Technical Report

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RD&D-Programme 2004

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

September 2004

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Preface

SKB, Svensk Kärnbränslehantering AB (the Swedish Nuclear Fuel and Waste Management Co), which is owned by the companies that operate the Swedish nuclear power plants, has been assigned the task of managing and disposing of the spent nuclear fuel from the reactors. The Nuclear Activities Act requires a programme of comprehensive research and development and other measures that are needed to manage and dispose of nuclear waste in a safe manner and to decommission and dismantle the nuclear power plants. SKB is now presenting RD&D-Programme 2004 in fulfilment of this requirement. The programme describes SKB's plans for the period 2005–2010. The period of immediate concern is 2005–2007. The level of detail for the three subsequent years is naturally lower.

The programme provides a basis for designing systems for safe management and disposal of the radioactive waste from the nuclear power plants. SKB's plan is to implement deep disposal of the spent fuel in accordance with the KBS-3 method. In the RD&D-Programme we describe our activities and planning for this line of action and the work that is being conducted on alternative methods. Review of the programme can contribute valuable outside viewpoints. The regulatory authorities and the Government can clarify how they look upon different parts of the programme and stipulate guidelines for the future. Municipalities and other stakeholders can, after studying the programme, offer their viewpoints to SKB, the regulatory authorities or the Government.

The goal for the period up to the end of 2008 is to be able to submit permit applications for the encapsulation plant and the deep repository. This RD&D-Programme therefore differs from the preceding ones in that it concentrates on questions relating to technology development for these facilities. The programmes for safety assessment and research on the long-term processes that take place in the deep repository are then linked together with the programmes for technology development. Another new feature of this RD&D-Programme is that we also present our programme for social science research, which was requested by several reviewing bodies in connection with the review of RD&D-Programme 2001. Finally, the programmes for alternative methods, decommissioning and other long-lived waste are also described in this RD&D-Programme.

In the review statement regarding RD&D-Programme 2001 which SKI submitted to the Government in March 2002, the Inspectorate called for a report that would explain more clearly SKB's plans for the remainder of the nuclear fuel programme. As a reason for this request, SKI said that the competent authorities will need to know which regulatory reviews are anticipated over the next ten years and the extent to which these reviews depend on each other. Such a report is appended to this RD&D-Programme.

It is our hope that the above structure and perspective provide a clear picture of how far the technology development work has come and what factors are most important for safety in the deep repository.

Stockholm in September 2004

Swedish Nuclear Fuel and Waste Management Co

Claes Thegerström	Tommy Hedman
President	Head of Technology

Summary

The preceding RD&D-Programme from 2001 was concentrated on research and technology development. Research with a focus on the assessment of long-term safety was emphasized and viewpoints from previous reviews of SR 97 and RD&D-Programme 98 were dealt with in depth. SR 97 was an assessment of the long-term safety of a deep repository for spent nuclear fuel. This RD&D-Programme 2004 focuses its attention on the development of technologies for fabrication and sealing of canisters for final disposal of spent fuel. These technologies are needed for the application for a permit for an encapsulation plant which SKB intends to submit during the coming programme period.

An overall goal for SKB is that the first stage of the deep repository for spent nuclear fuel should be ready for initial operation in 2017. Regular operation should then be able to be commenced in around 2023, before the storage chambers in Clab have become full. Timetables covering such long periods of time naturally involve uncertainties and must be updated periodically, but at the same time they provide an important basis for decisions regarding strategy and priorities for the next few years. In 2002, SKB started a phase with site investigations in Östhammar and Oskarshamn. Investigations of the bedrock are being conducted on sites near the Forsmark plant and the Oskarshamn plant. The goal of the site investigation phase is to obtain the permits that are needed to site and build the deep repository and the encapsulation plant.

The next RD&D programme, which will be submitted in 2007, is expected to pay particular attention to the deep repository technology and the continued work on alternative deposition methods. The subsequent RD&D-Programme 2010 will above all given an account of SKB's system for managing and disposing of the low- and intermediate-level waste.

This RD&D programme presents the plan of action which was called for in the review of RD&D 2001 and later also requested by the Government in connection with the approval of this programme. The plan of action is summarized in Chapter 2 and presented in its entirety in Appendix A. In accordance with the plan, SKB is now compiling the material that is needed to apply for a permit for the encapsulation plant in 2006 and for the deep repository in 2008. The licensing process and the decisions required to build the planned deep repository system should then be able to be implemented so that construction can begin in around 2010 and operation in 2017.

The technology for disposal of fuel in accordance with the KBS-3 concept will be developed in preparation for the permit applications for the encapsulation plant and the deep repository. The work is focused on a reference design for each of the different parts of the system, and the detailed design is emerging stepwise. The final choices will only be made after thorough evaluation of safety, technology, costs and environmental aspects.

The canister, in which the spent fuel will be encapsulated prior to disposal, is in the focal point of the technology development. In the reference design, the canister has a cast insert of nodular iron and a five centimetre thick copper shell. The copper shell protects against corrosion and the insert against deformation. The work of designing the canister in detail and evaluating the fabrication, sealing and testing methods continues, see Chapter 5. The parts of the canister will be fabricated by various suppliers and subsequently assembled and inspected in the canister factory prior to delivery to the encapsulation plant.

In the encapsulation plant, the canisters will be filled with the spent fuel and then sealed. Two welding methods are being developed in parallel at the Canister Laboratory: electron beam welding (EBW) and friction stir welding (FSW), see Chapter 6. Methods for nondestructive testing (NDT) are also being developed there. Qualification of the methods for fabrication,

welding and nondestructive testing is an important step that must be taken before production can begin at the encapsulation plant, see Chapter 7.

SKB has started a project to design and plan for the construction of the encapsulation plant. It can be sited adjacent to either Clab or the deep repository. It is an advantage if the plant can be coordinated with existing activities, and SKB's main alternative is therefore to co-site the plant with Clab. Design of the plant will be based on the results of technology development and will be coordinated with environmental impact assessment (EIA) – which leads to an environmental impact statement (EIS) – as well as safety assessment and system analysis, see Chapter 8. Transportation of the finished canisters from the encapsulation plant to the deep repository is dealt with in Chapter 9.

The deep repository will be designed and engineered prior to the permit application. Technology will be developed for mining of tunnels and sealing the rock around them, fabricating and emplacing the buffer, handling the canisters, and finally backfilling and plugging the deposition tunnels. Other areas being studied are sealing of boreholes and technology for retrieving canisters after initial operation, if this should prove necessary. The programme is described in Chapter 10. Design of the deep repository will be based on the results of technology development and the site investigations, and coordinated with the EIA work as well as safety assessment and system analysis, see Chapter 11. The reference design, KBS-3V, consists of vertical deposition holes in horizontal tunnels. An alternative design will also be investigated during the coming years, namely horizontal deposition of copper canisters, KBS-3H. This will be done in close cooperation with the Finnish organization Posiva.

The deep repository must be safe even without supervision and maintenance, but some kind of surveillance or monitoring may nevertheless be justified, for example to gain a better scientific understanding of the site and the repository. Another important task is to ensure that no fissile material can leave the facility while it is in operation. What requirements may be made and how this can be handled is discussed in Chapter 12.

Safety assessment and research. The long-term safety of the repository is examined and evaluated by means of the safety assessment. The first step is to describe the initial state of the repository, after which possible long-term changes are explored, and finally the consequences for man and the environment are described. Knowledge regarding long-term changes is obtained from the research, whose purpose is to support the safety assessment and furnish it with the necessary models and data. Input data for the safety assessment are also obtained from the investigations of possible repository sites and the details of the technical systems. Conversely, the needs of the safety assessment drive the need for research in the field and are essential for both design studies and site investigations.

The safety assessment utilizes models that are developed in the research work and devises special modelling tools for integrated modelling, see Chapter 14. The repository's evolution is simulated by system models. Transport of released radionuclides is calculated using both numerical and analytical models.

The immediate goal of the safety assessment is a safety report that deals with deep disposal of spent fuel and will be included in the permit application for an encapsulation plant. The project is called SR-Can and will later be followed by SR-Site, aimed at an application for a deep repository.

SKB's research is largely aimed at analyzing the long-term safety of a deep repository with spent fuel. The research programmes for the fuel, the canister as a barrier, the buffer, the backfill and the geosphere are described in Chapters 15 to 19. Each part deals first with the research on the initial state and then all processes, subdivided into radiation-related, thermal, hydraulic, mechanical and chemical (including microbial), as well as processes related to radionuclide transport. Chapters 20 and 21 deal with research aimed at charting the changes to which the evolution of the biosphere and the climate give rise.

The spent fuel is the waste which the repository is supposed to isolate. Several processes affect the waste, an important one being dissolution of the fuel if groundwater should enter via a breach in the canister. It is essential that this is dealt with in the safety assessment, and research on fuel dissolution is a prioritized research area, see Chapter 15. Models of fuel dissolution will be examined in SR-Can.

The canister is the most important barrier for isolating the spent fuel. The canister must withstand mechanical loads and corrosion. The strength of the canister is being tested and calculated, and corrosion of copper and iron will continue to be an active research area where different types of experiments are conducted, see Chapter 16.

The buffer is supposed to protect the canisters and retard radionuclide transport. In evaluating long-term safety, it is essential to be able to predict the state of the buffer after deposition. A number of processes – hydraulic, mechanical and thermal – are involved, and the course of events is being studied both in the field and with models. The buffer is simpler to describe after water saturation, but a long span of time has to be considered, and important processes that need to be studied are gas transport, colloid release and erosion, and interaction between buffer and canister, see Chapter 17.

The backfill is supposed to stabilize the tunnels, keep the buffer in place and prevent water flow through the tunnels. Different concepts for tunnel backfilling and different clay-based materials are being tested. Processes that are still being studied are swelling and anything that can affect it, for example chemical action, colloid formation and erosion, see Chapter 18.

The geosphere protects the canisters and is furthermore a barrier to the escape and transport of radionuclides. Models are being developed that describe how the rock around the repository would move if an earthquake should occur in the future, for example after an ice age. Other models being developed describe the movements of the groundwater in the rock and the chemistry of the groundwater. They are needed so that we can understand the sites that are being investigated for the deep repository, determine how stable the conditions that will protect the canister are, and perform the calculations of radionuclide transport that are essential in assessing safety, see Chapter 19. Experiments and measurements that need to be done are carried out in laboratories or directly in the rock, for example at the Äspö HRL.

The biosphere is where we human beings live and where any releases from the deep repository would ultimately have consequences. There has been considerable development of the biosphere model, but in order to be able to calculate the transport of radionuclides, a coherent description from the geosphere to the biosphere is needed. SKB has addressed this need in the research programme. Continued efforts will also be devoted to further defining and describing the most important processes in different types of ecosystems, see Chapter 20. To assess safety, it is important to investigate the site but also necessary to predict what changes may take place there in the future. There is therefore a strong link to the programme that deals with the evolution of the climate.

The climate changes continuously and affects shoreline displacement and development of permafrost and ice sheets in Sweden. This in turn affects both the biosphere and the geosphere. An important question for the safety assessment, and the goal of the research described in Chapter 21, is to determine what climate changes are possible and describe how they might affect the long-term safety of the deep repository.

Social science. SKB has decided to conduct and fund social science research in order to compile a broad and complete body of material on societal aspects for the environmental impact statement (EIS) that will be submitted with the applications for permits to build the encapsulation plant and the deep repository. Four areas of social science research have been selected: socioeconomic impact, decision processes, psychosocial effects and global changes. A screening group consisting of researchers in the social and behavioural sciences has been appointed to help in defining the research projects, see Chapter 22.

Alternative methods. SKB is following the development of two alternatives to the KBS-3 concept: partitioning and transmutation (P&T) and disposal in boreholes several kilometres deep, see Chapter 23. It is far from certain that either of these two methods will ever be practical, but it may nevertheless be useful to follow what is being done internationally. Basic research on P&T is being conducted in Sweden with SKB's support. The researchers are participating in the international projects and thereby helping SKB to keep track of developments in the field.

Decommissioning. Decontamination and decommissioning (including dismantling) of end-of-life installations is ultimately the responsibility of the owner. When it comes to the nuclear power plants, SKB has been assigned the task of conducting general studies of decommissioning in order to ensure that the necessary competence exists and that costs are estimated correctly. Then the NPPs themselves are responsible for planning, licensing and making sure that the plant is decontaminated and decommissioned. SKB helps to dispose of the decommissioning waste, see Chapter 24. A method for dry interim storage of core components has been developed, along with a system for registration of waste intended for disposal in future repositories. Major decommissioning activities are not expected to begin before 2020 at the earliest.

Low- and intermediate-level waste. In terms of volume, most of the waste from the NPPs is short-lived low- and intermediate-level waste (LILW). It arises both during operation and when the plant is finally shut down. This waste goes to SFR in Forsmark, which has been in operation since 1988. There the operational waste from the NPPs is disposed of, together with a smaller fraction of radioactive waste from research, medicine and industry that is delivered via an interim storage facility in Studsvik. The short-lived waste from decommissioning is planned to be disposed of in a future extension of SFR.

When the NPPs are decommissioned, even larger quantities of long-lived scrap from reactor internals and core components will have to be disposed of, together with long-lived waste from research and industry. The repository does not have to be sited and built for another 30 years at least, so for the time being activities are limited to research in preparation for future assessments of long-term safety, see Chapter 25.

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Part I
SKB's programme and plan of action

1 The nuclear waste system

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1 The nuclear waste system

The Swedish power industry has been generating electricity by means of nuclear power for more than 30 years. Operation of the nuclear power plants gives rise to various types of radioactive waste, called nuclear waste. The total quantities of nuclear waste that must ultimately be disposed of are dependent on the number of nuclear reactors and their operating time. The waste quantities influence the required capacity of the different waste facilities. The quantities do not, however, influence the fundamental steps needed to dispose of the waste.

