelling of the Laxemar area has been done with the modelling tool Ecoflow /27-37/. The results showed very good agreement with the results of the calculations with MIKE SHE for most of the catchment areas investigated. MIKE SHE has also been used to calculate the effects on the near-surface hydrology of an open repository, including the access tunnel and elevator and air shafts /27-38, 27-39/. The site investigations have included extensive investigations of the near-surface hydrology and the sea currents, and the results are currently undergoing thorough analysis.

MIKE SHE has also been used to study the water flows and the accumulation of substances in a mire /27-40/. Three areas were studied: Bolundsfjärden, Eckarfjärden and Puttan. These areas are described and modelled with respect to soil depth and hydrogeological properties, see further the GeoEditor, section 27.10. The analyses of the future wetlands show that the hydraulic conditions that prevail today will change as a peat layer develops. Different types of vegetation will develop into different types of peat, which affects solute transport. Vertical solute transport follows the recharge and discharge areas, with the highest concentrations near the source. Lower concentrations are obtained in the discharge areas and beneath clay sediment /27-40/. This was also compared with an alternative tool /27-41/. One result from these studies is the realization that when a lake becomes silted up (terrestrialization), a main stream must be kept open for drainage from large drainage basins, i.e. a watercourse is needed through the future wetland.

Generic modelling studies have been carried out of radionuclide transport in running waters and their sediments /27-42, 27-43/, see also section 27.6, showing that retention in sediments can sometimes be of importance.

The CoupModel, see section 27.5, has been used to study transport processes. The model has mainly been used to calculate evapotranspiration in vegetation-covered ecosystems /27-44/ and to calculate the radionuclide flux from the groundwater table /27-45/. The development of the radionuclide model for forest also focuses on these variables, but also simulates further transport of radionuclides in soil, plants, mushrooms and mammals /27-27/.

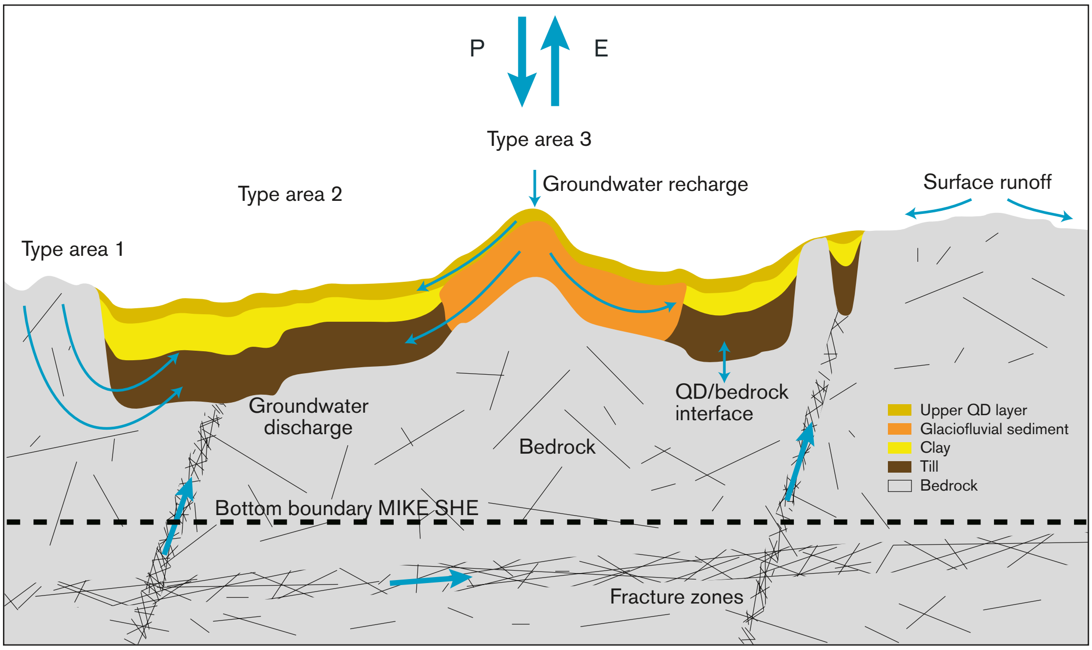


***Figure 27-4.** Schematic cross-section illustrating the near-surface hydrology in the Simpevarp area, showing that MIKE SHE is used a way down into the rock and thereby overlaps the geohydrological model. Type areas 1, 2 and 3 identify the hydrological type areas /27-35/.*

A masters thesis at Uppsala University /27-14/ described some important radionuclides that were analyzed by gamma spectrometry in a soil profile from a peatland in Oskarshamn. The study showed that radionuclides had been redistributed after immobilization in the profile. The study of the peatland profile was supplemented by additional analyses of stable substances /27-46/. A possible similar study has been started in the Krycklan area in the Vindelälven River's catchment area in northern Sweden in order to permit comparisons with Forsmark and Oskarshamn.

In the site descriptions for the surface ecosystems /27-3 to 27-5/, new efforts were made regarding overall material transport in the surface ecosystems. These efforts were based on previous workshops /27-47/. The flux of above all organic carbon in the landscape was studied and compared with the water flux. Several of these studies have been published in scientific journals /27-36, 27-48 to 27-53/.

Initial modelling of solute transport from rock to soil layers and further in the surface ecosystem has been reported in /27-33, 27-36, 27-39/. This modelling consists primarily of particle tracking simulations done with MIKE SHE. The results indicate mainly vertical flow and transport in the soil layers, and relatively small differences in the locations of the discharge points compared with the more large-scale models that include the deep rock. However, more systematic modelling, based on updated site models, needs to be done before the effects of solute transport in the near-surface system can be judged.

Solute transport in the surface system, both the locations of the flow paths and retention along the flow paths, is currently being investigated. These modelling activities are aimed at further developing existing conceptual models to create a basis for detailed planning of further modelling in site descriptions and safety assessment. It should also be noted that the site investigations during the past two years have included investigations focused on possible discharge areas for radionuclides from great depth, see for example /27-54/. These investigations will comprise an important part of the basis for the future site-specific transport modelling.

Programme

The results of the site investigations will be analyzed during the coming year. We expect new site-specific insights regarding the near-surface hydrology, which may require further investigations of discovered phenomena.

The surface hydrological models will be developed and updated as new data become available. An effort is planned to study future conditions at the sites with MIKE SHE or a similar model in order to provide answers for SR-Site regarding how the surface hydrology will change with land uplift.

Particle transport in the sea will be modelled, both as trajectory calculations and by modelling of resuspension of sediments on shallow bottoms, aimed at providing sufficient data for SR-Site.

A study of radionuclide transport in the Krycklan area in the Vindelälven River's catchment area and of SKB's investigated sites will continue as a doctoral project. Important results will be published prior to SR-Site.

A summarizing report dealing with conceptual models and transport properties in the interface zone between geosphere and biosphere for the Forsmark and Laxemar areas is planned as a part of the site description.

Activities are being planned aimed at gaining greater knowledge of site-specific sorption conditions. These activities will probably consist of both evaluations of concentration data from the sites and laboratory investigations of sorption properties.

27.5 Terrestrial ecosystems

The terrestrial ecosystems – i.e. forests, agricultural land and wetlands – are characterized by the fact that they normally have a groundwater table that lies below the ground surface. The dominant transport processes from the groundwater up to these systems are root uptake, capillary force and level fluctuations in the groundwater table. Root uptake and accumulation in biomass are, however, the most important processes for radionuclide transport to humans and other consumers. Mires and other wetlands are the special cases where the groundwater table fluctuates around the level of the ground surface during most of the year, but otherwise these areas have properties similar to land types where the groundwater table is always below ground level. General soil processes will be dealt with in this section, after which forest and wetlands will be treated as special cases.

Forest is the dominant ecosystem for the considered sites /27-5/ and can be a possible recipient, see Figure 27-5. However, the results of studies of groundwater discharge (see section 27.4) show that few streamlines end up in the forest. Most exit in streams, in the shorelines of lakes and seas, and in wetlands. In recent years SKB has studied the terrestrial environments (see below) and simulated the uptake of different substances in vegetation /27-27, 27-45/. The most important long-term processes are accumulation of nuclides in the soil profile and biological leaching processes that move nuclides to biota. The upward transport of radionuclides from the groundwater table into the roots and vegetation is also essential. The processes in the forest ecosystems are closely linked to the near-surface hydrology and the evolution of the wetlands. It is above all forests in depressions, for example swamp forests, that will be of interest with respect to the effects of a final repository – not highland forests such as flat-rock pine forests.

Figure 27-5. *The forest in the Laxemar area looking out towards the Baltic Sea.*

Mires and wetlands are important recipients for the hypothetical sitings. In SR 97, the mire was identified as the typical ecosystem that gives the potentially highest dose to man, higher for many radionuclides than the doses that can be obtained from wells. This was confirmed in SR-Can, but it was also shown there that the yield of food from mires is limited. In most cases the food from a given mire does not suffice for a year's consumption by one human being. Furthermore, several steps of changes of mires are required to result in an exposure of humans, for example drainage ditching, cultivation or burning of peat. It was noted in SR-Can that mires are common in many areas. They are a probable discharge point from the geosphere and a probable result of the natural future evolution of the biosphere after postglacial land uplift in a coastal area. Furthermore it has been common to drain wetlands by ditching in order to obtain agricultural land in parts of northern Uppland /27-55/ and in the Simpevarp area /27-7/.

It is therefore important to obtain a more profound understanding of mires and wetlands and to study processes that can affect radionuclide transport and potential exposure pathways in connection with these areas.

Conclusions in RD&D 2004 and its review

In RD&D-Programme 2004, further studies were planned of the distribution of biomass, primary production and the carbon cycle in different forest types, including swamp forests. Studies of historical and potential exploitation of different types of land on the sites in question were also planned, along with further development of wetland models, including studies of the hydrology of mires. The results are presented below.

Newfound knowledge since RD&D 2004

In the past few years, extensive knowledge has been obtained about the terrestrial ecosystems from the site investigations and the site descriptions (see below). In SR-Can, different ecosystems were interconnected in a landscape for the first time /27-6 to 27-8/.

The development of a general vegetation model, with the forest as an example for the dose calculations, was carried out and applied in SR-Can /27-8/. Previously, few models have been available for long-term simulations of radionuclide transport in forests, but with the aid of the tool Pandora (see section 27.3), it is possible not only to calculate nuclide transport, but also to estimate the concentration of radionuclides in soil, plants, mushrooms and mammals.

Work on the CoupModel has also continued at the same time. The CoupModel is a model developed by the Swedish University of Agricultural Sciences (SLU) and the Royal Institute of Technology (KTH) that can handle transpiration, nutrient uptake and growth /27-56/. Its advantage is that it is process-based and uses mass flow, transpiration and primary production, and that it is coupled to an extensive database compiled by SLU. The model has been modified for SKB's needs and can now also handle radionuclide transport in different ecosystems, such as forests, agricultural land and wetlands /27-45, 27-56/. The CoupModel has also been used to calculate production and evapotranspiration for some typical ecosystems on the sites /27-44, 27-57/, which has also been published in Ambio /27-51/. Continued efforts are being made to adapt the CoupModel for radionuclide transport with different case studies and sensitivity analyses.

In the site descriptive models, several material flow models have been developed /27-3 to 27-5/. They also compile the most important compartments of organic matter in the soil and compare them with compartments in sea and lake sediments. This provides guidance to where radionuclides that have once been bound to organisms can accumulate. The results have been published in scientific articles /27-50, 27-53/.

Knowledge of the vegetation is essential in order to be able to calculate the flux of matter. This includes, for example, the quantity of living biomass, but also the speed of processes such as photosynthesis that build up organic matter (primary production) and the decomposition of organic matter, which produces mineral substances (respiration) and new organic matter. Most production models and global models for climate, hydrology and biochemistry need vegetation data to enable photosynthesis, evapotranspiration and net primary production to be calculated. One way to calculate the productivity of the vegetation is with the aid of satellite data, based on for example the leaf area index (LAI), which is a measure of the quantity of green biomass per unit area, or the fraction of photosynthetically active radiation (FPAR), which relates the amount of light available for photosynthesis to the amount of light absorbed by the plants for photosynthesis. The current research situation and the possibilities of calculating LAI, FPAR and primary production by remote sensing are summarized in /27-58/. The report also provides recommendations for continued work in SKB's investigation areas in Forsmark and Oskarshamn. A calculation of LAI has also been done at the sites /27-59/. Data on biomass and primary production for the field and ground layers, as well as the size of the litter layer, have also been collected in the field for different vegetation Studies of decomposition of litter are under way.

Primary production, and thereby also the carbon cycle, are dependent on soil temperature, soil moisture, the amount of sunlight and the dominant vegetation, for example pine forest, deciduous forest or pastureland. The rate of decomposition of dead wood can also vary /27-61, 27-62/. This has been investigated in a degree project at Lund University /27-15/, which has been published in a scientific journal /27-63/. This information is important for understanding changes in cycling times for radionuclides.

In terrestrial ecosystems, the flux of radionuclides is dependent on the uptake of substances via roots. Root translocation and uptake of different substances in plants have been investigated in the laboratory at Stockholm University /27-64/. The study included nine stable elements with different properties and shows that uptake is dependent on the plant's growth rate and water uptake, see Figure 27-6. Uptake of different elements by fungi has also been studied in Forsmark /27-65/. The element composition for different organisms and soil types has been studied in the site investigations /27-66, 27-67/. The results of these studies are currently being processed /27-68, 27-69/ so they can be used to simulate element-specific mechanisms. Similar studies /27-70/, which are being conducted in Posiva's programme in Finland, will supplement SKB's database. Root formation and root depth are other important data that are needed in the simulations. How deep the roots penetrate into the soil has been studied in the site investigations /27-71 to 27-73/. The results have been used in SR-Can. Another project is studying the dynamics of fine root formation and the annual dynamics at both sites. Radionuclides are transported vertically in the soil (bioturbation) by animals, for example earthworms. This has been studied on both sites /27-74/.

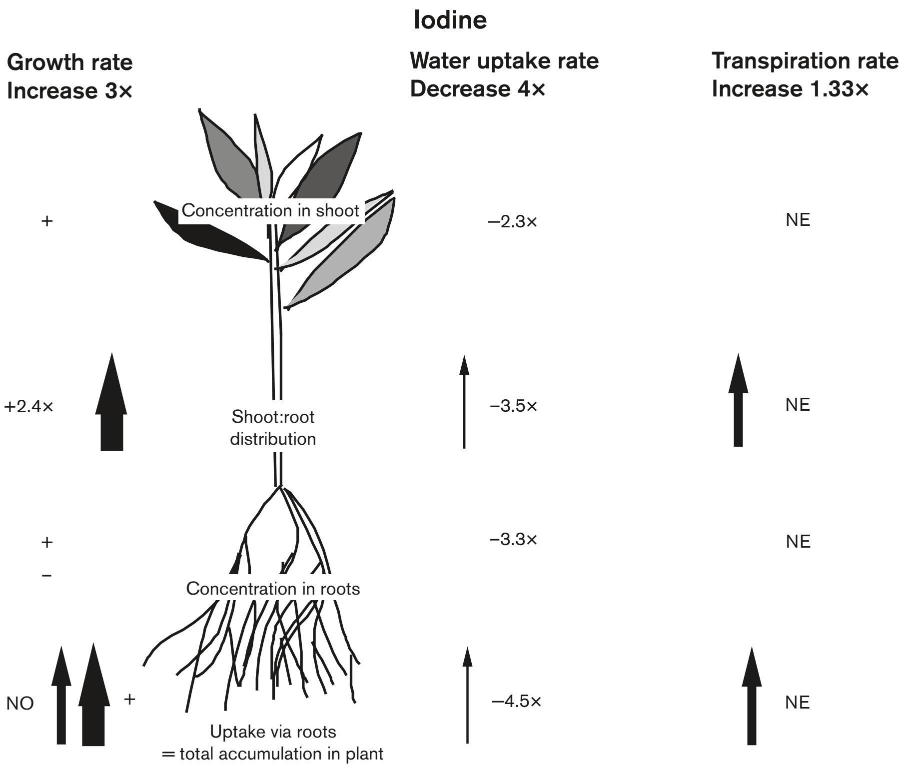


__Figure 27-6.__ Illustration of results of laboratory experiment with iodine uptake in relation to water uptake, transpiration and growth /27-64/.

Important information for modelling the terrestrial ecosystems is the properties of the soil, such as mineral composition and topography. Most studies have been conducted in connection with the site investigations, whose results are presented in section 27.10. The topography controls the distribution of recharge and discharge areas in the landscape, which is of importance for the geohydrological models, see section 27.4, but also for the landscape evolution. The evolution of land areas, formation of lakes and infilling of lakes to wetlands have been simulated in GIS /27-75/, and this has served as a basis for describing the two sites in SR-Can /27-6, 27-7/. This evolution drives the changes in the landscape model /27-8/.

The function of future wetlands in Forsmark has been evaluated, see section 27.4. Three areas are described and modelled with respect to soil depth and hydrogeological properties /27-76/. The tool GeoEditor has been used to describe the stratigraphy, see further section 27.10. Moreover, stratigraphy and chemical composition, including radionuclides, have been studied in the Klarebäcksmossen bog in Oskarshamn Municipality in order to describe leaching and enrichment of radionuclides /27-14, 27-46/, see section 27.4. Mires have also been used to describe historical climate variations /27-13, 27-77, 27-78/, see further section 27.7.

The size of the most exposed group is calculated in SR-Can /27-1/ with the aid of human food ingestion in relation to food production in the potentially contaminated ecosystems /27-8, 27-11/. Food production is calculated using the above-described models, but is also based on site data available in current /27-79, 27-80/ and historical statistics /27-81, 27-82/. This has resulted in a scientific publication in the theme issue in Ambio /27-10/.

Programme

Prior to SR-Site the available knowledge from the site will be compiled and compared with other knowledge regarding terrestrial ecosystems in Sweden and the rest of the world. Efforts will be needed to review and compile the scientific literature.

The radionuclide model for forests will be supplemented with knowledge on the most important mechanisms for radionuclide transport. These will come from the development and sensitivity analysis of the CoupModel. The results of studies of the root zone and the litter fall will augment the forest model with important data. Parts of the model may then be possible to validate with data from an upcoming study of the age of organic matter in the soil.

Mires at the edge of lakes will be specially studied with respect to interactions due to water level variations in the lakes.

27.6 Aquatic ecosystems

Knowledge of the dominant processes for solute transport in aquatic ecosystems (running waters, lakes and seas) is relatively good /27-83, 27-84/. Figure 27-7 shows a schematic illustration of the food webs in the sea. The most important work with regard to these environments is to use and develop models and modelling tools that can handle the knowledge and to gather data from the sites. Model development and transport processes are described in previous sections in this chapter, and data from the site investigation is described in section 27.10.

In many possible discharge areas, the radionuclides will pass a sediment layer. In this way, the sediments in the sea, rivers and lakes will potentially exercise a strong influence on the transport of radionuclides to biota. The permeability of and adsorption in the sediment affect the pattern of dispersal and dilution. A marked change in redox conditions, salinity and biological activity takes place in the boundary layer between sediment and water, which can influence the radionuclide flow. In the short term, these processes will probably reduce the outflow of radionuclides and result in lower doses. In the long term, however, radionuclides can accumulate in sediments, only to be released later due to land uplift, resuspension and the like, resulting in higher doses. Furthermore, the organisms that live in sediments are exposed to elevated levels, which can then be passed on in the food chains, for example via fish to man.

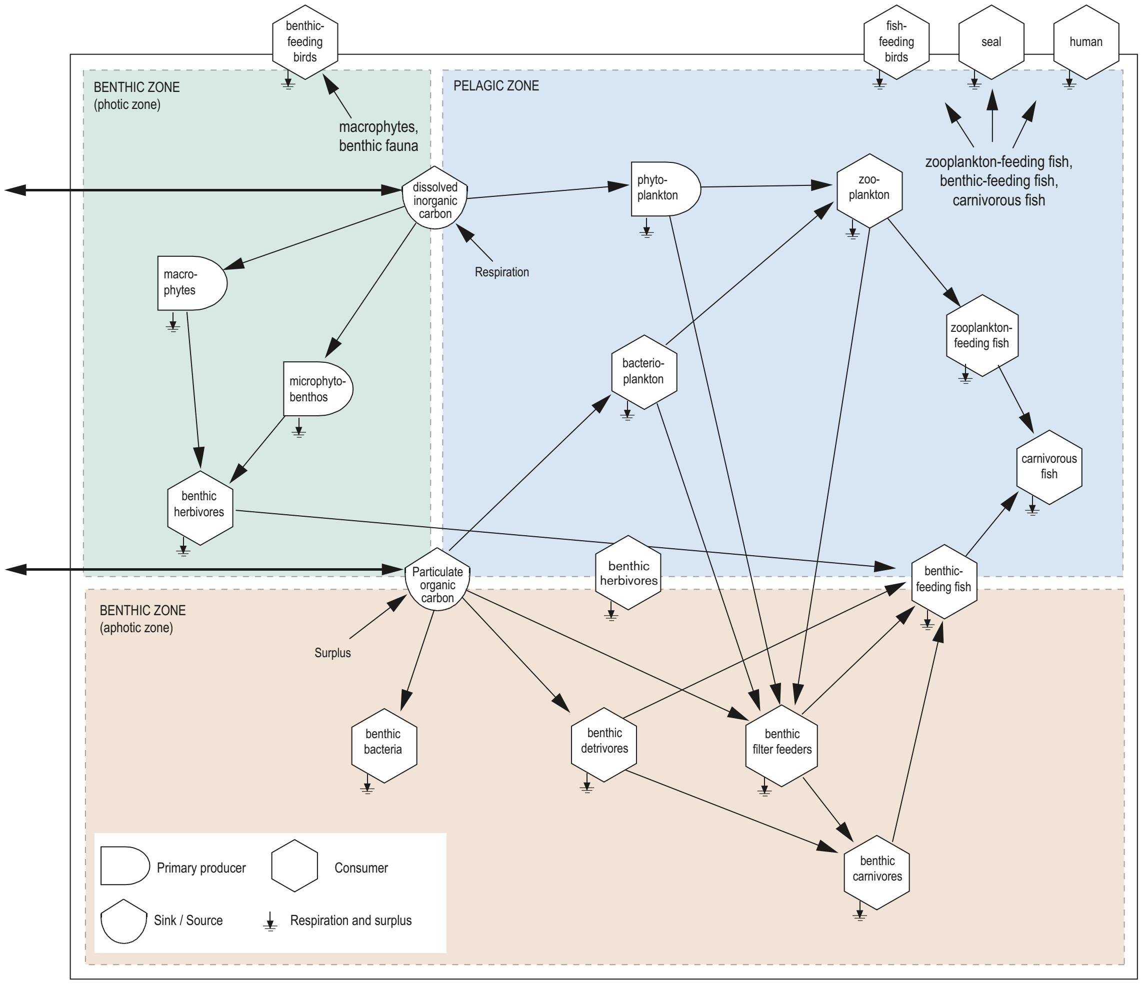


__Figure 27-7.__ Schematic food web in the sea /27-48/.

Conclusions in RD&D 2004 and its review

RD&D-Programme 2004 proposed a modelling of migration processes beneath and through sediments and of reworking and accumulation of sediments, supplemented by collection of field data. Development of a systems ecology model for the lakes on the sites was also planned, along with a general model for radionuclide transport in sea bays. Development of a model that describes sorption processes in bodies of running water was also planned.

In the review, SSI particularly welcomed the studies of the importance of sediments, but thought it was unclear how this research fits into a larger perspective.

Newfound knowledge since RD&D 2004

The sediments have been studied on the sites, partly via the site investigations /27-85 to 27-89/ but also in targeted research efforts /27-90 to 27-92/. The results provide information on the stratigraphy of the sediments /27-85 to 27-88, 27-92/, which makes it possible to measure their accumulation rate and history. Furthermore, the studies provide valuable insights regarding processes such as reworking and accumulation of chemical substances /27-88, 27-89/, for example by bioturbation /27-91/. Sediment dynamics and reworking processes as a function of shoreline displacement have been simulated /27-75/, along with the importance of the hydraulic properties of the sediments /27-40, 27-41/ for hydrology and sorption of solutes /27-42, 27-43/. This knowledge has been directly applied in the safety assessment SR-Can, where the historical data provide insight into landscape evolution and how sedimentation and water flux in the sediments influence the accumulation of different substances /27-6, 27-7/. The processes in the sediments are also important variables in the dose models /27-8, 27-93/.

Knowledge of the unique oligotrophic hardwater lakes in the Forsmark area has been documented in a doctoral dissertation at Uppsala University /27-12/. Among other things, it contains a systems ecology model of Eckarfjärden in the Forsmark area /27-94/. Furthermore, it describes the importance of the benthic areas of the lake as traps for nutrients /27-95, 27-96/ and thereby also for many other substances and radionuclides. The site description for Laxemar included a first compilation of material flows in the landscape, where the mass balance in lakes was also calculated /27-5/. This work has been followed up by several mass balance models devised for the lakes on the sites and has been published in international journals /27-52, 27-94, 27-97/. The modelling work has also led to the identification of some necessary supplementary investigations /27-98, 27-99/.

A good body of data was already available for the sea in Forsmark as a result of a doctoral dissertation /27-84/. This has been supplemented by a mass balance for the bays in the Oskarshamn area /27-5, 27-48/. A number of studies concerning simulation of the flux of radionuclides in the sea have also been published in scientific journals /27-9, 27-50, 27-100, 27-101/. Another study tests the possibility of using a general model such as Ecopath /27-25, 27-26/, which was originally developed to calculate fish production in developing countries. A field study has been conducted at Forsmark where the concentration of 48 elements was measured and compared in different parts of the marine ecosystem: the water, sediments, benthic algae, plankton and fish. The work provides site-specific information on K_d and uptake in organisms of radionuclide analogues.

In order to perform mass balances and calculate radionuclide concentrations in the sea, water exchange calculations are used, which are presented in the site descriptions /27-3, 27-5/. A comparison was made between two methods for transport calculations in the sea /27-49/, see section 27.4. Besides the comparison that was published in the theme issue of Ambio, a scientific article has also been published in Deep Sea Research /27-102/. The oceanographic model is also used by Svealands Kustvårdsvattenförbund to calculate water exchange in the Stockholm archipelago, as it has been used for the Åland and Turku archipelagos in Finland in the EU project Bevis /27-103/.

A new model for describing radionuclide transport in running waters has been developed /27-42/. It includes transport along the entire watercourse. The study was supplemented by a sensitivity analysis /27-43/.

Programme

Prior to SR-Site, the available knowledge from the site will be compiled in a report for lakes and streams and in a report on the sea. Comparisons will be made in these reports with other knowledge on aquatic ecosystems in Sweden and the rest of the world. A description of the most important processes will also be included. Considerable efforts with reviews of foreign literature are expected in this work.

Further development of dose models is planned for lakes.

Mires at the edge of lakes will be specially studied with respect to interactions due to water level variations in the lakes.

27.7 Long-term variations in climate, land uplift and salinity

Conditions in the biosphere are largely controlled by the climate and the distribution between land and water. The salinity influences which ecosystems will dominate in the Baltic Sea and the speciation of the radionuclides. These factors are also important boundary conditions for the transport models in the geosphere. Shoreline displacement influences which ecosystem is dominant in an area. Water flux, groundwater recharge and surface runoff are important physical factors that influence the dose. These factors are highly variable. The range of variation can be studied with models of present-day conditions and a reconstruction of the conditions since the most recent ice age.

In SR-Can, a dose calculation for an interglacial period is applied for the first time in the landscape models and in the calculation of LDFs /27-6 to 27-8, 27-104/. Shoreline displacement is the driving factor that describes the evolution from the end of the glacial cycle to about 8,000–10,000 years in the future. Since both of the studied sites are situated close to the present-day coast, the period around today's conditions is the most eventful. Further back in time the sites were beneath the sea, and about 5,000 years ago they were in a relatively stable terrestrial environment. SR-Can also shows that the highest doses occur when the sites are above the sea, but that relatively few humans have been exposed to them, due to the fact that the ecosystems generally provide little food yield.

Chapter 21 describes in large measure the effects of changes during an interglacial period, for example shoreline displacement and isostatic changes in section 21.3, permafrost growth in section 21.4 and climate and climate variations in section 21.5.

Conclusions in RD&D 2004 and its review

RD&D-Programme 2004 planned studies of climate change in Scandinavia during interglacials in the form of a compilation of information from completed studies, the results of which are reported in Chapter 21. Furthermore, a knowledge compilation regarding permafrost and the importance of the tundra for radionuclide transport in the biosphere was planned, which has not yet been done. Moreover, the discussion on global warming was to be followed, the results of which are reported in SR-Can.

SSI noted in its review that it is important to describe future sea level changes and whether they could lead to a release of activity accumulated in sea sediments.

Newfound knowledge since RD&D 2004

The knowledge that has been acquired since RD&D-Programme 2004 is presented in Chapter 21. To this can be added a doctoral dissertation /27-13/, partially funded by SKB, about mires as climate archives, and a study of a mire in Uppland in a 150-year perspective /27-78/. Moreover, two sediment cores have been analyzed at Oskarshamn /27-87/ and Forsmark /27-86/. The sediment cores describe the Baltic Sea about 4,000 years ago, see Figure 27-8.

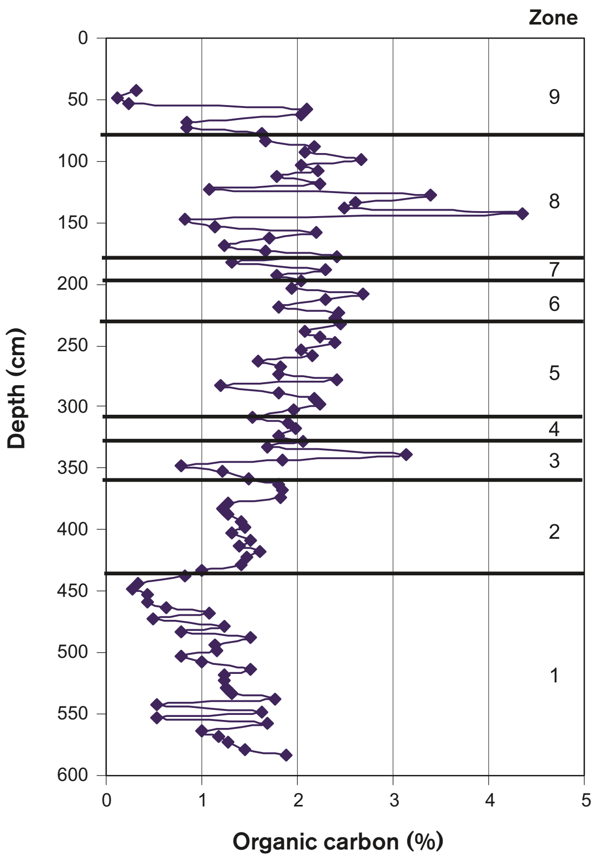


__Figure 27-8.__ Sediment profile from Gräsödjuprännan in Öregrundsgrepen, Forsmark. Organic carbon is plotted versus depth in the sediment. The zonation is subdivided by means of diatom analysis that shows the stages of the Baltic Sea. Zone 1 corresponds to the Yoldia Sea (about 11,000 years ago), the boundary between zones 1 and 2 represents a c. 4,000 year long hiatus corresponding to the Ancylus Lake and the Littorina Sea. Zones 2–9 correspond to the Littorina Sea /27-86/.

Programme

Besides the climate programme described in Chapter 21, which includes the permafrost domain, a description is planned of what the biosphere might reasonably be expected to look like at the sites beneath the permafrost.

27.8 International work and dissemination of information

Standards, methodology and legislation are being discussed in the international work within e.g. the IAEA, EU, ICRP and NKS. In addition, new findings are being presented within radiation biology, nature conservation, environmental protection and systems ecology research that are of importance for the biosphere work. It is also important to disseminate SKB's knowledge internationally in order to obtain viewpoints and scientific peer review.