Swedish law regulates nuclear waste management. The legislation is very clear concerning producer responsibility. The owners of the nuclear power plants are responsible for managing and disposing of the nuclear waste in a safe manner. This includes decommissioning the facilities at the end of their service life, conducting research and development on final disposal, and studying alternative options. The owners have to pay all costs for this. An account of the activities must be submitted to the authorities every third year. This programme for research, development and demonstration, RD&D 2004, is such an account.

The power utilities that have nuclear power plants in Sweden are Vattenfall AB (Ringhals), Sydkraft Kärnkraft AB (Barsebäck), OKG Aktiebolag (Oskarshamn) and Forsmarks Kraftgrupp AB. The jointly owned company Svensk Kärnbränslehantering AB (Swedish Nuclear Fuel and Waste Management Co, SKB) has been assigned the task of managing and disposing of the nuclear waste in such a manner than human health and the environment are safeguarded in the short and long term. This mission is an important part of the national environmental objective of creating a safe radiation environment. SKB's activities are overseen by the Swedish Nuclear Power Inspectorate (SKI) and the Swedish Radiation Protection Authority (SSI).

1.1 Facilities for nuclear 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.

Other long-lived waste also arises in connection with 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 bombardment 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 (disintegration) 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 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.

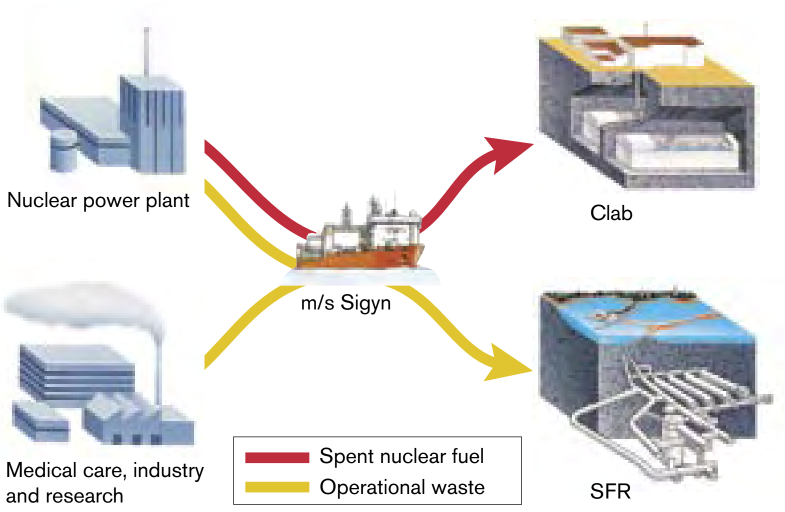


***Figure 1-1.** The spent nuclear fuel is interim-stored in Clab. Low- and intermediate-level operational waste is finally disposed of in SFR.*

SKB has been operating a final repository for short-lived waste, an interim storage facility for spent nuclear fuel and a system for transporting the nuclear waste between the different facilities for many years now, see Figure 1-1. Several new facilities are needed to manage and dispose of all nuclear waste in Sweden, including an encapsulation plant to encapsulate the spent fuel and a deep repository to dispose of it.

1.1.1 SFR

There is a final repository for radioactive operational waste (SFR) for the short-lived low- and intermediate-level operational waste from the nuclear power plants. SFR is located at the Forsmark Nuclear Power Plant and has been in operation since 1988. The facility is located at a depth of 50 metres beneath the seabed.

The storage chambers consist today of four 160-metre-long rock caverns of various configurations, plus a 70-metre-high cavern in which a concrete silo has been built. One of the four rock caverns contains low-level waste enclosed in ordinary freight containers. The waste in this part of the facility can be handled without any kind of radiation shielding. Three of the caverns receive intermediate-level waste, which requires radiation shielding. The concrete silo is also intended for intermediate-level waste, mainly filters for purification of reactor water. At the end of 2003, there was 30,059 m^3 of waste deposited in SFR. The total deposition capacity is 63,000 m^3. An expansion of the capacity will be necessary in the future.

1.1.2 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. The facility was put into service in 1985. 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 five pools. 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.

Clab has been expanded in recent years. The second rock cavern was completed at mid-year 2004 and is scheduled to be taken into service at the end of 2004. At year-end 2003 there were 4,069 tonnes of fuel (counted as 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.

1.1.3 Transportation system

In Sweden, nuclear waste shipments go by sea, since all nuclear power plants and nuclear waste facilities are situated along the coast. The transportation system consists of the ship m/s Sigyn, a number of transport containers/casks and vehicles for loading and unloading. The system has been gradually built out and augmented since the start of operation in 1982. Normally Sigyn makes between 30 and 40 trips per years 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 at the nuclear power plants. The waste then is shipped in transport containers with 7–20 centimetre thick walls of steel, depending on how radioactive it is. The spent fuel is shipped in transport casks with approximately 30 centimetre thick steel walls. These casks are also equipped with cooling fins to dissipate the decay heat.

1.2 Facilities for research, development and demonstration

Much of the research and development for encapsulation and final disposal of spent nuclear fuel needs to be done on a full scale and in a realistic setting. SKB has therefore built two laboratories – the Äspö HRL (Hard Rock Laboratory) and the Canister Laboratory – to carry out different research and development projects. The results of these projects will provide a basis for designing the deep repository and the encapsulation plant, as well as for safety.

1.2.1 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 enable research, development and demonstration to be done in a realistic and undisturbed rock environment down to repository depth. The underground laboratory consists of a tunnel from the Simpevarp Peninsula to the southern part of the island of Äspö, where the tunnel runs in a spiral down to a depth of 460 metres, see Figure 1-2. The total length of the tunnel is 3,600 metres. At ground level there are office buildings, workshops, laboratories and premises for information activities that are gradually being built out. During the summer of 2003, another branching of the tunnel was blasted out to accommodate new experiments concerned with, among other things, rock mechanics and grouting technology.

Activities at the Äspö HRL

The role of the Äspö HRL has changed in recent years from developing methods for rock investigations to developing methods for construction and operation of the deep repository. The first goal of the activities at the laboratory has thereby been achieved. The next step is to carry out the following tasks:

- Develop and demonstrate methods for construction and operation of the deep repository.
- Test alternative technology that can improve and simplify the design of the deep repository without compromising its high quality and safety.

Figure 1-2. The Äspö HRL consists of a 3,600 metre long tunnel that goes down to a depth of 460 metres.

- Improve our scientific understanding of the deep repository's safety margins and gather data for assessments of long-term safety.
- Train personnel for execution of various parts of the deep repository project.
- Provide information on technology and methods that are being developed for the deep repository.

According to the plans, the activities at the Äspö HRL, which are largely being pursued in collaboration with other countries, will continue until the initial operation of the deep repository is concluded. The evaluation of the results of initial operation and of ongoing experiments in the Äspö HRL will serve as a basis for an application for a licence for regular operation of the deep repository. An important role for the Äspö HRL in this perspective is therefore to conduct long-term experiments where different aspects of the function of the deep repository are tested over a long period of time, in some cases 15–20 years.

Activities are being conducted within the following areas:

- Natural barriers (mechanical, hydrological and chemical properties of the rock).
- Engineered barriers (buffer and backfill).
- Deep repository technology (rock extraction, design, handling technology).

The different experiments and development projects being pursued in the Äspö HRL are presented in this programme under the appropriate research heading. An overview of the experiments and their location is provided in Figure 1-3.

Äspö research school

In 2002 the University of Kalmar established an environmental science research school with activities at the Äspö HRL. A professor is associated with the school, and four doctoral candidates where working there at the beginning of 2004. SKB and Oskarshamn Municipality are

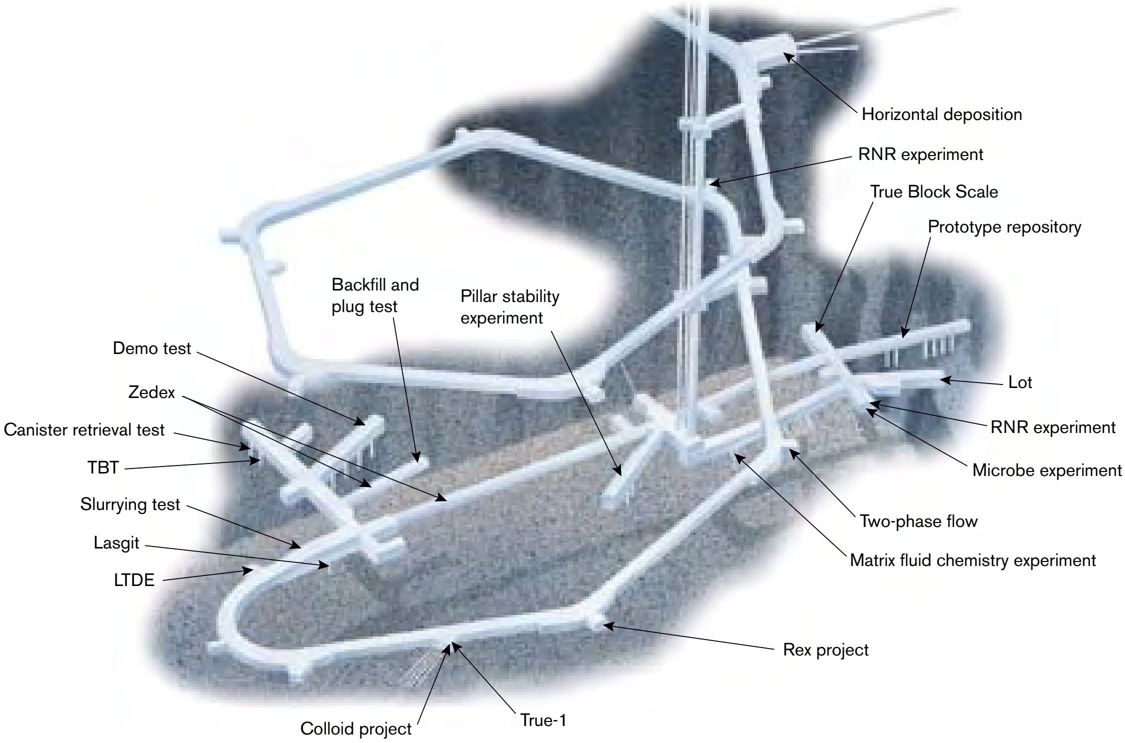


***Figure 1-3.** Ongoing and previously concluded experiments in the Äspö tunnel.*

supporting the research school, along with the University of Kalmar. The University of Kalmar wants to conduct advanced post-graduate education and research in environmental science, with a focus on geoscience, and for this purpose the Äspö HRL constitutes a unique resource in the region for conducting research on transport and migration mechanisms for pollutants in rock, soil layers and biosphere. For its part, SKB is interested in the research results and needs to ensure future competency in the field. The municipality is interested in having a facility where advanced research is conducted, providing jobs for young, well-educated residents of the municipality.

1.2.2 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 was used for shipbuilding, has been converted for the development of sealing technology for the copper canisters. It is used mainly for the development of equipment for welding of copper lids and bottoms and for nondestructive testing of the welds. 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 for commissioning of the encapsulation plant. The Canister Laboratory is therefore intended 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 an electron beam welder, a friction stir welding and an ultrasonic testing machine. An interior picture from the Canister Laboratory is shown in Figure 1-4.

Figure 1-4. *Interior from the Canister Laboratory.*

1.3 Planned facilities

With Clab, SFR and the transportation system, SKB can already manage the radioactive waste from the nuclear power plants today. The additional facilities that are needed for disposal of the spent nuclear fuel in a manner that is safe even in a long-term perspective are an encapsulation plant for encapsulating the fuel in copper canisters and a deep repository where the encapsulated fuel can be permanently emplaced. A transportation system designed to serve these facilities is also needed. In addition, repositories are needed for the low- and intermediate-level waste that arises when the nuclear installations are decommissioned and for other long-lived waste. Figure 1-5 shows an overview of a fully built-out system for spent nuclear fuel and radioactive waste.

1.3.1 Encapsulation plant

The work of planning and designing the encapsulation plant has been going on since the end of the 1980s. Fabrication of the copper canisters is separate from the encapsulation plant. In the encapsulation plant, the spent nuclear fuel is placed in copper canisters. The facility is designed for sealing of up to 200 canisters per year.

The encapsulation process begins with lifting of the fuel from the pools in the encapsulation plant to a radiation-shielded handling cell. There it is dried and placed in the canister. When the canister is full, a copper lid is welded on. Then the quality of the weld is checked by nondestructive testing. If the weld is not approved, either it is redone or the fuel assemblies are transferred to a new canister.

After the filled and sealed canister has been approved, it is examined externally to make sure it is clean. If the canister should be contaminated with radioactivity, it is washed and re-examined. When the canister has been approved, it is placed in a transport cask and taken to the deep repository to be deposited.

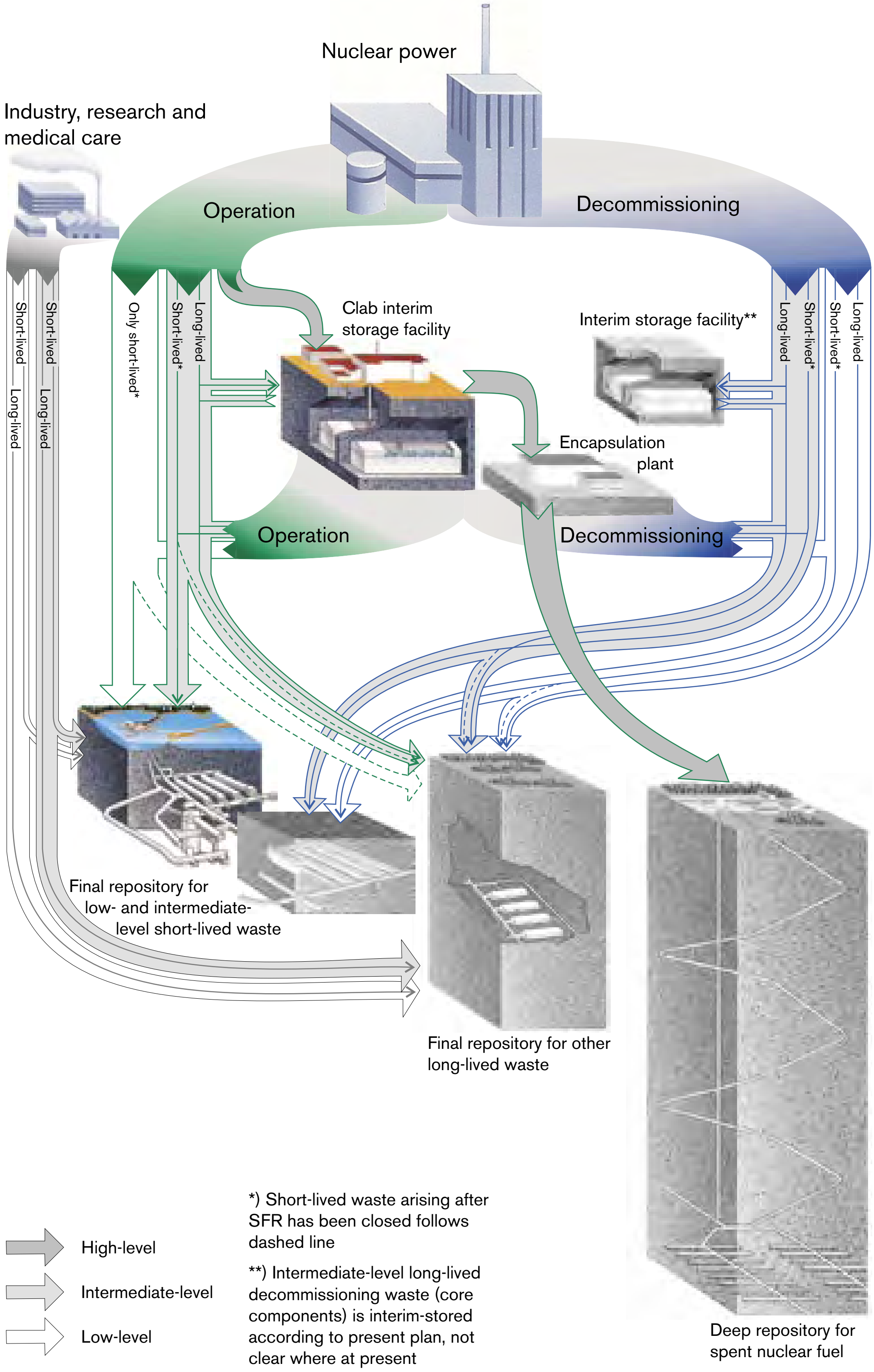


***Figure 1-5.** The complete system for managing and disposing of nuclear waste.*

Siting

SKB's main alternative is to build the encapsulation plant adjacent to Clab so that it can be coordinated with existing activities. The spent fuel can then be transferred directly from the storage pools in Clab to the pools in the encapsulation plant. At Clab there are also personnel with expertise in and experience from radiological work.

SKB has conducted a feasibility study of a standalone encapsulation plant /1-1/ as well as a comparison between different alternative sitings /1-2/. The standalone encapsulation plant is assumed to be located near the deep repository's surface facility. The primary technical difference between the planned encapsulation plant at Clab and the one at the deep repository is the way in which the fuel is handled and prepared prior to encapsulation. In the latter case, pools are not used to receive the spent fuel. The fuel is instead stored under dry conditions before being encapsulated.

1.3.2 Deep repository

SKB's reference method for disposal of spent nuclear fuel is called the KBS-3 Method, where the abbreviation KBS stands for kärnbränslesäkerhet = Nuclear Fuel Safety. The method involves encapsulating the fuel in copper canisters which are then deposited, surrounded by a buffer of bentonite clay, in deposition holes in a tunnel system at a depth of approximately 400–700 metres in crystalline bedrock, see Figure 1-6.

The purpose of the three barriers (canister, buffer and rock) is to isolate the radionuclides in the fuel from the surrounding environment. Only if the radionuclides are brought up to the surface by the moving groundwater do they become harmful to man and the environment. In the deep repository it is primarily the canister that provides the isolating function. If radionuclides should escape from a leaky canister, their transport must be retarded. All barriers contribute to the retarding function. A partially damaged copper canister can effectively contribute to retardation by impeding inflow and outflow of water. The bentonite buffer has the capacity to retain many of the long-lived radionuclides, since they adhere to the surfaces of the clay particles. The rock contributes to the retardation by virtue of the low water flux at such great depth. Furthermore, radionuclides can adhere to fracture surfaces or penetrate into microfractures containing stagnant water.

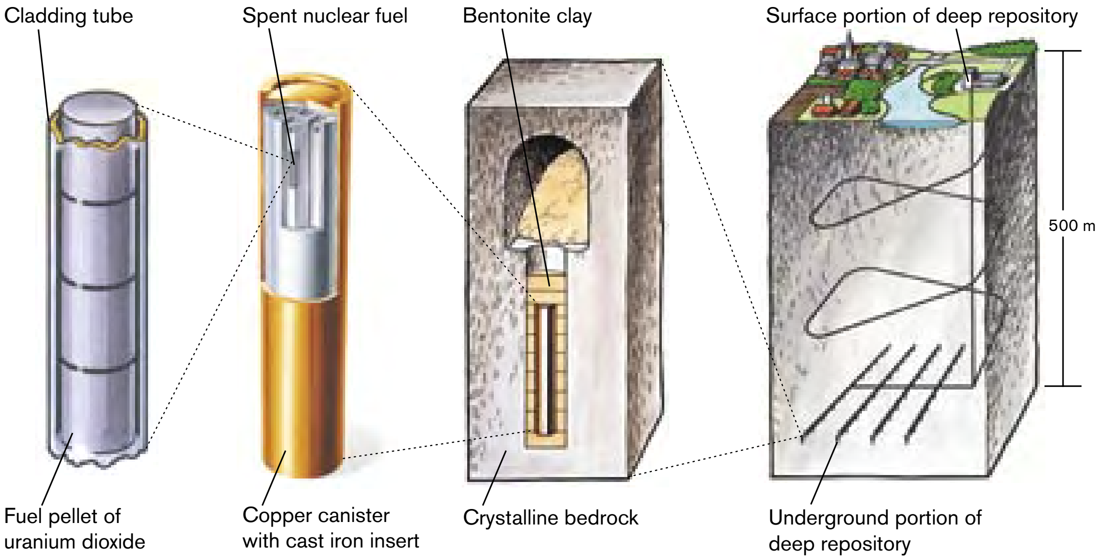


***Figure 1-6.** The KBS-3 method is based on multiple barriers (canister, buffer and rock) that prevent the radionuclides in the fuel from harming man and the environment.*

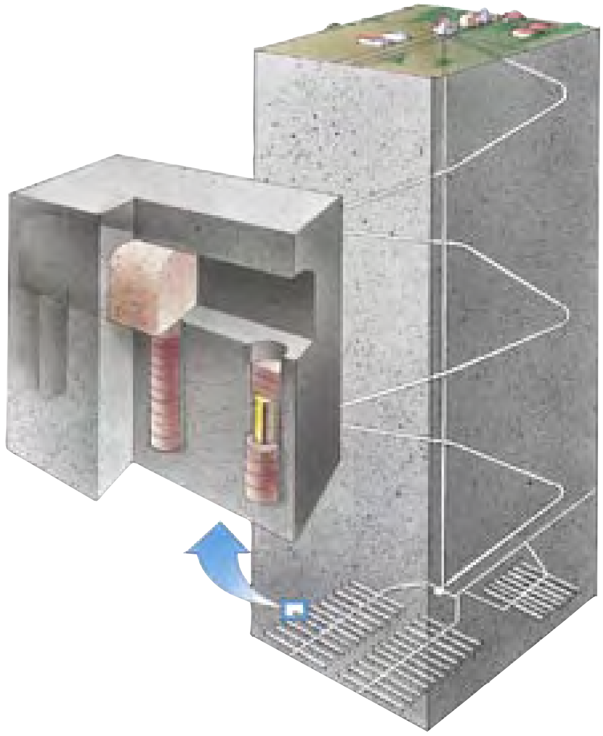


Figure 1-7. *Basic layout of the deep repository.*

The KBS-3 method has been under development since the early 1970s. The method was first described in a report in 1983 as a basis for the decision to commission the most recently built nuclear power reactors /1-3/. It has since served as a basis for SKB's programmes for research and development, at the same time as other methods have been studied in general terms.

In its basic configuration, the deep repository consists of a descent tunnel, shaft, central area and a number of deposition tunnels, see Figure 1-7. In each deposition tunnel there are a number of deposition holes. The location of the deposition tunnels, as well as the spacing between the deposition holes, is determined above all by the consideration that the temperature on the canister surface may not exceed 100°C. After the canisters have been emplaced in the deposition holes, surrounded by impervious bentonite clay, the tunnel is backfilled with a mixture of bentonite clay and crushed rock. Other chambers are also backfilled when all fuel has been deposited.

An alternative layout of the KBS-3 repository, which has been a part of the picture since the early 1990s, is horizontal deposition. In this case the canisters are emplaced in long horizontal holes instead of short vertical holes, see Figure 1-8. The volume of extracted rock and backfill in the deep repository would then be greatly reduced, since deposition tunnels are not needed. Development of rock drilling technology has now come so far that this layout is an interesting alternative to vertical deposition. Development of horizontal deposition, KBS-3H, will therefore be conducted in parallel with the work on vertical deposition, KBS-3V, for the next few years.

Siting

The work of finding a suitable site for the repository goes on. In 2002, site investigations were commenced in the municipalities of Östhammar and Oskarshamn. The selected sites are situated near the Forsmark and Oskarshamn nuclear power plants. The initial phase of the site investigations will last around two years and will include ground surveys and drilling of exploratory holes down to a depth of one kilometre. The results from the initial phase will then serve as a basis for preliminary safety evaluations, which can result in the investigations on a site being interrupted prematurely if the site is not judged to have potential for meeting the requirements.

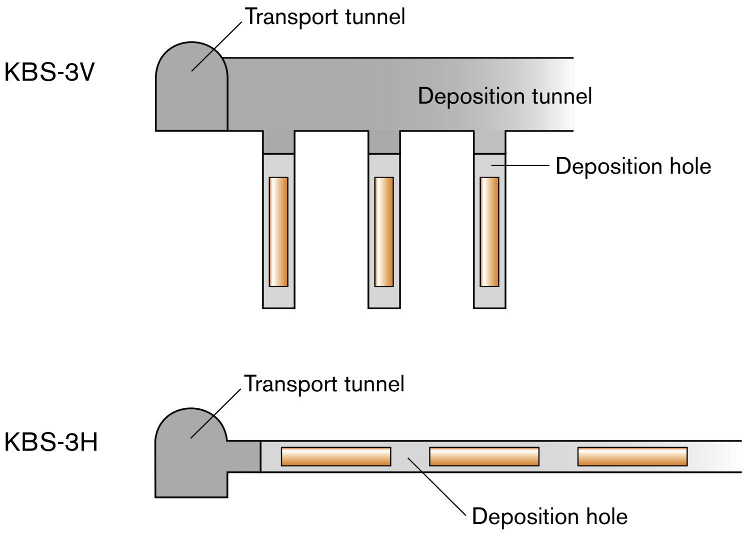


Figure 1-8. *The principle of vertical and horizontal deposition.*

During the site investigation phase, descriptive models are devised for geology, groundwater flow and biosphere on each site. These models serve as a basis for assessing the long-term safety of the deep repository.

SKB's goal for the site investigation phase is to obtain the permits that are needed to site and build the deep repository and the encapsulation plant. For the deep repository, the construction phase will then be able to be commenced on the selected site. The primary task for SKB during the coming years is to assemble supporting material for the applications, carry out consultations and prepare environmental impact statements (EISs) in compliance with the requirements of the law. Permit or permissibility review takes place primarily under the Nuclear Activities Act, the Environmental Code and the Planning and Building Act. An EIS must be appended to the applications. This document shall identify and describe the direct and indirect effects which the planned activity may have on man, the environment and society. The scope of the EIS is arrived at within the framework of the consultations that are held.

1.4 Repositories for low- and intermediate-level waste

The volumes of short-lived low- and intermediate-level waste will increase when the nuclear power plants are decommissioned. SKB believes that expansion of SFR is the best solution for this type of waste. Such an expansion does not have to be finished before decommissioning of the nuclear power plants has begun.

If the nuclear power plants are still in operation in the mid-2020s, an expansion of the existing SFR may be considered for disposal of the growing quantity of operational waste.

Other long-lived waste is interim-stored today in Clab, at the nuclear power plants and in Studsvik. The volume of this waste is small so far, but is increasing and will increase further when the nuclear power plants are decommissioned. To relieve Clab, SKB plans to interim-store this type of waste under dry conditions. This can be done in a rock cavern at Simpevarp and later in SFR as well. According to current plans, the interim storage facility does not have to be ready for use until around 2020. A final repository will be needed 25 years later.

2 Plan of action

The planning for the future facilities can be 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 upcoming programme period 2005–2010 will be on the nuclear fuel programme. Planning and construction of the remaining parts of the LILW system are dependent on the timing of the decommissioning of the nuclear power plants.