Conclusions in RD&D 2004 and its review

Active participation in the EU project Erica, Bioprota and the International Union of Radioecology's (IUR) Task Group on Radioecology and Waste was planned in RD&D-Programme 2004. The collaboration with Posiva was planned to be deepened, and the work within the EU, NKS, ICRP and IRPA was planned to be followed. Other goals were to follow and present the work at important meetings on radiation biology, environmental protection and systems ecology and to follow the work at SKI and SSI. Another goal was also to present the biosphere work to interested researchers and students.

The regulatory authorities pointed out in their review that it is important to follow and participate in the international work. SSI also took a positive view of the fact that several articles and dissertations concerning the biosphere work have been published. Kasam agreed with SKB that the knowledge should be disseminated to Swedish and international research groups for independent peer review. In addition, Kasam pointed out that the Government should focus attention on current cutbacks in Swedish research in the area.

In the following it can be concluded that the regulatory authorities have got their wish. Furthermore, SKB views positively the fact that the Government has invested in radiation protection research, with grants to SSI that permit the creation of high research positions in radioecology and radiation protection.

Newfound knowledge since RD&D 2004

SKB continued its participation in the EU project Erica, whose final report was submitted in March 2007. SKB has been active in Bioprota and has, for example, supported a review of irrigation models /27-105/, but also actively participated in describing general site investigations /27-106/. SKB is supporting an evaluation of the movements of iodine in a Canadian peat bog. In Bioprota SKB has supported a critical evaluation of radionuclide data, for example transfer factors /27-107/. SKB has held a lecture on the situation in SKB's biosphere programme at the annual meetings. Furthermore, SKB has participated in the IUR Task Group on Radioecology and Waste, which presented its final report at the end of 2006 /27-108/.

SKB has tried to follow the work of the IAEA programme Emras (Environmental Modelling for Radiation Safety), but has not participated actively in the discussions at the meetings since the work of both Erica and Bioprota has overlapped with that of Emras. Future reports from Emras are expected to be valuable, especially the updates of radionuclide-specific data.

The collaboration with Posiva has continued, for example through the joint development of modelling tools /27-19/. Posiva's biosphere programme /27-109/ has been greatly developed in recent years, and there has also been formal cooperation with SKB /27-110/.

SKB participated in the Ecorad 2004 symposium with three speakers and two posters. SKB's employees have presented SKB's work at many other symposia both internationally (for example IEMS Japan, Setac Europe, American Nuclear Society /27-111/) and nationally (for example Svenska Havsforskarföreningen and Oikos. SCK in Belgium has also held symposia to which SKB has been invited to make presentations /27-112, 27-113/.

Publication in international journals is mentioned in the relevant sections. Nearly 30 scientific articles have been published since RD&D-Programme 2004. The theme issue of Ambio contains eleven articles. The special issue begins with an introduction about the strategy for site descriptions /27-114/, an article dealing with hydrology /27-36/ and an article on oceanography /27-49/. Several articles deal with fluxes of organic carbon in the forest /27-51, 27-53/, in lakes /27-52, 27-97/ and in the sea /27-48/. One article summarizes the fluxes of organic matter in the entire landscape /27-50/, and one describes the past, present and future of the cultivated landscape /27-10/. Finally, one article describes how the knowledge has been used to calculate doses in the safety assessment /27-115/.

Programme

SKB continues to participate as a partner in Bioprota. The dialogue and data exchange with Posiva will be deepened. SKB is not currently planning any work in EU projects with regard to the biosphere, but may be included in reference groups for the continuation of the Erica project called Protect, and for Futurae. SKB is planning to continue following Emras and to become actively involved in the description of available models.

Publication in scientific journals will be encouraged, as will active participation in symposia, such as ICEM (International Conference on Environmental Remediation and Radioactive Waste Management) and the International Conference on Radioecology and Environmental Radioactivity in Norway. Lectures and seminars at universities are expected to continue.

27.9 Treatment of the biosphere in the safety assessment

The purpose of the biosphere research programme as described in previous sections is to provide a scientific basis for conducting safety assessments. One of the most important tasks is to achieve a sufficient understanding of features, events and processes to be able to simplify and create numerical models needed for dose calculations. Beyond this, the research provides information on general data and uncertainties needed for the models and to supplement site data.

Over the years, the account of the biosphere in SKB's safety assessments has evolved from a pessimistic dose conversion factor for a well to increased realism with a number of different recipients corresponding to different types of ecosystems. The authorities' requirements have also increased for the biosphere.

In the most recent safety assessment SR-Can, a significant change has occurred with regard to the methodology for calculating doses and using site-specific information from the sites.

Conclusions in RD&D 2004 and its review

SKI commented on the lack of clear links between site investigations and model development, as well as the lack of a complete description of the models that are to be used in the safety assessment. Nor does SKB's account clearly specify how the different parts of the biosphere programme are to be coordinated to meet the needs of the safety assessment. In the biosphere research, SKB should take into account the possibility of using radionuclide concentrations and flows as complementary safety indicators.

SKI and SSI thought that SKB should clarify how environmental protection will be taken into account in model development and in the site investigations. SKB's claim that data already collected from the site investigations far exceeds the needs specified in the EU Fasset project needs to be proven.

SSI took a positive view of the fact that SKB plans to investigate how large a population may be affected by a contaminated area, but believes that time is short. Kasam points out that there are uncertainties regarding how SSI's regulations on environmental monitoring are to be applied

These questions have for the most part been answered in SR-Can, which the regulatory authorities are currently reviewing. Some of these answers are presented in the following summary.

Newfound knowledge since RD&D 2004

As mentioned previously, SR-Can is a breakthrough for how the biosphere is treated in SKB's safety assessments and is internationally regarded as an innovative approach to dose modelling /27-116/. SR-Can represents a giant step forward in the treatment of the biosphere, and for the first time site data have been used in the models to a great extent. Dose and size of the population have been presented in a new way. Furthermore, a new type of dose conversion factor (LDF) based on existing knowledge of the sites has been used. The landscape models make it possible to interconnect different biosphere objects in the catchment area, which permits several discharge points to be added together in, for example, lakes downstream. Similarly, any accumulation of radionuclides in areas downstream of the discharge points can be discovered /27-8/. It is possible to define the most exposed group in connection with the calculation. Based on the food yield of the area, the population can be calculated, along with how many receive different doses, see Figure 27-9.

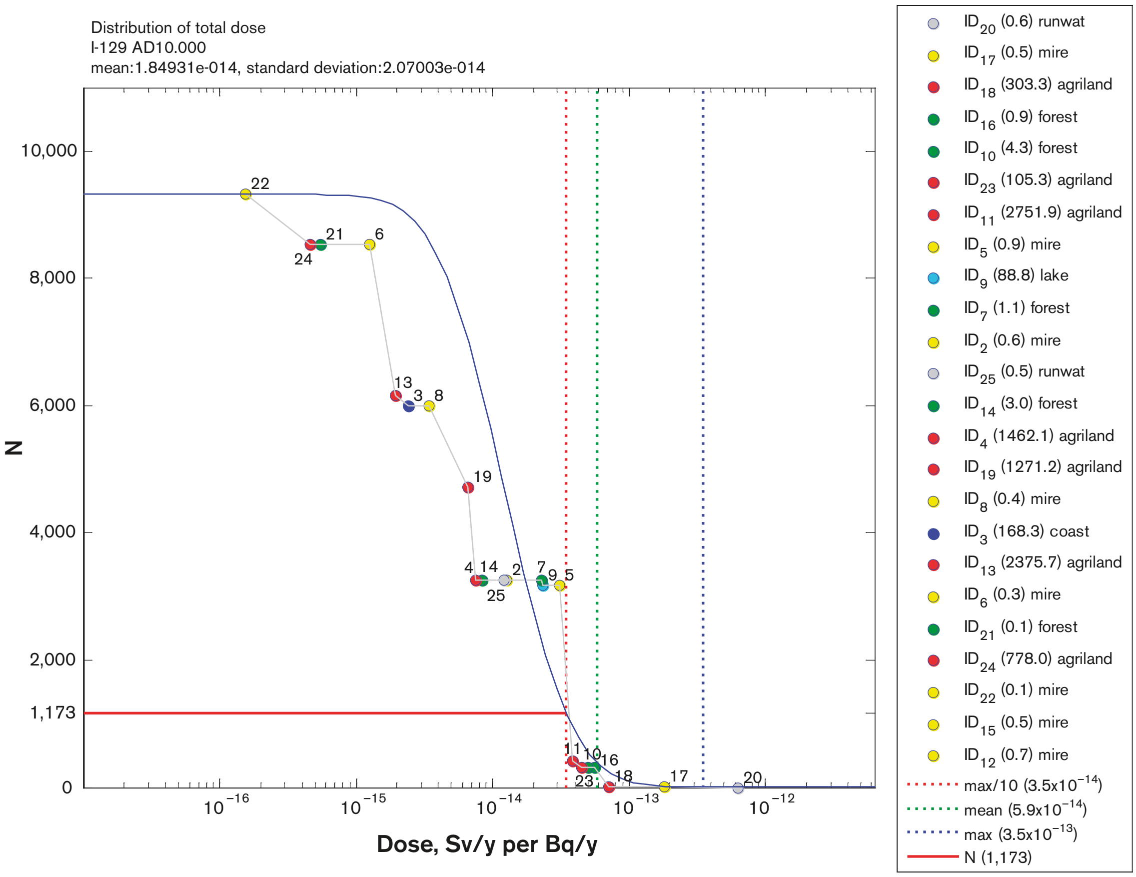


Figure 27-9. *The exposed cumulative population plotted against the dose conversion factor, i.e. the figure shows how many people receive a given dose during their lifetime at a unit release of 1 Bq/y at a repository in Forsmark around the year 10,000 AD. The numbers in the figure indicate ecosystem and number of people. The solid line is the fitted log-normal distribution, and the vertical dashed line indicates the maximum value of the dose conversion factor for a human being and 1/10th of the maximum value. The horizontal line indicates the number of people (1,173) who receive a dose between the maximum and 1/10th of the maximum dose /27-8/.*

The landscape models are site-specific, and data from the sites are used to as great an extent as possible /27-6, 27-7/. The digital elevation model for the site is important for classifying future ecosystems and their size. Some ecosystem models have been updated for SR-Can /27-27, 27-93/, as have radionuclide-specific data for dose conversion, K_d and transfer parameters /27-11/. The simulation tool has also been updated to Pandora in cooperation with Posiva /27-19/, see section 27.3.

Programme

The continued programme leading up to SR-Site is to develop models that use element flows and replace or supplement transfer factors with mechanistic models, see further model development. Sensitivity studies of landscape models will facilitate the prioritization of essential parameters and provide an overview of whether the models capture essential processes. SR-Can identified efforts to characterize other climate domains in the biosphere, see further section 27.7, and alternative evolutions of wetlands from a sea bay, see section 27.5.

27.10 Supportive research for site investigation programme

To support the development of dose models and to furnish site-specific data for the safety assessments, data need to be gathered during site investigations. A number of examples have been given in the above paragraphs. In the research programme, methods have been developed at the same time as available knowledge and resources have been compiled. The goal, however, is that most of the data collection for the site descriptions should take place within SKB's site investigation organization. The site investigation programme is one of the most extensive data collection efforts ever undertaken in Sweden for simultaneous measurement of parameters on a limited site. Variables and parameters judged to be important to collect in a site investigation were given in a report /27-117/. How the data are used in site modelling and description is described in /27-118/. The site investigation has also been coordinated with the geosphere programme in order to find common needs of data for boundary conditions, material for the environmental impact assessment, material for future monitoring programmes, and measures to reduce environmental disturbances in connection with the site investigations. A great emphasis has also been placed on identifying the impact different investigations have on each other.

The programme for site investigations is presented in /27-119/, and the latest summarizing results can be found in version 1.2 of the site descriptive model /27-3 to 27-5/ for the surface ecosystems for the respective site. The site descriptions are based on a series of background reports which describe the various parts of the ecosystems, for example vegetation, fauna, topography, climate, land use and deposits.

Conclusions in RD&D 2004 and its review

SKI thought it was unclear when, for example, critical R&D results and models must be available to meet the needs of the site investigations. SSI wrote that the connection between data from the site investigations and the requirements made by the site-adapted ecosystem models and the models for the interface zone between geosphere and biosphere must be clear. The results that answer these questions can be found in SR-Can with background documentation and in section 27.4.

Newfound knowledge since RD&D 2004

The support given by the research to the site investigations has above all been to participate in the network for surface ecology modelling and description (SurfaceNet) and to train and identify experts who participate in the site descriptions. Furthermore, the research has developed methodology and tools that have been used in site investigations and modelling. An example is GeoEditor /27-76/, which is used to describe the stratigraphy of both sites /27-5, 27-76, 27-120/, and where the description can then be used directly in the hydrological tool MIKE SHE /27-33 to 27-35, 27-38, 27-39/. Research projects have also been conducted on the sites. Important data have been gathered during the work with the projects, for example the marine element composition (see section 27.6), important root data (see section 27.5), radionuclide and element profiles in a mire /27-14, 27-46/

(see section 27.4) ad sediment profiles in the lakes in Forsmark /27-92/. A doctoral dissertation has studied the lakes in the Forsmark area and provided important site data and developed methodology that has been used in the site investigations /27-12/, see section 27.6. An important task has been to initiate and support the scientific publication of the knowledge acquired during the SurfaceNet work with site descriptions and data collection via the theme issue of the scientific journal Ambio (volume 35, issue 8) /27-10, 27-36, 27-48 to 27-53, 27-97, 27-114/, see also section 27.8.

The research and the safety assessment have obtained important information from the site investigations and the site descriptions, many of which have already been mentioned in previous sections. The results are summarized in the site description /27-121, 27-122/. The data have then been used in SR-Can, which is presented in /27-6, 27-7/.

The site investigations and the modelling in connection with the site descriptions have yielded new insights that have deepened our understanding of various processes in the surface ecosystems. The numbers and occurrence of mammals serve as input to carbon flow models, enabling the potential food choice that has been used to analyze the number of people who can get their food from the different ecosystems at the sites to be calculated /27-123 to 27-126/. Living conditions for humans in the areas have been studied. In a study done by the Dept. of Social and Economic Geography at Stockholm University, historical land use and production, settlement and other impacts on the landscape at the sites were studied. Large parts of the study were analyzed and presented by means of GIS /27-81/, see Figure 27-10. A survey of today's natural and cultural (including socioeconomic) values on the sites has also been carried out, providing important information for the environmental impact assessment /27-127/.

An important part of the ecosystem modelling work is the diffuse interface zone from geosphere to biosphere, where the upper ground layers and the properties of the soil layer are crucial for solute transport in the surface ecosystems, see further sections 27.4 and 27.5 /27-54, 27-120, 27-128, 27-129/. Additional analyses have therefore been performed with regard to Quaternary deposits, soil depth and the sedimentary deposits on each site. In order to acquire additional knowledge of ecosystem processes, extensive investigations have been conducted in cooperation with SLU of vegetation conditions, soil hydrology, Quaternary deposit geology, pedology, and soil sampling for laboratory analyses of physical and chemical conditions /27-71/.

The site-specific knowledge of the aquatic systems in the areas has improved as a result of a series of investigations. The surface water chemistry investigations outside Forsmark have been followed up and improved /27-130/. Similarly, the quantity of chlorophyll in plankton has been analyzed for use in the ecosystem modelling /27-131/. In one investigation, production and respiration of organic carbon are being estimated on different types of bottoms in Bolundsfjärden /27-132/. An inventory of the plant and animal communities and an estimate of the biomass have also been made at the site investigation area in Forsmark /27-133 to 27-136/.

Programme

The research will mainly concentrate on providing additional knowledge on unsolved questions, further development of analysis methodology, and scientific publication of obtained data. The results of site investigations and analyses of these results in the site modelling will be used for the research programmes and the safety assessment described in the other sections.

Figure 27-10. *Top: Map from 1680 of the area around the crofter's holding in the Laxemar area. Bottom: Photo from today on the field at the crofter's holding /27-83/.*

28 Other methods

Besides the KBS-3 method, SKB is also studying other methods to dispose of spent nuclear fuel, such as partitioning and transmutation and deposition in deep boreholes. These methods are described in sections 28.1 and 28.2.

28.1 Partitioning and transmutation (P&T)

Transmutation – conversion of long-lived nuclides to stable or short-lived nuclides – is mainly done by neutrons in a nuclear reactor, i.e. the same nuclear reactions as those that occur in an ordinary nuclear reactor. Nuclear fission is the most effective conversion method for transuranium elements (transuranics). For other long-lived nuclides it is neutron capture. In nuclear fission, large quantities of energy are evolved which can be utilized for electricity production, for example.

The purpose of transmutation is to greatly reduce the quantity of long-lived radionuclides that have to be disposed of. One technical goal that is sometimes given for transmutation is to reduce the quantity of long-lived radionuclides by a factor of 100. If this goal were achieved, the radiotoxicity of the remaining high-level waste after approximately 500 years would be at a level comparable to the level the spent fuel would reach after about 100,000 years. The remaining long-lived substances would still require a geological repository, however.

In order for the process to achieve its purpose, the long-lived nuclides to be transmuted have to be separated from the remaining uranium. Otherwise new long-lived nuclides would be formed by nuclear reactions between uranium and neutrons, which is how the transuranics were originally formed (neutron capture) in the power reactors. Uranium constitutes approximately 95 percent of the remaining fuel from a light water reactor. Reprocessing, including separation (partitioning) of different nuclides, is thus a prerequisite for transmutation. Partitioning and transmutation, or P&T, is therefore considered a unified concept.

Conclusions in RD&D 2004 and its review

RD&D-programme 2004 /28-1/ pointed out that effective transmutation requires a system based on fast neutrons. This can either be a fast reactor with a self-sustaining chain reaction or an accelerator-driven system (ADS), where the actual nuclear reaction is subcritical and is fed with neutrons from a neutron source driven by a proton accelerator. RD&D-Programme 2004 provides a general description of the system.

It was further observed that there are two main routes for reprocessing and partitioning: the first is a further development of extraction between an aqueous and an organic solution, which is the process used in existing industrial reprocessing plants, while the other is a development of pyrochemical partitioning processes. The main advantage of the latter is that they are less sensitive to radiation from the high-level material. On the other hand they require more development and the higher temperatures entail potentially greater risks.

Some important conclusions in RD&D-Programme 2004 were:

- There is no consensus among experts on which technical route to follow for the important parts of a P&T system.
- Interest in P&T is mainly concentrated to the national research laboratories in the USA, Europe, Japan and a few other countries. Universities in many countries, including Sweden, also show strong interest in P&T. Numerous important research programmes are being pursued at universities and research laboratories in many countries. The research is attracting considerable interest among researchers and students in the nuclear sciences.
- The nuclear energy industry has shown only a limited interest in this work, which is mainly being pursued in France and a few other countries with large nuclear programmes. The nuclear energy industry's long-term interest is more focused on new types of reactors – often called Generation IV.

- National and industrial R&D efforts on spent fuel and high-level waste management in nearly all countries are (and should be) primarily focused on resolving questions surrounding geological disposal. Despite all the delays and setbacks experienced in many countries, the prospects of achieving this goal are much better and lie much closer in time than the very long-term and costly goal of developing, implementing and operating P&T efficiently.
- When all of these circumstances are weighed together, the conclusion can be drawn that it is unlikely that industrial-scale ADS facilities can be put into operation before 2050.
- Successful development of P&T will not render geological disposal obsolete. The complex processes will inevitably generate some waste containing long-lived radionuclides. A geological repository is required for this waste. Successful development of P&T may, however, reduce the requirements on the engineered barriers in the final repository, as well as the volumes.
- For Sweden it is important to follow international development efforts and to maintain a reasonable level of competence in the country as long as a substantial part of the country's electricity is produced by nuclear power. Competence developed through research and development in the P&T field is also valuable and useful in the work of maintaining and developing safety and fuel supplies for the existing light water reactors. It is also important for assessing the further development of the nuclear waste management programme.
- As already noted, development of P&T for large-scale operation can be expected to take several decades. Transmuting all nuclear fuel from already existing nuclear power reactors alone would take at least another 100 years. P&T on an industrial scale requires large nuclear facilities that must be accepted by society.
- Introduction of P&T in order to efficiently reduce the quantity of long-lived radionuclides that must be disposed of in a geological repository would thus require a long-term commitment to nuclear energy.
- The costs of P&T cannot be predicted with any accuracy before the systems have been better defined and tested. The estimates that have been made point towards electricity production costs that are between 10 and 50 percent above the costs for modern light water reactors. The investments needed in R&D and in new nuclear facilities are extremely large. However, they are spread over long time, and most should be regarded as investments in energy production. It is not economically defensible to implement P&T without making use of the energy generated by the process. This is particularly true of transmutation of plutonium. Some experts believe that it might be feasible to build small ADS facilities for transmutation of americium, curium and neptunium.

The review of RD&D-Programme 2004 did not give rise to any dissenting viewpoints on the conclusions presented in the programme. Nor were any comments made on SKB's goal for RD&D efforts for P&T. Kasam noted that it is reasonable that SKB should follow and support research and development on transmutation inside and outside Sweden. Kasam further points out that in deference to possible progress with P&T, the repository should be built so that retrieval of the fuel is possible.

Newfound knowledge since RD&D 2004

At the request of SKB, a reference group of Swedish researchers published a report on the status of P&T research in early 2007 /28-2/. The information for the following brief summary of the current state of knowledge on P&T is taken from this report. The report summarizes developments since 2004, when a similar report was produced for SKB /28-3/. For a more detailed account of the state of knowledge, the reader is referred to these reports. See also the annual reports /28-4 to 28-12/.

The gradual increase in the research and development work for P&T that took place internationally during the period 1990–2003 has not continued since 2003. The financial support given by the European Commission to P&T projects in the Union has levelled out, and it is unclear what support will be available for future programmes. However, P&T research still plays a prominent role in the programme for future nuclear power and nuclear fuel cycles. This is being focused on internationally within the joint work on advanced reactors called Generation IV.

The P&T research is concentrated on transmutation of transuranium elements, while the interest in fission products is a sidetrack. However, several studies point out that if the actinides plus caesium and strontium are removed, a sharp reduction can be achieved of the volume needed for the high-level waste in a final repository. These are the elements that account for most of the decay heat in the spent nuclear fuel.

A fast neutron spectrum is required in order to obtain an efficient transmutation of transuranics. The previously strong interest in accelerator-driven systems (ADS) has declined slightly in favour of fast reactors. ADS is now seen mainly as an instrument for transmutation of americium and curium, if this is done separately. A "double strata" fuel cycle is now spoken of, where energy production takes place in light water reactors and fast reactors, while the heavier transuranics are transmuted in an ADS. In an energy production system based on fast breeder reactors, however, it is possible to burn americium and curium as well. In this case, ADS could be of interest during an interim period.

Development of ADS is being pursued in Europe, mainly within the EU project Eurotrans. This project started in 2004 and will be concluded in 2007. Eurotrans is an integrated project with five "domains": design, experimental work concerning the coupling between an accelerator and a sub-critical reactor, fuels, materials and nuclear data. The design studies concern an experimental facility (XT-ADS) with lead-bismuth coolant of about 60 MW thermal capacity, plus a demonstration-scale plant of about 400 MW thermal capacity with lead coolant. The safety work in this domain is being coordinated by KTH. KTH is also participating in domains two to four in Eurotrans.

The experiments regarding reactor-accelerator coupling were planned to take place in Italy, but had to be discontinued when the Italian funding was not approved. The resources for these studies have now been allocated to three other projects in Belgium, Russia and the USA. The work in this area is greatly delayed and will start in 2007. It is doubtful whether this domain can achieve the goals stated in the project plan due to the fact that facilities are currently lacking for studying the coupling in a relevant manner.

Within the fuel domain, irradiation of americium fuel is planned in the French reactor Phénix. Irradiation will begin in the spring of 2007 and continue until the reactor is shut down in 2009. The plutonium nitride fuel that was fabricated in the Confirm project (the EU's Fifth Framework Programme) and that should have been irradiated in the Studsvik R2 reactor will now be irradiated in the Dutch Petten reactor.

Within the material domain, corrosion problems in connection with lead-bismuth cooling are above all being studied. A ferritic steel plated with a thin coating (20 microns) of iron and aluminium is being tested for fuel.

Much less work is being done in the nuclear data domain within Eurotrans than within the previous framework programme. A small experiment has been conducted in Uppsala.

As mentioned above, research in partitioning is focused on two main routes: hydrochemical processes and pyrochemical processes. In Europe the efforts are coordinated within the EU-project Europart, which started in 2004 and will be concluded in June 2007. The project is a so-called integrated project within the Sixth Framework Programme and is a continuation of the projects Partnew, Calixpart and Pyrorep within the previous framework programme. Partnew was focused on separation of actinides and lanthanides from aqueous solutions by liquid extraction and use of nitrogen donating ligands such as malonamides. Calixpart also investigated liquid extraction of aqueous solutions, but using calixarenes. Pyrorep studied pyrochemical methods for partitioning in salt or metal melts.

Europart is divided into nine work packages, including five in hydrochemistry and four in pyrochemistry. A brief overview of the project is provided in the situation report /28-2/. Participants in the project include 24 different organizations in 11 EU countries plus Australia and Japan. Sweden is represented by the nuclear chemistry group at Chalmers in Göteborg. The Swedish research on partitioning is currently well integrated with the EU-projects /28-9/.

The research on partitioning for transmutation has made important progress in recent years. In some cases it has even been possible to separate americium and curium. Many challenges remain, however. Sufficiently good distribution and separation factors have been achieved within hydrometallurgy. The focus is now on developing a workable process. The search for ligands that provide sufficiently good extraction and separation will continue, but with much less intensity. The emphasis will instead be on improving stability against hydrolysis and radiolysis. This can be accomplished either by the use of solvent additives or by the choice of a suitable solvent. The development of processes and equipment needs to be intensified.

Pyrochemical research is looking into methods for recovery of uranium and for separating fission products with large neutron cross-sections. The purpose is to avoid separation of plutonium from other transuranium elements and in order to simplify non-proliferation safeguards. The future work is focused on improved selectivity and technical development. Design of processes and equipment is difficult due to the aggressive properties of the melts and the relatively high temperatures required.

The fabrication of fuel for transmutation and the reprocessing of transmutation fuel require considerable development, which cannot be full carried out until the fuel to be used for transmutation has been defined. The development of this part of an advanced fuel cycle will thus require more time.

The consequences of partitioning and transmutation, as applied to spent nuclear fuel in connection with the phaseout of the present-day Swedish power reactors, have been studied in a report produced on behalf of SKB /28-13/. The study is based on an analysis of different scenarios /28-14/. One conclusion of the study is that due to the long lead and operating times that are associated with transmutation, responsibility is shifted to future generations. It is therefore doubtful whether P&T as a strategy for final disposal in a phaseout scenario meets the requirement of the IAEA's radioactive waste convention, i.e. that undue burdens shall not be imposed on future generations. Even if partitioning and transmutation can be done efficiently, waste will remain that must be managed and disposed of. In other words, P&T is not an alternative to final disposal. P&T presumes continued nuclear energy production on a time scale of 100 years or more. It may offer a realistic alternative in a long-range perspective where a considerable portion of the energy supply is based on new types of nuclear reactors to replace the current ones. This requires a long-term commitment to nuclear technology and P&T, which in turn requires long-range national energy policy decisions.

Kasam presents an overview of P&T in its latest state-of-the-art report /28-15/. The basic principles for P&T are described. A summary of the state-of-the-art and of ongoing and planned research is then given. Three different scenarios are discussed from a Swedish perspective:

- An exclusively Swedish transmutation system.
- A system where Sweden completely relies on the technology and resources developed in other countries.
- Partitioning and fuel fabrication abroad, transmutation in Sweden.

The concluding part of the account discusses advantages and disadvantages of P&T. Kasam draws the following general conclusions:

The application of P&T to Swedish nuclear waste will be a question for future generations. With present-day knowledge of this technology, it is not acceptable to interrupt or to postpone the Swedish nuclear power programme, citing P&T as an alternative. On the other hand, this possible future alternative reinforces the requirement that the repository should be designed so that waste retrieval is possible. According to the ethical principles that Kasam and others have established, each generation should take care of its own waste and not force future generations to develop new technologies to solve the problems. Therefore, it is reasonable for resources to be put aside for further research on P&T. This research could also pay off in ways which are of value for other areas, such as nuclear physics, chemical partitioning technology and materials technology. Swedish P&T research should be coordinated with the research and development being conducted in other countries. To allocate resources for further P&T research at this stage is also in line with the view that our generation should give future generations the best possible conditions to decide whether they want to choose P&T as a method for taking care of spent nuclear fuel, instead of direct disposal alone (in accordance with the KBS-3 method, for example).

Programme

The goal of SKB's research on partitioning and transmutation of long-lived radionuclides is to:

- Examine how this technology is developing and how it will influence waste streams from nuclear installations and their nuclide content.
- Judge whether, and if so how, this can be utilized to simplify, improve or develop a system for disposal of the nuclear fuel waste from the Swedish nuclear power plants.

Research is being pursued in accordance with annual activity plans. Overall assessments are made prior to important decisions in the nuclear waste programme.

SKB's research activities mainly serve as support for ongoing research at universities and institutes of technology. This research is being pursued in broad international cooperation, above all within the EU through active participation in projects funded within the EU's periodic framework programmes.

Interest in the development of accelerator-driven systems (ADS) has declined somewhat in recent years as work on the fourth generation of reactor systems (GEN-IV) has increased. These systems include fast reactors, with or without breeding. Fast reactors have the same potential for efficient transmutation as ADS. Another development route within GEN-IV is high-temperature gas-cooled reactors (HTGRs). These reactors have a fuel that tolerates very high burnups. Some experts believe that spent fuel from an HTGR is a much more stable form of waste than spent fuel from a light water reactor. Furthermore, an HTGR has a much higher efficiency and thus produces a smaller quantity of spent fuel per kilowatt-hour of electricity generated. There is thus good reason to keep an eye on developments in these areas.

In the area of reprocessing and partitioning, most international efforts are still concentrated on aqueous systems, even though pyrochemical processes are considered important for certain types of fuels with high concentrations of americium and curium. For the time being, the Swedish work should continue to focus on the aqueous systems. The development of other systems is being monitored.

It is important for Sweden to follow international development efforts while maintaining a reasonable level of competence within the country, at least as long as a large proportion of the country's electricity is produced by nuclear energy. Competence gained from research on advanced nuclear fuel cycles and nuclear waste strategies is also valuable and useful for development of safety, fuel supply and waste management for existing light water reactors. It is also important for being able to assess the future development of the nuclear waste programme.

The research efforts should primarily be aimed at gathering knowledge of importance for safety, feasibility and reliability. Materials and fuels are of central importance in this context. It is also important to learn more about the processes that may be included in future advanced fuel cycles so that the different types of radioactive waste that may arise can be identified.

The scope of SKB's research work over the past five years has been on the order of SEK five million per year. A certain increase and broadening of the work on future advanced systems is taking place in the EU that may be of importance for the development of partitioning and transmutation. Following up these efforts requires some increase in resources and, in some cases, more in-depth studies. An increase in the scope of SKB's research efforts is therefore warranted during the coming period. An annual budget of SEK 6-7 million is estimated for the period 2008–2010.

28.2 Deep boreholes

In the disposal method known as "Very Deep Holes", or simply deep boreholes, the rock is the most important barrier for isolating the waste and preventing radionuclides from spreading to the biosphere. The concept is based on the assumption that groundwater conditions are very stable at great depths. The reason for the stable conditions is that the groundwater has high salinity (and thereby also high density) and therefore tends not to mix with the overlying, lighter fresh water. Figure 28-1 shows how properties such as water flux, salinity, temperature and rock stresses change with depth. Juhlin et al. /28-16/ proposed a conceptual model for the uppermost five kilometres of the bedrock in Sweden, see Figure 28-2. Any groundwater movements that do occur are not believed to have any contact with the ground surface. This means that no radionuclides can be carried up to the surface by the groundwater.