In the review statement regarding RD&D-Programme 2001 which SKI submitted to the Government in March 2002, the Inspectorate called for a clearer account of SKB's plans for the remainder of the nuclear waste programme. As a reason for this request, SKI said that the competent authorities will need to know which regulatory reviews are anticipated over the next ten years and the extent to which these reviews depend on each other. Based on this, the Government stated in a decision from December 2002 that they "assume that SKB is conducting a dialogue with concerned authorities and municipalities and that an account of SKB's timetable with associated plan of action concerning a safe final disposal of the nuclear waste will be included in RD&D-Programme 2004".

Against this background, SKB began the work of updating its planning and compiling the material requested by the regulatory authorities. A milestone was passed in the spring of 2003, when SKB decided to revise the timetable for the nuclear fuel programme. A similar revision has since been done of the programme for low- and intermediate-level waste. The plans that have been drawn up have been presented on different consultation occasions. Figure 2-1 shows SKB's plan for the remainder of the Swedish nuclear waste programme.

A brief description of SKB's activity plans is provided in sections 2.1 (the nuclear fuel programme) and 2.2 (the LILW programme). Appendix A contains the complete plan. The plans for the research, development and demonstration activities needed to carry out the programmes are presented in Chapters 4–25.

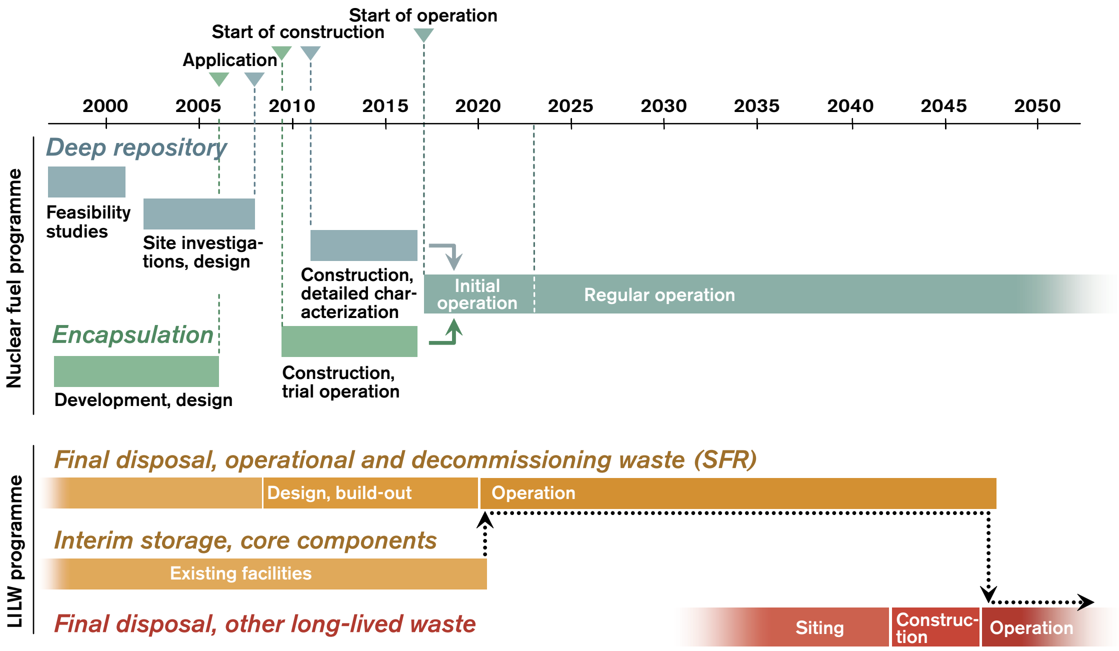


Figure 2-1. *Plan for the remainder of the Swedish nuclear waste programme.*

2.1 Nuclear fuel programme

In Sweden the intention is to implement geological disposal of the spent nuclear fuel. Behind this decision lies the principle that currently living generations should dispose of the waste. The reason for this is that it is today's generations who have benefited from the nuclear power, and that the future evolution of society is shrouded in uncertainty.

SKB's continued efforts to manage and dispose of the spent nuclear fuel are based on the following principles:

- A stepwise programme for the implementation of deep geological disposal of spent fuel.
- A continued active programme for research and development of technology and safety for the deep disposal method, but also for alternative methods.

It will take another 50 years at least to carry out all the steps needed to manage and dispose of all high-level waste in a long-term safe manner. It is therefore advisable to proceed in steps and keep the door open for technological development, changes and possible retrieval of deposited waste. This will ensure freedom of choice for the future, at the same time as the deep disposal method is demonstrated on a full scale and under actual conditions. Decisions on siting, construction and operation of an encapsulation plant and a deep repository will also be taken in steps and based on progressively more detailed investigation results.

The planning for the nuclear fuel system is based on a reference scenario with an operating time of 40 for the reactors that are currently in operation. This will give rise to around 4,500 canisters, equivalent to 9,300 tonnes of uranium. According to this plan, deposition in the deep repository will be concluded in around 2050. The different repository parts can then be sealed and the buildings decommissioned prior to 2060. If the operating time for the power plants is extended to 60 years, the number of canisters will increase to 1,500 and the operating time for the system to 20 years. The programme enables both smaller and larger fuel quantities (compared with the reference scenario) to be handled. The variables that are affected are mainly the operating time of the system and the space requirement for the deep repository.

Siting of the remaining facilities is also based on a stepwise process with well-underpinned and firmly anchored decisions. The process is fully transparent and allows concerned municipalities to decide freely whether they wish to participate or not. This model has proved to lead forward.

The basic ambition in SKB's planning for the remainder of the nuclear fuel programme is to complete the work in broad collaboration with the parties concerned. It is therefore necessary to strive for a balance between the justified requirements on time and space for the decision processes and the continuity and intensity that are required if the result is to be good. This attitude continues to permeate the way all the stakeholders work, including those who play a leading role in the licensing processes.

2.1.1 Current situation

The current situation in the nuclear fuel programme can be summarized in the following points:

- The development of the KBS-3 method is in a phase featuring pilot- and full-scale tests of parts of the system. The activities are largely being pursued at the Canister Laboratory and the Äspö HRL.
- Design of an encapsulation plant is under way, at the same time as development of the encapsulation technology is proceeding. The encapsulation plant should preferably be sited adjacent to Clab. A siting at a possible deep repository in Forsmark will be studied as an alternative for comparison.
- There are two candidate sites at which a deep repository can be sited: Forsmark in the municipality of Östhammar and Simpevarp/Laxemar in the municipality of Oskarshamn.

- Investigations and design of a deep repository are being pursued at both of these sites. SKB will apply for a permit to locate the deep repository on one of these sites at a later stage.
- Both the encapsulation plant and the deep repository require permits under the Environmental Code and the Nuclear Activities Act. Statutory consultation procedures for this have been commenced. The coming decision processes are relative well defined.

On this basis, SKB has updated the plans of action for the remainder of the programme. The main goal is to be able to put the entire system, including the remaining facilities, into operation. Important interim goals are to obtain the permits needed to establish the encapsulation plant and the deep repository.

2.1.2 Planning

The overall goal for SKB's work of managing and disposing of the spent nuclear fuel is that the encapsulation plant and the first stage of the deep repository should be completed in 2017, see Figure 2-1. A period of initial operation can then be commenced. Between 200 and 400 canisters of spent nuclear fuel will be deposited during this phase. The initial operation period should also serve as a final test and demonstration of the method.

If evaluation of the initial operation period provides support for a transition to regular operation, the latter should be able to be commenced in 2023. If regular operation gets started later, the storage capacity in Clab will not suffice and the facility will have to be expanded. If the last reactor is taken out of service in around 2025, the last canisters will be able to be deposited in the deep repository in around 2050. The deposition rate during regular operation will then be about 160 canisters per year on average. The whole programme can then be concluded in around 2060.

The plan has been revised somewhat compared with the previous RD&D-programme. The timetable that spans such a long period of time naturally contains many uncertainties. However, it also comprises a basis for decisions concerning strategies and priorities for the years to come and is continuously updated as better data becomes available. A prerequisite for the execution of this deep disposal programme is that it continues to receive the broad support it enjoys today.

The goal for the period up to the end of 2008 is to be able to submit permit applications for the encapsulation plant and the deep repository, see Figure 2-2. The prerequisites for being able to realize this goal are:

- Application for a permit to build an encapsulation plant assumes that it is sited adjacent to Clab. If the Clab siting is rejected as the main alternative, the timetable must be revised. The second-choice alternative is a siting at Forsmark. However, this assumes that the deep repository is also located on this site.
- The two site investigations for the deep repository are carried out within the planned timeframe, i.e. by the middle of 2007. The results of the investigations must also be favourable enough to warrant an application for a permit to build the deep repository on one of the sites. If siting at one of these sites is not possible and the programme has to be extended to additional sites, the timetable will have to be revised.
- Development of the technology for encapsulation and deep disposal continues at the planned pace and with the anticipated progress. Unexpected problems in some critical point may lead to delays and revisions.

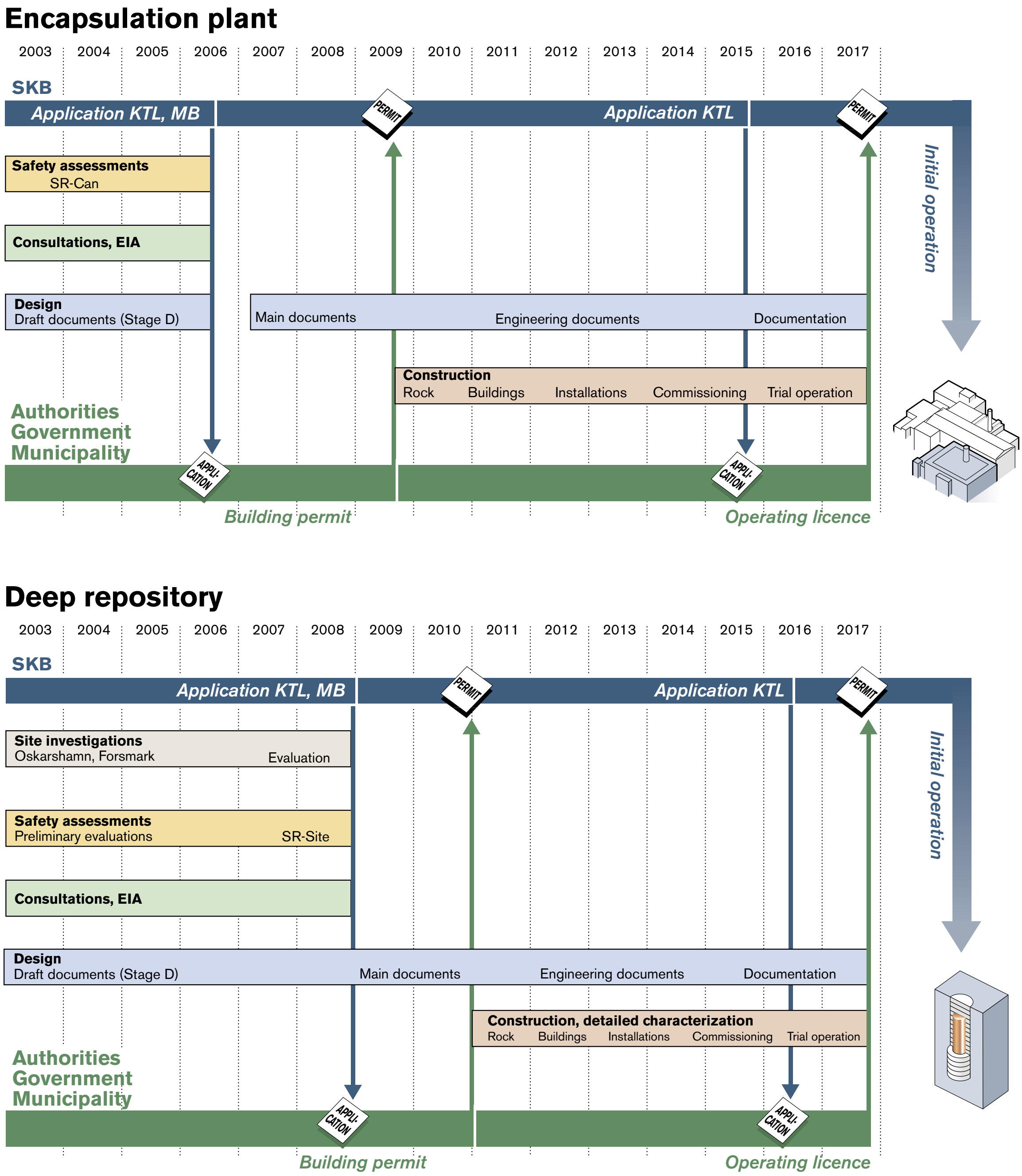


***Figure 2-2.** Plans for the encapsulation plant and the deep repository 2004–2017.*

SKB's planning in the short term is dependent on the time required for the site investigations and for producing the site-specific supporting material (facility design, safety assessment, EIS) based on the results of these investigations. Producing and compiling this material is of high priority for SKB. The planning must also take into account the linkage between the facilities. This linkage means that the production of supporting material must be coordinated in important respects. In view of the construction times for the facilities, the licensing process for the encapsulation plant must lie slightly ahead of that for the deep repository. Much of the supporting material to be compiled for a permit application for the encapsulation plant is also relevant to the deep repository. According to the plans, a permit application for the encapsulation plant is supposed to be submitted in 2006 and for the deep repository at the end of 2008, see Figure 2-3.

The time required for review of these applications is affected by several factors:

- The quality of SKB's supporting material.
- The resources and capacity of the regulatory authorities and the Environmental Court to handle and coordinate the matters.
- The will of the political bodies to make the final decisions.