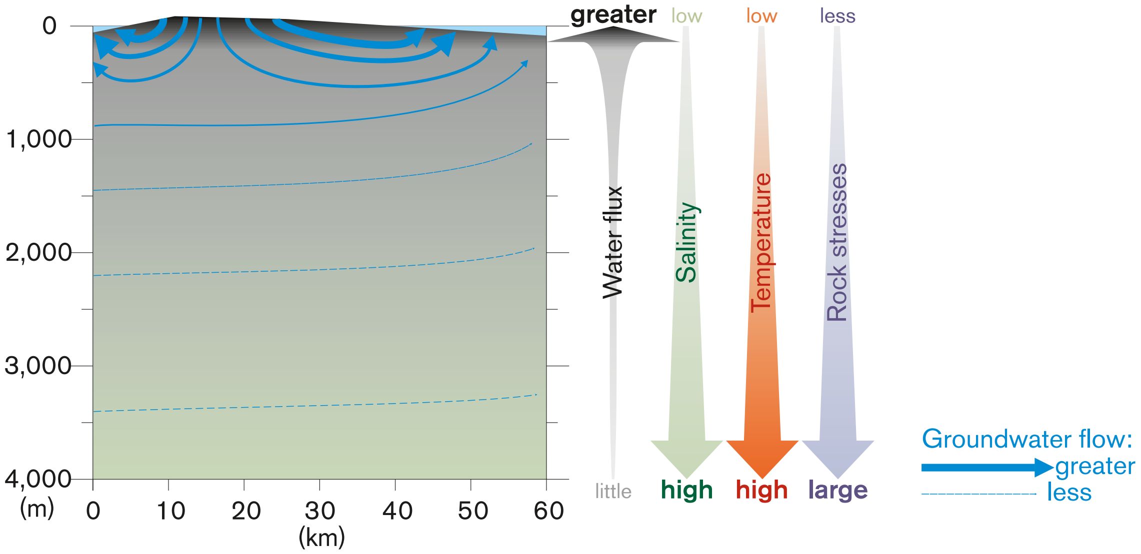


Figure 28-1. *Change in the properties of the Swedish bedrock with depth.*

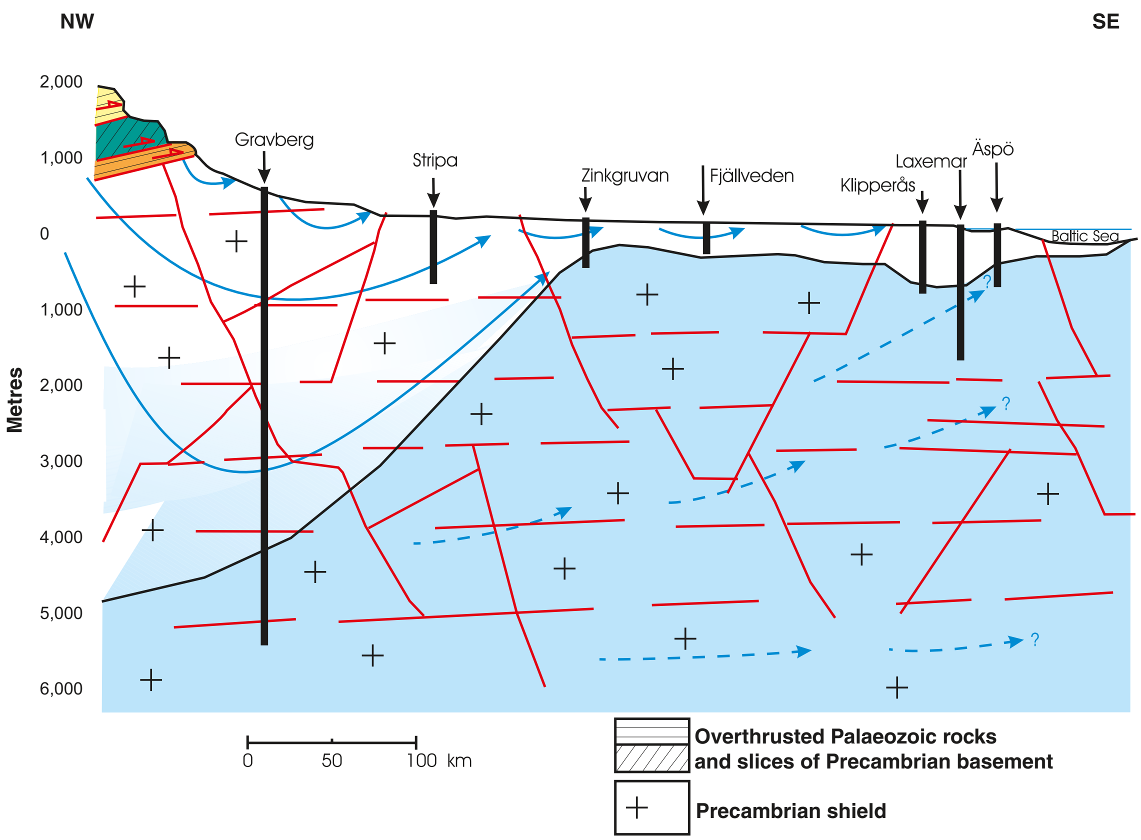


Figure 28-2. *Water circulation and variations in salinity along a profile through Sweden.*

The long-term safety of deep boreholes thus lies in the function of the rock. But there are other barriers. The canister will be designed to withstand the mechanical stresses that arise at a depth of four kilometres. The main function of the buffer is to fix the canisters in their positions after deposition. The high salinity and high temperature make the chemical environment very aggressive, however. Furthermore, due to the difficulty of effectively checking the deposition procedure, the possibility of canister damage cannot be ruled out. We can therefore not count on any long-term safety function of the canister or the buffer.

Siting an area for deposition in deep boreholes is associated with greater uncertainties than the equivalent siting of a KBS-3 repository. But the principle is the same: a suitable site is selected based on bedrock maps. The suitability of the site must be confirmed by drilling. The difference is that the KBS-3 repository can be adapted to the bedrock, partly thanks to the possibility of visually inspecting the deposition holes. The deposition holes in a KBS repository can be bored from the start in suitable positions, and holes that prove to be unsuitable can be rejected. In the case of deep boreholes, the conditions as a whole must be either accepted or rejected. It might be possible to deposit canisters in limited parts of the hole. Moreover, our knowledge of the surrounding rock volume can never be as good with deep boreholes as with KBS-3.

Technology exists today for drilling deep boreholes. But it needs to be developed to drill the large diameters required here. The necessary deposition equipment does not exist today, nor do the methods that will be needed for radiation shielding or canister retrieval.

28.2.1 Previous studies of deep boreholes

During the past 20 years, SKB has studied other methods for geological disposal in parallel with the KBS-3 method. RD&D-Programme 86 /28-17/ and RD&D-Programme 89 /28-18/ included studies of how a geological repository for spent nuclear fuel could be designed.

In the early 1990s, the studies of alternative designs were conducted in a joint project: Project on Alternative Systems Study (Pass) /28-19/. The three alternative geological disposal methods that were investigated in the Pass project were deep boreholes (VDH = Very Deep Holes), medium-long tunnels (MDH = Medium Long Holes) and long tunnels (Very Long Holes = VLH). All these methods were compared with deposition according to the KBS-3 method with respect to technology, long-term performance and safety, and costs. Of the three alternative methods, Medium Long Holes was judged to have the greatest potential, see Table 28-1. Very Deep Holes was given the lowest ranking in all three interim comparisons. The result was conclusive with regard to both technology and costs. The result was less conclusive with regard to long-term performance and safety. The lower ranking was mainly due to the fact that the ability of the system to isolate the spent nuclear fuel in a long-term perspective was mainly dependent on one barrier: the rock.

In 2000, SKB performed another comparison between different methods for geological disposal. KBS-3 was compared with very long tunnels, WP-Cave and deep boreholes /28-20/. This time the evaluation was based on the requirements embodied in acts and ordinances and in international agreements. The following comparison grounds were taken into account:

- Not impose burdens on future generations
- Environmental requirements
- Safety requirements
- Radiation protection requirements
- Safeguards
- Costs

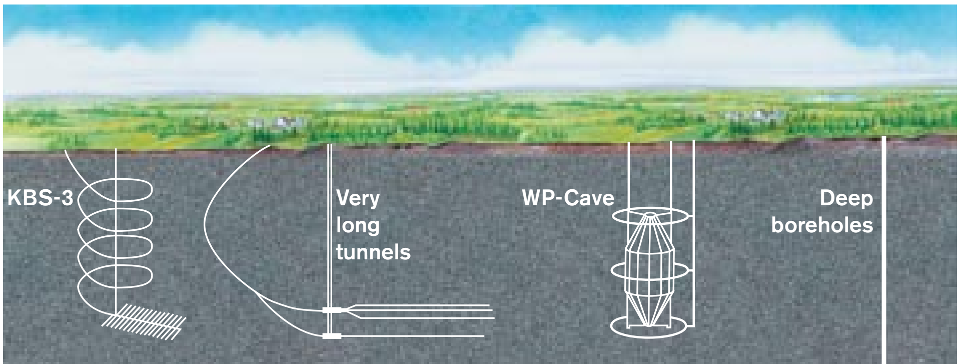
Table 28-1. Summary of results from the three interim comparisons of repository systems in the Pass report /28-19/. A ranking of 1 is the best.

Geological disposal method	Technology	Long-term performance and safety	Costs
KBS-3V	1	1	2
Medium Long Holes (MLH) (KBS-3H)	2	1	1
Long tunnels (VLH)	3	1	2
Deep boreholes (VDH)	4	4	4

This time as well, KBS-3 and Medium Long Holes were judged to have the greatest potential, see Figure 28-3. SKB concluded that there was a great need for knowledge acquisition and technology development when it comes to deep boreholes.

The scope and content of an RD&D programme needed to judge the deep boreholes (VDH) concept on the same grounds as KBS-3 /28-21/ were also investigated. The results of the Pass project and a compilation of geological conditions at great depths /28-22/ served as a basis for the programme. The study dealt with the state of knowledge and the need for research and development within:

- Geoscience
- Drilling and deposition technology
- Engineered barriers
- Safety assessment



Requirements/ Comparison ground	KBS-3	Very long tunnels	WP-Cave	Deep boreholes
Not impose burdens on future generations	=	–	–	–
Environmental requirements	=	+	–	+
Safety requirements	=	–	–	–
Radiation protection requirements	=	=	–	–
Safeguards	=	=	=	+
Costs	=	=	–	–

= meets requirements as well as KBS-3
+ has advantages compared with KBS-3
– has disadvantages compared with KBS-3

Figure 28-3. *SKB's assessment of different methods for geological disposal.*

Furthermore, the study presented timetables and costs. The results showed that it would take more than 30 years and cost four billion kronor to achieve the same level of knowledge as for KBS-3. Most of this time would be required for geoscientific research. SKB has no intention of carrying out the programme due to the judgements presented in section 28.2.3.

In connection with the research and development programme for deep boreholes, SKB also had the German company Deutag give its viewpoints on the technical aspects of drilling four-kilometre-deep holes with a diameter of 80 centimetres /28-22/. The conclusion of this report is that the author deems that it is possible to drill such holes, but that this represents one of the biggest challenges ever faced by the drilling industry. A possible technology for depositing the canisters is also described in the study of drilling technology.

28.2.2 Deep boreholes in other countries

No other country in the world recommends deep boreholes as its preferred alternative for disposal of spent nuclear fuel. Many countries, such as Finland and France, are not conducting any studies at all. They are therefore not doing any more work on the concept. Aside from in Sweden, quite a bit of work has been done in the field in the USA by the United States Department of Energy. They have shown an interest in both low-temperature and high-temperature repositories. In the latter, the fuel is packed so tightly that the emitted heat partially melts the surrounding bedrock. The USA has shown interest in deep boreholes for final disposal of waste from nuclear weapons manufacture.

The British nuclear waste organization Nirex published a study in 2004 /28-23/ on how various concepts for deep boreholes have been developed since 1970. The conclusion of this report was that most of the work carried out in the USA is actually based on work already carried out by SKB in the Pass project. Nirex also concludes that no practical demonstration of the application of the deep boreholes concept has ever taken place, and that it would probably cost considerable sums of money to bring this concept up to the same level of understanding as for other types of geological repositories.

During 2007, Nirex is conducting a study of the technology for drilling and deposition in deep boreholes.

28.2.3 Deep boreholes in the Swedish nuclear fuel programme

Conclusions in RD&D 2004 and its review

Prior to RD&D-Programme 2004, SKB conducted a literature review to supplement previously gathered information on conditions deep down in the Earth’s crust /28-24/. The review included the geoscientific information that had been published in the open literature since 1997. The emphasis was on drilling in crystalline rock types. The literature review summarized the most recent results and drew a series of conclusions regarding what this means for disposal in deep boreholes. As far as thermal properties are concerned, it is difficult to estimate temperature and thermal conductivity at great depths, particularly if the bedrock is heterogeneous. Much of the information indicates that virtually stagnant conditions prevail at a depth of several thousand metres, and that the high salinities contribute greatly to this. At the same time there are observations that indicate that rapid transport of solutions is possible even in environments with very high salinities. Claims that flows and transport occur at great depths can be difficult to disprove. The occurrence of bacteria is also discussed. The temperature will presumably not exceed 115°C. This would make bacterial life possible.

SKI observed that the only barrier that can be assumed to work in the deep borehole concept is the rock, providing that the rock type at repository depth is relatively homogeneous. Short and long-term properties of the bentonite or other buffer material in the borehole are difficult to assess at great depths. Similarly, it is difficult to predict how long the canister will remain leaktight. Based on available knowledge, it may be difficult from the time of deposition to count on anything else besides the rock as a barrier. This would be in breach of SKI’s regulations governing safety in the disposal of nuclear material.

SKI upheld its opinion from the review of RD&D-Programme 1998. Disposal in deep boreholes is associated with such great uncertainties that it should not be considered to be a realistic alternative to the KBS-3 method.

SKI considered that there were good reasons to clarify the account of deep boreholes prior to the final choice of method and prior to licensing under the Environmental Code. SKI and SSI shared the view that a more thorough comparison should be made with the KBS-3 method. SKI was of the opinion that such a comparison should be made in a systematic manner, based on the same principles that SKB has developed for the safety assessment of other repositories, and agreed with SSI that the comparison could be illustrated by simplified calculations.

Kasam's assessment is that deep boreholes is not a realistic method. The possibility of retrieving the spent nuclear fuel with such a disposal method would be virtually non-existent, which means that demonstrating such a disposal method would also present significant difficulties. Kasam believes that it would also be difficult to assess the thermal conditions and the hydraulic transport conditions at such great depths.

Newfound knowledge since RD&D 2004

SKB has investigated the possibilities of carrying out a safety evaluation /28-25/ for disposal in deep boreholes according to SKI's and SSI's wishes, but concluded that the uncertainties are so great that it is not meaningful. In connection with this, a model study was also carried out of the isolating capacity of the geological barrier /28-26/. The calculations show that the combination of heat output from the fuel, surface hydraulic gradient and fracture zone orientation is not sufficient to drive the saline groundwater upward in such a way that it leads to rapid transport pathways. The travel times are on the order of 1–100 million years, which is much longer than the duration of the heat output from the canister. Future glaciations were not included in the study. The current body of data comes from a very limited number of deep boreholes. The bedrock in these holes is not representative of the environment in which a final repository would be built. The measurements that have been performed have been done for another purpose than disposal of nuclear waste.

In 2006, the Swedish NGO Office for Nuclear Waste Review (MKG) published a literature review about deep boreholes /28-27/. In this report, MKG points out that we do not know what happens with the transition between the two types of groundwater during a glaciation. SKB agrees with this. An ice sheet would, for example, cause the boundary between near-surface and heavier, deeper groundwaters to move vertically. Extensive studies clearly show that the greatest changes over time for a geological repository take place during glacial periods when an ice sheet covers the site /28-28/. Glaciations cause the greatest increase in the groundwater flow, as well as the greatest increase in hydrostatic pressure. They are furthermore something that must be expected to occur during the time required by a repository for spent nuclear fuel, regardless of which method is used.

It is true that an ice sheet scenario entails risks, in the sense of increased stresses, for all types of final repositories in Sweden. At present, however, it is not correct to say that existing data show that the risks decrease the deeper the waste is placed in the bedrock, regardless of method. In discussing these risks, it is necessary to distinguish between different types of repository system and evaluate the performance of their barrier systems as a whole. If by "risks" is meant the risk of releases of radionuclides from a final repository, the picture is complex since the risk of releases is dependent on the performance of the barrier system as a whole. SKB's judgement is that at the time of the glaciation, no credit can be taken for the barrier functions of either the canister or the buffer in deep boreholes due to stresses at deposition, limited (if any) possibilities to check the deposition procedure, and the chemical, thermal and mechanical conditions at great depths. Current knowledge and existing data show that it is uncertain whether disposal in deep boreholes could be shown to be safe in conjunction with glaciation and the expected associated changes in groundwater flow and increased frequency of major earthquakes, since only the barrier function of the rock can be counted on.

When the ice sheet advances and retreats, relatively rapid isostatic changes also occur, which alters the stress conditions in the rock, which could in turn also affect the groundwater flow. This further increases the uncertainty around how groundwater at great depths behaves in connection with glaciations.

The same line of reasoning can be applied to earthquakes, which is the other factor that contributes to the total risk picture for a geological repository for spent nuclear fuel /28-27/. Earthquakes in Sweden are often initiated at depths of around 5–25 kilometres. Figure 28-4 shows the depth distribution of all earthquakes recorded by the Swedish National Seismic Network (SNSN) between

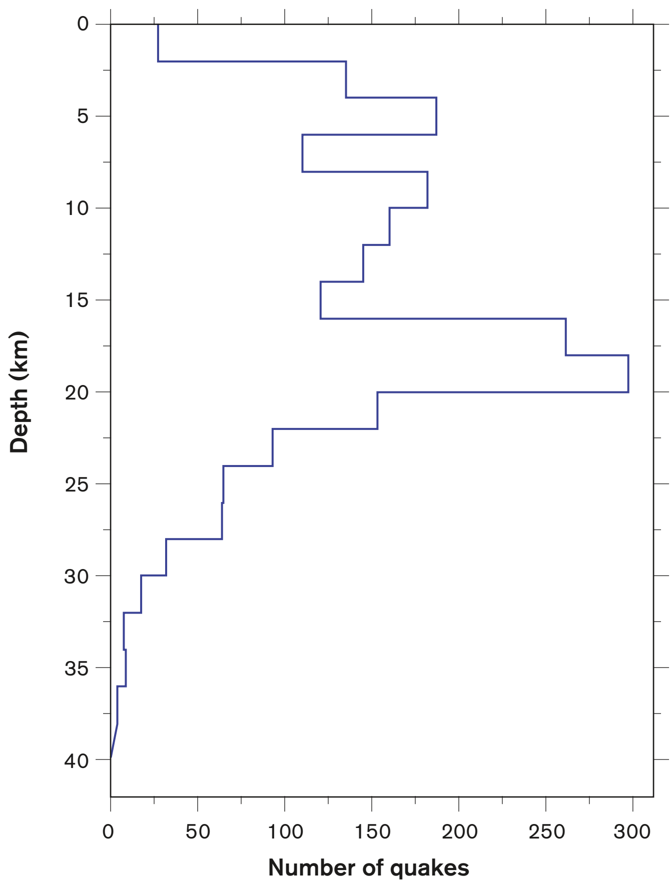


Figure 28-4. *Depth distribution of all earthquakes recorded by the Swedish National Seismic Network (SNSN) between August 2000 and January 2007 (2,081 earthquakes). The depth determinations were made in SNSN's routine analysis, which means that the results are preliminary. However, no great changes are expected in the depth distribution for the uppermost 5–7 km in future improved analyses. The data were collected at the Department of Geosciences (Geophysics) at Uppsala University.*

August 2000 and January 2007, a total of 2,081 earthquakes. Under non-glacial conditions, between five and six times more quakes occur at a depth of 2.5–6 kilometres than at depths shallower than 2.5 kilometres. In other words, considerably more quakes occur at the depths that are relevant for deep boreholes than at the depths that are relevant for a KBS-3 repository.

As ice sheets come and go, a significant increase in the frequency of earthquakes can be expected /28-29, 28-30, 28-31/. It is probable that depth distribution of glacial earthquakes, with respect to the "quiet zone" (few quakes in the uppermost 1–2 kilometres and many quakes in the lower seismogenic zone), is similar to the distribution in Figure 28-4 /28-32/. The stresses in the uppermost part of the crust are generally lower than those required for earthquakes. The same should apply under glacial conditions (even including the contribution from glacially induced flexural stresses).

Quakes of lower magnitude affect smaller areas in the bedrock than quakes of high magnitude. In this context it should be possible to consider the effect of quakes of a magnitude of three as small. Most of the quakes in Figure 28-4 are of a low magnitude, less than three. In conjunction with a glaciation, however, considerably more quakes of magnitude three or more are expected than is the case for the observations in Figure 28-4 /28-32/. As mentioned above, these larger quakes are usually expected to occur at depths greater than 1–2 kilometres. This should mean that a repository at a depth according to the deep boreholes concept, which is closer to the starting point for most earthquakes, is more exposed to earthquakes than a shallower KBS-3 repository. This would apply both under non-glacial conditions and above all in connection with glaciations, when there are more earthquakes.

Volumetric changes occur in the bedrock during earthquakes due to compression and extension of the rock mass and the fracture systems it contains. Observations from Iceland show that a clear mobilization of the groundwater can occur on these occasions /28-33/. Theoretically, this should also apply to deep-lying saline groundwaters. Regardless of what depth is chosen for a repository according to the deep boreholes concept (2–5 kilometres), such a repository could be affected by glacial earthquakes. This is particularly unfavourable, since the engineered barriers in the deep boreholes concept may be used up due to the difficulty of checking the deposition procedure and the aggressive environment at the depths in question. Glacial quakes could therefore theoretically result in radionuclide transport between the repository and the more superficial flowing groundwater or between the repository and the ground surface.

The deep boreholes concept has been discussed widely in recent years, both in connection with the consultations preceding permit/licence applications and at a seminar in the transparency programme being conducted by Kasam.

Programme

SKB's assessment from RD&D programmes 2001 and 2004 remains valid. There is no reason to believe that disposal in deep boreholes could increase the safety or reduce the costs of the final disposal of the spent nuclear fuel. Fundamental weaknesses remain, such as the fact that the concept is based on a difficult-to-check deposition procedure, a single barrier after a short time and great uncertainties regarding the evolution of the repository, particularly during a future ice age.

The reasons for SKB's assessment will be reported prior to the submission of an application for the final repository system in a general comparison between the KBS-3 method and deep boreholes in which both methods are followed through the entire chain, including:

- premises for siting as well as characterization and selection of repository site,
- current drilling technology and its potential for development,
- premises for construction, operation and closure,
- nuclear safety in connection with the handling of encapsulated spent nuclear fuel,
- physical protection and safeguards,
- long-term safety of a closed repository.

SKB will continue to follow the development work in the field of deep boreholes. However, carrying out a research programme on deep boreholes is not justified. Available resources should instead be concentrated on realizing a final repository according to the KBS-3 method.

Part V

Social science research

29 Overview – social science research

An Environmental Impact Statement (EIS) must be appended to the applications for a permit to build the encapsulation plant and the final repository for spent nuclear fuel. The EIS must contain descriptions of what environmental impact and what effects the planned facilities and activities will have. The EIS must also contain descriptions of projected consequences for man and the environment. Since the nuclear fuel programme must also be subjected to democratic scrutiny, locally and nationally, SKB would also like to be able to present material dealing with important societal aspects, above all to decision-makers and the public. SKB therefore conducts and funds research in the social sciences.

The Swedish National Council for Nuclear Waste, Kasam, was early to draw attention to the need for advanced social science research in the nuclear waste field. They did this, for example, in connection with their review of RD&D-Programme 2001. The need for further studies of the societal and democracy-related aspects of the nuclear waste issue has also been noted by the concerned municipalities. Kasam has devoted considerable energies to the special requirements that are made on activities with consequences far in the future. Kasam first expressed this concern in its state-of-the-art report back in 1998 /29-1/. These requirements apply not only to the technology, but also to issues of reliability, trust and stability in the face of changing external conditions. How can stabilizing factors in the form of institutions, knowledge transfer, values and responsibility from generation to generation be promoted?

Kasam has organized a series of seminars for researchers and decision-makers to address issues of democracy, decision-making in complex issues and, not least, ethical aspects. A number of publications dealing with these central issues have been produced by Kasam and contributed to a better state of knowledge /29-2 to 29-5/. In the autumn of 2006, for example, a seminar was held on the regulatory system and the roles of different actors during the decision process /29-2/. With its broad expertise, Kasam is highly qualified to continue to ensure that societal issues are given due consideration and proper treatment in the research.

In the eight feasibility studies SKB carried out between 1993 and 2000, considerable interest was devoted to the societal aspects. The feasibility study reports /29-6 to 29-13/ contain descriptions and analyses of population trends, the business sector, psychosocial aspects, labour market, municipal activities and economy, transport and communications, tourism, property values, etc. The reports contain forecasts and evaluations of the development of the municipality and the region, both with and without the establishment of a final repository. During the feasibility studies, SKB (as well as others) also published a number of other reports dealing with the social sciences, such as /29-14 to 29-16/.

In 2003, in preparation for a social science research programme, SKB surveyed all important research relating to the waste issue that had been done in Sweden, as well as the most important international research. The results of the survey have been compiled in a searchable database of 400 records accessible to the public. Two preparatory research seminars were held in 2002 and 2003 where scientists and municipalities had an opportunity to offer their viewpoints on the structure and content of the programme.

The purpose of the social science research supported by SKB is to:

- Get a broader perspective on the societal aspects of the nuclear fuel programme. This will facilitate evaluation and assessment of the programme in a larger context.
- Provide deeper knowledge and a better body of data as a basis for site- and project-related studies and analyses. The results of the social science research will thereby provide a sounder basis for various decisions.
- Contribute background data and analyses for research on the societal aspects of large industrial and infrastructure projects. In this way, experience gained from the nuclear fuel programme can benefit other similar projects.

In the preparatory work, four general areas of research emerged as being relevant for the waste issue and the municipalities:

- Socioeconomic impact – Macroeconomic effects.
- Decision processes.
- Public opinion and attitudes – psychosocial effects.
- Global changes.

The main emphasis in the research areas supported by SKB should be on applied research, but there may also be interfaces with basic research. The different research areas are presented in greater detail in Chapters 30 to 33. Conclusions, newly-found knowledge and the programme are described on a more general level below.

Conclusions in RD&D 2004 and its review

SKI concluded that SKB has heeded the requests of several reviewing bodies to include social science research in its RD&D programme as well. Oskarshamn Municipality finds that the programme that was established in 2004 includes relevant areas and has a commendable breadth. However, some of the reviewing bodies wanted SKB to clarify the relationship between the permit/licence applications, EISs and studies. SKI called for a clearer account of how the process surrounding programme planning, calls for proposals, selection, criteria and review has been designed and carried out. Kasam and the environmental movement called for research that is independent of SKB.

Newfound knowledge since RD&D 2004

The relationship between research and other documents

A number of reviewing bodies, including Östhammar Municipality, want SKB to clarify the relationship between societal research, permit/licence applications, EISs and study activities.

The EIS should describe how the planned activity could affect man and the environment. The purpose of the research programme is to provide a basis for a broad political and social analysis and for the licensing of the final repository. The main target group is decision-makers, local and national.

Compared with the societal studies that are being conducted, the societal research is not primarily municipality-specific, but aims at acquiring new and generally applicable knowledge. A study is governed by a clear order where the client formulates the issues, while research is characterized by an open-minded approach and a high degree of independence when it comes to formulating the research issues, choosing a methodology and drawing conclusions from obtained results. The most suitable university researchers are recruited for research tasks, while studies of local conditions require not only expert and specialist knowledge, but also local knowledge.

Research and studies also differ when it comes to the review procedure. The research undergoes customary academic review and is also reviewed, via RD&D programmes, by the scientific committee and at open seminars. When it comes to studies, the review is carried out by the client, SKB, and concerned municipalities. In other words, research and studies work from different premises. Since both often treat the same topics, a mutual exchange of knowledge and experience is sometimes fruitful, but is not an end in itself.

The questions of reviewing bodies regarding how the results are to be communicated to the municipalities, the regulatory authorities and SKB's programme can in part be answered by saying that the results are presented regularly at open seminars, published in articles in the research programme's yearbook and the final project reports, and posted on SKB's website.

Work forms

SKI wants SKB to describe more clearly how the process surrounding programme planning, calls for proposals, selection, criteria and review has been designed and carried out.

The social science research programme was started in 2004 and has been planned gradually. This stepwise planning process enables the consulting parties and reviewing bodies to offer viewpoints and thereby influence the contents of the programme. The programme is open so that new topics can be introduced during the coming years.

Call for proposals

An initial call for proposals within the four general research areas was sent out to a number of universities and institutes of technology in the spring of 2004. Eight research projects were prioritized in this first round of applications. Additional calls were then issued in 2005 and 2006. Invitations were sent on these occasions to all universities in Sweden. In the later rounds of applications, the researchers were urged to give particular consideration to projects dealing with today's use of media in relation to future issues, democracy and risk perception. Studies of how young people view technology and democracy, and how they perceive risk and safety in relation to new technologies and opportunities to influence the world around them and their future, were also called for. The ethical judgements and priorities of social institutions and interest organizations in relation to the siting of a final repository were additional issues that were to be particularly elucidated. The calls for proposals resulted in funds being granted for four new projects.

The research programme has so far engaged researchers from the universities in Lund, Göteborg, Örebro, Linköping, Stockholm, Uppsala, Umeå and Halmstad, which may be regarded as a good geographical distribution. The programme also has good breadth in terms of research topics, embracing disciplines such as history, cultural geography, jurisprudence, psychology, sociology, human ecology, media science, theology, history of science and technology, social sciences, economics and ethics. Most of the projects in the programme are two-year projects. The purpose is to keep the consultation parties informed of the findings of the research and to enable new projects to be added to the programme.

Communication of findings

Decision-makers and other stakeholders should be given an opportunity to share in the findings of the research programme. The research task therefore includes communicating interim findings and final results to various target groups through seminars and to publish the research results both in scientific journals and in more popular form, such as the societal research yearbook /29-17, 29-18/. Information on the social science research programme and its results is also posted on SKB's website. Via these channels, municipalities, private citizens, regulatory authorities, environmental organizations and scientists can follow the progress of the projects.

Three research seminars have been held in 2004, 2005 and 2006 for the purpose of presenting the results of the ongoing research. The seminars are an important meeting place for a direct dialogue between researchers and other stakeholders. The next seminar in this series will take place in November 2007.

A finalization of the programme was begun at the end of 2006. Interviews have been held with representatives of municipalities, regulatory authorities, scientists and the environmental movement. The interviewees were asked to offer viewpoints on the programme to date and propose new research projects that should be carried out in the next few years.

Scientific committee

A special scientific committee has been appointed to support the contents and development of the programme. It is responsible for ensuring that the research projects have the necessary scientific quality and relevance and that the tasks are assigned to suitably qualified researchers and research groups. The scientific committee consists of researchers in the social and behavioural sciences. The scientific committee also oversees the progress of the work. The projects submit semi-annual reports, on which the scientific committee comments.

An important task of the scientific committee is to review articles for SKB's yearbook /29-17, 29-18/ and the final reports /29-19 to 29-26/ that are published within the programme. Peer review also takes place at open seminars. This review does not entail any scientific control of the research, but is aimed at achieving greater clarity and relevance in articles and reports. The scientists who have been engaged for various research tasks formulate their own research topics and are responsible for methodology, results and conclusions. A clear division of roles and tasks in combination with effective research communication lays the foundation for independent research. The work forms that have been established for the social science research programme are aimed at achieving this.

Programme

A fourth call for proposals was issued in the spring of 2007 in response to the viewpoints on the programme that had been received from municipalities, regulatory authorities and other reviewing bodies. The main emphasis in this application round was on interdisciplinary research projects that study various aspects of the coming decision process. This includes legal, ethical, economic, democratic and organizational aspects, but also the consequences of the distribution of decision-making powers, profits, risks and knowledge – locally and centrally. The call for proposals entails that another step has been taken to develop the social science research programme.

The following three research projects were ranked highest among the proposals received after the fourth call for proposals in the spring of 2007.

- "Assumption of responsibility in the back end of the nuclear fuel cycle in a legal perspective," Göteborg University.
- "Ethical and philosophical perspectives on the nuclear waste issue," Royal Institute of Technology.
- "The picture of the site – on risk perception and legitimacy of decisions," Umeå University.

SKB also intends to fund societal research during 2008 and 2009. Since the societal research is supposed to contribute to a broader body of data for municipal decision-making, new and supplementary topics may be introduced during the decision process that follows SKB's permit applications. It is, however, SKB's ambition that the contents of the research programme should meet existing needs to have various societal aspects illuminated even before 2010. The ongoing dialogue that is held during the course of the programme increases the probability of achieving this.

30 Socioeconomic impact – macroeconomic effects

The purpose of research in the area of socioeconomic impact is to gain better knowledge and understanding of how the local community's economy and population structure is affected by the establishment of a large new facility. This knowledge can in turn make valuable contributions to SKB's, the concerned municipalities' and other stakeholders' assessments of how the establishment of the deep repository will affect the community's economy and demographic development.

Socioeconomic impact includes both narrow economic aspects such as employment, industrial establishment, entrepreneurial spirit, property values, municipal economy and tourism, and broader macroeconomic effects such as travel to and from the community, in- out-migration to or from the community, and the community's reputation and attractiveness.

Conclusions in RD&D 2004 and its review

The reviewers did not make any concrete comments on this research area. SKI did point out, however, that the stakeholders should generally be able to apply the research findings in ongoing and future consultation processes.

Newfound knowledge since RD&D 2004

The research area fulfils SKI's wish for applicability in the ongoing work. The results show how the concerned municipalities may be affected by the planned investments. Two research projects have been carried out within the area. The projects are "Local development and regional mobilization around technical and large-scale projects" and "Long-term socioeconomic effects of large investments in small and medium-sized communities." Final reports from these projects were published in the autumn of 2006 and spring of 2007 /30-1, 30-2/.

Local development and regional mobilization around technical and large-scale projects

The purpose of this study was to investigate the long-term socioeconomic effects of a nuclear power investment by studying, from an economical-historical perspective, changes in demographic trend and industrial structure in two nuclear power municipalities and several reference municipalities over a period of about 50 years. The results were then compared with the situation in other industrial municipalities in Sweden.

One result is that nuclear power led to a lasting population increase in the two municipalities, see Figure 30-1. Even though the rapid population growth levelled off relatively quickly and the nuclear power communities tended to revert to their former development patterns, the populations nevertheless stabilized at higher levels than they would have without the nuclear power plants. This fact suggests that the nuclear power establishment produced knock-on effects in the local economy and may have caused a structural change that has led to a lasting change in the socioeconomic structure of the communities. The nuclear power municipalities managed better than the reference municipalities and other industrial municipalities during the 1970s and 1980s. With economic-historical comparisons as a basis for the discussion, the conclusion is that an investment in a final repository will have effects on the local level, but that this is not enough in the final analysis to drive the socioeconomic development of the community forward. Even though the project focuses on the socioeconomic effects, the nuclear power establishments are also of macroeconomic importance for the nation as a whole. Factors surrounding the political decision process and the public debate on nuclear power may also have affected the local economic outcome.

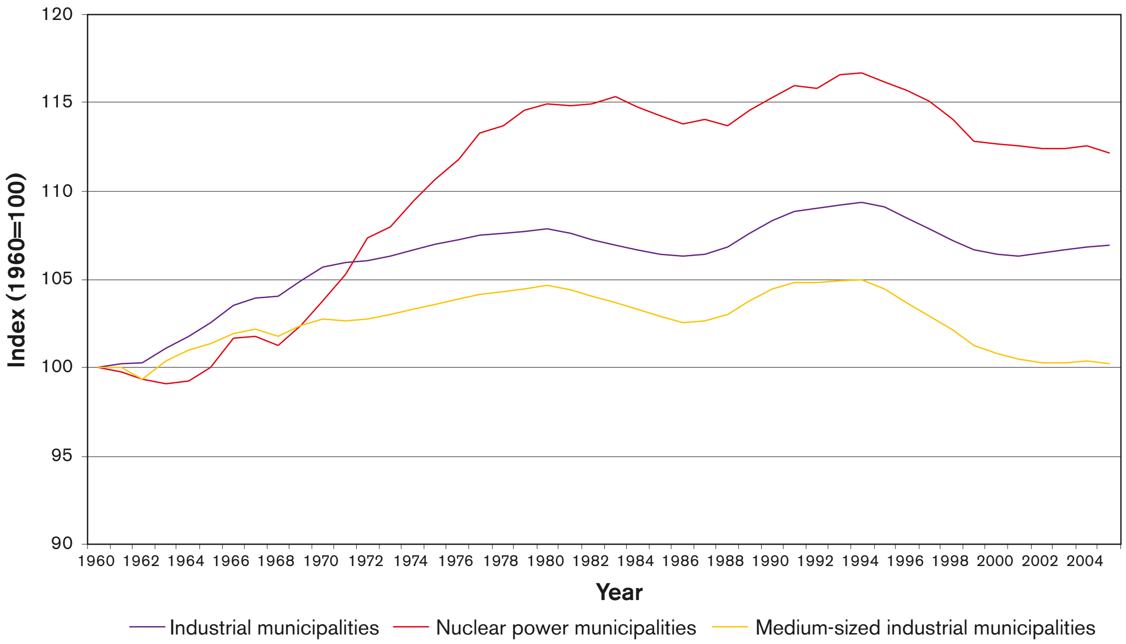


Figure 30-1. *Rate of population change in the nuclear power municipalities of Oskarshamn and Östhammar, medium-sized industrial municipalities and industrial municipalities as a whole during the period 1960–2006.*

Long-term socioeconomic effects of large investments in small and medium-sized communities

This study poses the question of what local knock-on effects a final repository for spent nuclear fuel will have. Site investigations are currently being conducted in Östhammar and Oskarshamn, and the final repository will probably be built in one of these municipalities. The final repository investment consists of several different investments: final repository, expansion of SFR, construction of an encapsulation plant and a factory for assembly of canisters. Figure 30-2 shows the procurement need for the final repository investment over time. The siting premises differ between the two locations. The expansion of SFR must take place in Östhammar, since SFR is already there. According to SKB, the encapsulation plant should be built adjacent to Clab, which is situated in Oskarshamn. These circumstances mean that parts of the total investment sum for the final repository system – approximately SEK 15 billion – can already be tied to specific sites. The canister factory is not site-bound in the same way.

The results of a questionnaire survey conducted in connection with the study show that the local business communities in the two municipalities differ with respect to their ability to deliver the goods and services needed for the final repository. In a comparison between delivery capacity and procurement need, it appears as if the local business community in Oskarshamn has a composition that better matches the needs of the final repository investment. The local knock-on effects of the final repository investment are not, however, limited to the activities associated with the construction of the facilities. Operating and service activities at the facilities also generate jobs and income.

The final repository with secondary investments will generate knock-on effects in both Östhammar and Oskarshamn, regardless of in which municipality the final repository is sited. However, the economic knock-on effects differ due to differences in the delivery capacity of the local business community and the predetermined sitings of certain secondary investments. The analyses show that the knock-on effects will be relatively great in Oskarshamn if Östhammar gets the final repository, while the effects in Östhammar will be very limited if the final repository is located in Oskarshamn, see Table 30-1. Note, however, that the siting of the canister factory and the fabrication of the copper canisters is not limited to the municipalities of Oskarshamn and Östhammar. In Table 30-1 it is assumed that the canister factory is located in the same municipality as the final repository.

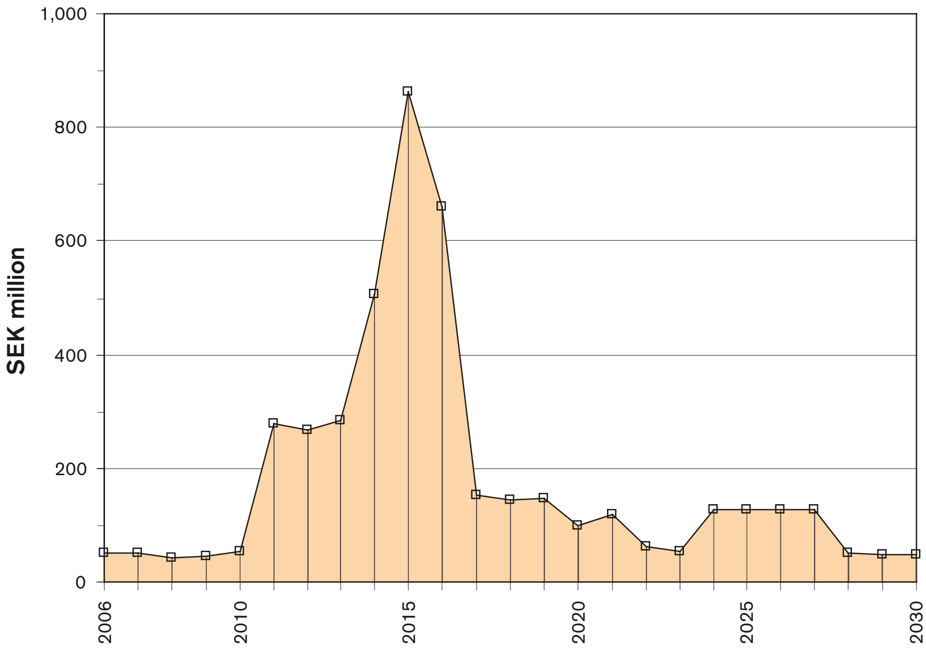


Figure 30-2. *Procurement need for the final repository investment over time.*

Table 30-1. Alternative geographic cost allocations for the final repository investment.

	Investment	Cost (SEK million)	Alternative 1: Oskarshamn gets the final repository		Alternative 2: Östhammar gets the final repository	
			Oskarshamn	Östhammar	Östhammar	Oskarshamn
Construction	Final repository	3,860	3,860		3,860	
	Encapsulation plant	2,280	2,280			2,280
	Canister factory	200	200		200	
	Expansion of SFR	445		445	445	
Operation and decommissioning	Final repository	3,300	3,300		3,300	
	Canister factory	3,550	3,550		3,550	
	Encapsulation plant	1,960	1,960			1,960
	TOTAL	15,595	15,150	445	11,355	4,240

Programme

The research project "Long-term socioeconomic effects of large investments in small and medium-sized communities" has resulted in a follow-up of the research results via the procurement study that is being conducted in Oskarshamn and Östhammar during 2006–2007. This is an example of the connections that can exist between research and study activities and should be viewed as an added value deriving from the programme, but not an end in itself.

31 Decision processes

The siting of a final repository for spent nuclear fuel is a controversial issue, in part because it is a complex activity with a time perspective that is difficult to grasp. The issue has repercussions for local community planning, national energy policy and international developments. By addressing political questions of this special character, the research is attempting to lay the foundation for general knowledge concerning decision processes in complex issues. This knowledge can in turn make valuable contributions to consultations, studies, planning and decision-making. SKB, the concerned municipalities and other stakeholders, for example the municipal inhabitants, thereby stand to benefit from the research. The actual nature of the decision process for a deep repository establishment is one thing, while how it is perceived is another. Lessons can be learned from many Swedish and foreign studies of decision processes, for example to what extent decisions are perceived to be legitimate, fair and effective.

Conclusions in RD&D 2004 and its review

The reviewers did not make any specific comments on this research area.

Newfound knowledge since RD&D 2004

Two projects have been initiated in the area. A final report from the project "Public, experts and deliberation – Rolf Lidskog, Örebro University" was published in the autumn of 2006 /31-1/. The final report from the other project, "Resource or waste? - international decision processes relating to spent nuclear fuel" is being published in the autumn of 2007.

Public, experts and deliberation

The purpose of the project was to learn more about the relationship between experts and a broader general public in participatory processes dealing with complex scientific and technical issues. The specific case that is being studied is the Swedish consultation process regarding a final repository for nuclear waste.

Questions being asked are: How is the public delimited and defined, and what methods are used for this? What arenas are being created for citizen dialogue, and what are their institutional premises for participation? Are there mechanisms that promote or hinder negotiation regarding the boundaries of expertise? What is the attitude of participants in consultation activities to the experts? How are local and transboundary environmental consequences discussed in consultations? The study makes use of qualitative field study methodology. The empirical material comes from observations, formal and informal interviews and document studies.

A conclusion drawn by the researchers is that the way in which the consultations are organized results in a special focus on the municipalities, the local population and local environmental issues. However, changes made during the course of the process have not altered the institutional premises for participation in the consultation arenas. SKB's local information and communication programme leads to good relations but does not justify the dominant role of the activity operator in relation to other parties. Regional and public consultation meetings differ with respect to who participates and the way SKB's strong position is balanced.

The process incorporates mechanisms that both promote and hinder discussions and negotiations regarding the boundaries of expertise. One hindering mechanism is when participants consider EIA a legal tool and make references to legal interpretations that support their own standpoint. The boundaries of expertise are challenged by viewpoints concerning the long time spans that are involved in the final disposal issue.

Resource or waste? – international decision processes relating to spent nuclear fuel

The project was initiated in the autumn of 2005 and the report will be published in the autumn of 2007. By means of comparative studies of a number of countries, the project will examine to what extent and in what way different societal dimensions influence political decision processes and technological change processes. The dimensions can be described in the form of a number of questions that are posed for each country that is studied. Does the country produce nuclear weapons? Does the country have an expansive or a stagnant nuclear power sector? Does the country have strong or weak nuclear expertise? Does the country have a strong or a weak anti-nuclear movement? Does the country have experience of nuclear power accidents? To what extent does the country have access to domestic uranium resources? Does the country have good conditions for a final repository? Is the country a democracy or a dictatorship? Does the country have strong or weak local political power? Does the country have a strong or a weak national identity? The countries included in the study are Finland, Germany, Russia and Japan. The project is following the process from the time of the nuclear power establishment up to how the nuclear power issue is handled today.

Programme

A new project in the area of decision processes, "The picture of the site – on risk perception and legitimacy of decisions," will start at the end of 2007. Planning and measures to reduce the risks of, and prevent or mitigate the effects of, future crises must be done at both the societal and the individual level. It is therefore important to have good communication between planners and decision-makers at the state, regional and municipal level on the one hand and private citizens on the other. In order for this communication to work, the decision-makers must know how people perceive different kinds of risks and threats.

Multi-level governance focuses on the relations between the different actors who are involved in a decision process from the local level up to the international level. A multi-level governance perspective often shows that decision-making takes place in networks consisting of both private and public actors, at the same time as it does not favour any single level. This approach is also suitable for evaluating the roles of different actors in a decision process and what legitimacy the actors possess in a situation with overlapping authorities. In this context it can also be relevant to study the issue of what legitimacy different actors give the other actors in the decision process, including their own organization, and how they think the roles should be divided. The multi-level governance approach is also suitable for investigating the level of acceptance for a process and the democratic methods that are used.

The study is concerned with how the decision process as a whole is perceived, above all at the municipal and regional level. More specifically, the following questions are addressed:

- What do clients perceive is the existing context of risk and the balance that should be struck between environmental considerations, perceived risks and other societal effects, as well as the role different groups should have in the process?
- What formal decision-making powers exist at different levels, how is this perceived by the clients and what are the potential problems and opportunities?

32 Public opinion and attitudes – psychosocial effects

Opinions and attitudes are changeable phenomena and are influenced by various forces, as well as by personal characteristics. As phenomena they are therefore complex research topics. The establishment of a final repository is furthermore a drawn-out process, involving different actors in different phase. The purpose of research in this area is to study how opinions and attitudes are formed and change. This knowledge can make important contributions to an understanding of the decisions made by the different actors and to the conduct of the consultations. Opinions and attitudes are not just a reflection of decision-making, actual events and communicated messages. Individual characteristics and perceptions of reality also play a role. Deep-seated values and norms, group identification, perceived fears, anxiety about risks, and self-interest are some examples of factors that are also of importance. It is therefore also important to shed light on the "symbolism" surrounding the final repository and its activities.

Conclusions in RD&D 2004 and its review

Review comments have been offered by Oskarshamn Municipality to the effect that the media's treatment of the waste issue should also be studied. The municipality also thought that differences between men's and women's attitudes is another important aspect that needs to be further elucidated.

Newfound knowledge since RD&D 2004

Three research projects have been carried out in the area. "Identity and security in time and space – cultural-theoretical perspectives on the nuclear waste issue" /32-1/, "Public opinion and attitudes towards disposal of spent nuclear fuel" /32-2/ and "The nuclear waste – from energy reserve to disposal problem" /32-3/. Final reports from these projects were published in the autumn of 2006.

A new project that deals with the handling of the nuclear waste issue entitled "Like night and day despite the same nuclear origin" started at the end of 2005. The project is in line with Oskarshamn Municipality's viewpoints in the review of RD&D-Programme 2004 that the programme should include research on the media's treatment of the nuclear waste issue. The final report was published in the spring of 2007 /32-4/.

Identity and security in time and space – cultural-theoretical perspectives on the nuclear waste issue

The project has studied the underlying thought structures surrounding the concepts of time and space in the ongoing discussion of a final repository in Oskarshamn and Oskarshamn. This has been done from a human-ecological perspective, with a focus on the cultural aspects of the relationship between man and nature. The concepts that characterize debates and texts, as well as the authors' own formulations, have been studied primarily by means of metaphor, argumentation and discourse analysis. One result that surprised the researchers is the high consistency of the findings, but some clear differences are nevertheless apparent. As far as perception of time is concerned, the time up until a decision is made to site a final repository is perceived as graspable. The actual construction time is perceived as comprehensible, while the long "final repository time" is regarded as incomprehensible. People appear to conceptualize two kinds of time in this context: "societal time" and "final repository time". Depending on which type of time dominates the thought process, people reason differently with regard to responsibility for future generations and the final repository issue. As far as the spatial dimension is concerned, there is a predominantly optimistic attitude to the final repository in the both Östhammar and Oskarshamn municipalities. The interview subjects claimed that a final repository would give the district a revitalizing injection in socioeconomic terms. The few sceptics questioned both the socioeconomic values and the entire siting process. Much of the work on the nuclear waste issue in Oskarshamn is being done by LKO, Local Competence Building in Oskarshamn Municipality – Nuclear Waste Project. LKO calls for local resistance, but has incorporated this resistance by its mode of working. In conclusion, it can be said that both the temporal and spatial conceptualizations are based on the notion of a stable present, which people trust will continue to operate in the future, at the same time as great uncertainty exists as to whether this is really the case.

Public opinion and attitudes to a repository for spent nuclear fuel

Attitudes and risk perceptions concerning a final repository for spent nuclear fuel have been studied in Östhammar and Oskarshamn, in the control municipality of Finspång and in the nation as a whole, see Figure 32-1. Data were collected via a large mail survey. The results show that there are great differences in attitudes. The attitude towards a final repository is more positive in Oskarshamn and Östhammar compared with Finspång and the nation. The risks of nuclear waste are judged to be small in the two former municipalities. There is a clear majority in favour of a final repository among the men in Oskarshamn and Östhammar, while there is some doubt among the women, see Figure 32-2. These differences can only be partially explained by the fact that the respondents have a nuclear-related job or a positive attitude towards nuclear power. In Oskarshamn and Östhammar the most positive attitude is found in the younger age groups. Trust in society is of some limited importance, while trust in science is more important. Nimby attitudes ("Not In My Back Yard"), in other words a positive attitude to nuclear power in general but a negative attitude to having a final repository in one's own municipality, account for only a minor portion of the negative attitudes. In a final analysis of the variations between the municipalities and the nation, the most important variable in explaining the differences is the benefit such a facility would have for the municipality.

Nuclear waste – from energy resource to disposal problem

What risks are associated with handling of high-level nuclear waste? Where should it be disposed of? Who should bear responsibility for its safe disposal? How should a safe final repository be designed? Can there be any solution that is safe for all future time? If so, how can we know this? A great deal of attention has been devoted to these questions in the public debate in Sweden ever since plans for a Swedish nuclear power programme gained support in the Riksdag in the 1950s. If the questions have remained more or less the same, the answers have varied all the more. Representatives of both the nuclear power industry and the environmental movement have changed their attitudes and positions as the technical, political, economic, scientific and cultural circumstances have changed.

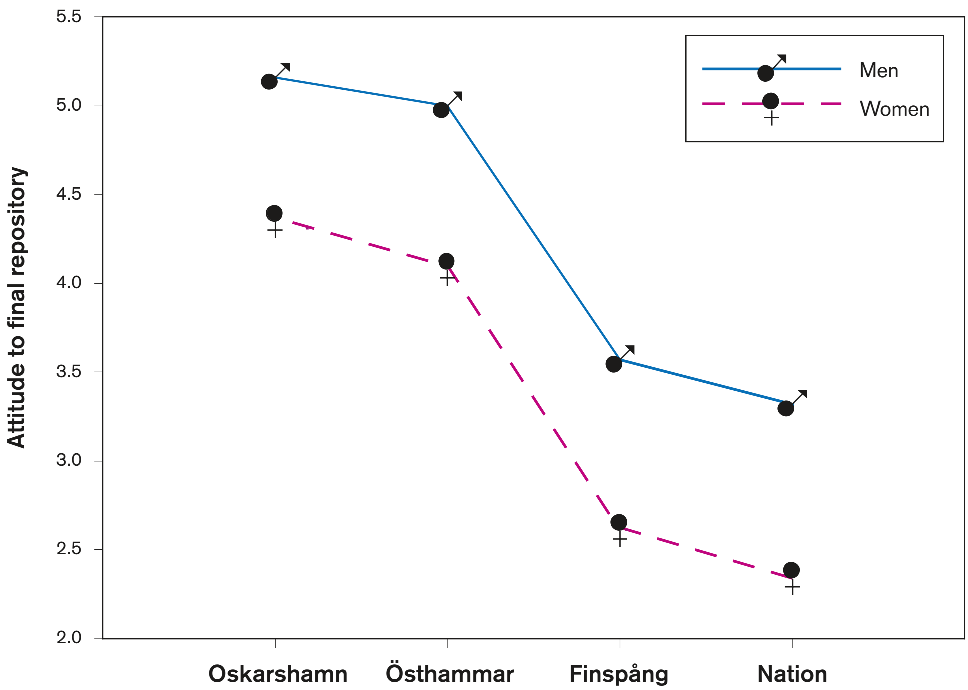


***Figure 32-1.** Attitude to a final repository in one's own municipality.*

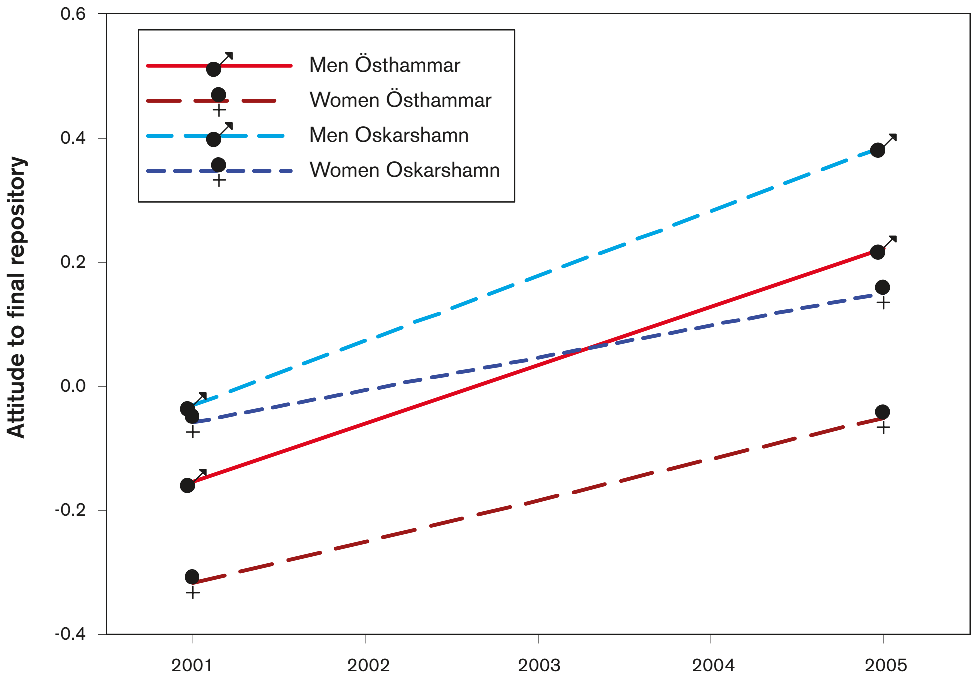


Figure 32-2. *Attitude to final repository 2001–2005. Standardized scale.*

The study describes shifts in value patterns when it comes to the management of the spent nuclear fuel. In the 1950s, the nuclear waste was viewed as an energy resource in the breeder reactors of the future. This attitude stands in sharp contrast to the heated debates of the 1970s regarding whether there was any way at all to safely dispose of the spent nuclear fuel. The study also sheds light on the differences of opinion surrounding the siting of the final repository during the 1980s and 1990s. An analysis is also made of the diverging perceptions regarding risks, responsibility, knowledge, technology, science and nature that existed in the public debate.

Like night and day despite the same nuclear origin

The purpose of the project is to analyze, quantitatively and qualitatively, similarities and differences in the media coverage of the nuclear waste issue at the national and local level from the start of the site investigations up to the present. Another purpose is to provide an overview and a deeper understanding of the influence and democratic role of the media in the decision process. Newspapers and TV news programmes in national, regional and local media have been investigated in the study. A total of 1,118 articles and 77 TV reports from fifteen different mass media have been analyzed. Quantitative content analysis is the method used to find out what topics have been taken up in the media, as well as who or which actors have participated and how the journalistic coverage and media debate have been distributed over time.

The results show that there are both similarities and differences in the media coverage. The modes of expressions used by journalists have varied, both in content and over time. The greatest coverage occurred in early 2002 when Östhammar, Tierp and Oskarshamn made decisions on their further participation in the process. Surprisingly few examples of investigative journalism can be identified in the material. The use of pictures in the different media exhibits great similarities. “Site investigation” and “SKB” are the most common themes in the print media texts and television news broadcasts. The site investigations and the local work on the final repository issue receive a great deal of attention in both local and regional media, but hardly any in the national media. The national media do, however, discuss transmutation as a possible solution to the nuclear waste problem. This theme receives very little attention in the local debates.

Programme

The results of the above-mentioned project “Public opinion and attitudes to disposal of spent nuclear fuel” showed that there are significant differences in attitudes between men and women and between different age groups. In its statement of comment on RD&D-Programme 2004, Oskarshamn Municipality emphasized the importance of shedding further light on the differences in attitudes between the sexes.

A new project concerning “How young people view democracy and technology issues” was therefore initiated in the autumn of 2006 with the aim of studying differences in attitudes between the sexes and how they interact with age. Greater knowledge in this area is of interest in view of the fact that today’s young people will be tomorrow’s decision-makers. In-depth studies of differences in attitudes between the sexes also add an important democratic dimension for future decision processes. The final report will be published in the spring of 2009.

33 Global changes

The establishment of a final repository is a unique project with unique features. In the end, only one location in Sweden will be chosen. At the same time it is a question that is very clearly interrelated to what is happening in the rest of the world. The purpose of research in the area is to gain greater knowledge about relevant global factors and global changes. This knowledge can make a very valuable contribution to planning, studies, consultations and decision-making before and after the permit applications. The knowledge may also be important for the future operation of the final repository. The economic situation and development of the local community is dependent on a variety of circumstances in the surrounding world. What will the Swedish state, which bears ultimate responsibility for the final repository, look like in the future? Legislation, regulation and financing, as well as the country's economic situation, are factors of importance. Another important global change is Sweden's participation in the development of the European Union. What kind of relationship will Sweden have with the EU in 30 years? What will the EU look like? What impact will a deeper European integration in the future have in general on nuclear waste management, and to what extent will this affect Sweden's own waste management programme?

Conclusions in RD&D 2004 and its review

SKI, Kasam and Oskarshamn Municipality point out that the research area "Global changes" should have been more comprehensive and included more projects.

Newfound knowledge since RD&D 2004

A central project in the research area "Global changes" is the study "National nuclear waste policy in the European Union." The final report was published in the spring of 2007 /33-1/.

Several reviewing bodies thought that the research area "Global changes" should have been given more attention, but, as mentioned previously, the research programme is being planned gradually. The projects that were described in RD&D-Programme 2004 were the result of a first call for proposals and should not be regarded as the last research activities in the area "Global changes". The programme should yield more useful knowledge and experience for the benefit of both SKB and the surrounding world, and ideas for new research projects can be proposed during the course of the programme. Some of the funded projects in the area "Public opinion and attitudes" also have a bearing on "Global changes". "Nuclear waste – from energy resource to disposal problem" is a historical study that can serve as a good platform for a discussion of future global changes. In other words, there are thus no strict borderlines between the different research areas. Two more projects in the area "Global changes" started in 2006.

National nuclear waste policy in the European Union

The principle of national responsibility has two sides: One has to do with how Sweden takes responsibility for the waste that arises in the country when nuclear energy is generated. The other side has to do with the right Sweden considers it has to stop spent nuclear fuel from other countries from being disposed of or temporarily stored in Sweden. The latter right has been embodied in law in a prohibition against final disposal and interim storage of foreign nuclear fuel in Sweden. The question of how Sweden should take responsibility for the spent nuclear fuel that arises within the country is not regulated by law in a corresponding way. At the multilateral level, the question of responsibility is regulated in the 1970 Non-Proliferation Treaty and the Joint Convention on the Safety of Spent Fuel Management and on the Safety of Radioactive Waste Management adopted at an IAEA conference in 1997. The Non-Proliferation Treaty confirms the sovereign right of all states to develop a national civilian nuclear power industry. This sovereignty includes the competence to make decisions on the design of the back end of the nuclear fuel cycle. This sovereignty is also confirmed in the IAEA convention. However, since the early 1990s the IAEA has initiated studies concerning the legal, political and physical premises for establishing multinational facilities for interim storage or final disposal of spent nuclear fuel.

The question of responsibility for the spent nuclear fuel is not directly regulated within the EU. Joint legislative initiatives from the Commission concerning the method for interim storage and final disposal of spent nuclear fuel have been blocked by the Member States. At first glance, the national character of the responsibility issue, which has in some Member States found expression in legislation that discriminates on the basis of nationality, conflicts with the idea of European integration. At the same time, it is noted that there is no binding community legislation embodying the principle of national responsibility, even though national legislative competence in the area is expressed in various political documents. There is, however, a hypothetical possibility that the question of the right of the Member States to assert the principle of national responsibility will be considered by the European Court of Justice.

Programme

Two new projects in the area "Global changes" started in the autumn of 2006. One is entitled "Towards activism or indifference? How Swedish young people view democracy and technology in an international and longitudinal perspective". The project will study legitimacy aspects of long-range political decisions. How have views on these issues changed over the past 60 years, and what changes can be expected in a long-term perspective? Data are available from a representative selection of the population of some 80-odd countries from the period 1981 to 2006, inclusive. A final report on the project will be published in the spring of 2008.

The second project is "Ethical argumentation in the final repository issue". The purpose is to identify and formulate the ethical issues and problems that have come up in conjunction with the final disposal issue. The ethical aspects of the nuclear waste issue is a perspective which Kasam has pursued in a commendable fashion for many years. This perspective has so far been lacking in the social science research programme. The final report is expected to be published in 2008.