Figure 2-3 shows a reasonable plan and timetable for the licensing process. The licensing process begins with SKB's permit application for the encapsulation plant in mid-2006, and the total time estimated to be required for the process is 4.5 years.

Besides a detailed description of the plant, its safety and environmental impact, the permit application for the encapsulation plant will also include:

- An account of alternative methods for spent fuel disposal.
- A comprehensive system assessment for encapsulation, transportation and deep disposal.
- An analysis of the long-term safety of encapsulated fuel in a deep repository.

It is assumed that the decision on the encapsulation plant will not be able to be made until some time (around nine months) after the application for the deep repository has been submitted, at which point SKB's choice of site and a complete safety assessment for this site will be available to all concerned. According to SKB, the review of the deep repository application should be greatly facilitated by the fact that the review of the encapsulation plant (which delivers the product that will be emplaced in the deep repository) will have been under way for two years when the licensing process for the deep repository is begun.

Furthermore, it should be noted that according to the Government's decision regarding SKB's integrated account of method, site selection and programme prior to the site investigation phase, the KBS-3 method is a planning premise for the site investigations. The final approval of a given method for final disposal will not be given before a final decision is announced on the permit applications. In order to provide the necessary supporting material for such a decision, SKB will, as is evident above, include in the permit application for the encapsulation plant and associated environmental impact statement a description and evaluation of alternative methods for management and final disposal of spent nuclear fuel. This means that the regulatory authorities and the Government will be able to take a standpoint on SKB's choice of method when they consider the application for the encapsulation plant.

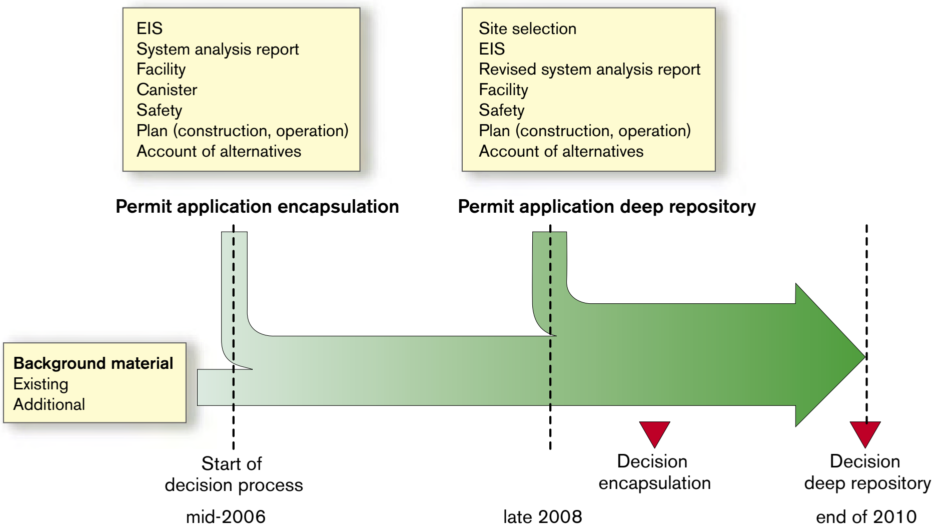


***Figure 2-3.** Applications and decision process for encapsulation plant and deep repository.*

2.2 LILW programme

Parts of the system for management of low- and intermediate-level waste have been in operation since the 1980s. This includes, for example, final disposal of various types of short-lived low- and intermediate-level waste (LILW) in SFR at Forsmark. Experience from these activities provides a good knowledge base for the remaining steps.

SKB will have an important role in the decommissioning of the Swedish nuclear power plants. The power utilities bear primary responsibility for the actual decommissioning of the plants, while SKB will dispose of the waste. By this time we must have modified the transportation system and expanded SFR. As a final step, a final repository for long-lived waste is also needed.

2.2.1 Current situation

The current situation in the LILW programme can be summarized in the following points:

- Short-lived LILW is disposed of in SFR.
- Long-lived LILW is interim-stored today in Clab, at the nuclear power plants and at Studsvik. The volume of this waste is small so far but will increase, especially when the nuclear power plants are decommissioned.
- So far there have not yet been any large-scale decommissioning projects in Sweden. But there is a lot to be learned from rebuilds of nuclear power plants. As of the closure of Barsebäck 1, however, planning for a future decommissioning has assumed more concrete forms.
- Since the middle of the 1980s, SKB has been following what has been happening internationally in the decommissioning field as regards technological development and research.

2.2.2 Planning

Prior to the decommissioning of the nuclear power plants, additional disposal chambers are needed for short-lived LILW. The waste types that will arise then are similar to those that arise in connection with operation and maintenance of the nuclear power plants and are disposed of in SFR. An expansion of this facility to accommodate short-lived decommissioning waste was foreseen in conjunction with planning and licensing and is still judged to be the best solution for this waste. An expansion of SFR to accommodate decommissioning waste does not need to be finished before decommissioning of the nuclear power plants has begun. If the nuclear power plants are operated for 40 years, the first of these chambers will not have to be put into use before 2020 at the earliest.

Operation and decommissioning of the nuclear power plants give rise to small quantities of other long-lived waste, for example core components. These are interim-stored today in Clab. To relieve the load on Clab (and to avoid a further expansion), SKB plans to interim-store core components under dry conditions. Special packages and transport casks need to be developed for this purpose.

Immobilization of the waste for final disposal takes no more than ten years. This work cannot be begun too early if it is to be effective. Waiting as many years as possible also simplifies the final treatment work by allowing the radioactivity, consisting largely of cobalt-60, to decay. Another advantage is that a certain degree of freedom is retained when it comes to the design of the waste containers. If interim storage of the fuel is prolonged until around 2050, the final repository for other long-lived waste (such as core components) will not have to be put into operation until around 2045 at the earliest.

Siting of a repository for other long-lived waste will therefore not be necessary until around 2035. Rock vaults for this type of waste can then be located either at SFR, the deep repository for spent nuclear fuel or another site.

The planning is presented in greater detail in Appendix A. Work during the coming RD&D period is described in Chapters 24 and 26.

3 RD&D-programme

The long-term safety of the various repositories is at the focus of SKB's research, development and demonstration work. Safety is evaluated by means of safety assessments, which simply put can be said to consist of first carefully describing the state of affairs in the repository at some initial point in time, and then predicting what changes might take place in the repository and finally describing the consequences for man and the environment.

There is a constant interplay between safety assessment, research and repository design. The safety assessment is based on a given repository design and on the knowledge concerning long-term changes in the repository environment delivered by research. The results of the safety assessment can be used to prioritize new research and as a basis for designing the facility. New materials or fabrication methods can give rise to a further need for research or analyses.

3.1 RD&D-Programme 2004 – nuclear fuel

The technical solutions for managing and disposing of spent nuclear fuel can be designed in a variety of ways. SKB's goal is to provide solutions that are safe, cost-effective and cause as little impact on man and the environment as possible. All of society's requirements on protection of human health and the environment must be met. SKB's existing facilities fulfil these goals. The deep repository and the encapsulation plant must do the same.

SKB's principal efforts in the RD&D-programme for spent nuclear fuel can be divided into two main areas: 1) technology development, 2) safety assessment and research. Very brief overviews of these areas are provided in sections 3.1.1 and 3.1.2. The complete programme for spent nuclear fuel is presented in Chapters 4–23.

3.1.1 Technology development

A deep repository according to the KBS-3 method is based on the deposition of copper canisters with spent nuclear fuel, embedded in a buffer of bentonite clay, at a depth of 400–800 metres. The deep repository can take several different forms. The final design is affected by optimization of the technical systems and by adaptation to the prevailing geological conditions on the site. At the same time, the requirements on safety must be met, both during construction and operation and in the post-closure period. SKB's primary goal for the coming RD&D period is to compile supporting material for an application for a permit to build an encapsulation plant adjacent to Clab.

The canisters in which the spent nuclear fuel is to be deposited are designed to resist the pressure to which they will be exposed in the repository. The copper shell is supposed to resist corrosion processes so that it remains intact over a 100,000-year timespan. In the reference design, the canister consists of a cast insert of nodular iron and a copper shell with a thickness of five centimetres. The work of designing and evaluating fabrication, sealing and testing methods for the canister continues. Much of this work is being done at the Canister Laboratory.

The experience gained at the Canister Laboratory will influence the final design of the encapsulation plant. During the next few years we will conduct a systematic evaluation of the encapsulation process and make improvements and simplifications where possible. This work will then serve as a basis for a permit application for the encapsulation plant.

The current reference design of the deep repository is general and will be adapted to the conditions on the sites in the municipalities of Oskarshamn and Östhammar where site investigations are being conducted. In the further work with we will study, among other things, how different repository layouts and different buffer and backfill materials affect safety and the external environment. The barriers can also be given different dimensions, and deposition depth and layout can vary. We wish to preserve freedom of choice for as long as possible, since this provides greater flexibility and makes it possible to make use of the latest technical and scientific advances.

In the next few years, horizontal deposition of the copper canisters will be studied as an alternative to vertical deposition, see section 11.4. The final choice of deposition method will be based on an evaluation of safety, technology, costs and environmental aspects.

3.1.2 Safety assessment and research

The goal of the research on long-term safety which SKB is conducting is to understand the processes (long-term changes) that occur in a deep repository and how they affect the repository's ability to isolate the spent nuclear fuel. The results delivered by the research are then used in the safety assessments conducted at regular intervals by SKB. At present work is proceeding on SR-Can, the safety assessment that will be submitted as supporting material for the application for a permit to build the encapsulation plant. After that, another safety assessment, SR-Site, will be appended to the application for a permit to build the deep repository.

A new aspect of SKB's research programme compared with previous years is that we have started a programme for social science research. This is in response to the review of RD&D 2001, where a number of municipalities, universities and interest organizations wanted the RD&D-programme's technical and scientific focus to be broadened to include a social sciences aspect with research on e.g. attitudes, decision making in complex societal issues, and the long-term evolution of society. There are four general research areas of relevance to the waste issue which SKB intends to support:

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

The emphasis should be on applied research. The results must be able to be put to practical use, but there should also be an interface with basic research. Furthermore, SKB's research areas, site-specific studies and investigations should have clear links with each other and support each other.

3.2 RD&D-Programme 2004 – LILW

The facilities included in the LILW programme are the Swedish nuclear power plants and SKB's facilities. In addition, SKB may manage and dispose of radioactive waste from Studsvik, the fuel factory in Västerås, Ranstad and Ågesta. This lies beyond SKB's undertaking for its owners and therefore requires that special agreements be signed.

3.2.1 Decommissioning

In Sweden, decommissioning of the nuclear power plants will take place relatively soon after the spent fuel has been removed from the plant. The greatest quantity of waste obtained during decommissioning is conventional building material, which is not radioactive at all. Of the radioactive material, a large portion is very low-level. Following decontamination or melting, a large portion of this waste can be reused. How large a portion depends partly on how reliable the measurement methods that are used are, and partly on what rules are applied for free release. Today there are no general rules; instead, the regulatory authorities decide this from case to case.

The waste that is not released for unrestricted use will be disposed of in special repositories. The short-lived decommissioning waste is planned to be disposed of in an extension of SFR. Long-lived waste must be disposed of at greater depth than short-lived waste. Chapter 24 contains an account of SKB's planned work on decommissioning during the coming programme period.

3.2.2 LILW

The research activities concerning low- and intermediate-level waste are mainly aimed at generating data and models for analyzing long-term safety in a repository for long-lived waste. During the coming RD&D period, SKB will in particular investigate how the alkaline environment created by concrete affects radionuclide transport. The programme is described in its entirety in Chapter 25.

An initial safety assessment of a final repository for long-lived waste was performed in 1999 /3-1/. When the site investigations for the deep repository have been completed in 2007, time and resources will be available for a new assessment. The exact time will be chosen with a view towards other safety assessments and resources.

3.3 RD&D-Programme 2004 – international cooperation

Joint international research has been pursued at the Äspö HRL for more than ten years now and has been a good basis for SKB's collaboration with sister organizations in other countries. In recent years SKB has also become increasingly involved in EU projects. Under the EU's Fifth Framework Programme, SKB participated in 18 different projects and was in charge of three of these.

The biggest project was the establishment of the Prototype Repository in the Äspö HRL. This work was concluded in 2003, when the experimental area was sealed. Information is now being collected from more than 1,000 measurement instruments. At the same time the modelling work continues with comparisons between the predictions of processes and phenomena indicated by the mathematical models and the actual outcomes in the Prototype Repository.

Under the EU's Sixth Framework Programme, SKB will participate in the following projects:

- Esdred, which is developing and testing different disposal methods and methods for building and sealing a geological repository in a safe manner.
- NF-Pro, which is investigating the importance of the near field for long-term safety.
- Red-Impact, which will estimate quantities and types of waste from partitioning, transmutation and conditioning of spent fuel, as well as the costs and other aspects of such treatment.

Conditions in Sweden and Finland are very similar as far as final disposal of spent nuclear fuel is concerned, and both countries are planning to use the same method. SKB and its Finnish counterpart Posiva have therefore signed an agreement for far-reaching cooperation. Posiva has chosen the site for the Finnish final repository and began the first stage of construction and detailed characterization this year. Posiva and SKB are collaborating intimately on canister fabrication and sealing technology. The most important joint project is conducting fabrication trials using different methods at different suppliers.

SKB has bilateral agreements on information exchange with organizations in eight countries: Canada, Finland, Germany, Japan, Spain, Switzerland, UK and USA. Special agreements on cooperation regarding experiments in the Äspö HRL exist with organizations in six countries: Canada, Finland, France, Germany, Japan and Spain.