A new research project entitled "Assumption of responsibility in the back end of the nuclear fuel cycle" will be initiated in the spring of 2008. The purpose is to identify and problematize how current legislation regulates the assumption of responsibility in the back end of the nuclear fuel cycle by different actors. The point of departure is a composite responsibility that includes different types of responsibilities: implementation responsibility, economic responsibility and supervisory responsibility. These types of responsibility exist within functionally separate areas: nuclear safety responsibility (including responsibility for non-proliferation), radiation protection responsibility and environmental responsibility. The responsibility issues are also closely related to the division of ownership and right of disposition during different parts of the back end of the nuclear fuel cycle. Of special importance for the study is the balance that has been established between public responsibility and producer responsibility and the extent to which this corresponds to the actual situation as regards ownership and right of disposition.

The project also aims to provide a basis for a constructive discussion of the need for legal forms that take into account the legal interests of the democratic state, such as predictability, equality, transparency, participation, etc. The reality which the body of rules is intended to regulate has undergone extensive changes since the Swedish principles for division of responsibility were established in law. These changes include the ownership structure of the nuclear energy industry, the level of technological knowledge and the emergence of new national security threats. No overall analysis has yet been done of how these internal legal and external societal changes have affected the clarity of the Swedish responsibility model. In light of this, the project also intends to investigate whether the division of responsibilities that has been established in Swedish legislation is appropriate today in the light of the objectives that have been formulated in the travaux preparatoires (legislative history) of the legislation. Can these objectives be realized with the current body of legislation, or do the changes that have occurred necessitate legal reforms? The point of departure of the study is the Swedish national legislation. It will be related to the regional regulatory framework that has been created under the EU and to relevant multilateral regulatory framework that has primarily come into being under the aegis of the IAEA.

Yet another project in the area "Global changes" entitled "Ethical and philosophical perspectives on the nuclear waste issue" will be initiated at the end of 2007. The project will result in a number of essays on the following topics:

"Radiation as an ethical problem" presents some central ways of thinking about risks and how the concept of risk can be applied to radiation. The probabilistic risk assessment, with its expected benefit model, has an important role, but other analysis tools taken from moral philosophy will also be presented. The section is concluded with a discussion of the new research area "Radiation ethics", where it is said that traditional radiation protection is based on thought structures that lie very close to the central concepts in moral philosophy.

"Ethics and the distant future" discusses an aspect of the nuclear waste that has received a great deal of attention. This essay presents the two main perspectives in which the long-term effects of what we do today are discussed: economic discounting and sustainable development. Comparisons are also made with other societal issues involving long time perspectives: preservation of species, preservation of cultural monuments, consumption of natural resources, etc.

"What does the precautionary principle say?" examines what may be meant by the terms "precautionary" and "precautionary principle". A common argument for far-reaching measures in nuclear waste management is that we should apply the precautionary principle. But what exactly is the precautionary principle, and what consequences does it have in practice? The different interpretations of the precautionary principle are discussed and illustrated with examples from both the nuclear waste field and other fields.

"How much is a life worth?" takes up the controversial question of how much we are willing to pay to save a life. A common point of view in risk management is that the amount we are prepared to pay to save a human life should be the same no matter what the context. If this principle were strictly applied, the nuclear waste repository would emerge as being disproportionately costly, according to the risk calculations that have been done. The purpose of this essay is to show that this point of view is highly simplified and that it is ultimately a societal judgement that should be supported, but not dictated, by a cost-benefit analysis.

"The limitations of science" is about the art of minimizing our dependence on uncertain information. The controversies concerning nuclear waste have mainly been concerned with how much we can know about what will happen in the future. Expert assessments have been questioned, and faith in the ability of science to answer these questions has sometimes been low. Even if we cannot be completely sure, we must nevertheless make decisions and take action. This essay argues that the best we can do is to act at every given time on the basis of the best available science, while at the same time estimating the level of uncertainty in this science to the best of our ability.

"Engineering – more than just numbers." In recent years, the words "engineer" and "engineering" have taken on a negative connotation, and we sometimes think of engineers as being incapable of taking into account anything that cannot be expressed in numbers. This essay is a defence of engineers and engineering, particularly in the field of safety. The essay uses examples from different fields to illustrate the use of principles such as inherent safety, safety factors and multiple safety barriers. Such comparisons can help us to understand and evaluate the design of the repository in a more thorough and accurate manner.

"Ultimately a political question" looks at the nuclear waste issue in a sociopolitical context. The nuclear waste issue is politically very complex, in part due to factors dealt with in the previous essays, and in part due to a lack of clarity regarding local decision-making. What legitimacy does the state possess in matters covering such a long time span? What weight can be given to local interests? Does society have any obligations to the community in the area where the repository is located? What division of responsibility should be striven for between experts and elected representatives in the crucial decisions? How much freedom of choice should be give to future generations? Do we have an obligation to restrict their freedom of choice, or should we assume that they are better able to protect their own interests that we are? These questions are addressed from the standpoint of modern decision theory and political philosophy.

Part VI

LILW programme and decommissioning

34 Overview – LILW programme and decommissioning

The LILW programme embraces all low- and intermediate-level waste that will be disposed of in SKB's facilities. The facilities covered by the LILW programme are SKB's own existing and future facilities for final disposal of waste from the Swedish nuclear power plants. Interim storage of long-lived low- and intermediate-level waste from the nuclear power plants in BFA (rock cavern for waste) is also included in the programme. The Nuclear Waste Fund finances the final disposal of decommissioning waste and long-lived low- and intermediate-level waste. SKB may also dispose of radioactive waste from Studsvik, the Ågesta reactor, the fuel factory in Västerås and Ranstad. Disposal of the waste from these facilities will then be financed separately. Final disposal of the operating waste from the nuclear power plants is financed directly by the licensees.

In preparation for decommissioning and dismantling of the nuclear power plants, decommissioning studies will be carried out for the purpose of estimating costs and waste quantities, both radioactive and non-active, as well as free-release material. The studies are based on the strategies and technologies that are developed in cooperation with the power plant owners. SKB will only dispose of the radioactive waste, but in the studies SKB calculates the volumes and the costs of all decommissioning waste.

The most important milestones during the coming three-year period are:

- Completion of a new safety analysis report (SAR) for the final repository for radioactive operational waste (SFR 1), which will be submitted to the regulatory authorities at the end of 2007.
- Design and modification of the existing BFA on the Simpevarp Peninsula for interim storage of core components.
- Licensing and manufacture of the ATB-1T waste transport container for intermediate-level long-lived waste. The supporting material for licensing will be ready in 2009. Manufacture will start one year later.
- Planning for an extension of SFR begins in 2007. The extension should be ready for operation by 2020. Investigations of the bedrock will start during 2008.

The next six-year period also includes the following milestones:

- Start of operation of dry interim storage of long-lived waste from other power plants than Oskarshamn in BFA, no earlier than the end of 2011. OKG is already using BFA today for dry interim storage.
- Preparation of a preliminary safety analysis report (PSAR) and an environmental impact statement (EIS) for an application for a permit to extend SFR. According to the plans, the application will be submitted to the regulatory authorities in 2013.

The planning for the final repository for long-lived low- and intermediate-level waste (SFL) will begin after the application for a permit to extend SFR has been submitted. SFL is not expected to start operation before 2045. The waste quantities to SFL are relatively small, and the facility will be the last one to be closed, since it will receive waste from other facilities (the nuclear power plants, Clab and the encapsulation plant) until they are decommissioned and dismantled. In view of the small volumes in question, SKB judges that it is reasonable to wait with the extension until most of the waste is available for deposition.

35 Low- and intermediate-level waste

35.1 Origin of the waste

The programme for disposal of low- and intermediate-level waste, the LILW programme, includes low- intermediate-level operational waste from the Swedish nuclear power plants and similar waste from Studsvik. The operational waste that is so low-level that the power utilities choose to dispose of it in their own near-surface repositories is not included. The programme also includes future decommissioning waste from the nuclear power plants.

The LILW programme may also include radioactive waste from the activities in Studsvik, the Ågesta reactor, the fuel factory in Västerås, Ranstad and waste from other use of radioactive material in, for example, research and education, at hospitals and in industry. However, this lies beyond SKB's undertaking for its owners and therefore requires that special agreements be signed.

The waste can be treated and packaged at the NPPs and at Studsvik. The radioactive non-nuclear waste is treated at Studsvik and can be transferred to SKB's facilities after special agreement.

35.2 Waste quantities and types

35.2.1 Short-lived waste

Today, short-lived LILW is waste from operation and maintenance of the NPPs. This waste is well-characterized and has been handled routinely for nearly 30 years. The portion for which SKB is responsible has been disposed of in SFR 1 (the final repository for operational waste) since 1988. When the phase-out of the NPPs begins, decommissioning waste will be added to this category. This waste consists of the same types of waste as those that arise in the operation and maintenance of the NPPs, but in different proportions. The decommissioning waste will be able to be treated, transported and disposed of in the same way as the operational waste. It consists mainly of scrap metal and concrete residues.

The short-lived waste is packaged in different types of containers for transport to the final repository, depending on its origin, activity and radiation level. The types of containers that exist in the system at present are metal drum, metal mould, concrete mould, concrete tank and ISO container, see Figure 35-1. All containers – except the ISO container – are transported in special radiation-shielded waste transport containers (ATBs) to the repository.

SKI pointed out in its review of RD&D-Programme 2004 that it is positive that that SKB has now also included short-lived waste in the RD&D report.

Kasam noted that it is necessary for a national system to be created, not only for waste from nuclear power production but also for radioactive waste from non-nuclear activities. SKB is positive towards managing radioactive waste from non-nuclear activities – for reasonable compensation and if it fits in with SKB's regular activities.

Originally, the forecasts showed that approximately 52,000 m^3 of operational waste would arise by 2000 and approximately 90,000 m^3 by 2010. The actual quantity of waste that has arisen so far is much less (just over 31,000 m^3 at the end of 2006). This is partly due to the use of new treatment methods and waste containers. The waste now being produced is smaller in volume but has a higher concentration of radionuclides than the forecasts originally assumed. Furthermore, shallow land burial at most power plants has become possible for waste with a very low activity content, see section 35.2.3. Finally, operation has gone better than originally assumed. Among other things, fuel damage has occurred less frequently, leading to a smaller quantity of waste.

Figure 35-1. Waste containers for short-lived waste. Photo: Bengt O Nordin.

The volumes of short-lived low- and intermediate-level waste increase in connection with major rebuilds and when the nuclear power plants are eventually decommissioned. The single most important factor that determines the total quantities of operational waste is how long the nuclear power plants will be in operation. Forsmark and Ringhals plan to operate their reactors for 50 years, and OKG has decided on an operating time of 60 years. The increased operating time for the reactors means that larger quantities of operational waste must be disposed of. At the same time, waste management is improving with the introduction of volume-saving methods. Despite operating times of up around 60 years, the waste volume are not expected to be greater than was originally estimated for 25 years of operation.

The programme for the short-lived low- and intermediate-level decommissioning waste consists for the most part of research relating to long-term safety in the final repository and development aimed at the extension and relicensing of SFR to receive both operational and decommissioning waste. The research is dealt with in Chapter 37 and the extension of the final repository in section 35.3.1.

35.2.2 Long-lived waste

The long-lived LILW consists mainly of two categories:

- Core components (control rods, core grids etc) and the internal components in the reactor that are highly neutron-irradiated. This waste arises in connection with both maintenance and decommissioning.
- Long-lived waste from activities at Studsvik and from medical care, research and industry. This waste arises continuously and is not associated with the operation or decommissioning of the NPPs.

The long-lived waste from the NPPs is interim-stored today either in storage canisters in the pools in Clab or in at-reactor pools. In the future, dry interim storage will also be an option for this waste, before the final repository for the long-lived waste is ready.

The long-lived waste from medical care, research and industry is packaged in moulds or drums and stored together with Studsvik's own waste in a special rock cavern at Studsvik awaiting deposition in the final repository for long-lived low- and intermediate-level waste.

The volume of long-lived waste is relatively small so far, but it will increase in connection with ongoing and planned modifications of the reactors and subsequently in conjunction with the decommissioning of the NPPs, Clab and the encapsulation plant. Prolonging the service life of the NPPs presumably also leads to greater volumes of long-lived waste that arise in connection with maintenance and repairs.

SKI pointed out in its review of RD&D-Programme 2004 that SKB should provide a more detailed description of the programme for long-lived low and intermediate-level waste in its next RD&D programme. Against the background of SKB's other activities, RD&D Programme 2010 will focus on the LILW programme.

A system for documentation of the long-lived waste has been developed by SKB. The system is called Draak (Swedish acronym for "data register for active waste and components") and is similar to the one that already exists for SFR waste. Draak also takes into account the fact that documentation takes place gradually, in view of the fact that the waste is sometimes stored as raw waste for a long time before it is given its final form for disposal.

The planning for the long-lived waste will be developed in RD&D Programme 2010. Interim storage of long-lived waste is dealt with in section 35.3.2. The work of preparing a safety analysis report and conducting a waste inventory for the final repository for long-lived waste will be done when an application for a permit to extend SFR has been submitted in 2013.

35.2.3 Very low-level waste

The very low-level operational waste is disposed of in the NPPs own near-surface repositories and is treated in greater detail in section 35.3.4.

SKB plans to conduct a feasibility study of the possibilities of disposing of the very low-level waste from the decommissioning of the NPPs in near-surface repositories. The feasibility study will be conducted in the initial phase of the planning for the extension of SFR.

35.3 Facilities for low- and intermediate-level waste

SKB's existing and planned future facilities for low- and intermediate-level waste include:

- Final repository for radioactive operational waste (SFR 1).
- Final repository for decommissioning waste (SFR 3), which will comprise an extension of SFR 1.
- Facility for dry interim storage of intermediate-level long-lived waste, which will comprise a part of BFA.
- Part of Clab for interim storage of core components.
- Final repository long-lived low- and intermediate-level waste (SFL).

In addition to these facilities, SKB is operating a transportation system for low- and intermediate-level waste (the ship m/s Sigyn and waste transport containers, ATBs).

According to SKB's plans, the short-lived waste from decommissioning of the nuclear power plants will be disposed of in an extension of SFR 1, called SFR 3. In conjunction with this extension, SKB intends to relicense the facility so that all of SFR can be utilized for optimal disposal of waste from both operation and decommissioning. After relicensing, the whole facility will be called the final repository for short-lived low- and intermediate-level waste, SFR.

Long-lived low- and intermediate-level waste is interim-stored today at Clab, at the nuclear power plants and at Studsvik. SKB is planning for dry interim storage of core components from other power plants than Oskarshamn in the existing rock cavern for waste waste (BFA) on the Simpevarp Peninsula to relieve the load on Clab. OKG is already using BFA today for dry interim storage. Interim storage of long-lived waste is needed until a final repository for this waste is put into operation.

The final repository for long-lived low- and intermediate-level waste (SFL) is planned to be ready to receive waste in 2045 at the earliest, when most of the waste is available for deposition.

A schematic illustration of the waste types that arise and the path they take to the different final repositories is shown in Figure 35-2 below.

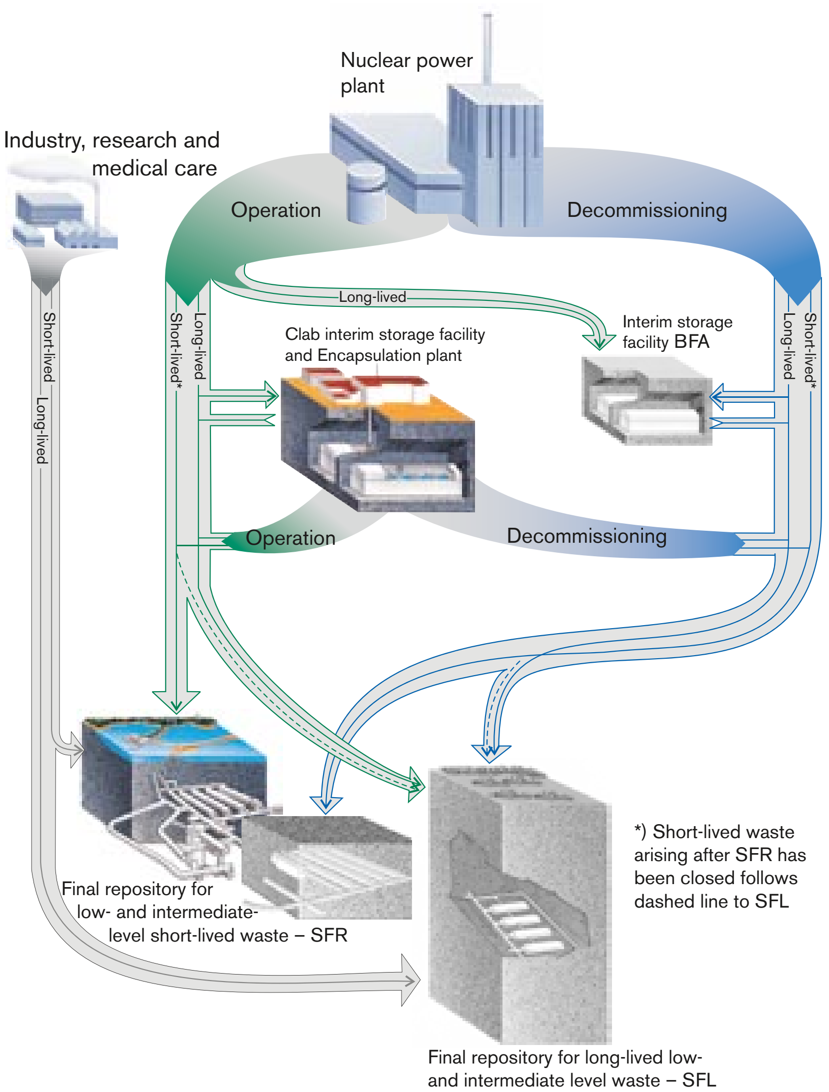


Figure 35-2. *Transport flows and storage of low- and intermediate-level waste.*

35.3.1 Final repository for short-lived low- and intermediate-level waste, SFR

In the review of RD&D-Programme 2004, SKI commented that there may be good reason to review the timetables for final disposal of decommissioning waste in view of Barsebäck 2, but recognized the difficulty, in terms of resources, of handling the application, design and construction of more than one repository. Furthermore, SKI pointed out that SKB should investigate how soon a licensing process for the disposal of decommissioning waste can start, if possible within the next few years, and that the account of how the decommissioning waste is to be managed needs to be more exhaustive. During 2007 SKB has started a pilot project in preparation for the extension of SFR to manage and dispose of decommissioning waste. The timetable for the project, which includes licensing, is presented below.

SSI pointed out that the planning premises for an extension of SFR will be changed when Barsebäck 2 is shut down. SKB should therefore announce a new strategy for the extension as soon as possible. SKB prioritizes an extension of SFR to receive the decommissioning waste as soon as possible.

Kasam pointed out that SKB should consider whether the plans for extending the activities at SFR for decommissioning waste are compatible with the Environmental Code, and that SKB should shed light on these issues in RD&D Programme 2007. An environmental impact statement will be included in SKB's application for a permit to extend SFR.

A periodic overall assessment of the safety of SFR-1 /35-1/ was carried out in 2005 in accordance with SKIFS 2004:1. The main purpose of the report was to obtain an evaluation of experience from the operation of SFR 1, both technically and organizationally. This experience then serves as a basis for coming improvements. An important general conclusion in the report was that the operating period will be much longer than originally planned. Despite this, the total waste volume at repository closure will be less than was assumed in the original design framework. Another conclusion was that the waste inventory has changed in comparison with the original design-basis inventory, and strategies may need to be developed for this. It was also concluded that the operating personnel have long experience and good familiarity with the facility, but that the need for new recruitment and competence transfer must eventually be given due attention.

Research has been conducted for the purpose of finding better and more reliable methods for estimating the nuclide inventory in SFR 1, and to analyze long-term safety at the facility, where the different barriers play a crucial role. The research is described in greater detail in Chapter 37.

Radioactive operational waste

SKB obtained a Government licence to build and operate a facility for final disposal of low- and intermediate-level waste in June 1983. The licence included disposal chambers with capacity for a total of 90,000 m^3 of packaged waste. This facility is called SFR 1, and its construction was planned to take place in two stages: 63,000 m^3 and 27,000 m^3. The preliminary safety report that served as a basis for the application also described possible future extensions with disposal chambers for core components (SFR 2) and decommissioning waste (SFR 3). SFR 2 has now been replaced in the planning by the final repository for long-lived low- and intermediate-level waste (SFL). SKB's application did not include these future facility parts, however.

Due to the fact that smaller waste volumes are assumed today, there is no longer any need for an extension of SFR 1 with a second stage. The reason for construction in two stages was primarily uncertainties in the data on which predictions are based. The first construction stage was designed for a quantity of waste that would be disposed of up until 2000, according to the prediction. With the predicted waste quantities and the planned transport pace, this corresponded to approximately 52,000 m^3. Stage 1 of SFR 1 was thereby assumed to provide enough margin and flexibility for the first operating period (up to 2000). At the end of 2006, more than 31,000 m^3 of the repository capacity had been utilized, i.e. much less than had originally been predicted. It is currently predicted that an operating time of 50 years for Forsmark and Ringhals, and 60 years for Oskarshamn, will result in approximately 57,000 m^3 of operational waste.

Rebuilds such as today's capacity-boosting projects and rebuilds to extend the service life of the NPPs will increase the space needed for final disposal.

The disposal chambers today consist of four 160-metre-long rock caverns of different kinds and a 70-metre-high rock cavern in which a concrete silo has been built, see Figure 35-3. One of the four rock caverns contains low-level waste in ordinary ISO containers. This rock cavern is called BLA (rock cavern for low-level waste). The waste in this part of the facility can be handled without any special radiation shielding. Three of the caverns contain waste that requires radiation shielding: BMA (rock cavern for intermediate-level waste) and BTF 1 and 2 (concrete tank repository). The concrete silo is intended for intermediate-level waste, mainly filters and ion exchange resins used for purification of reactor water.

A stakeholder agreement between SKB and the owners of the nuclear power plants regulates the volume shares the owners are entitled to utilize for disposal of operational waste in SFR 1. The volume agreement is important for ensuring that none of the power plants in operation today risk running out of room for their waste, which would in turn have consequences for the operation of the plants. There is no risk today that any waste producer will fill their volume share in SFR 1 before the end of 2020. The waste predictions are regularly renewed and strategies for disposal and long-term planning are updated. The owners of the reactor units that are in operation today have decided to extend the operating time of the units. Along with additional decommissioning waste, this means that SFR will have to be extended to prevent a shortage of space after 2020. The planning for the extension is described in greater detail below.

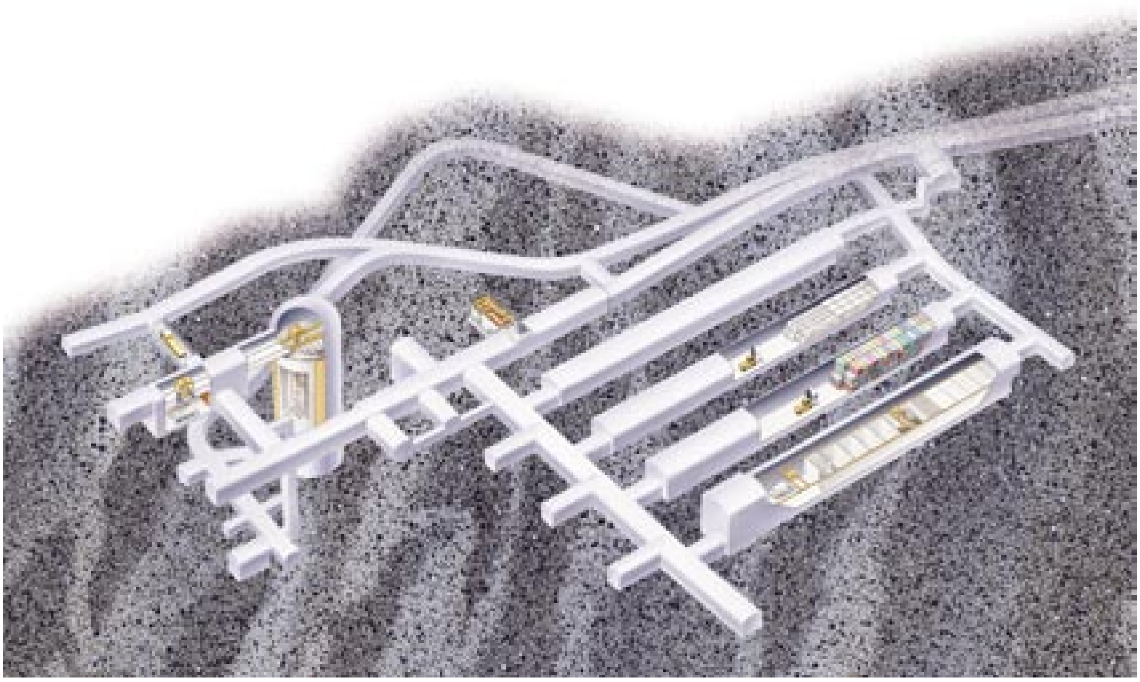


Figure 35-3. Final repository for radioactive operational waste (SFR 1).

Radioactive decommissioning waste

SKB judges that an extension of SFR is the best solution to deal with the quantities of short-lived low- and intermediate-level waste that arise on decommissioning of the nuclear power plants. A permit is currently lacking for disposal of decommissioning waste. In conjunction with the extension, a relicensing of the entire facility is planned to include both operational and decommissioning waste. The purpose of the relicensing is to be able to distribute waste from operation and decommissioning in the facility in an optimal and safe manner.

The size of the extension of SFR depends on what waste volumes are projected to come to SFR. Forsmark and Ringhals plan to operate their reactors for 50 years and OKG for 60 years. Even before all reactors have been shut down there will be a demand to dispose of waste from the already deactivated plants. The extended operating time also means that BMA needs to be expanded. A stepwise extension of the final repository for the short-lived decommissioning waste should be planned for, since the need for disposal space will arise at widely separated points in time. Chambers for receiving waste from the previously deactivated plants will be built in stage 1 of SFR 3. Chambers for the decommissioning waste from the units in operation today will be built in stage 2.

The size of the volume of the stage 1 extension is mainly dependent on the following factors:

- The quantity of decommissioning waste that arises in connection with the decommissioning of Barsebäck 1 and Barsebäck 2.
- Increased quantity of operational waste due to extended operating time.
- The need of disposal space for large odd components (above all from power increase projects).
- Separate agreements may mean that the extension has to allow for waste from decommissioning of, for example, facilities in Studsvik.

One rock vault of the BMA type will be built in stage 1, while other rock vaults are planned to be of the BLA type.

Planning

A pilot project for the extension of SFR commenced in 2007. Site investigations with rock investigations will begin in 2008.

An application for a permit for an extension of the final repository for reactor waste (SFR) will be submitted to the regulatory authorities in 2013, according to current planning. The application will include a preliminary safety analysis report (PSAR) and an environmental impact statement (EIS) on the extension. It is estimated that it will take at least two years to obtain a permit.

The work on the stage 1 extension of SFR is expected to be able to begin in 2016, so that start of operation can take place in 2020.

The stage 2 extension will be ready to receive decommissioning waste from the nuclear power plants in Forsmark, Oskarshamn and Ringhals when they begin to be decommissioned. The date for the start of operation of stage 2 is estimated to be around 2030, considering planned operating times.

An application timetable for extension and operation of SFR will be prepared.

35.3.2 Rock cavern for waste, BFA

SKB and the Swedish nuclear power utilities believe that a chamber for dry interim storage of core components is needed as a complement or substitute for wet interim storage in Clab. Interim storage in Clab is expensive and space-taking and can in the long term lead to a shortage of space in Clab for spent nuclear fuel. The core components are in need of radiation shielding, but not cooling. This is due to the fact that the quantity of activity is relatively great, but that the components do not generate heat.

SKB and the Swedish nuclear power utilities have together prepared a proposal for how core components from all Swedish nuclear power plants can be stored under dry conditions. The proposal calls for the components to be sent to BFA (rock cavern for waste) in Simpevarp, which OKG is already using today for dry interim storage.

The operating licence for BFA is held by OKG, while SKB has a right of use in BFA by agreement. A relicensing of BFA is required to permit its future use for interim storage of core components from other power plants than OKG. Since BFA is OKG's facility, OKG is responsible for the relicensing and the updating of the safety analysis report. OKG obtained a new permit for its environmentally hazardous activities in 2006 and then obtained a permit to use BFA as a common storage site for core components from Sweden's nuclear power plants. This means that it is permitted from an environmental viewpoint to store core components in BFA. OKG also sent in an updated safety analysis report (SAR), including safety-related technical specifications (STF), for BFA to SKI in 2007. When it has been approved by the Inspectorate and a permit has been issued, then core components from other nuclear power plants can also be interim-stored in BFA. SKB will also build a transloading station inside OKG's area. This will require a building permit and possibly an update of the safety analysis report (SAR).

There is waste suitable for interim storage according to the dry method at all nuclear power plants today. Larger quantities will be generated by repairs and rebuilds of the reactor internals. At present, dry storage does not include control rods and equipment containing fissile material; this waste will continue to be stored in Clab.

The waste containers, steel cases (1.3 × 2.3 × 3.3 metres) in which the core components will be transported and interim-stored, are designed so they can be transferred to the final repository for long-lived low- and intermediate-level waste without further treatment. The option of reconditioning is left open, however, since the criteria for disposal have not yet been established.

The proposal to use dry interim storage entails that a new waste transport container, ATB-1T, needs to be developed that fits the dimensions of the waste containers (steel cases). The project to develop the ATB-1T waste transport container is under way, and is the time-critical factor for when BFA can be taken into operation. A rebuild of parts of BFA is also necessary, including installation of a new overhead crane. Interim storage of core components in BFA is estimated to be able to start no earlier than the end of 2011, when the delivery of ATB-1T is planned.

With reference to the timetable for the start of operation of interim storage in BFA and Forsmark's plans for replacement of reactor internals, Forsmark will build its own interim storage facility which they will use until the waste can be shipped to BFA.

35.3.3 Final repository for long-lived low- and intermediate-level waste

SKB plans to dispose of heavily neutron-irradiated long-lived waste, such as core components and reactor internals, in a facility similar to SFR but located at greater depth. The waste consists in part of components from the reactor core that have been replaced during the reactor's operating time (such as control rods, fuel boxes and detector probes), and in part of structural parts from the reactors (such as core grids and core barrels).

SKI and SSI said in the review of RD&D-Programme 2004 that the design of a repository for long-lived low and intermediate-level waste should be prioritized in the research programme and that this should be stated in the next RD&D Programme. SKI further urged SKB, in the next RD&D-programme, to provide a coherent justification for the construction requirements that must be made on the repository for long-lived low- and intermediate-level waste from the perspective of long-term safety. Examples of questions that need to be elucidated in greater detail are:

- Choice of repository depth.
- A possible distance between the final repository for long-lived low- andintermediate-level waste and the final repository for spent nuclear fuel.
- Backfill material and the hydraulic cage principle.
- The repository's dimensions.
- The quantity of cement and the type of cement.

SKI pointed out that SKB should give an account of how long-lived low and intermediate radioactive waste is to be managed if it arises earlier than planned, and a "zero alternative" should also be described. SKB interprets this comment as indicating that SKI wants to know what happens if SKB's predictions turn out to be wrong with regard to time. Long-lived waste arises in connection with modernization projects, for example, and a "zero alternative", i.e. continued management in the same manner as today without action being taken, is included in the project for dry interim storage of core components in BFA.

Planning

SKB will give an account of its plans for SFL in RD&D Programme 2010.

The goal is to be able to provide a more detailed account of how SKB plans to design the final repository for long-lived low- and intermediate-level waste in RD&D Programme 2010. The account may include a strategy for choice of site and repository depth as well as studies of the dimensions of the repository.

A decision on the siting of the final repository for long-lived low- and intermediate-level waste will be made in a couple of decades at the earliest, which means this is still an open question.

An update of the waste inventory, and a conceptual safety evaluation for the facility after an application for an extension of SFR has been prepared, is currently planned.

35.3.4 Near-surface repository for very low-level waste

There are near-surface repositories at the nuclear power plants in Oskarshamn, Ringhals and Forsmark. The licensees for the NPPs are also licensees and operators of the near-surface repositories. The conditions for disposal are established by SSI. A new application is submitted prior to each deposition campaign. The activity content in the waste that is allowed to be deposited in the near-surface repositories is very low and for the most part short-lived.

SKB will manage and dispose of the radioactive waste arising in conjunction with the decommissioning and dismantling of the nuclear power plants. Conventional and free-release material will be managed by the licensees. Current plans call for all radioactive material to be disposed of in SFR or, if it is long-lived, in the final repository for long-lived low- and intermediate-level waste which SKB is planning to build. From an Alara and BAT viewpoint, it may be advantageous to deposit slightly radioactive material in near-surface repositories similar to those that exist at the NPPs today. A simplified handling of the very low-level waste should give a lower dose to the personnel who, according to current plans, will either handle and package the material so that it fits in SFR or decontaminate the material to a level that enables it to be released for unrestricted use.

Planning

SKB is planning to conduct a feasibility study of the possibilities of shallow land burial of the very low-level waste from decommissioning of the NPPs in near-surface repositories. Since this will impact SFR, the feasibility study will be conducted in the initial phase of the planning of the extension of SFR.

35.4 Financing

SKB's activities in the field of low- and intermediate-level waste are partially financed by money from the Nuclear Waste Fund (the final repository for decommissioning waste and the final repository for long-lived low- and intermediate-level waste) and partially directly by the part-owners (existing repository for short-lived operational waste).

The financing is updated annually and presented by SKB in a Plan report /35-2/. The Plan report is in part a compilation of estimated costs for decommissioning and dismantling of the nuclear power plants.

In its review of RD&D-Programme 2004, Kasam pointed out that SKB needs to critically review previously prepared cost estimates for the future decommissioning work. SKB notes that this is a constantly ongoing process in the revision of the Plan report. Further background material for review is the decommissioning study that has been carried out and that is described below.

Since the previous RD&D-programme, SKB has carried out a decommissioning study for Oskarshamn 3 /35-3/, where alternative technologies, methodology and waste quantities are described, along with an estimate of the decommissioning costs. The study comprises a reference for all BWR units. For other BWR units it is possible to obtain equivalent information by using unit-specific input data in the calculations.

The decommissioning study is dealt with in greater detail in Chapter 40.

Programme

Comparative studies will be done for all units. Studies of the BWR units will be based on the completed reference study for Oskarshamn 3. A new study of decommissioning of one of the PWR units at Ringhals will be carried out in an equivalent manner as for Oskarshamn 3, and used as a reference for the other PWR units. Read more about this in Chapter 40.

36 Safety analysis reports

The safety analysis reports that are being prepared in the LILW programme pertain to existing facilities as well as future extensions and new facilities for final disposal of low- and intermediate-level waste.

RD&D-Programme 2004 did not include a programme for safety assessments of facilities for final disposal of low- and intermediate-level waste.

In its review of RD&D-Programme 2004, Kasam emphasized the value of safety assessment as an instrument for identifying and focusing the research conducted in the programme.

The level of knowledge has increased in a number of areas since RD&D-Programme 2004. The most important ones are discussed in Chapter 37, which deals with research that supports the safety assessments.

Programme

Described in sections 36.2 through 36.5 for the different types of final repository.

36.1 Regulations for safety and radiation protection

The design of a safety assessment – and above all the criteria that are to be used to determine whether the repository is safe – is specified in regulations from the safety and radiation protection authorities. The regulations are based on overarching laws. The most important of these laws are the Environmental Code and the Nuclear Activities Act. Radiation protection is also overseen by a number of international bodies. National legislation is often based on international rules and recommendations.

36.1.1 Application of the regulations to the final repository's operating phase

SKIFS 2004:1 and SSI FS 2000:12 apply to the operating phase of the final repository for radioactive waste. They are applied to the operation of SFR 1.

In accordance with SKIFS 2004:1 and the operating licence from 1988, an ASAR (As-operated Safety Analysis Report) was carried out for SFR 1 in 2005, which is described in section 35.3.1. The next ASAR for SFR 1 will be carried out and communicated to the regulatory authorities in 2015.

36.1.2 Application of the regulations to the final repository's post-closure phase

Regulations on the Protection of Human Health and the Environment in connection with the Final Management of Spent Nuclear Fuel and Nuclear Waste, SSIFS 1998:1, were issued after SFR 1 was taken into service in 1988. The parts of the regulations that relate to site selection, design etc are therefore not applicable to the facility. The assessment of long-term safety at the facility is, however, judged against the regulations. Thus, the risk concept is also applied to SFR 1, instead of only a dose target, which was the requirement in the original licensing of SFR 1.

SKIFS 2002:1, Regulations concerning Safety in connection with the Disposal of Nuclear Material and Nuclear Waste, were issued by SKI along with associated General Recommendations. The conclusions in the safety assessments are compared with the SKI regulations. Allowance is made for the fact that SFR-1 was designed and built before the regulations were issued.

36.2 SKB's safety strategy

SFR and SFL must meet society's requirements on safety and a good environment as they are expressed in laws and regulations. The facilities must also meet the owners' requirements on safety and efficiency.

Some important safety and radiation protection principles underlying the design and operation of SKB's facilities for final disposal of low- and intermediate-level waste are:

- The multiple barrier principle: safety should be based on multiple safety functions provided by multiple barriers.
- In-depth defence: safety and safety awareness should permeate both the design of the barriers and the procedures intended to limit radiation doses and prevent accidents.
- Humans, animals and the environment should be protected from the harmful effects of ionizing radiation, and future generations and environments may not be exposed to greater radiation doses and/or risks than are acceptable today.
- A balance should be struck between radiation protection during operation and long-term (post-closure) safety.
- Good and reliable technology should be used in order to limit uncertainties and optimize radiation protection.
- The facility should have physical protection that hinders intrusion by unauthorized persons.
- Furthermore, the facility should be designed with a view to the environment and the safety of the users and nearby residents. The facility should also be able to receive visitors.

In view of the above, the goal of SFR and SFL is to dispose of low- and intermediate-level waste in a manner that is safe in all respects, with a limited impact on the environment, and at acceptable costs.

The level of knowledge has increased in recent years in several areas. The most important advances are described in Chapter 37. In addition to these research activities for assessments of long-term safety at SFR 1, the calculation model Amber has been applied as an alternative to the calculation models previously used for SFR 1.

Planned safety analysis reports for the final repository for low- and intermediate-level waste:

Report, type	Report, year	Principal scope of report
SAR SFR 1 (existing SFR)	2007/2008	Operational and long-term safety in existing SFR 1 (operational waste)
PSAR SFR (extended SFR)	2013	Operational and long-term safety for the extended SFR containing both operational waste and decommissioning waste
ASAR SFR 1	2015	Experience feedback from operation of SFR 1
PSAR SFL	2016	Assessment of long-term safety for repository for long-lived waste

36.3 Final safety analysis report (SAR) for SFR 1

New models for assessment of the long-term safety in the facility have been applied since the most recent update of the safety assessment for SFR 1. Transport calculations for radionuclides are now carried out probabilistically with the calculation program Amber. Knowledge from e.g. the safety assessment SR-Can /36-1/ is utilized. Background material has been compiled for the safety assessment from studies and research.

Programme

A new SAR concerning operational and long-term safety in an existing final repository for short-lived low- and intermediate-level waste from operation and maintenance of the nuclear power plants will be completed at the end of 2007. It describes safety during operation of the facility as well as long-term (post-closure) safety. The safety analysis report is being made complete in the sense that it is sufficiently comprehensive and detailed to replace previous studies.

Normal conditions and the consequences of postulated incidents, such as handling mishaps and fires in the facility, are analyzed for the operating phase. For the assessment of post-closure safety, new and improved knowledge is available in a number of areas, see Chapter 37.

The new waste predictions show that the relative proportions between different radionuclides in the waste are slightly different than was assumed in previous safety assessments. Important changes such as these must be taken into account in the new assessment. This means that certain nuclides will exceed the values that have been set as radiation protection conditions by the regulatory authorities. Since the nuclide quantities on which current radiation protection conditions (issued in 1988) are based were predicted quantities and not based on limit values for permitted doses to the environment (or risk, a concept that has subsequently come into use), a higher content of certain nuclides can still be acceptable as far as meeting regulatory requirements on long-term safety is concerned. Neither new nor old predictions of the total quantity of radionuclides in the repository exceed the activity quantities that have been assumed for a full repository. In the safety assessments, the risk is calculated both for a realistic radionuclide inventory (predicted value) and for a full repository, i.e. when the predicted values have been adjusted to the maximum total inventory in the repository according to the licence. Besides showing that safety at the facility is satisfactory with the new nuclide inventory, new radiation protection conditions must also be applied for, based on the new nuclide inventory for the operational waste.

When an application for an extension of SFR is submitted in 2013, it will contain a nuclide inventory that reflects both the operational waste from the nuclear power plants and the expected quantities of activity in the decommissioning waste, see section 36.4. The new nuclide inventory entails that a new Government licence will be required after the application has been submitted in 2013.

In the coming update of the safety assessment for SFR, most of the transport calculations will be carried out with probabilistic methods. This applies to central parts such as sorption data, flow paths for groundwater in both engineered barriers and in the rock, and in the biosphere modelling. In this way a better idea is obtained of the uncertainty in input data and calculations compared with previously used deterministic methods.

36.4 Preliminary safety analysis report (PSAR) for extended SFR

The studies of decommissioning and dismantling of nuclear facilities that have been and are being conducted are yielding increasingly detailed information on the waste – from both operation and decommissioning of nuclear facilities – that is to be disposed of in the final repository for short-lived low- and intermediate-level waste. This information is used as a basis for planning of the design of the final repository and for assessment of the operational and post-closure safety of the facilities.

Programme

The safety analysis report is an important part of the ongoing project for the extension of SFR, since it is supposed to show that the safety and radiation protection requirements can be met with the planned extension. A PSAR will accompany the application for a permit to extend SFR. The application is planned to be submitted to the regulatory authorities for consideration in 2013.

The design and the safety analysis report of the extended facility are largely based on what has been and is being done for the existing SFR. Predictions of the waste from decommissioning of the nuclear power plants and from other nuclear facilities under separate agreements with the licensees of these facilities will be added to the waste predictions for SFR.

Additional data on the repository site will be gathered by further investigations of the rock in the area for the extension, and the hydrogeological model will be modified. The safety assessment is planned to include the existing SFR as well as additional waste for stage 1 of the extension. To illustrate the consequences of a fully extended repository, it is assumed that all predicted activity from decommissioning and operational waste is disposed of in the existing SFR and in stage 1 of the extension. For optimization of the utilization of the final repository, an application is planned to be submitted for a joint licence for the existing and extended repository, so that the waste can be optimally distributed between the different repository parts.

36.5 Preliminary safety analysis report (PSAR) for SFL

No systematic safety assessment of final disposal of long-lived LILW has been done since the previous RD&D programme. Assessments of the possibilities for final disposal of new waste types and waste packages have, however, been carried out based in part on the assessment of a possible final repository that was carried out in 1999 /36-2/ and in part on experience from operation and assessment of SFR. For now, the assessments of new waste types for SFL are being done with the reservation that reconditioning is possible.

Planning

When the permit application for extension of SFR has been completed, a renewed waste inventory and an update of the safety evaluations for SFL are planned. Since a site has not yet been selected for the final repository for long-lived low- and intermediate-level waste, general site data will be used. Data from one or more of the sites that have been investigated as candidates for the final repository for spent nuclear fuel may possibly be used. The detailed planning will be presented in subsequent RD&D programmes.

36.6 Safety evaluation of near-surface repository

In conjunction with the decommissioning and dismantling of the nuclear power plants, some of the decommissioning material will contain very small quantities of radioactivity. In these cases, decontamination and release of the material for unrestricted use can be a large and costly undertaking, making disposal in a near-surface repository (shallow land burial) a preferable alternative. Shallow land burial can also contribute to a lower radiation dose to personnel and the environment than decontamination and free release.

Shallow land burial in a near-surface repository entails that a period of institutional control of the facility is required after closure. The proposed regulations for near-surface repositories which SSI has presented make it possible to design repositories for very low-level material, which can be released for unrestricted use after a control period of 50–100 years.

Shallow land burial under SKB's auspices has not previously been presented. RD&D-Programme 2004 indicated that a study is planned for the period up to 2010.

Planning

SKB intends to investigate the possibilities of building near-surface repositories for very low-level decommissioning waste. Several alternatives will be investigated: expansion of existing near-surface repositories at the NPPs, new local repositories and a central near-surface repository. The waste quantities that might be eligible for shallow land burial will be estimated based on the decommissioning studies that have been done and will be done for the NPPs in the years to come.

37 Research

The research being conducted by SKB in the LILW programme is aimed at producing data and models for estimating the nuclide inventory and assessing the long-term safety of the barriers in SFR. SKB does not conduct its own research in the area of decommissioning, but does gather experience from various decommissioning projects in other countries.

Kasam is positive to SKB's programme for research related to low- and intermediate-level waste.

SKI calls for requirements and criteria for the physical integrity of the concrete. These are included in the safety assessments. Research is improving our knowledge of the properties of the concrete, which means that less conservative assumptions can be used in the safety assessment. This research is being conducted constantly, though not always under SKB's auspices.

Newfound knowledge since RD&D 2004

SKB has carried out a detailed decommissioning study for Oskarshamn 3 /37-1/, which was presented in 2006. This study includes technologies and strategies for decommissioning, calculated waste and activity quantities, as well as timetables and cost calculations. The study constitutes a reference for other BWR plants and is described in detail in Chapter 40. A study of the operation of nuclear power plants during the decommissioning period has been conducted, as well as a study of dismantling and demolishing of buildings /37-2, 37-3/.

Studies that pertain to SFR 1 have been or are being conducted in the areas of concrete and bentonite degradation as well as estimation of activity in the waste by studies of correlation factors between difficult-to-measure nuclides and key nuclides.

It is not possible to determine the exact nuclide content of all waste packages, since some nuclides are difficult to measure. Since a large portion of the operational waste has not yet been produced, an estimate of the total nuclide inventory for a final repository cannot be based on measurement data alone. SKB uses correlation factors between measurable and difficult-to-measure nuclides and a prediction of the future waste quantity.

In order to be able to estimate the nuclide inventory in the operational waste in SFR 1, studies have been carried out to determine correlation factors between the measurable key nuclides (cobalt-60, caesium-137, plutonium-239 and plutonium-240) and the difficult-to-measure nuclides (for example carbon-14, nickel-59, nickel-63, molybdenum-93, technetium-99, iodine-129 and caesium-135). The differences in correlation factors between different reactor types (BWR/PWR) have been analyzed. The analyses also include different operating modes, such as HWC (hydrogen water chemistry) or NWC (normal water chemistry). The studies are thoroughly described in numerous reports /37-4, 37-5, 37-6, 37-7, 37-8, 37-9, 37-10, 37-11, 37-12, 37-13/.

Uncertainties in correlation factors for nearly 40 different nuclides have been quantified in a study based on both statistical methods and qualitative assessments /37-5/. Since the nuclides in the waste have been formed in different ways (activation, fission, transuranics), it is assumed in the study that the activation products correlate to cobalt-60, the fission products to caesium-137 and the transuranics to plutonium-239 and plutonium-240. It was noted in the study that the uncertainty in the correlation factors for a number of nuclides is very great. This is caused to a great extent by a lack of sufficiently good measurement data. The correlation factors are generally estimated to suit all kinds of waste. It is pointed out in the study /37-5/ that in order to achieve greater accuracy, the correlation factors can be made specific for different waste types. The disadvantage is that it is then more complicated to estimate the nuclide inventory.

The sorption coefficient is a key parameter in the models that estimate the transport capacity of the nuclides through the different barriers in a final repository. A study was done concerning the uncertainties of the sorption coefficients of different nuclides in e.g. concrete and bentonite /37-4/. A semi-quantitative approach was used in the study.

Measurements were made on the ion exchange resins at the NPPs in order to estimate the total activity of nickel-59 and nickel-63 that arises during the NPPs' total operating time /37-6/. Based on these measurements, calculations were performed to estimate the total activity content of the ion exchange resins that will be deposited in SFR, assuming that the reactors have an operating time of 40 years (except for Barsebäck 1 and 2). Measurements of the Ni content of PWR waste will continue to be made.

Researchers at Lund University have performed carbon-14 measurements on ion exchange resins and process water systems in both BWR and PWR plants. Carbon-14 has high mobility and is one of the nuclides that must be modelled in scenarios for future releases from SFR, since it makes a dominant dose contribution in a probable future scenario. In order to model future releases and migration of carbon-14 from SFR, satisfactory data on the carbon-14 inventory are needed. The nuclide is difficult to measure in the operational waste, and the inventory has previously been calculated via correlation factors based on cobalt-60. The correlation factors are associated with large uncertainties. Being able to measure carbon-14 directly in the ion exchange resins is therefore of great importance for obtaining reliable data. A new method has been developed where both organic and inorganic carbon-14 can be measured in the ion exchange resins and in the process water systems. The method and the results are described in a report /37-7/. More measurements of carbon-14 will be made in the future to verify the method. Owing to the great uncertainty in the correlation with cobalt-60, carbon-14 will in future be correlated with the energy produced in the power plants and with a factor of produced quantity of carbon-14 that gives the calculated quantity of carbon-14 in the waste.

One of the fission products is iodine-129, which has a long half-life and a low radiation yield on decay. This, combined with low activity in reactor water and waste, means that the nuclide cannot be measured, even with reasonably sophisticated methods. Owing to its long half-life, however, I-129 is of radiological interest in a long-term perspective. A method has been developed for determining activity quantities of iodine-129 in reactor waste. The method is based on the measurable nuclides iodine-131 and caesium-137 in combination with fuel leakage models for BWR and PWR fuel. Based on this, an estimate is made of the accumulated activity of iodine-129 through 2004, and a prediction for reactor operation up to 2020. The correlation factors are derived from previously collected measurement data. The method and the results are described in detail in a report /37-8/.

The model that is used to estimate iodine-129 in the operational waste has been further developed to include the long-lived nuclides molybdenum-93, technetium-99 and caesium-135. A model has been introduced for activation of the corrosion product molybdenum as a source of both molybdenum-93 and technetium-99. The fuel leakage history has been cross-checked against measured values of iodine-131 and caesium-137 in coolant and waste. A cross-check has also been made against measured values of molybdenum-99 and technetium-99 in the coolant. Both of these are parent nuclides of technetium-99. New correlation factors for the aforementioned nuclides have been derived and the results are described along with the estimated activity inventory in a report /37-9/.

A literature review has been conducted /37-10/ for the purpose of updating the correlation factors presented for the final repository for long-lived low- and intermediate-level waste in 1998. These correlation factors have also been used to estimate a reference inventory for the waste deposited in SFR 1. The waste in SFR 1 consists of operational waste such as ion exchange resins and contains no or very little induced activity. A new valuation for Crud was done in the literature review /37-10/. But it should be pointed out that data for ion exchange resins were given higher priority than surface contamination in determining the correlation factors. No studies are included for transuranics and strontium-90.

Researchers at Luleå University of Technology are conducting a study of how concrete and bentonite are affected and degraded by freezing during permafrost. This is interesting in a long-range scenario for SFR. The study is not finished, so no new results can be presented in this RD&D programme.

A literature review has been conducted of how the soil and the rock are affected by permafrost /37-11/. The study started in 2001 and was concluded in 2003. The report summarizes the state of knowledge with regard to permafrost evolution and examines both the occurrence of permafrost and its extent on the surface and in depth. Hydrological issues as well as mechanical and chemical effects are also dealt with.

Another study estimates the uncertainty in the calibration of the hydrogeological model of SFR. One purpose of this study was to see how the calibration affects the mass flow in the different tunnels. Premises and results are described in /37-12/.

In a study conducted for SKB, BRGM in France has developed a model /37-13/ of the geochemical evolution of the multiple barrier system in the silo in SFR. The model will be used in the safety assessment. The calculations were carried out using the PHAST code for 500, 10,000 and 100,000 years.

Chemical degradation of concrete and bentonite are currently being studied, and the study, which is specific for SFR 1, is based on a thermodynamic model. The model takes the influence of the salt water into account. Furthermore it deals with a longer time perspective (the time after permafrost) than previous studies. The study also examines how varying porosity in the concrete and the bentonite affects long-term safety.

The calculation model Amber has been used for the transport calculations in the assessment of long-term safety at SFR 1. Amber is an alternative to the calculation models previously used for SFR 1 /37-14/.

Studies are under way concerning complexation of radionuclides with organic degradation products. Laboratory studies of cellulose degradation and measurement of the complexing strength of the degradation products are being carried out at Chalmers University of Technology. Moreover, development work is being pursued at Enviros in Spain to model the influence of complexing agents on radionuclide release from SFR 1.

Programme

A pilot project for the extension of SFR began during 2007, which will include rock investigations, among other things. There may be a need for research in the pilot project, as well as in a later project phase.

No further research – aside from the already ongoing studies of concrete, complexation and correlation factors – is planned at this point.

38 Strategies for decommissioning

The decommissioning of a nuclear facility begins when the principal activity ceases, with the intention of not being resumed, and continues until the facility is released for unrestricted use and there are no radiological reasons preventing the establishment of another activity on the site. During this interval the licensee must ensure that the facility is maintained in a condition such that man and the environment are protected.

The work of developing strategies to decommission and dismantle the nuclear power plants is being pursued in cooperation between SKB and the licensees. Representatives from SKB and the four nuclear power plants are discussing this in a joint working group. The strategies for decommissioning and dismantling the NPPs will differ between the different facilities. This is in part due to the fact that the NPPs have different owners with differing interests. SKB's task is to coordinate the strategies so that they are compatible with safe and efficient management and final disposal of the resulting waste. The differences in decommissioning strategies are most obvious for the two reactors in Barsebäck that have already been taken out of service. Planning is underway for decommissioning of these reactors. The other units are being modernized instead in order to extend their lifetime beyond 40 years. Forsmark and Ringhals plan to operate their plants for 50 years. The board of directors of OKG has decided that their reactors are to be operated for 60 years.

In this chapter we present three different decommissioning strategies:

- SKB's main strategy, see section 38.1.
- Time for decommissioning, see section 38.2.
- The licensees' strategy, see section 38.3.

38.1 SKB's main strategy

It is important to point out that it is the licensees' own planning that counts in the decommissioning of the nuclear power plants. SKB conducts research on behalf of its owners and has an advisory role in matters relating to strategies, but SKB makes no requirements as to how or when the owners have to decommission their reactors.

This section deals with SKB's main strategy for management and disposal of the radioactive waste arising in connection with the decommissioning of the NPPs.

Kasam pointed out in its review of RD&D-Programme 2004 that decommissioning of nuclear power plants is not controversial from a technical/scientific standpoint. Kasam also pointed out that SKB should present a more in-depth analysis of the reasons behind its planning, for example with respect to interim storage of core components. A clarification from SKB is presented below under the heading "Programme".

In its review of RD&D-Programme 2004, SSI stated that decommissioning should begin as soon as possible after shutdown. This is also SKB's and the licensees' strategy, with deference to the fact that a final repository must be available for most of the waste. SKB and the licensees wish if possible to avoid interim storage of large volumes of decommissioning waste pending the completion of a final repository.

SSI also believed that SKB should intensify its work with decommissioning so that detailed plans and strategies can be presented in RD&D Programme 2007. The decommissioning plans the reactor owners are obliged to prepare should thereby be taken into consideration, for example with respect to analysis of the plant's status, activity content and competence in decommissioning matters. Finally, SSI considered that it should be a condition for SKB's continued activities that a better account of strategy and timetables for decommissioning and disposal of decommissioning waste be produced for RD&D Programme 2007, including plans for a near-surface repository, in view of the decision to stop operation of Barsebäck 2.

Planning

Extensive work has been devoted over the past few years to the development of decommissioning and dismantling strategies in the nuclear power industry's joint project Skapa. The results of this work have been summarized in /38-1/.

SKB's and the licensees' strategy is to start dismantling a plant as soon as it has been taken out of service (deactivated) and the resulting waste can be sent to an approved final repository. In this way a long period of shutdown operation is avoided. In order for this to be possible, SKB plans to extend SFR to be able to receive short-lived low- and intermediate-level waste from the decommissioning of the units. The extension of SFR will be finished in 2020. The main strategy can thus not be applied to the Barsebäck plant.

A pilot project for the extension of SFR began during 2007. The plan is to extend the facility in two stages. The first stage will accommodate the decommissioning waste from Barsebäck 1 and 2. Special agreements may be signed for disposal of the waste from the Studsvik R2 reactor and the Ågesta reactor. The initial phase will also accommodate the increased quantity of operational waste that arises when Forsmark, Ringhals and Oskarshamn extend their operating times.

Rock investigations will be commenced in the vicinity of the existing facility in 2008 in order to find out more about the structure of the rock. The rock investigations will be finished in 2010. The results will serve as a basis for the decision on where to locate the stage 1 extension.

The licensing work, including the work of producing the preliminary safety analysis report (PSAR), will begin at the same time as the rock investigations. The same applies to work on the environmental impact assessment, and on design and a construction plan. Co-review and completion of the documentation for the licensing work and the environmental impact assessment will be done in 2013, according to the plan. Then an application for a permit for the extension can be submitted to the authorities.

An approval for start of construction is expected some time in 2015–2016. The work with the extension can thereby start in 2016 and will take an estimated four years. The extension can be divided into the following steps: procurement of contract, blasting, excavation, installation and interconnection of systems with existing SFR. The trial operation of the extended SFR is planned to start no earlier than the end of 2019, while the start of routine operation is planned to take place in 2020.

The timetable for the extension makes no allowance for delays due to postponement of the building permit or the operating licence due to possible appeals. The time for the second stage of the extension has not yet been determined, but with an operating time of the NPPs of 50–60 years followed by immediate dismantling the extension should be finished by around 2030.

Long-lived waste is stored today in pools in Clab. Interim storage of core components in Clab is expensive and takes up space which could instead be used to store spent nuclear fuel. Long-lived waste, such as core components from both operation and decommissioning of all nuclear power plants, is therefore planned to be placed in dry interim storage in a facility called BFA (rock cavern for waste) on the Simpevarp Peninsula. OKG is already using BFA today for dry interim storage. Under an agreement, SKB is entitled to use part of the space in BFA. In order for the facility to be permitted to receive core components from other nuclear power plants than Oskarshamn, it must be relicensed. OKG is handling this, since they currently have the operating licence for interim storage of waste in BFA.

The key issue relating to interim storage of core components is the development of a new type of waste transport container: ATB-1T. This is time-critical for when the transport and reception of core components from other NPPs than Oskarshamn can get started. According to the plans, interim storage of core components cannot start until 2011 at the earliest.

The long-lived low- intermediate-level waste will be stored in BFA until the repository for low- and intermediate-level waste (SFL) is finished. This facility is expected to be ready for operation in 2045 at the earliest, when most of the Swedish NPPs will have been dismantled. The decision on where SFL will be built will be made in a couple of decades.

When it comes to dismantling and disposing of free-release and conventional waste, the question lies beyond SKB's undertaking for its owners. SKB therefore has no strategy for this. It is up to the licensees whether they want to dismantle the non-active components as well, and if so when.

38.2 Time for decommissioning

Barsebäck 1 was shut down on 30 November 1999 after a settlement was reached between the state, Vattenfall and Sydkraft. Just after RD&D-Programme 2004 had been published, the Government decided that Barsebäck 2 should also be shut down. This finally took place on 31 May 2005. Following the shutdown of both reactors at the Barsebäck plant, as well as the shutdown of the Studsvik R2 reactor on 15 June 2005, the regulatory authorities have addressed the question of the decommissioning and dismantling of the nuclear power plants.

In their review of RD&D-Programme 2004, the regulatory authorities emphasized that leading up to RD&D Programme 2007, SKB should put a great emphasis on questions relating to decommissioning and decommissioning waste. The Government's decision regarding RD&D-Programme 2004 states that a study should be conducted to determine the shortest time required to begin a licensing process for final disposal of decommissioning waste. The following section contains an assessment of the scenarios that lead to the quickest possible disposal of decommissioning waste.

The Government said that SKB should review the reasons for waiting to build a final repository for long-lived waste until most of the power plants have been decommissioned. The final repository for long-lived low- and intermediate-level waste (SFL) is expected to be finished in 2045 at the earliest, according to SKB's main timetable. SKB does not believe there is any reason to begin the construction of the final repository for long-lived low- and intermediate-level waste today, since the waste volumes are still small and the facility will be the last of SKB's facilities within the LILW programme in operation. Early construction is judged to result in an unjustifiably long operating time.

SKI observed that the short-lived decommissioning waste from the Barsebäck reactoris probably covered by already approved type descriptions for waste intended for SFR. SKB shares this opinion. However, the concession and licence for SFR 1 only apply for operational waste today. The facility must therefore be relicensed to receive decommissioning waste, even though the waste as such conforms to existing type descriptions.

The preliminary timetable for extending SFR to receive decommissioning waste contains no margins for allowing start of operation before 2020. In order to be able to start decommissioning of Barsebäck earlier than 2020, an alternative scenario proposed by SSI is that SKB relicense SFR 1 now to receive decommissioning waste from Barsebäck even before SFR is extended.

Since Barsebäck's share in the existing SFR 1 is not enough to accommodate more than a fraction of the radioactive decommissioning waste that is expected to be produced by decommissioning, Barsebäck would need to lay claim to other stakeholders' shares. It is not realistic to expect other stakeholders to abstain from their shares in SFR. These shares are intended for operational waste, which could lead to undesirable consequences for the operation of the units in Forsmark, Oskarshamn and Ringhals in the event of a delay in the start of operation of the extended repository.

Only waste that has been treated and packaged in a manner that is not necessary for most of the decommissioning waste may be deposited in the chambers in SFR where disposal is possible. The result is a longer time for decommissioning and higher radiation doses to the personnel than with the planned design of the decommissioning projects.

Another scenario that would permit the dismantling of Barsebäck 1 and 2 to be started before 2020 is to build a temporary interim storage facility for decommissioning waste, before the extension of SFR is finished. The most time-consuming factor leading up to the construction of an interim storage facility is licensing. According to a study presented for Barsebäck, licensing and construction of an interim storage facility for decommissioning waste would take roughly the same length of time as relicensing and extending SFR. The possible time saving is estimated to be about one year /38-2/. Another factor to be taken into consideration if it is decided to build an interim storage facility is that the environmental impact is greater due to the fact that the number of shipments is far greater. The waste must first be transported to the interim storage facility and then further from there. The construction of an interim storage facility, followed by decommissioning and dismantling a few years later, also leads to an extra environmental impact.

SKB's assessment is that the fastest possible alternative, taking into account Alara and BAT, for disposing of the radioactive decommissioning waste is SKB's main strategy, which is described in section 38.1. According to this strategy, the short-lived decommissioning waste can begin to be disposed of in 2020 and the long-lived waste can begin to be interim-stored in BFA at the end of 2011, at the earliest.

38.3 Licensee strategies

The current general strategy for decommissioning the nuclear power plants is described below. This strategy may very well be modified and above all be defined in greater detail in the future.

In its review of RD&D-Programme 2004, SKI emphasized that it is it is essential for the parties involved in decommissioning to conduct an active and progressively in-depth dialogue over the next few years. SKB agrees with this. An decommissioning group with participants from all nuclear power plants and SKB has existed since the early years of this century.

SSI was of the opinion that the licensees should not rule out the possibility that the facility sites will be able to be completely remediated and then released for unrestricted use. SKB believes that this is a strategy issue for the licensees. After the buildings and the land have been released for unrestricted use, it is up to the licensees how they want to utilize the remaining buildings.