The international cooperation at the Äspö HRL is coordinated by an International Joint Committee (IJC). Technical Evaluation Forums (TEFs) are arranged in conjunction with the IJC's meetings to provide advice and opinions on programmes and results. In practical terms, this cooperation entails that the organizations have personnel at the site who participate in the execution of different experiments. Several of the participating organizations have started investigations and experiments beyond those included in SKB's programme.

The international cooperation makes it possible to gather the world's foremost experts within many different disciplines for an exchange of ideas and experience regarding questions of importance for the disposal of radioactive waste. An example of this is the cooperation that is taking place in so-called Task Forces consisting of members from the participating organizations. Such Task Forces exist for modelling of groundwater flow and transport as well as for modelling of engineered barriers. The results of the international cooperation are published in a separate report series: Äspö International Progress Reports.

3.4 Coming RD&D-programmes

During the coming programme period, SKB plans to apply for a permit for an encapsulation plant and has therefore placed the emphasis in RD&D-Programme 2004 on encapsulation technology. The purpose is to describe the state of development in canister fabrication and sealing technology, and to obtain the comments of the reviewing bodies prior to submission of this application. The account is intended to show that methods exist for the various fabrication and inspection steps that meet stipulated quality requirements and that can be developed to meet stringent requirements on reliability in the process as well.

The work of developing the deep repository technology and assessing long-term safety is being pursued in parallel with the work of developing the encapsulation technology. The deep repository technology is planned to be the focus of RD&D-Programme 2007. Development of the methodology for safety assessment continues. Next in line is the safety report SR-Can. It will comprise a part of the supporting documentation for the permit application for the encapsulation plant and is a first step towards the safety report that will be prepared for the site selected for the deep repository. A planning report /3-2/ and an interim report /3-3/ have been published and will be subjected to review and comment by the regulatory authorities. This is an important step in order to obtain viewpoints on the methodology for the safety assessment. The viewpoints can then be incorporated in the final version of SR-Can.

The intention is that the structure of the RD&D reports should spotlight those parts of the activities that are most important at various points in time. According to the plans, the coming RD&D-programmes will focus on the following parts of the activities, depending on which phase SKB is in:

- RD&D 2007 Deep disposal technology.
- RD&D 2010 The LILW system.

Part II
Technology development

4 Overview – technology development

Development of the technology for the KBS-3 method is currently in an intensive phase in preparation for the upcoming permit applications for the encapsulation plant and the deep repository. SKB's strategy for the work is to focus on a reference design for each of the different parts of the system. Vertical deposition, KBS-3V, is the reference for the design of the deposition area in the rock. The work of designing the details follows a step-by-step process, where the final choices for different parts are made as late as possible so that they can be based on the most recent findings and investigations concerning alternative designs. Horizontal deposition of the copper canisters, KBS-3H, is one such alternative. The final choices are based on an evaluation of safety, technology, costs and environmental aspects.

Questions relating to canister and encapsulation technology are dealt with in Chapters 5–8. Chapter 9 deals with the transportation of encapsulated spent nuclear fuel between the encapsulation plant and the deep repository. The technology for building and operating the deep repository is dealt with in Chapter 10, while the methodology for designing it is described in Chapter 11. Finally, long-term observations and monitoring of the deep repository are discussed in Chapter 12. Sections 4.1–4.8 contain short summaries of the programmes within each technology area.

4.1 Canister fabrication

Copper tubes for canisters have been trial-fabricated using different methods such as roll forming, extrusion, pierce and draw processing and forging. The trials show that these methods are feasible for fabricating copper tubes. Various methods for casting the inserts are also being tested and evaluated. The development work is continuing in order to improve the fabrication technology, and SKB intends to report which methods are feasible for the future serial production of canisters in connection with the permit application for the encapsulation plant. The complete programme for canister fabrication and nondestructive testing of canister components is presented in Chapter 5.

Fabrication of canisters will not take place at a single location. The inserts will be cast at different foundries and the copper tubes will presumably be made at some plant that has the requisite machinery. Machining of inserts and copper tubes will then take place at a machine shop or in the canister factory, which is a special facility for assembly and final inspection of the copper canisters before they are delivered to the encapsulation plant. The lids for the inserts and the copper lids are also components that will be fabricated by an external supplier.

4.2 Sealing technology

SKB is currently working simultaneously to develop two welding methods to seal the copper canisters: electron beam welding (EBW) and friction stir welding (FSW). Equipment for testing of the two methods is in operation at the Canister Laboratory. The tests show that both methods work. Development work is continuing on the sealing technology to ensure that at least one method that meets the quality requirements will be available and that it can be used in serial production.

Methods for nondestructive testing, above all ultrasonic and radiographic techniques, are also being developed in the Canister Laboratory. Work on this and to establish acceptance criteria will continue and be reported on in preparation for a permit application for the encapsulation plant. The programme for sealing technology for the canister and nondestructive testing of the sealing weld is described in Chapter 6.

4.3 Qualification

Before the encapsulation plant and the canister factory are put into operation, qualification (investigations showing that the methods meet stipulated requirements) of methods for fabrication, welding and nondestructive testing of canisters will be carried out. Qualification will be done to relevant criteria. A programme for qualification will be prepared and presented in connection with the permit application for the encapsulation plant. The qualification work is described in Chapter 7.

4.4 Encapsulation

In the mid-1990s, SKB presented a preliminary design of an encapsulation plant built adjacent to Clab /4-1/. During the next few years we will conduct a systematic evaluation of the encapsulation process and make improvements and simplifications where possible. Experience gained from the Canister Laboratory will serve as a basis for the final design of the encapsulation plant. Important factors in determining what the encapsulation process will look like are development of the welding and testing technologies.

SKB will design the plant on the basis of the results of the above-mentioned technology development. The design work will also be coordinated with the results of the EIA (environmental impact assessment) process and the safety assessments and system analyses that are performed. The programme for encapsulation is presented in its entirety in Chapter 8.

4.5 Transportation of encapsulated fuel to the deep repository

A feasibility study of a transport cask for canisters with spent nuclear fuel was conducted in the mid-1990s. An updating and more detailed design of this cask is currently under way. Custom-tailored transport frames are needed for the new transport casks.

The operation of the deep repository and the encapsulation plant is based on more or less continuous transport of sealed canisters between the two facilities. Since the encapsulation plant is designed to seal 200 canisters per year, the transportation system must be able to handle this number. The canisters will be transported by sea if the deep repository is located at Forsmark and by land if it is located at Oskarshamn. Chapter 9 provides a more detailed account of transport between the encapsulation plant and the deep repository.

4.6 Deep repository technology

In preparation for an application for a siting permit for the deep repository, work continues on selecting methods for building and operating the deep repository and designing different parts of it. The development work mainly includes:

- Rock mining and sealing technology for tunnels.
- Manufacture and emplacement of buffer.
- Handling technology for canisters.
- Backfilling and plugging of deposition tunnels.

Another area currently being studied is cleaning and sealing of boreholes. Exploratory holes from the surface and from tunnels must be sealed no later than when the deep repository is closed. Technology for retrieving canisters after initial operation has been developed and will be tested in an ongoing full-scale test in the Äspö HRL. The complete programme for deep disposal technology is presented in Chapter 10.

4.7 Design of the deep repository

The current reference design of the deep repository is based on generic data on Swedish bedrock at a depth of 400–700 metres. The layout is general and will now be adapted to conditions on the sites in the municipalities of Oskarshamn and Östhammar where site investigations are being conducted. In the continued work we will study how different repository designs and different buffer and backfill materials affect safety and the external environment on the sites to be investigated.

The barriers can also be given different dimensions, and deposition depth and layout can vary. SKB wishes to preserve freedom of choice for as long as possible, since this provides greater flexibility and makes it possible to make use of the latest technical and scientific advances. The design work is being pursued stepwise in accordance with a model developed for the nuclear power plants and SKB's existing facilities Clab and SFR. The design process is based on the above-mentioned technology development and is being coordinated with the results from the site investigations, the EIA work and the safety assessments and system analyses. The programme for design is presented in its entirety in Chapter 11.

4.8 Long-term observations

The deep repository will be designed so that it is safe even without monitoring or maintenance. However, this requires long-term observations and measurements to gain a better scientific understanding of the site and the repository. With this in mind, SKB has drawn up guidelines for conducting long-term observations during the site investigation, construction and operating phases. Requirements on fissile material controls (safeguards) and on physical protection of such materials are tough. Work is being pursued internationally to define the requirements on the post-closure safeguards system for a closed geological repository. When SKB designs the deep repository, we will do so with a view towards the requirements and viewpoints of the supervisory authorities as regards safeguards and physical protection. Chapter 12 deals with long-term observations and monitoring.

5 Canister – fabrication

The purpose of the canister in the deep repository is to isolate the spent nuclear fuel from the surrounding environment. As long as the canister is intact, no radionuclides can escape from it. To achieve isolation, the canister must:

- Be intact at deposition.
- Be resistant to the chemical environment expected in the deep repository.
- Withstand the mechanical loads expected in the repository.

Furthermore, it should be designed to provide high safety during encapsulation, transport and deposition.

SKB's reference canister consists of an outer corrosion barrier (shell) of copper and a pressure-bearing insert of nodular iron, see Figure 5-1. The canister holds either twelve BWR assemblies or four PWR assemblies. It has a diameter of just over one metre and a length of nearly five metres. The total weight, including fuel, is about 25 tonnes for a BWR canister and about 27 tonnes for a PWR canister.

The copper in the shell contains approximately 50 ppm phosphorus to increase the material's creep ductility. The pressure-bearing insert is made of nodular (spheroidal graphite) iron. The spacing between the fuel channels is five centimetres and the minimum distance from the fuel to the outside of the insert is about five centimetres, see Figure 5-2.

An important milestone has been reached in the development of the encapsulation technology with the fabrication and sealing of a full-scale canister according to the quality plan.

50 mm copper

Estimated weight (kg):

Copper canister	7,400
Insert	13,600
Fuel assemblies (BWR)	3,600
Total	24,600

Figure 5-1. *Copper canister with cast iron insert for BWR fuel.*

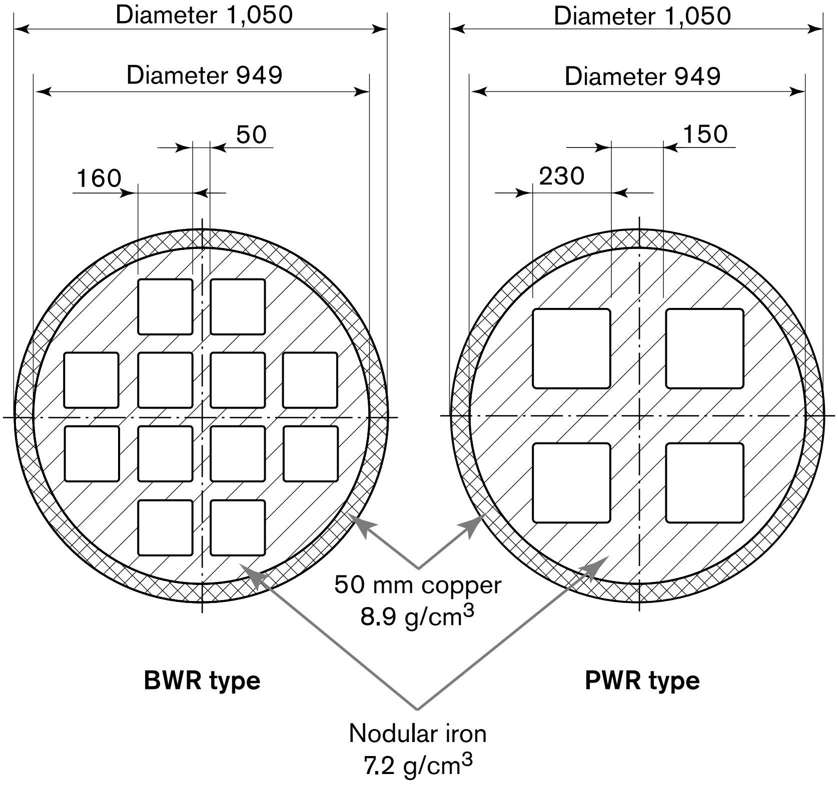


Figure 5-2. *Cross-section of canister. All dimensions are given in millimetres.*

5.1 Design premises

The design premises for the canister were presented for the first time in RD&D-Programme 98 /5-1/ and were established in the overall design premises /5-2/. These serve as a basis for the work of designing the canister in detail and entail in brief that:

- The canister must withstand all known corrosion processes so that it is expected to remain intact in the deep repository for at least 100,000 years.
- The canister must be designed to withstand the mechanical stresses that arise in a deep repository in granitic rock down to a depth of 700 metres.
- The calculated strength of the canister must also take into account the loads that can be expected during an ice age.
- The surface dose rate on the outside of the canister must not exceed 1 Gy/h.

Conclusions in RD&D 2001 and its review

SKI takes a positive view of the fact that SKB has compiled the state of knowledge on copper corrosion. As SKI has previously stated, the next step must be to apply this knowledge in the safety assessment and in the work on the design premises, since the reasoning from this work will result in the determination of the thickness of the copper.

SKI views the ongoing work with the design premises for the repository, and the acceptance criteria for the canister, as very important. Delays in this work may delay other parts of the canister work. The design premises should serve as controlling conditions for many activities and may need to be revised after the consequence analyses that must be performed in order to show that the design premises and acceptance criteria are adequate.

Newfound knowledge since RD&D 2001

Since RD&D 2001 the overall design premises for the deep repository in the KBS-3 system have been compiled /5-2/. The work of transferring the design premises to database form has also commenced, see section 11.2.1.

In the design premises for the canister /5-3/, possible extra loads from the overlying continental ice sheet during an ice age were regarded as extreme cases for which no extra safety margins were required.