SSI found that the account should be augmented with the planning and measures for which the power plants bear individual responsibility. The account is clarified in this RD&D-programme.

SSI desired clarification as to how the licensees intend to carry out decommissioning and dismantling, and how they intend to manage the large quantities of waste. SKB believes that it is a strategy issue for the licensees how they want to carry out their decommissioning. The same applies to the large quantities of non-active waste that SKB does not dispose of.

Planning

The goal (and requirement) when the nuclear power plants are decommissioned is to remove radioactive material and remediate the facility to a state such that it can be released for unrestricted use. This is achieved when there are no longer any regulatory restrictions on the use of land or buildings. This means that the entire facility, i.e. buildings with all equipment and land, will be released from regulatory control.

The common goal of the power utilities with regard to the decommissioning of the nuclear power plants is that the site should be used for energy production after decommissioning. This is the best way to make use of the extensive and valuable infrastructure with power lines, roads, harbours, cooling water channels etc. Buildings should also be left standing after they have been released for unrestricted use and exempted from the requirements of the Nuclear Activities Act. They can be utilized for other purposes on the site.

The power utilities (except Barsebäck) base their strategy and planning on the premise that they will operate the power plants as long as there is no competitive alternative technology and as long as there are no financial or safety-related reasons to start decommissioning. The planning today is that Forsmark and Ringhals will operate their plants for 50 years and OKG for 60 years.

Decommissioning of a unit is not begun until adjacent units with common buildings and/or systems have been taken out of service. The following units have common buildings and/or systems: Barsebäck 1 and 2, Forsmark 1 and 2, Oskarshamn 1 and 2, Ringhals 1 and 2 and Ringhals 3 and 4. Dismantling will then begin as soon as possible after the spent nuclear fuel has been removed from the last unit to be shut down. Alternatively, the common units' operating time will be adjusted so that they are taken out of service at the same time in order to avoid a long period of shutdown operation.

Dismantling is assumed to take place after a relatively thorough decontamination of the facility's process systems. This is done to reduce the radiation dose to the personnel. If the plant has low radiation levels from the start, this system decontamination may possibly be omitted. This is a judgement that has to be made for each nuclear power unit from an Alara standpoint. When dismantling is begun, it is assumed that system dismantling is done first and that this takes at least three years. Then buildings are decontaminated and contaminated building parts are dismantled, after which the site can be released for other use. With a dismantling period of about five years, a unit can be expected to be released for other use about seven years after shutdown. This is assuming that there are no other adjacent units in operation, in accordance with what is said above.

38.3.1 Barsebäck

With the shutdown of Barsebäck 2 on 31 May 2005, all units at Barsebäck have been deactivated. Barsebäck 2 officially entered into shutdown operation on 1 December 2006 when the last spent nuclear fuel was shipped to Clab. A new SAR (safety analysis report) and a new STF (safety-related technical specifications) for shutdown operation have been submitted to the regulatory authorities and are thereby in effect. Approximately five persons are working with decommissioning planning at Barsebäck today.

Shutdown operation will continue until around 2017, when there will be a transition to dismantling operation via a period for re-establishment operation. Preliminary design for decommissioning will start at the same time. The long period of shutdown operation is due to the fact that the final repository for decommissioning waste will not be ready until 2020.

Since both Barsebäck 1 and Barsebäck 2 were deactivated before their technical lifetime was over and are not earning any revenues, the state, together with the Nuclear Waste Fund, is financing defuelling operation and shutdown operation. This financing will cease in 2015 for Barsebäck 1 and 2017 for Barsebäck 2. After that, Barsebäck will use funds from the Nuclear Waste Fund to finance further shutdown operation and then re-establishment and dismantling operation.

Barsebäck has received an environmental permit for shutdown operation. This permit is valid until 2012. A new court process is then required to renew the permit. According to the current environmental judgement, Barsebäck may not be dismantled. An application for dismantling must first be submitted to the regulatory authorities. A new permit review procedure in the Environmental Court is also required.

The dismantling of Barsebäck 1 and 2 will probably be conducted as a common project. The final goal is to release the facility for unrestricted use or to remediate the site. This has not yet been decided.

The timetable for dismantling Barsebäck 1 is 2020–2026. For Barsebäck 2 the timetable for dismantling is 2020–2028. Parts of the work will take place simultaneously at both units.

39 Division of responsibilities for decommissioning

One of the most important comments made in the regulatory review of RD&D-Programme 2004 was that the division of responsibilities between SKB and the individual licensees for the nuclear power plants should be clarified and specified, with respect to the choice of methods both for decommissioning and waste management and for cost estimates. Another comment was that it should be clarified that SKB's responsibility only includes disposing of the radioactive waste for which the power utilities do not choose their own solutions, such as near-surface repositories and interim storage facilities.

A clarification is given in this RD&D programme as to how responsibility is divided between the licensees and SKB when it comes to decommissioning, dismantling, waste management and cost calculations.

According to Section 10 of the Act (1984:3) on Nuclear Activities, the licensees for the nuclear facilities in Sweden shall be responsible for ensuring that all measures are taken that are required for ensuring the safe management and final disposal of nuclear waste arising in the activities or nuclear material arising therein that is not reused. The licensee shall also safely decommission and dismantle plants in which activities are not longer to be conducted.

It is the licensee who is responsible for the decommissioning and is in charge of planning, permits, licences and execution of the dismantling.

SKB is responsible for disposing of the radioactive waste from decommissioning. This means that SKB must transport the waste to a final repository and deposit it there. For this purpose SKB must build a final repository for decommissioning waste, and make any necessary modifications of the transportation system. SKB is also responsible for the transportation and interim storage of core components, and for transporting these core components from the interim storage facility to the final repository. Furthermore, SKB must ensure, in consultation with the licensees, that the waste is treated and packaged in such a way that it is suitable for final disposal.

As a part of the work of gathering background material for general fee calculations, SKB is responsible for carrying out general cost calculations for decommissioning of the Swedish nuclear power plants. This includes gathering material that is of importance for calculating the decommissioning costs. One way this is done is by compiling experience from completed rebuilding projects at the nuclear power plants. SKB also keeps track of global developments in the decommissioning field, including advances in technology, by for example participating in joint OECD/NEA programmes. SKB cooperates with the licensees in gathering background material for cost calculation and estimation of waste quantities and waste types. Through a special decommissioning group, SKB obtains viewpoints and advice regarding the technology and strategy choices we use as a basis for our decommissioning studies.

As the time for decommissioning of the nuclear power plants approaches, detailed unit-specific decommissioning studies will be carried out. This is the case with the decommissioning of Barsebäck today, for example. SKB can be used as a resource in the detailed planning work.

40 Technology for decommissioning

This chapter describes the planning for unit-specific decommissioning studies plus a summary of a completed detailed decommissioning study of Oskarshamn 3, where different techniques for decommissioning are described.

40.1 Unit-specific decommissioning studies

SKI emphasizes that it is important that total decommissioning studies be carried out so that detailed calculations of decommissioning costs are available for each individual power plant by 2010.

Unit-specific decommissioning studies concerning waste quantities, waste types and activity contents are needed for planning the extension of SFR, modifying the transportation system, and for the safety assessments that will accompany the extension permit application that will be submitted in 2013. With the previous wording of the Financing Act calling for an earning time of 25 years, it was also worthwhile to perform cost calculations for dismantling at an early stage. But with the current wording of the Act, there is no need for detailed cost calculations before deactivation of a unit.

After RD&D-Programme 2004, SKB ordered a detailed decommissioning study of Oskarshamn 3, which is intended to be a reference plant for the BWR units. The study was carried out by Westinghouse Electric Sweden /40-1/. The decommissioning study presents different techniques for dismantling, resulting waste quantity and activity quantities. Timetables and cost calculations for decommissioning are also presented. The study is described in section 40.2.

Planning

SKB and the power utilities will carry out plant- and unit-specific decommissioning studies aimed at providing more reliable and detailed data for estimating the waste volumes and activity quantities from the different nuclear power plants. The studies will be prepared on an individual basis and will, in the case of the BWR plants, be based on the detailed study that has been carried out for the reference plant, Oskarshamn 3. The investigations will be adapted to the specific conditions prevailing at other power plants with regard to the physical design of the plants and the licensees' plans for decommissioning their own plants. An update of the existing study for Ringhals 2 /40-2/ will serve as a basis for the PWR plants.

Studies of this kind are intended to reflect current knowledge and planning. In all likelihood they will be subject to adjustments and revisions when more experience becomes available and when the licensees' decommissioning plans have been concretized.

40.2 Reference study

A detailed decommissioning study of Oskarshamn 3 /40-1/ has been carried out. It is intended to be a general decommissioning study for the BWR units and can easily be adapted to other BWR plants by adjustments of unit-specific input data.

40.2.1 Premises of the study

The study includes an estimate of the plant's inventory (both contaminated and non-contaminated material), a radiological survey of the plant, available techniques and procedures for dismantling, and a calculation of the expected costs. Systems that are common with other units in Oskarshamn are not included in the study.

Two different strategies are discussed when it comes to dismantling of the reactor vessel. One is to segment the reactor vessel into parts that can be transported and disposed of like other decommissioning waste. The other is to remove the reactor vessel from the reactor building intact and transport it as a single package. The study only analyzes the alternative of segmenting the reactor vessel.

The costs of decontaminating the components are compared with the cost of disposal. The assumption is that moderate decontamination measures are carried out. It is assumed that large components and building parts with smooth surfaces are contaminated, while smaller objects with more complex geometries are not decontaminated at all, but transported to the repository. A complete survey of different systems and the radioactive inventory in the plant is also presented in the study. It is assumed that repositories and landfills are available to receive the resulting decommissioning waste. It is assumed that an interim storage facility is available for long-lived core components.

40.2.2 Operating phases

The study covers all operating phases, from final shutdown of the plant until the buildings have been decontaminated and released without restrictions for other industrial use ("free release").

The operating phases identified in a decommissioning study for Oskarshamn 3 /40-1/ follow SKB's decommissioning scenario /40-3/ and are defined below. The different techniques used in the different steps are described in section 40.2.3.

Defuelling operation

The period from final shutdown of the unit until all fuel has been removed from the unit. In this operating phase the unit is adapted to new requirements, for example the plant is relicensed (new safety analysis report), after which it goes into shutdown operation. A reorganization is also carried out in this phase in preparation for shutdown operation and dismantling operation.

Shutdown operation

Shutdown operation begins when all the fuel has been removed from the unit and lasts until more extensive dismantling of process systems and plant components begins.

Re-establishment operation

Re-establishment operation begins when the unit is prepared for dismantling after a long period of shutdown operation. Re-establishment operation involves checking and upgrading the process systems etc that are to be used during the next stage: dismantling operation. Examples of systems that may need to be upgraded are hoists, overhead cranes, water, compressed air, electric power supply, purification and ventilation systems. Re-establishment may not be needed if shutdown operation has been of short duration.

Dismantling operation

Dismantling operation is the operation of the unit during the period from the start of physical dismantling until free release of the entire unit.

Site remediation

The licensees make the decision as whether to demolish buildings. The demolishing is dependent on what activity is planned for the site. It is assumed that energy production will continue, since the infrastructure already exists, for example power lines and roads.

The period includes conventional demolition of buildings and remediation of the site.

In the decommissioning study for Oskarshamn 3 /40-1/ it is assumed that defuelling operation lasts for two years and that shutdown operation, including re-establishment, lasts for three years. This means that dismantling of the plant begins five years after the unit has been taken out of service. There is some overlap between active and non-active dismantling in order to shorten the dismantling time.

40.2.3 Technical solutions

The technical solutions presented in the decommissioning study for Oskarshamn 3 /40-1/ for decontaminating and dismantling different systems, components and buildings are summarized in this section. The philosophy adopted in the study is that only proven existing techniques will be analyzed. This is so that SKB and the utilities can be confident that the described technique really works and so that time and money does not have to be spent on developing tools and methods to be used for dismantling. In some cases the most appropriate technique for dismantling an item will be the same technique as was used for maintenance when the plant was operational.

Decontamination

The first step prior to dismantling/demolition is a chemical decontamination of the primary systems. This is done from an Alara viewpoint in order to minimize the radiation dose to the decommissioning personnel. The decontamination techniques used after the unit shutdown are much more aggressive than the methods used during the operation of the unit. The reason a more aggressive method is not used during operation is that it degrades the pipe systems. Thin layers of the pipes and any corrosion protection disappear, which is naturally not acceptable during plant operation. The advantage of an aggressive method is that decontamination is more effective.

Reactor internals segmentation

Segmenting and removing the reactor internals is one of the most time-critical steps in the decommissioning project. For this reason it should be completed as quickly as possible. At the same time, the Alara principle must be taken into consideration.

Different segmentation methods must be used, since the geometries of the reactor internals differ. Furthermore, the activity levels are relatively high, so that segmentation must take place with remote-controlled tools under water.

Reactor vessel

There are two strategies for dealing with the reactor vessel:

- Lift out the reactor vessel in one piece and then transport and deposit it in the repository as a separate package.
- Segment the reactor vessel and transport it in parts like other dismantling material to a final repository.

The strategy chosen depends above all on the size of the reactor vessel (bigger in BWR) and the feasibility of lifting the reactor vessel out of the reactor building. The feasibility of transporting the reactor vessel in one piece to a final repository that can receive a package of this size is also an important consideration. In most decommissioning projects carried out in the USA, the reactor vessel has been removed in one piece. In the decommissioning study for Oskarshamn 3, the strategy chosen was to segment the reactor vessel and remove it in parts.

Pipe cutting

A number of techniques are available for pipe cutting. The preferred method will generally be selected on the basis of the radiological condition of the pipe to be cut and the working area around it. For higher dose rate areas it is generally preferable to use techniques that can be quickly set up on the pipe and then remotely operated by the decommissioning personnel from a lower dose rate area. For lower dose rate working areas contact working methods are acceptable.

Other steelwork

The location and shape of the object to be cut will determine which method is most appropriate. Some steelwork items may best be removed by dismantling them in the same way they were once assembled, particularly items such as stairs and platforms. The advantage of dismantling these parts is that it can save time and does not give rise to any secondary waste in the form of metal chips from the cutting operation.

In the case of surface contaminated steelwork, sprayed coatings may be applied to fix contamination prior to dismantling in order to minimize generation of airborne contamination.

Ventilation ducts

Contaminated ductwork will be sprayed with contamination fixing spray coatings and then dismantled by removing bolts and rivets. The removed sections will then be crushed flat before being packaged. The duct sections will only be cut when their size or geometry makes them too big for packaging in the selected container in one piece.

Cables

Special cable cutters will be used to cut cables into suitable lengths. Since cables contain material of great value, much of the material will go to recovery and recycling. Cables in plant parts with high contamination can be recovered after the protective plastic insulation has been removed from the copper conductors.

Concrete surfaces

At various places within the power plant the concrete will be contaminated, and in some cases the contamination may have penetrated into the concrete. In these cases the concrete surface must be removed for controlled disposal. It is generally very difficult to clean contaminated concrete surfaces. Previous decommissioning projects have made use of techniques where the surface of the concrete is removed to such a depth that the remaining concrete is not radioactive. The remaining concrete can then be demolished using conventional techniques. During the dismantling phase, two main categories of techniques will need to be employed to remove the concrete surface:

- Techniques that remove the contaminated surface layer of concrete until the clean concrete beneath is revealed.
- Techniques that remove bulk concrete, for example in cases where the contamination is sufficiently deep that all or a much of the concrete volume must be removed.

Demolition

It is assumed in the study that all buildings, both contaminated and clean, are demolished using similar techniques. Contaminated buildings will first be cleaned and then demolished using conventional techniques.

Buildings will first be stripped of easily removed recyclable material. The concrete building parts will be demolished in the conventional manner. Parts of the crushed concrete waste will be used to fill below-ground voids or transported off site as required.

Steel frame buildings represent an opportunity for relatively easy metals recycling and these will be demolished using mobile cranes, machine excavators and thermal/mechanical cutting tools.

Explosive demolition techniques may offer a safer demolition option on some taller structures, but may not be acceptable due the presence of other nearby facilities.

40.2.4 Doses to decommissioning staff

Under contract to SKB, TLG has carried out a study of doses to personnel in connection with the decommissioning of a nuclear power plant. TLG Service Inc. has been involved in the decommissioning planning for a number of nuclear power plants in the USA. They have also participated in the decontamination and dismantling work at three reactors in the USA. Their experience from the USA has been applied to Swedish conditions. Plant data regarding layout, activity content and dose rates have been taken from Barsebäck. TLG's study is based on more empirical data than other companies can offer.

As a basis for the study it has been assumed that Barsebäck 1 has been out of service for about 20 years when dismantling begins. The equivalent time from shutdown for Barsebäck 2 is about 16 years. The radiological survey that has been conducted for unit 1 has generally been considered to apply to unit 2 as well, with correction for different decay periods.

The approach in the study has been that doses to decommissioning personnel can arise in eight different stages during the dismantling phase:

1. Dismantling of components.
2. Dismantling and segmentation of reactor internals and reactor vessel.
3. Dismantling of the biological shield.
4. Dismantling of the lining in the fuel storage pools.
5. Decontamination of concrete surfaces.
6. General work access to active areas (this phase is related to component dismantling).
7. Waste management.
8. Project management and surveillance. Doses in this phase come mainly from surveillance rounds and inspections of the dismantling work.

Summation of radiation doses to staff

Based on experience from decommissioning of nuclear power plants in the USA and data from Barsebäck, the total radiation dose to the decommissioning staff is estimated to be between 2 and 3 manSv if the nuclear power plant has been out of service for a long time (15–20 years) and dismantling is carried out using current techniques. If dismantling is carried out after a shorter post-shutdown time, the radiation doses will be higher, which can be compensated for by decontamination of system surfaces prior to dismantling. In SKB's early decommissioning studies with limited access to experience values, the radiation dose was estimated to be over 12 manSv.

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Chapter 27

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Appendix A

Canister for spent nuclear fuel – design premises

A1 Design premises

SKB has presented a new edition of the design premises for the canister /A-1/ describing status and state of knowledge. In view of the importance the regulatory authorities have attached to design premises and design basis data in the review of RD&D 2004, important parts of SKB's new edition of the design premises are presented in this appendix. In some cases, information has been corrected in the light of the current state of knowledge (section A1.3.3 with regard to particles from the welding tool, section A1.4.2 with regard to tensile stresses during the water saturation phase and section A1.4.4 with regard to newer calculations of the strain in the insert). The programme for the continued work is presented in section 14.2 in Part III.

A1.1 Design of the canister

SKB's reference canister consists of an outer corrosion barrier of copper and a loadbearing insert of nodular iron. The canister is available in two versions: one that holds twelve BWR assemblies and one that holds four PWR assemblies. The detailed design is described in SKB's quality and environmental management system for canister fabrication /A-2/.

The performance requirements that determine the design of the canister and the choice of materials are:

- The canister must contain and prevent the dispersion of radionuclides from the spent nuclear fuel.
- The canister must resist the corrosion attacks expected in the final repository.
- The canister must resist the loads expected in the final repository.
- The canister must have negligible thermal, chemical and mechanical effects on contribution made by the other barriers and the fuel to isolation and retardation.
- The canister must be able to be transported, deposited and otherwise handled in a safe manner.

Furthermore, canisters with specified properties must be able to be fabricated, sealed and inspected with high reliability in production, and their properties must be able to be tested against specified acceptance criteria.

How these requirements have been taken into account in designing the canister's copper shell and insert is explained below.

A1.2 Contain the fuel

The canister is supposed to contain the spent nuclear fuel and prevent radioactivity from leaking into the environment. The canister will hold the different types of spent nuclear fuel included in the Swedish nuclear power programme, and the geometry of the fuel assemblies is the basis for determining the size of the channels for the fuel assemblies in the canister.

The design basis for the permissible decay heat in the canister is that the chemical stability of the bentonite buffer must be maintained. A requirement on maximum temperature on the canister surface after deposition is a determining factor for the encapsulation process (permissible decay heat of the encapsulated fuel) but not for the design of the canister.

A1.3 Chemical resistance during repository lifetime

A1.3.1 Overview of repository evolution

Three characteristic climate domains are expected to occur during the period the repository must function. These climate domains affect the environment at repository depth and thereby the chemical resistance of the canister. They are described in brief below.

The temperate/boreal domain is the period during which the climate gradually changes. During this domain, changes in the shoreline comprise the important process for groundwater composition.

The permafrost domain entails a lower water flux than under current conditions. Salt exclusion and a low water flux can together lead to a considerable increase in the salinity of the groundwater /A-3, A-4/.

During the glacial domain the groundwater flow is controlled by the ice sheet and its extent. This will drive glacial meltwater down to great depths. Calculations show that it is possible that glacial meltwater will reach repository depth. Calculations also show that the redox-buffering ability of the water will ensure that only oxygen-free water reaches repository depth /A-5, A-6/.

A1.3.2 The copper canister in the final repository

The groundwater at repository depth will be oxygen-free and reducing, except during the operating phase and for a relatively short period thereafter. Copper is immune to corrosion in pure oxygen-free water. In order for copper to corrode in aqueous solutions, the presence of dissolved oxygen, high chloride concentrations, low pH or dissolved sulphide is required.

The canister is surrounded by compacted bentonite. Since bentonite does not contain any chlorine-containing minerals of importance, the chloride content of the groundwater will determine the chloride content of the bentonite as well. Nor are the sulphide concentrations expected to be higher than in the groundwater, and the pH is expected to lie in the interval 7–9. Even at the highest expected chloride concentrations, copper is immune to chloride corrosion at the expected pHs.

During the initial phase until oxygen-free conditions are reached in the repository, only insignificant aerobic corrosion of the copper will occur, equivalent to a material loss of three microns. This process is a crucial factor for the design of the canister. After the oxygen has been consumed, corrosion (anaerobic corrosion) will be completely controlled by the supply of dissolved sulphide to the canister. With the model /A-7/ that was used in SR-Can /A-8/, the corrosion loss on the most exposed parts of the canister is calculated to be less than six millimetres.

In view of the fact that FSW welds do not have a different corrosion potential with oxygen present, galvanic corrosion can be ruled out even under anaerobic conditions.

An interaction of several parameters is required in order for *stress corrosion cracking* to occur /A-9, A-10/. Two necessary parameters are specific chemical conditions combined with tensile forces in the canister surface. It is highly unlikely that stress corrosion cracking could occur under repository conditions /A-4/, which means that *stress corrosion cracking* is not a design-basis process for the canister.

After water saturation, *radiolysis* of water will occur near the canister. The permissible surface dose rate is therefore limited to a maximum value of 1 Gy/h. The reference canisters (for BWR and PWR assemblies) meet the surface dose rate requirement.

Uncertainties

Uncertainties in models are discussed in SR-Can, especially with regard to bentonite erosion and its consequences for anaerobic corrosion. Further knowledge is needed on bentonite erosion before these uncertainties can be eliminated.

Conclusions

With current knowledge, *anaerobic corrosion* is a design-basis process for the copper canister, and the copper cover must be at least six millimetres. The scratches and other geometric deviations in the surface of the copper shell that can arise during working or handling of the canister do not affect anaerobic corrosion. There is therefore no reason to stipulate requirements on, for example, the permissible depth of scratches and dents from a corrosion point of view, as long as they do not risk penetrating the copper shell to a depth equivalent to the minimum permissible corrosion barrier (six millimetres).

A1.3.3 Materials – the copper shell, corrosion aspects

Anaerobic corrosion is a crucial process for the choice of copper grade. Copper with low oxygen content should be chosen to eliminate the risks of intergranular corrosion due to oxide segregations in the grain boundaries. To ensure sufficient chemical resistance, the oxygen concentration must be kept below 30 ppm. For the same reason the copper must have low concentrations of impurities that could corrode selectively or segregate to the grain boundaries and increase the risks of intergranular corrosion. Here as well, the maximum permissible concentrations of aluminium, cobalt, chromium and nickel are 30 ppm. SKB has chosen friction stir welding (FSW) as a reference method. As regards weldability with FSW, no additional requirements on the copper material can be derived beyond those discussed above. If FSW is done in air, the oxygen concentration in the weld metal may increase, and this has been demonstrated in the form of oxide particles /A-11/. Tests with welding under shielding gas (argon) show that the oxide particles can be almost completely eliminated. Small quantities of metal from the welding tool have also been observed in the weld. The impurities detected are aluminium, cobalt, chromium and nickel, and the concentrations are at most a few tens of ppm. However, it has not been clarified whether the impurities occur as discrete microinclusions or dissolved in the copper.

A few particles from the tool on the weld surface will not affect the life of the canister. Selective (galvanic) corrosion will probably consume these particles, and the loss of corrosion barrier will be completely negligible. Studies at Kimab /A-12/ have shown that the corrosion potential of the weld does not deviate from that of the parent metal even under anaerobic conditions. The small quantities of impurities from the welding tool will thus not degrade the corrosion properties of the weld or give rise to galvanic corrosion of the weld. Recent findings show that leakage of alloying elements from the welding tool into the copper material can be eliminated by coating the probe with a ceramic layer, see section 14.5.1 in Part III.

A1.3.4 The insert in the final repository

The insert is protected by the copper shell as long as the latter is intact. Nevertheless, some chemical effects on the insert may be caused by the fact that small quantities of water can accompany the fuel at encapsulation. If there is air in the canister, radiolysis reactions between the water and the nitrogen in the air can form nitric acid. The acid can cause stress corrosion cracking. The canister is therefore designed so that the air in the insert can be exchanged for an inert gas, for example argon. Any residual oxygen and water in the canister will be consumed by corrosion of the iron. When the oxygen is consumed, hydrogen will be formed by anaerobic corrosion by the water. Investigations are being conducted to clarify whether the hydrogen affects the properties of the canister materials.

Uncertainties

Additional knowledge is needed regarding the presence of water in the fuel and the effects of hydrogen on the canister materials in order to rule out the possibility that chemical processes could affect the insert.

Conclusions

Changing the atmosphere in the insert prevents stress corrosion cracking.

A1.3.5 Materials – the insert, corrosion aspects

No material requirements are made on the insert from the corrosion viewpoint.

A1.4 Mechanical resistance

A1.4.1 Repository evolution, overview

The canister is part of a complex mechanical system in the final repository. Climate changes on the Earth's surface such as glacial cycles affect the canister both mechanically and hydraulically. Nearest the canister is a chemical/mechanical buffer consisting of 35 centimetres of bentonite, which causes mechanical stresses on the canister when it swells.

The evolution of the mechanical stresses on the canister can be divided into the following phases:

- Water saturation phase.
- Temperate/boreal phase and permafrost phase.
- Glacial phase.
- Postglacial phase.

The water saturation phase begins immediately after deposition. A pressure build-up then occurs around the canister due to increasing groundwater pressure and swelling bentonite. The groundwater pressure is dependent on the repository depth. The inflow of water into the deposition holes causes the bentonite to swell. The swelling pressure that is built up depends on the density of the buffer /A-13/.

The temperate/boreal phase and the *permafrost phase* that follow the water saturation phase provide stable mechanical conditions for the canister. However, certain pressure differences may exist after the water saturation phase due to uneven swelling of the bentonite and the possible influence of the geometry of the deposition hole.

The glacial phase, ice formation, causes a slow isostatic pressure build-up in the repository. This pressure increase depends on the thickness of the ice, which in turn depends on the geographic location of the repository and climatological factors. The maximum isostatic pressure on the canister will be 45 MPa for the Forsmark case and 42 MPa for the Laxemar case, based on the thickest ice sheet that has existed over the past two million years (the Saale Ice Age) /A-8/.

The postglacial phase entails a slow pressure decline in the repository back to the conditions that prevailed before the glacial phase. When the rock is unloaded, earthquakes can occur under certain conditions, which can affect the canister mechanically. An earthquake can cause existing fractures intersecting deposition holes to be activated and sheared. An earthquake with a magnitude of six causes a shear movement through a deposition hole of 0.1 metre /A-8/.

A1.4.2 The copper canister in the final repository

Stresses on the copper shell are ultimately determined by the processes in the repository, but the design of the canister must also be taken into consideration when determining these stresses.

The pressure build-up during the water saturation phase causes the copper shell to be deformed up against the insert. The size of the plastic and/or creep strains to which this gives rise depends on the size of the gap between the copper canister and the insert. Due to manufacturing tolerances, the radial gap between the insert and the copper canister does not exceed 1.75 millimetres. The strain to which the copper shell is subjected amounts to 4 percent.

The calculations have been performed for a canister whose ends are fixed by the bentonite and under the pessimistic assumption that the supply of water only took place on one side of the canister. The uneven swelling then led to local tensile stresses in the copper shell of up to 59 MPa /A-14/, i.e. local plasticization of the copper shell. Experience from the Prototype Repository and the Canister Retrieval Test in the Äspö HRL can lead to more realistic scenarios for uneven swelling of the bentonite than the one used in the analysis /A-14/.

Shear movements in the deposition hole in connection with postglacial earthquakes can affect the copper shell. After the initial plasticization of the buffer/canister system, a recovery occurs due to creep. Calculations /A-13, A-15/ show that 0.1 metre of shear with a shear rate of 1 metre per second and a bentonite density of 2,000 kg/m^3 gives an initial plastic strain in the copper shell of 7 percent. A pessimistic estimate of the creep strain in the copper shell gives a result of 7.7 percent.

Shear of deposition holes is a design-basis process for the copper material that requires a plastic strain of 7 percent and a creep strain of 7.7 percent.

Uncertainties

The input data that have been used regarding pressure differences in the deposition hole, caused by uneven water inflow in the deposition hole, as well as the distribution of the density of the bentonite are conservative, and in some cases very conservative (very improbable). As a result, the calculations of the stresses on the canister must include the plasticity of the bentonite and are thereby complicated and associated with greater uncertainty.

As far as calculation of isostatic glaciation loads is concerned, these are conservative but uncomplicated.

A1.4.3 Materials – the copper shell, mechanical properties

The results of creep testing show that modifications of the composition of the oxygen-free copper are necessary in order to achieve satisfactory creep ductility /A-16/. Adding 30 ppm phosphorus increases the creep ductility and creep life of the material. In the case of the phosphorus-containing copper, sulphur concentrations in the interval 6 to 12 ppm and grain sizes in the interval 100 to 800 microns have no measurable effect on creep ductility. Corrosion testing has shown that the addition of phosphorus does not increase the material's susceptibility to grain boundary corrosion (intergranular corrosion), either in the parent metal or in the weld metal /A-17, A-18/.

The copper material must have low concentrations of certain insoluble elements – lead, tellurium, selenium and bismuth – that embrittle copper. The extra requirements in this respect have been taken from the material standards EN 1976 Cu-OFE and EN Cu-OF1. In addition, requirements are made on the hydrogen concentration, since hydrogen can give rise to hydrogen embrittlement at the high temperatures that occur in the hot-forming processes.

In addition to the parent metal, welds made by FSW have also been creep-tested. The creep tests have not revealed any great differences between the weld metal and the parent metal in terms of creep ductility and creep life /A-19, A-20/.

No detectable damage or changes are expected to occur in the canister materials during the life of the canister as a result of radiation from the spent nuclear fuel. The effects of radiation on the canister material can therefore be disregarded in designing the copper shell.

When it comes to the effect of temperature on the mechanical properties of the copper material, uniaxial tensile tests reveal a marginal temperature dependence in the interval 0–100°C, with a gradual decline of yield strength and ultimate strength with increasing temperature, while elongation at break and contraction at break are not affected. Compared with at room temperature, ultimate strength and yield strength decrease by 8 percent at 100°C. If the temperature is instead reduced from room temperature to 0°C, an equivalent increase in ultimate strength and yield strength occurs.

A1.4.4 The insert in the final repository

All phases in the evolution of the repository will cause mechanical effects on the insert: the water saturation phase, the temperature/boreal and the permafrost phase, the glacial phase, and the postglacial phase.

The properties of the bentonite buffer affect the load on the canister. There are two buffer parameters that determine the load transfer in different situations: swelling pressure and shear strength. Both properties are directly dependent on the water saturation density of the buffer.