The lifetime estimate /5-4/ showed that a two-millimetre wall thickness is sufficient for the canister to have a lifetime of a million years. Experimental studies /5-5/ and literature data /5-6/ show that surface defects do not increase the sensitivity of copper to local corrosion. Previously conducted fracture toughness measurements /5-7/ have shown that there is no risk of crack growth either. Acceptance criteria for a canister sealed by electron beam welding will be formulated on the basis of this information.

Programme

The design premises for the canister will be updated prior to the application for a permit to build the encapsulation plant.

Research aimed at conducting a probabilistic analysis of the strength of the canister has been under way since 2002. The results of this project will serve as a basis for a final determination of the dimensions of the canister insert. According to plans, the project will be concluded during 2004. The results will determine whether further research and development are required during the coming three-year period.

Roughly the same corrosion properties can be expected in a weld made by friction stir welding as in an electron beam weld and in the parent metal. Data on the fracture toughness of a weld made by friction stir welding are lacking, however. Such data will be gathered during the coming three-year period.

5.2 Acceptance criteria

Acceptance limits is the general concept used to describe the limits within which various parameters of importance to canister performance must lie. In many cases, these limits are expressed in the form of specifications, for example drawing dimensions with tolerances for copper thickness. Certain parameters have more complex limits, however. These parameters are called acceptance criteria. An example of an acceptance criterion is permissible occurrence of discontinuities.

In order to ensure that the canister remains within the acceptance limits, we are developing methods for quality inspection. Certain inspection methods are relatively simple and aimed at ensuring that the canister meets various specifications. An example of this is a standardized measurement procedure for dimension measurement. Other inspection methods are more complicated in terms of execution and interpretation of the results. An example of this is nondestructive testing (NDT), where the method must have high reliability in order to be able to sort out canisters that do not meet the specified acceptance criteria, see Chapter 7.

When SKB determines acceptance criteria for permissible material defects, we depart from a survey of what discontinuities can arise in the various process steps during fabrication of the canister (defect descriptions) and how they affect the canister's ability to meet the design premises (defect tolerance analysis). The quantification of the acceptance criteria is complex. The criteria are primarily intended to guarantee the functional safety of the canister. At the same time, they must correspond to the fabrication quality and be commensurate with detection and resolution capabilities of the inspection methods.

Conclusions in RD&D 2001 and its review

SKB's conclusions in RD&D 2001 can be summarized in the following points:

- Acceptance criteria will be established for all parts of the canister, including the welds. It must be possible to determine by means of the testing methods whether the acceptance criteria for e.g. the welds are satisfied. SKB is producing a derivation of the acceptance criteria.
- The consequences of larger defects than those stipulated by the acceptance criteria are being examined. Established acceptance criteria regarding defects must be able to be verified by NDT.
- The ongoing work of choosing suitable equipment and methodology is continuing.
- The lessons learned from the trial fabrication of all canister parts will be applied to and influence the further development of the factory. The work of investigating and establishing acceptance criteria and testing methods will make it possible to specify modified equipment for NDT and other quality inspection more precisely.

SKI regards the ongoing work with design premises for the repository and acceptance criteria for the canister as very important. Delays in this work may delay other parts of the canister work. The design premises should be a controlling factor for many activities. They may need to be revised after the consequence analyses that must be performed to show that design premises and acceptance criteria are adequate.

The work with acceptance criteria must be given high priority.

Newfound knowledge since RD&D 2001

Work is being pursued to gather data as a basis for assessing the defects that can arise in the various fabrication steps for fabricating copper canisters and cast iron inserts, and finally for sealing the finished canister in the encapsulation plant. A project is being pursued in cooperation with the German Bundesanstalt für Materialforschung und -prüfung (BAM) on the reliability of nondestructive testing for inspecting sealing welds.

Based on knowledge about corrosion of copper in the deep repository environment and knowledge from the fracture toughness measurements on copper, we can formulate preliminary criteria for permissible discontinuities in the copper shell, see section 5.1. In summary, a coherent discontinuity from the surface inward, a so-called surface-breaking discontinuity, does not pose any threat to the canister's integrity in the deep repository over long periods of time. The corrosion assessments also show that a copper cover of a few millimetres is fully adequate to guarantee a canister lifetime of over a million years /5-4/. There is still some uncertainty regarding how a possible influx of oxygenated water during future ice ages will affect corrosion. Our judgement is that a copper cover of 1.5 centimetres will provide full corrosion protection, even allowing for uncertainties regarding the consequences of ice ages. SKB has set 3.5 centimetres in radial extent as a preliminary criterion for the largest permissible discontinuity in both sealing welds and the rest of the copper shell. This means that the minimum permissible copper cover is 1.5 centimetres at a copper thickness of five centimetres.

As mentioned in section 5.1, a project is under way concerning probabilistic analysis of canister strength. In parallel with this project, computer simulations are being done at the Swedish Foundry Association to identify those areas in the canister insert where the probability of casting defects is greatest. A survey of actual casting defects in inserts and testing of methods for nondestructive testing has also been commenced. These projects will provide a basis for judging the damage resistance of the insert, which in turn provides a basis for establishing acceptance criteria.

Programme

The work of probabilistic analysis of canister strength will be concluded during 2004. The results will serve as a basis for the optimization of technical specifications and the formulation of acceptance criteria.

Additional inserts for BWR assemblies will be cast and evaluated against these acceptance criteria. Inserts for PWR assemblies will also be fabricated and analyzed.

5.3 Materials technology

The design of the canister and the choice of materials in the constituent components have been based on the design premises. The properties of the canister, and thereby its function in the deep repository, are determined by its design and the material properties of its components. This section deals with materials technology aspects that can be related to the fabrication technology for canister components. Section 5.4 deals with the scope and results of trial fabrication. For further details, see /5-8/ and /5-9/.

There are detailed technical specifications with precise material requirements for fabrication of all canister components. Technical specifications and procedures are included in the quality system that has been developed for canister fabrication. This is intended to cover the entire canister fabrication chain from material suppliers to finished canisters. The quality system is a part of SKB's quality system, certified to ISO 9001 and 14001. Both technical specifications and procedures are updated continuously as a consequence of the ongoing development work.

5.3.1 Canister inserts

The canister insert is the pressure-bearing component in the canister and must meet the strength requirements that follow from this. The inserts are made of cast iron. The chosen material is a so-called nodular (spheroidal graphite) iron with a principally ferritic matrix structure. Cast iron is the generic term for iron-carbon alloys with more than about two percent (by weight) carbon. The cast irons used for fabrication normally have carbon contents in the range 2.5–4 percent. In one group of cast irons, carbon that is not bound in any other way is precipitated as free graphite when the molten iron cools and solidifies. The graphite can occur in different shapes. It is the shape of the free graphite that gives different types of graphitic cast irons different properties. These types have been standardized, see Figure 5-3.

Iron with graphite shape I is called grey iron. Grey iron is the most widely manufactured cast metal and is used in many different contexts. Nodular iron with graphite shape VI is also produced in large volumes. Components of the same or larger size as SKB's insert are produced in many foundries in both grey iron and nodular iron.

The shape of the graphite has a great influence on the properties of the material. In grey iron, the flakes of graphite act as stress concentrators inside the material. Grey iron is therefore a relatively brittle material. Nodular iron has a much higher strength and ductility than grey iron since the graphite is of nodular shape. These strength properties, plus the fact that nodular iron has good casting properties and is easy to machine, explain why nodular iron has been chosen as the material in the inserts.

The shape, size and distribution of the graphite can be controlled by the addition of small quantities of elements to the melt. Magnesium is widely used in nodular iron, along with an "inoculant", generally ferrosilicon. The properties of the cast iron can also be affected by different concentrations of such alloying elements as manganese, nickel, chromium and copper.

The mechanical properties of the cast iron are tested by tensile testing of test bars, which in the case of cast iron can be taken out in different ways. In this context we will differentiate between cast-on test bars and test bars made directly from a part of the casting. The latter of these alternatives is the most representative of the properties of the finished component. Cast-on test bars are obtained by providing suitable cavities in the mould wall. Test bodies of suitable size are then obtained as projecting parts of the product. Test bars for e.g. tensile testing can then be made from these bodies. The cast-on test bodies harden and cool together with the cast component and should therefore have a microstructure and properties equivalent to that of the

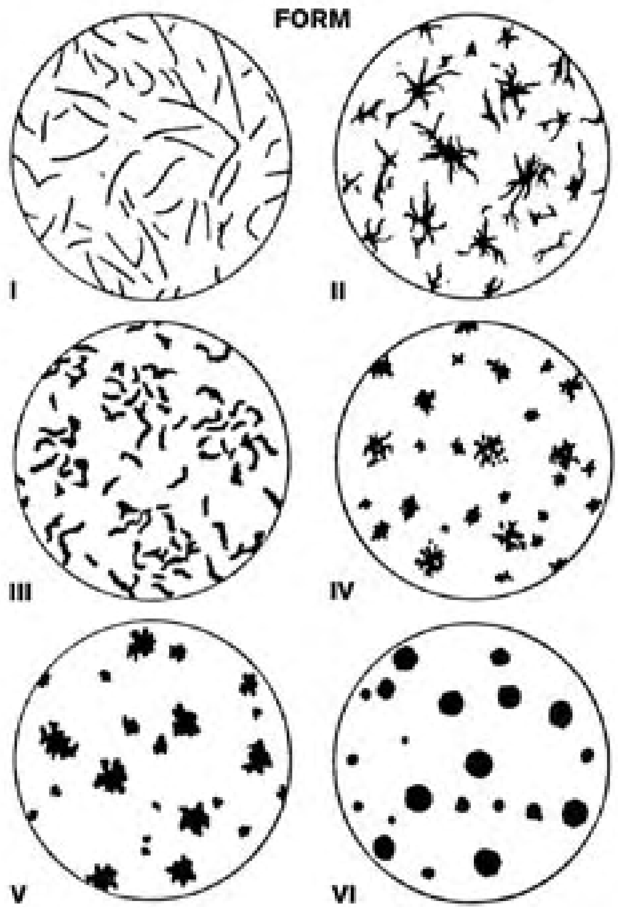


Figure 5-3. *Graphite shapes in cast iron according to EN-ISO 945. The dominant graphite shape in nodular cast iron is no VI (nodular graphite).*

cast iron in the finished product. The best agreement is obtained in the casting of small pieces. The advantage of cast-on test bodies is that they can be sawn of off the component without damaging it.

During the development work, SKB studied the material properties obtained in both cast-on test bars and discs cut from the insert itself. The inserts were cast with extra length so that a cut disc could be evaluated from the top of the insert. The extra length has made it possible to make inserts of the specified lengths despite removal of the disc. However, some inserts were cut up so that additional discs along the legnth of the inserts could be used for extensive material testing.

A number of nodular irons are internationally standardized in SS-EN 1563. The standard makes no requirements on chemical composition. But it does state that the graphite shape shall essentially correspond to shapes V and VI. Specified requirements are made on the mechanical properties of castings of different sizes. SKB's canister inserts represent a much thicker-walled casting than has been stipulated in this standard. However, the standard leaves open the possibility that specific material requirements can be agreed on with the supplier in each individual case. Precise material requirements that ensure that the inserts meet the design requirements can be established when relevant strength calculations and verified compression tests have been carried out in accordance with the following programme.

Conclusions in RD&D 2001 and its review

In RD&D 2001, SKB concluded that the mechanical properties of the nodular iron are highly dependent on the dimensions of the cast body. Material testing must therefore be performed on the finished inserts.

The results of this testing should serve as a basis for optimizing the fabrication processes, the material specification and the testing methods. Besides showing that the canister meets the design requirements, strength analyses should also be based on the actual material properties of fabricated canisters.

In its review of RD&D 2001, SKI concluded that SKB should to a greater extent verify the mechanical properties of the inserts by examining some fabricated inserts more thoroughly. SKI also offered the viewpoint that simulation programs should be run to achieve a satisfactory result in the casting of the insert.

Newfound knowledge since RD&D 2001

Extensive material testing has been conducted on a number of cast inserts, both with cast-on test bars and with test pieces from the actual inserts. To determine variations in properties between different specimen locations, test bars for tensile testing and microstructure examination have been made from discs cut from different locations in the inserts, see Figure 5-4. Examples of specimen locations are shown in Figure 5-5.

SKB has found a relatively wide range of variation in material properties in several individual inserts. The greatest variation in tensile testing is found in values for elongation at rupture. The ductility of this type of cast iron is highly dependent on the microstructure of the graphite and whether there are material defects such as porosities in the casting. The nodularity of the graphite (roundness as in type VI in Figure 5-3) has varied in some inserts. Some presence of porosities and slag particles has also been found. This has been detected by both microscopy and ultrasound.

An analysis by the Swedish Foundry Association employing e.g. computer simulations of the casting technique at each individual foundry has indicated some improvements. This and the foundries' own assessments regarding process parameters has resulted in measures being taken to obtain more uniform material properties.

An extensive development project has been started concerned with probabilistic analysis of canister strength. The participants include SKB, the Swedish Foundry Association, Ångpanneföreningen, the Royal Institute of Technology in Stockholm, the Joint Research Center (JRC) in the Netherlands, Det Norske Veritas and CSM Materialteknik AB. Three

***Figure 5-4.** Discs cut from cast insert for material testing.*

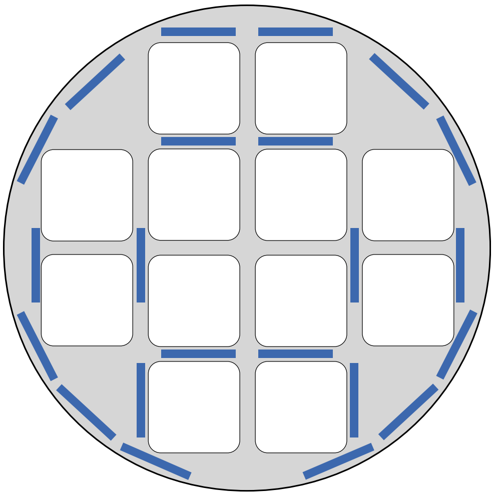


Figure 5-5. *Positions for test bars in disc from a cast insert.*

inserts from different foundries are included in the study. A relatively large number of test bars are taken from different locations according to the pattern in Figures 5-4 and 5-5. All test bars, as well as whole discs, are x-rayed to obtain values of the size and distribution of defects in the casting. The strength properties are evaluated by conventional tensile testing, but also by compression testing and fracture toughness testing. A fractographic analysis of the fracture surfaces is then performed, and the microstructure is examined metallographically. The large quantity of information will be used in a probabilistic analysis of the probability of failure, and a value will be obtained of the critical defect size at the stresses to which the canisters will be exposed.