The wetting of the bentonite buffer during the water saturation phase is expected to occur in such a way that the swelling pressure is built up evenly. However, there is a possibility that some unevenness will be obtained due to uneven wetting, differences in bentonite density or deviations in the geometry of the deposition hole.

The most unfavourable case identified during water saturation is asymmetric wetting so that swelling pressure develops in the buffer at one end of the canister and along one side of the canister, giving rise to a bending moment on the canister /A-21, A-14/. Calculations show that the plastic properties of the bentonite are a limiting factor for the stress in the canister. The largest bending stress in the insert should be less than 55 MPa and is limited by the plasticity of the bentonite. This stress is transient when the wetting of the buffer becomes complete.

However, at present the possibility cannot be ruled out that the density of the bentonite will vary in the deposition hole in the interval 1,950–2,050 kg/m^3 and that the canister will be positioned off-centre or tilted in the deposition hole, and that the deposition hole will have an unfavourable geometry. Even in this pessimistic case, the maximum bending stress is limited by the plasticity of the bentonite to 55 MPa. This stress is regarded as permanent.

Uneven swelling, either temporary during water saturation or permanent, is a design-basis process for the insert and gives rise to a bending stress that has been pessimistically determined to be 55 MPa.

The loads to which the canister will be subjected during the glaciation phase are composed of the hydrostatic pressure at repository depth, the bentonite's swelling pressure and the ice load. The maximum ice load has been pessimistically calculated to be 45 MPa.

The mechanical stress on the canister of a shear movement resulting from postglacial earthquakes is mainly dependent on the density of the buffer and the position of the shear plane, but the shear rate and the size of the shear movement also have a significant effect. Calculations show that with a buffer density of 2,000 kg/m^3 and a shear movement of 0.1 metre, the strain in the insert is less than one percent /A-22/.

A1.4.5 Materials – the insert, mechanical properties

The canister insert is made of nodular iron (spheroidal graphite cast iron). The material in the insert must meet the requirements in "EN 1563 grade EN-GJS-400-15U" (Number EN-JS1072, SS 07 17-00).

The insert's steel cassette, which contains channels for the fuel assemblies, is made of steel plate according to EN 10025 S355J2G3, SS 14 21 72 or a similar grade with at least the same strength and ductility.

The insert will be loaded for a long time. In addition to the strength calculations, a time-dependent mechanical analysis must be done. Time-dependent effects can arise due to creep in the nodular iron or other time-dependent phenomena.

A1.5 Ensure that criticality does not arise

Normal criteria for criticality safety will be applied to the management and final disposal of spent nuclear fuel. The fuel will remain subcritical with the current design of the insert /A-23/.

A possible fabrication defect in connection with welding of the insert is that partition walls contain major discontinuities. It is of interest to study how such discontinuities could affect the risk that criticality will arise. Supplementary calculations will therefore be carried out.

A1.6 Little effect on other barriers

The canister must not affect the final repository's multiple barrier system. The cases where effects on other barriers are considered to be possible are radiation effects and thermal effects on the buffer.

The canister must provide adequate radiation attenuation so that the bentonite buffer and the water chemistry in the near field are not affected by radiation. Radiation can cause radiolysis of water or humid air before water saturation. With the limitations provided by the decay heat and the canister's material and geometry, a surface dose rate < 1 Gy/h is obtained, which does not result in any effect on other barriers.

The bentonite buffer is negatively affected at excessively high temperatures. For this reason the temperature in the bentonite may not exceed 100°C. This requirement is not directly related to the canister design, but is a result of several factors: the decay heat in the fuel in the canister, the thermal conductivity of the rock and the distance between the canisters in the deposition tunnels.

A1.7 Important parameters that affect the canister

SKB's development strategy is based on defining a reference design for the final repository system. The reference design defines all essential parts and parameters in the system. By gradual knowledge accumulation, the reference design of the final repository system will be further refined and underpinned, and the tolerances for various parameters can be reduced. At present their are two alternative sites with differing geology and different parameters, which means that the tolerances in the parameters for the canister must cover both sites.

After site selection it will be possible to reduce the tolerances, but these parameters and their values cannot be established until detailed characterization on the selected site and a number of studies have been completed.

Important parameters in the system that affect the design-basis processes for the canister are shown in Table A-1.

A1.8 Fabrication and handling

The canister is designed so that it is possible to lift and handle it during fabrication, encapsulation, transport and deposition and in the event of retrieval. The canister lid is equipped with a lifting flange that is designed to be lifted with a special tool.

Limit values for permissible loads on the canister during transport will be determined within the framework of the safety analysis report for the transport cask.

The canister is not designed for the extreme stresses that can occur in connection with mishaps during the operating period. Three cases of mishaps in the encapsulation plant have been investigated and the results show that the canister cannot take being dropped from full working height. A similar mishap analysis is being performed in the final repository. The canister is not designed for these types of mishaps. Instead, the systems and processes used during encapsulation, transport and deposition are designed so that an acceptable risk level is obtained.

A1.8.1 Handling during fabrication, encapsulation, transport and deposition

The overall requirement is that the canister and its parts must be fabricated and handled so that they meet the requirements stipulated in the design premises when they leave the canister factory. The specifications that ensure this are stipulated in SKB's quality and environmental management system for canister fabrication /A-2/.

Table A-1. Natural and technical system parameters of importance for the canister in the final repository.

Parameters in the final repository system	Effect on the canister	Parameters for the canister
Natural		
Geographic location – thickness of the ice	Isostatic pressure during glaciation.	State of stress in insert and copper shell during the glaciation phase.
Repository depth	Isostatic pressure after water saturation.	Compressive strength.
Water inflow	Time for water saturation, load during the water saturation phase, duration of load during the water saturation phase.	Duration of state of stress in copper shell and insert during the water saturation phase.
Hydraulic conductivity	Possible effect on the corrosion process due to the effects of water chemistry and/or the fact that bentonite can be carried away.	Copper thickness.
Rock stresses	Risk of spalling influences the hole geometry.	State of stress in insert and copper shell during and after the water saturation phase.
Fracture frequency and size distribution	Risk of shear in connection with postglacial earthquakes.	Shear load on the canister.
Technical		
Drilling technology (deposition holes)	Hole geometry.	State of stress in insert and copper shell during and after the water saturation phase.
Variation in water saturation density in the bentonite	Permanent pressure differences.	State of stress in the canister after the water saturation phase.
Value of water saturation density in the bentonite	Plastic properties of the bentonite.	State of stress in the canister during the water saturation phase.
	Bentonite swelling pressure, isostatic pressure after water saturation.	State of stress in the canister after the water saturation phase.
	Bentonite swelling pressure, isostatic pressure during glaciation.	State of stress in the canister during the glaciation phase.
	Plastic properties of the bentonite, load transfer during postglacial earthquake.	State of stress in connection with earthquake. Plastic strain in the copper shell. The state of stress in the insert.
	Creep properties of the bentonite, load transfer after postglacial earthquake.	State of stress after postglacial shear. Creep strain in the copper shell. Relaxations of stresses in the insert.

In the planned process in the encapsulation plant, the canister will be lifted twice by its lid. After that it will be transported to the final repository, where the canister will be lifted out of the transport cask and handled further in the final repository system, where two more lifts will take place. A calculation has been made of lifting safety in accordance with applicable nuclear standards. The results show that lifting safety for the canister has very large margins and that up to 100 lifts can be made without risk.

Handling, encapsulation, transport and deposition of the canister should be done so that the loads on the canister do damage it. If such damage occurs, it must be evaluated with respect to the long-term safety of the canister, but also with respect to handling safety and subsequent process steps.

A1.8.2 Damage to the sealed canister

Handling damage will occur in the copper shell of the finished canister. Handling damage may consist of irregularities in the copper surface and/or cold working effects in the material. In extreme load cases such as dropped canister, however, the insert can also be damaged.

Handling safety

Attempts that have been made to determine the fracture mechanical properties of copper show that the material is extremely insensitive to stress risers, even if there is surface damage. In the event of extremely deep scratches in the tangential direction, however, lifting safety can be affected. A study of the canister's lifting safety shows that a 10 millimetre deep circumferential defect in the weld is acceptable from the viewpoint of lifting safety. The same criterion can be conservatively applied to other parts of the copper shell. However, it should be pointed out that all damage evaluation must take other interacting discontinuities into account.

Deformations entail cold working effects which cause a reduction in ultimate elongation in the material, but also strain hardening with increased hardness and ultimate strength. Generally speaking, lifting safety is not affected unless that material becomes so heavily plasticized that its thickness is reduced. The conservative criterion for this type of damage is to allow defects with a depth of up to 10 millimetres.

Long-term safety

The presence of defects does not affect copper corrosion. A minimum copper cover of 6 millimetres is therefore the design basis requirement for permissible defects from a corrosion viewpoint. The fact that the fracture mechanical properties of copper are extremely insensitive to stress risers means that limited local defects do not affect the mechanical integrity of the copper shell. But it is of interest to study whether creep ductility is affected by plasticization. Such experiments are planned.

A1.9 The reference canister – summarizing requirements

The requirements regarding the canister's design and materials are stipulated in the design premises, where the copper stock for the copper shell and the nodular iron for the insert are also specified. Additional requirements must be met to achieve adequate mechanical properties or fabricability and testability.

The stock chosen for fabrication of the copper shell is pure oxygen-free copper copper that meets the standard EN 1976, Cu-OFE (Table A-2) or Cu-OF1 (Table A-3).

Table A-2. Chemical composition of copper, EN 1976 Cu-OFE.

Element	Cu	Ag	As	Fe	S	Sb	Se	Te	Pb
	%	ppm[b]→							
	99.99[a]	25	5	10	15	4	3	2	5
	P	**Bi**	**Cd**	**Mn**	**Hg**	**Ni**	**O**	**Sn**	**Zn**
	ppm[b]→								
	3	1	1	0.5	1	10	5	2	1

[a] Including Ag.
[b] Max. content.

Table A-3. Chemical composition of copper, EN 1976 Cu-OF1.

Element	Cu	Ag	As	Fe	S	Sb	Se	Te	Pb
	remaining	ppm→							
		25[b]	5[c]	10[d]	15[b]	4[b]	2[e]	2[f]	5[b]

[a] Including Ag. [b] Max content. [c] Sum of As+Cd+Cr+Mn+Sb ≤ 15 ppm.
[d] Sum of Co+Fe+Ni+Si+Sn+Zn ≤ 20 ppm. [e] Sum of Bi+Se+Te ≤ 3 ppm. [f] Sum of Se+Te ≤ 3.0 ppm.

Additional requirements in the design premises, relative to the requirements stipulated in the standard, apply to the concentrations of sulphur (S) and phosphorus (P) and are aimed at ensuring adequate mechanical properties in the copper shell. Another additional requirement is a low hydrogen concentration in order to eliminate the risk of hydrogen embrittlement during heat treatment. If EBW is used for welding, a requirement is made on low oxygen concentration in the copper components. The standard's requirements on permissible concentrations of certain metals (Cr, Co, Al, Ni) provide the necessary margin to ensure adequate corrosion properties in the shell, even taking into account the fact that some elevation of these concentrations has been observed in FSW welds.

The requirement on permissible grain size may have to be made stricter than is specified in the design premises in order to ensure testability with ultrasound. Work is under way to specify this requirement.

In order to provide margins to the design premises, the requirements in SKB's specifications /A-2/ are generally stricter than those specified in the design premises, see Table A-4.

SKB has chosen to make the insert of nodular iron. In order for the insert to have the necessary mechanical properties (strength and ductility), the material must satisfy the requirements laid down in European standard EN 1563 grade EN-GJS-400-15U.

The requirements on the materials for the canister components are shown in Tables A-5 and A-6.

A1.10 SKB's continued work with design premises for the canister

Some work remains to be done to arrive at the final design premises for the the canister. The background material must be structured and augmented so that it contains the information that is required to assure the canister's performance and meet the needs of the regulatory authorities for review. Prior to permit application for the final repository, SKB continues to work to compile design premises and design basis data in accordance with the requirements set forth in SKI's study report 2006/109 /A-23/.

The programme for the continued work is presented in section 14.2 in Part III.

Table A-4. Requirements on the copper shell in design premises and requirements on weld metal, canister components and copper ingot.

Requirements in design premises – copper shell	Weld metal	Canister component	Copper ingot
Cr < 30 ppm	Cr < 30 ppm	KTS001 /A-2/	KTS001 /A-2/
Co < 30 ppm	Co < 30 ppm	KTS001	KTS001
Al < 30 ppm	Al < 30 ppm	KTS001	KTS001
Ni < 30 ppm	Ni < 30 ppm	KTS001	KTS001
O < 30 ppm	O < 30 ppm		O < 5 ppm
S < 12 ppm			S < 8 ppm
30 < P < 100 ppm	30 < P < 100 ppm		30 < P < 70 ppm
		H < 0.6 ppm	H < 0.6 ppm
Grain size < 800 µm	Poss. add. req. for NDT	Grain size < 360 µm, KTS002 Poss. add. req. for NDT	
Ductility > 30%	Ductility > 30%	> 40% (100°C)	
Creep ductility > 8%*	Creep ductility > 8%	Creep ductility > 8% (20–100°C)	

* Creep can occur during water saturation and in connection with postglacial shear. The stipulated value applies in connection with postglacial shear.

Table A-5. Design premises and detailed requirements on the nodular iron insert.

Performance requirements	Requirements stipulated in design premises /A-1/	Other related requirements and comments
Contain the fuel	The insert must hold twelve BWR or four PWR fuel assemblies. The dimensions of the channel tubes must be at least: BWR: 150×150 mm. PWR: 230×230 mm.	Technical specification KTS011 /A-2/. Change in drawing of PWR insert in progress. The dimensions of the insert tubes are checked with a gauge: BWR: 152×152 mm. PWR: change being studied.
Chemical resistance	The atmosphere in the insert must be able to be changed to > 90% inert gas.	The insert and the steel lid are designed for atmosphere change.
Mechanical strength	The insert must resist stresses during the water saturation phase, permanent loads due to uneven swelling pressure in the deposition hole, isostatic loads during glaciation and stresses in connection with postglacial earthquakes.The design basis load is an external pressure of 45 MPa.	Technical specification KTS011 /A-2/ specifies the following standard: EN 1563 grade EN-GJS-400-15U. Material structure/nodularity: forms V and VI (80%). Yield strength: min. 240 MPa (20°C). Ultimate strength: min. 370 MPa. Ultimate elongation: min. 11% (cast-on test bars), min. 7% (test bars from insert). Eccentricity of cassette > 5 mm. Corner radii 15–25 mm.
Negligible effects on other barriers and fuel	Material thickness according to reference canister.	Calculations show that the reference canister meets this requirement.
Criticality	The insert is designed so that it meets criteria for criticality safety even after water penetration.	Calculations show that the reference canister meets this requirement.
Testability	Must meet requirement on testability by NDT to reveal any discontinuities in the metal.	Requirements on surface finish, spacer plates in the cassette and material structure/nodularity are being studied.

Table A-6. Design premises and detailed requirements on copper components and welds.

Performance requirements	Requirements stipulated in design premises /A-1/	Other related requirements and comments
Chemical resistance	Min. 6 mm intact copper thickness. Material composition: The copper material in the canister must conform to the specification for pure copper with a low oxygen concentration. Permissible impurity concentrations in finished copper component: Cr < 30 ppm Co < 30 ppm Al < 30 ppm Ni < 30 ppm O < 30 ppm.	The design premises are complied with by choosing standard material that meets the following specifications: EN 1976 Cu-OFE (UNS C10100) or EN 1976 Cu-OF1 with additional requirement according to KTS001: O < 5 ppm.
Mechanical resistance	Mechanical properties of copper: Ductility: > 30%. Creep ductility: > 8%, leads to requirement on Grain size: < 800 μm. Additional requirements: P = 30–100 ppm S < 12 ppm	The following requirements are stipulated for finished components in KTS002*: Ductility > 40%. Creep ductility > 10%. Microstructure with grain size < 360 μm. Additional requirements according to KTS001: P = 30–70 ppm (creep ductility) S < 8 ppm (sulphur segregation) H < 0.6 ppm (hydrogen embrittlement during hot forming).
Negligible effects on other barriers and fuel	Material thickness according to reference canister.	
Transported, deposited and otherwise handled in a safe manner	Copper thickness: required thickness for sufficient lifting safety. The copper shell must be fabricable and compliance with requirements must be verifiable.	Lifting safety for canister with copper thickness of 4 cm has been calculated.
Testability	Must meet requirement on testability by NDT to reveal any discontinuities in the metal.	This refers particularly to ultrasound attenuation in the material and surface finish. Specifications for microstructure (e.g. grain size) and surface finish are being studied. Inspection by NDT, cleaning: possible requirements on surface finish are being studied.

* The requirements in KTS exceed those in the design premises and the requirement on grain size is being studied (regarding testability by ultrasound).

Appendix B

Abbreviations

Abaqus	Finite-element computer code used for THM model calculations.
ADS	Accelerator-Driven System.
AE	Acoustic Emissions.
AECL	Atomic Energy of Canada Ltd, Canada.
Amber	Computer code for safety assessment (biosphere).
AMF	Assessment flow model.
Andra	Agence National Pour la Gestion des Dechets Radioactifs, France.
Apse	Experiment at Äspö HRL, Äspö Pillar Stability Experiment.
ASAR	As-operated Safety Analysis Report. Recurrent overall assessment of the safety in a nuclear facility.
ATB	Radiation-shielded transport cask for radioactive waste.
Baclo	Cooperation project between SKB and Posiva. Development, testing and demonstration of backfill and closure in a final repository.
BAM	Bundesanstalt für Materialprüfung, Germany.
BBM	Barcelona Basic Model. Elastoplastic model.
BET	Adsorption isotherm describing adsorption in multilayers.
Bevis	EU project that is supposed to propose water protection measures in the largest archipelago area in the Baltic Sea (Åboland, Åland and Stockholm archipelagos).
BFA	Rock cavern for waste on Simpevarp Peninsula.
Big Bertha	Full-scale test for KBS-3H, swelling of bentonite out of supercontainer.
Biopath	SKB's computer code for radionuclide transport in the biosphere.
Bioprota	International collaboration on key technical issues in biosphere aspects of assessment of the long-term safety of the deep repository.
BIPS	Borehole image processing system.
BLA	Rock cavern for low-level waste in SFR 1.
BMA	Rock cavern for intermediate-level waste in SFR 1.
BMT	Benchmark test.
BTF	Concrete tank repository in SFR 1.
BWR	Boiling water reactor.
CAD	Computer aided design.
Calixpart	EU project. Cluster Partition, Selective extraction of minor actinides from high activity liquid waste by organised matrices.
CBI	Swedish Cement and Concrete Research Institute. Industrial research institute.
CCC	Critical Coagulation Concentration.
CEA	Commissariat à l'Energie Atomique.
CEC	Cation Exchange Capacity.
CEN	European Committee for Standardization.
CFM	Colloid formation and migration project at the Grimsel test site.
Chemlab	Probe for radiochemical investigations in boreholes, Äspö HRL.
Clab	Central interim storage facility for spent nuclear fuel.
Code Bright	Computer code for thermo-hydro-mechanical calculations.
Collage II	SKI's colloid transport model.
Colloid	Experiment in the Äspö HRL, the Colloid Project.
COMP23	SKB's computer code for calculation of radionuclide transport in the near-field.
Compulink	SKB's computer code for calculation of radionuclide transport in the near-field (alternative to COMP23).

Confirm	EU project. Cluster Feutra, Collaboration on nitride fuel irradiation and modelling.
ConnectFlow	Computer code for groundwater flow calculations.
CoupModel	Computer code that handles transpiration, growth and nutrient uptake for vegetation.
Crud	Chalk River Unidentified Deposits. Surface contamination.
CTH	Chalmers University of Technology, Göteborg.
DarcyTools	Computer code for groundwater flow calculations.
Decovalex	International project. International co-operative project for the Development of Coupled models and their Validation against Experiments in nuclear waste isolation.
DFN	Discrete fracture network.
DInSAR	Differential radar interferometry.
EBS	Engineered Barrier System.
EBW	Electron Beam Welding.
EC	European Commission.
Ecopath	General ecological model package.
EDZ	Excavation Disturbed Zone.
EFTA	European Free Trade Association
Eikos	Probabilistic modelling tool for dose calculations in the biosphere.
Emras	IAEA project. Environmental Modelling for Radiation Safety.
Enresa	Empresa Nacional de Residuos Radiactivos, Spain.
Equip	EU project. Evidence from Quaternary Infillings for Palaeohydrology.
Erica	EU project. Environmental Risk from Ionising Contaminants.
Esdred	EU project. Engineering Studies and Demonstrations of Repository Designs.
EU	European Union.
Europart	EU project. European research programme for partitioning of minor actinides within high active wastes issuing from the reprocessing of spent nuclear fuels.
Eurotrans	EU project. European project on transmutation.
Examine3D	Computer code for rock mechanical analyses.
FARF31	SKB's computer code for calculation of radionuclide transport in the far-field (Proper submodule).
FARF33	SKB's computer code for calculation of radionuclide transport in the far-field that can handle colloids.
Febex	Full-scale high level waste engineered barriers experiment, Grimsel, Switzerland.
FEM	Finite Element Method – a numerical method for solving partial differential equations.
FEP	Features, events and processes.
F factor	Transport resistance.
FHA	Future human actions.
FLAC3D	Computer code for rock mechanical analyses.
R&D	Research and development.
FPAR	Fraction of photosynthetically active radiation.
Fracod	Computer code for rock mechanical analyses.
FSW	Friction Stir Welding.
RD&D	Research, Development and Demonstration.
RD&D-K	Integrated account of method, site selection and programme prior to the site investigation phase, 2000.
Funmig	EU project. Fundamental processes of radionuclide migration.
Futurae	EU project. Assessment and management of the impact of radionuclides on man and the environment.
GEN-IV	International forum for development of the fourth generation of nuclear reactors.
GEUS	Geological Survey of Denmark and Greenland
GIA	Glacial Isostatic Adjustment.
GIS	Geographic Information System.
GPS	Global Positioning System.
Holocene	Current interglacial that began around 11,500 years ago.

HRL	Hard Rock Laboratory.
HTGR	High-Temperature Gas-Cooled Reactor technology.
HTO	Tritiated water.
HWC	Hydrogen water chemistry.
IAEA	International Atomic Energy Agency.
ICEM	Conference on Environmental Remediation and Radioactive Waste Management.
iConnect Club	Integrated continuum and network approach to groundwater flow and contaminant transport.
ICRP	International Commission on Radiological Protection.
IEMS	International Environmental Seminar.
IKA	Radioactive non-nuclear waste.
in situ	Latin for “in place”.
INE-FZK	Institut für Nukleare Entsorgungstechnik im Forschungszentrum Karlsruhe.
IPCC	Intergovernmental Panel on Climate Change.
ISI	Initial site investigation.
IRPA	International Radiation Protection Association.
ISO	International Organization for Standardization.
ISO 14001	International quality standard for environmental management systems.
ISO 9001	International quality standard for quality management systems.
ITU	Institute for Transuranium Elements, Karlsruhe.
IUR	International Union of Radioecology.
IVA	Royal Swedish Academy of Engineering Sciences.
JobFem	Computer code for thermomechanical analyses.
JRC	Joint Research Center.
Kasam	Swedish National Council for Nuclear Waste.
KBS-3H	Variant of KBS-3, horizontal deposition of the canisters.
KBS-3 method	SKB’s reference method for disposal of spent nuclear fuel.
KBS-3V	Reference variant of KBS-3, vertical deposition with one canister in each deposition hole.
Kd	Element-specific distribution coefficients.
CSI	Complete site investigation.
KTH	Royal Institute of Technology, Stockholm.
KTL	Nuclear Activities Act. SFS 1984:3 Act on Nuclear Activities
KTS 001	SKB’s technical specification – Copper Ingots and Billets for Canister Components.
KTS 002	SKB’s technical specification – Copper Components for Canisters.
KTS 011	SKB’s technical specification – Nodular Cast Iron EN 1563 Insert.
LAI	Leaf area index.
Lasgit	Experiment at Äspö HRL, Large Scale Gas Injection Test.
LDF	Landscape Dose Factors.
LKO	Local Competence Building in Oskarshamn Municipality – Nuclear Waste Project.
LILW	Low- and intermediate-level waste.
Lot	Experiment at Äspö HRL, Long Term Test of Buffer Material.
LTDE	Experiment at Äspö HRL, Long Term Diffusion Experiment (see LTDE-SD).
LTDE-SD	Experiment at Äspö HRL, Long Term Sorption/Diffusion Experiment.
M3	Computer code for hydrochemical analyses, Mixing and Mass Balance Modelling.
Marfa	Migration Analysis for Radionuclides in the Far Field.
Matlab	Commercial computer code for mathematical calculations.
MB	Environmental Code. SFS 1998:808.
Micado	EU project. Model uncertainty for the mechanism of dissolution of spent fuel in a nuclear waste repository.
Micomig	Microbial experiments in the Äspö HRL, radionuclide migration.
Micored	Microbial experiments in the Äspö HRL, redox potential.
Microbe	Microbial experiments in the Äspö HRL.

MIKE SHE	Commercial modelling tool used for surface hydrological modelling.
Minican	Experiment at Äspö HRL, Corrosion of canister insert.
MIS 11	Marine Isotope Stage 11 that lasted for about 30,000 years and occurred about 400,000 years ago.
EIS	Environmental Impact Assessment.
MKG	The Swedish NGO Office for Nuclear Waste Review.
MOX	Mixed Oxide Fuel.
MX-80	Sodium bentonite from Wyoming.
Nagra	Nationale Genossenschaft für die Lagerung von Radioaktiver Abfälle, Switzerland.
NDT	Nondestructive testing.
NDT Reliability	Research programme at BAM to determine the reliability of the NDT methods.
NEA	Nuclear Energy Agency, Paris.
NF-Pro	EU project. Understanding and physical and numerical modelling of the key processes in the near-field and their coupling for different host rocks and repository strategies.
Nirex	Nirex Ltd.
NKS	Nordic Nuclear Safety Research.
Numo	Waste management organisation of Japan.
NWC	Normal water chemistry.
OECD-NEA	Organisation for Economic Cooperation and Development/Nuclear Energy Agency.
NDT	Nondestructive testing.
OKG	Oskarshamnsverkets kraftgrupp.
Onkalo	Underground Rock Characterization Facility in Olkiluoto, Finland.
OPG	Ontario Power Generation.
ORIGEN-S	Computer code for calculation of radionuclide content, decay heat and radiation in spent nuclear fuel.
P&T	Partitioning and Transmutation.
Padamot	EU project. Palaeohydrogeological Data Analysis and Model Testing.
Pandora	SKB's and Posiva's modelling tool for dose calculations in the biosphere.
Particle Flow Code	Computer code for rock mechanical analyses.
PARTNEW	EU project. Cluster Partitioning, New Solvent Extraction Processes for Minor Actinides.
Pass	SKB's Project on Alternative Systems Study.
PFC	Particle flow code. Computer code for rock mechanical analyses.
PHREEQC	Computer code for coupled geochemistry and transport analyses.
PLC	Programmable Logic Controller, controls the mechanical parts in NDT systems.
POD	Probability of detection.
Posiva	Posiva Oy.
Precci	Research program on the long term Evolution of Spent Fuel Waste Packages, CEA, France.
Prism	Computer code for probabilistic calculations of radionuclide transport in the biosphere.
Protect	EU project. An evaluation of the practicability and relative merits of different approaches to protection of the environment from radiation.
PSAR	Preliminary Safety Analysis Report.
PSI	Paul Scherrer Institute, Switzerland.
PSS	Pipe String System for hydrogeological measurement.
PWR	Pressurized Water Reactor.
Pyrorep	EU project. Cluster Partition, Pyrometallurgical processing research programme.
Retrock	EU project. Treatment of geosphere retention phenomena in safety assessments.
Rex	Experiment at Äspö HRL. Redox experiment in detailed scale.
RH	Relative humidity.
RIXS	Resonant Inelastic X-ray Scattering.
RNR	Experiment at Äspö HRL. Radionuclide retention experiment.
RoCS	Experiment at Äspö HRL. Rock characterisation system.
RD	Reference design.

RVS	Rock Visualisation System. Tool for geometric modelling, administration and presentation of site descriptive models.
P&T	Partitioning and Transmutation.
SAR	Safety Analysis Report.
SAR	Synthetic Aperture Radar.
SAT	Site acceptance test.
SCK-CEN	Belgian Nuclear Research Centre.
SDM	Site descriptive model.
SER	Site Engineering Report.
SF	Final repository for spent nuclear fuel.
SFL	Final repository for long-lived low- and intermediate-level waste.
SFR	Final repository for short-lived low- and intermediate-level waste.
SFR 1	Final repository for radioactive operational waste.
SFR 3	Final repository for radioactive decommissioning waste.
SFS	EU project. Spent Fuel Stability under Repository Conditions.
SGU	Geological Survey of Sweden.
Sicada	SKB's database for data collected from site investigations.
Simfuel	Uranium dioxide containing non-radioactive fission product elements and metal particles similar to those in spent fuel.
Simulink	Commercial computer code for mathematical calculations.
SKB	Svensk Kärnbränslehantering AB (Swedish Nuclear Fuel and Waste Management Co).
SKB 91	SKB project. The importance of the bedrock for the long-term safety of the KBS-3 repository, 1992.
SKI	Swedish Nuclear Power Inspectorate.
SLU	Swedish University of Agricultural Sciences.
SNS	Swedish national seismic network.
SR 95	SKB project, template for safety reports with descriptive examples, 1996.
SR 97	SKB project, post-closure safety of the deep repository, 1999.
SR-Can	Report on long-term safety of the final repository (published by SKB in November 2006.
SR-Site	Report on long-term safety of the final repository. To be prepared for SKB as a basis for an application for a permit to build the final repository.
SSE	Site sensitive emulsion.
SSI	Swedish Radiation Protection Authority.
STF	Safety-related technical specifications.
SveBeFo	Stiftelsen Svensk Bergteknisk Forskning, Stockholm.
Swebrec	Swedish Blasting Research Centre. Centre of excellence for detonics and blasting technology at Luleå University of Technology.
Swiw	Single well injection withdrawal tracer test.
TBM	Tunnel boring machine.
TBT	Experiment at Äspö HRL. Temperature buffer test.
TDB	OECD-NEA project. Thermodynamic data bases.
Tensit	SKB's computer code package for numerical calculations of radionuclide transport.
TF EBS	Äspö Task Force on Engineered Barrier Systems.
TF GWFST	Äspö Task Force on Modelling of Groundwater Flow and Transport of Solutes.
THM	Thermo-hydro-mechanical
THMC	Thermo-hydro-mechanical-chemical.
TMS	Tunnel Measurement System. System for characterization of tunnels.
TOFD	Time-Of-Flight-Diffraction. NDT method.
TRL	Transmitter Receiver Longitudinal. Nondestructive ultrasonic testing method.
True	Experiment at Äspö HRL. Tracer Retention Understanding Experiments.
TSX	International project – Tunnel Sealing Experiment at URL in Canada.
TWI	The Welding Institute, Cambridge, England.
TWI	Topographic wetness index.

URL	Underground Rock Laboratory.
Wave	Computer code for rock mechanical analyses.
VLJ	Final repository for low- and intermediate-level waste (VLJ rock caverns) in Olkiluoto, Finland.
WP	Work package.
WP-Cave	Repository concept for geological disposal.
XANES	X-ray Absorption Near Edge Structures.
XAS	X-ray Absorption Spectroscopy.
XPS	X-ray Photoelectron Spectroscopy.
Canister Retrieval Test	Experiment at Äspö HRL. Freeing and retrieval of canister in deposition hole in a KBS-3 repository.
α radiation	Alpha radiation.
β radiation	Beta radiation.
γ radiation	Gamma radiation.
1D	One-dimensional.
2D	Two-dimensional.
3D	Three-dimensional.
3DEC	Computer code for rock mechanical analyses.

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