Strength calculations employing finite element methods are also being carried out within the framework of the project. In addition, verifying compression tests are being done in a cold isostatic press, see Figure 5-6. The test body, see Figure 5-7, consists of an insert about 70 cm long but with full diameter. Both ends of the insert are covered by a screwed-on steel lid and enclosed in a 5 cm thick copper tube with lid and bottom of copper. Aside from its length, the test body is thus very similar to a real copper canister.

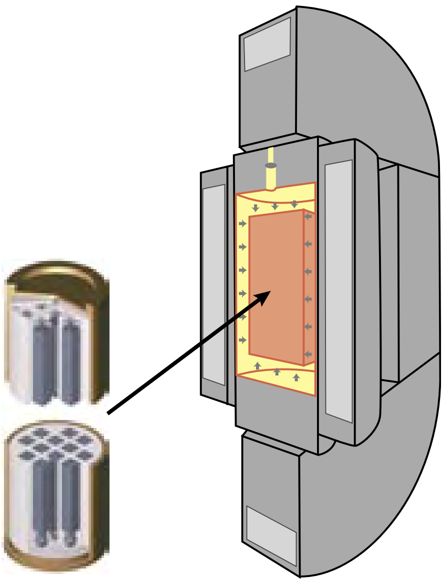


Figure 5-6. *Schematic illustration of a Quintus cold isostatic press, which is used for verifying compression tests of canister strength.*

Figure 5-7. *Part of cast insert and copper tube for compression testing.*

A strength calculation showed that the relatively short length of this test canister does not significantly affect the collapse load compared with a full-length canister.

Some presence of non-nodular graphite as well as casting defects such as small porosities, slag particles and occasional larger casting flaws will not be able to be completely avoided in such a large cast piece as a canister insert. Microscopic defects in occasional tensile test bars taken from different locations in inserts will also result in relatively low values of ductility in particular. This will cause some variation in obtained data. However, the results of strength calculations and compression tests in an isostatic press indicate that the inserts nevertheless have a strength that meets the design requirements with good margin. The continued work will be focused on establishing material requirements that will ensure the strength of the inserts. Figure 5-8 shows the graphite microstructure in different specimens from inserts.

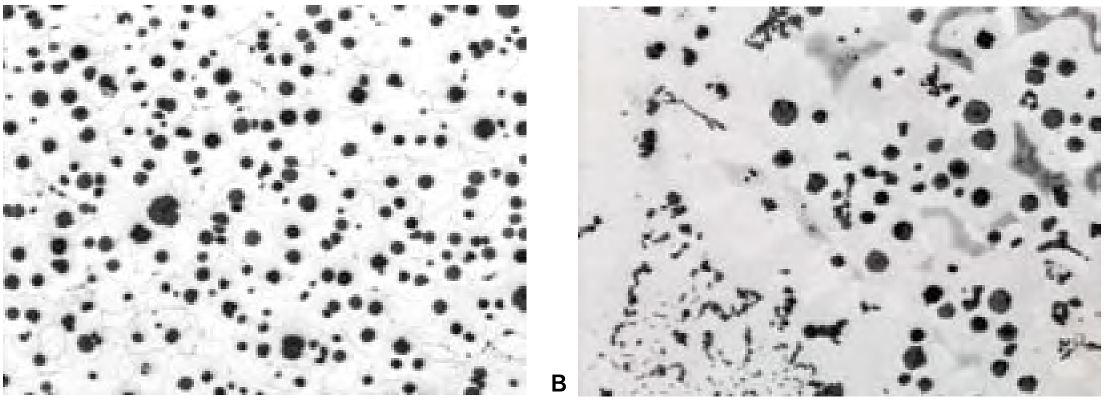
A  B

Figure 5-8. *Graphite microstructure in different specimens from inserts. Figure A shows a nodular iron microstructure with well-developed graphite nodules. Figure B shows a partially defective graphite microstructure with so-called "chunky graphite".*

Programme

The development project concerned with probabilistic strength analysis will be concluded during 2004. The results will serve as a basis for establishing acceptance criteria and precise material requirements that ensure that the inserts meet the design requirements.

Additional inserts for BWR assemblies will be cast and evaluated against established requirements. Certain inserts will be cut up for particularly thorough material studies.

Only one insert for PWR assemblies has been fabricated so far. Several additional inserts for PWR assemblies will therefore be fabricated and evaluated in a similar manner to inserts for BWR assemblies.

SKB will support and participate in a doctoral thesis project entitled "Improved graphite microstructure in thick-walled nodular cast iron" at the School of Engineering in Jönköping and the Swedish Foundry Association.

The possibilities of using ultrasound for inspection of the nodularity of the graphite in inserts will be studied, see also section 5.5.

5.3.2 Canister tubes, lids and bottoms

In order to meet the requirement on chemical resistance in the environment prevailing in the deep repository, copper has been chosen as a corrosion barrier. Copper is judged to have the necessary durability, as well as to have a minimal effect on other barriers in the deep repository. The fundamental requirement on corrosion resistance has led to the use of pure oxygen-free copper. Due to SKB's other special requirements on the material, there is no direct equivalent in Swedish or international standards. SKB has therefore compiled its own technical specification. According to this, the material must meet the requirements in standard EN 1976:1988 for Cu-OFE or Cu-OF1 but with the additional requirements: oxygen less than 5 ppm, phosphorus 30–70 ppm, hydrogen less than 0.6 ppm, sulphur less than 8 ppm, and the average grain size in forged blanks for lids and bottoms and in tubes must be less than 360 µm. The reasons for these tougher requirements compared with international standard can be summarized as follows:

- For fabrication-related reasons, there must be a clearance of a millimetre or so between the insert and the copper shell. This means that the copper shell will be plastically deformed by up to four percent in the deep repository. This deformation takes place chiefly by creep. The material must have enough ductility to withstand this with good margin. Elements such as hydrogen and sulphur have an adverse effect on ductility and must be reduced to low concentrations. Phosphorus has been found to have a favourable effect on creep ductility and is therefore specified in KTS 001 /5-10/ to concentrations between 30 and 70 ppm.
- If the material is to be able to be welded by electron beam welding, the oxygen concentration must be low.
- Large or uneven grain size is unfavourable for the properties of the material and also leads to difficulties in ultrasonic testing. The permissible grain size in the copper shell has therefore been set at no more than 360 µm (average grain size according to EN ISO 2624:1995).

The methods that have been tested for tube fabrication are roll forming, extrusion, pierce and draw processing and forging. Even though SKB has previously concluded that roll forming and longitudinal welding can be developed into a workable method, all tube fabrication since 1998 has been done using the other three methods, all of which entail fabrication of tubes without longitudinal weld seams. Blanks for lids and bottoms are fabricated by forging. In all of these cases, the hot-forming temperature is around 700°C.

Conclusions in RD&D 2001 and its review

SKB stated in RD&D 2001 that trial fabrication with the methods in question will continue.

Important aspects of the continued work are optimizing grain size, improving material yield and developing inspection methods. In parallel with development and trial fabrication at different suppliers, research projects will be conducted at trade research institutes, institutes of technology and universities. The purpose is, by means of computer simulation and laboratory-scale trials, as well as material testing, to obtain greater knowledge that can contribute to the optimization of technical specifications and fabrication technology.

SKI comments that SKB, by simulation, calculations, etc, must show that an adequate degree of working is obtained in the entire tube and straight through the copper thickness, regardless of fabrication method.

Newfound knowledge since RD&D 2001

Computer simulations have been carried out in a doctoral thesis project at the Royal Institute of Technology in Stockholm /5-11/. These simulations have primarily involved extrusion of copper tubes and forging of blanks for lids and bottoms. The results have yielded greater knowledge concerning how the material is deformed by different forming methods and what conditions must be met to obtain a microstructure with acceptable grain size. For forging of lids and bottoms, the results have been used to optimize the forging dies. A number of forgings done with the improved technique have shown that blanks for lids and bottoms can now be produced with very satisfactory results.

Simulation of pierce and draw processing for the purpose of fabricating copper tubes with integral bottoms has been carried out by Posiva Oy and Vallourec & Mannesmann Tubes. The results have been used to design the hot-forming tools. Fabrication trials with pierce and draw processing have so far indicated that a sufficiently fine-grained microstructure can be obtained in the integral bottom. Continued optimization of forging dies and process parameters will be able to further improve the results.

Trial fabrication of copper tubes by forging at Scana Steel Björneborg AB has shown that the method gives an acceptable grain size. This method needs to be further developed by optimization of tool design and process parameters.

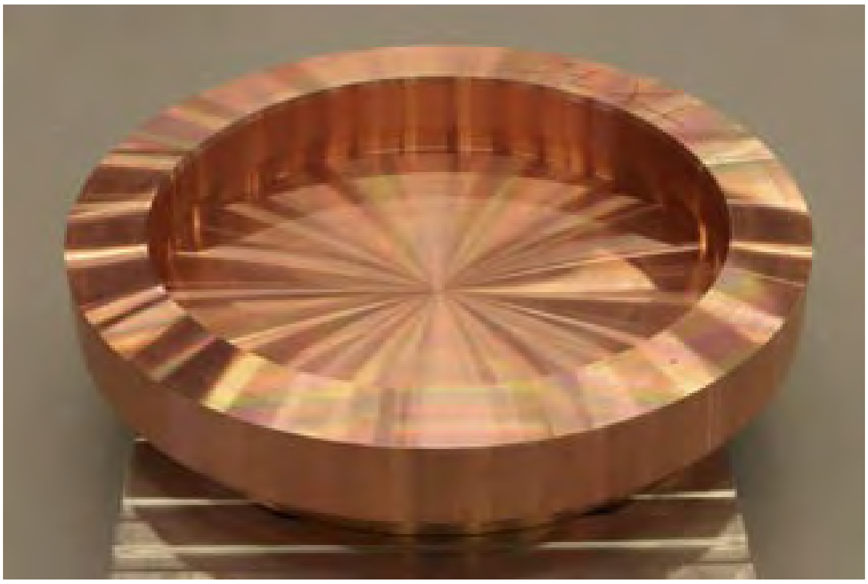


Figure 5-9. *Forged and machined copper lid.*

Programme

Trial fabrication of all copper components will continue in order to verify the reliability of the different methods and to further optimize the tools and the process parameters used in fabrication as well as technical specifications concerning material requirements.

Seamless copper tubes will be fabricated by means of the three methods: extrusion, pierce and draw processing and forging. Some tubes will be cut up for more thorough material studies.

The feasibility of fabricating copper tubes with integral bottoms by pierce and draw processing will be further explored.

The feasibility of using ultrasound for grain size inspection in copper components will be studied, see also section 7.2.

5.4 Trial fabrication

In order to further develop the fabrication technology for copper canisters with cast inserts, fabrication trials have continued on a full scale in recent years in accordance with the guidelines in RD&D 2001. The results are presented in a special report /5-9/.

5.4.1 Canister inserts

Altogether, 20 nodular iron inserts have been cast and evaluated so far. Six more inserts will be fabricated and evaluated during 2004.

Conclusions in RD&D 2001 and its review

In RD&D 2001, SKB stated that casting of nodular iron inserts with an integral bottom has the potential to develop into a workable method.

The authorities expressed the viewpoint that in order to achieve satisfactory results in the casting of the insert, simulation programs should be run, see also section 5.3.1.

Furthermore, the opinion was offered that SKB should to a greater extent verify the mechanical properties of the inserts by examining some fabricated inserts more thoroughly.

Newfound knowledge since RD&D 2001

Measures such as computer simulation of the casting processes and casting techniques at each foundry for the purpose of improving material properties and reducing their variation were discussed in section 5.3.1. Various improvements have been made in casting techniques. Computer simulations and analyses at each individual foundry have led to a greater understanding and improvements of such parameters as casting temperature and technique used in the addition of small quantities of certain substances that control the shape and distribution of the graphite in the finished insert.

Programme

The work of probabilistic analysis of the strength of the inserts will be concluded during 2004. The results will serve as a basis for establishing acceptance criteria and optimizing technical specifications.

Additional inserts for BWR assemblies will be cast and evaluated. A smaller number of inserts for PWR assemblies will also be fabricated and analyzed. In conjunction with continued trial fabrication, technical specifications and fabrication drawings for channel tubes and the welded cassette will be further developed.

Figure 5-10. *Finish-machined insert and steel lid for insert.*

The technology and procedures for casting, rough machining, inspection and delivery of inserts will be further developed in cooperation with the foundries.

Methodology and equipment for nondestructive testing by means of ultrasound as an inspection method will be developed. Besides detection of discontinuities in the casting such as porosities and slag, the possibilities of using ultrasound to inspect the nodularity of the graphite in the nodular iron will be studied, see also section 5.5.

5.4.2 Canister tubes, lids and bottoms

SKB started development of the fabrication technology for the canisters in 1994–1995. So far four different methods have been used to fabricate copper tubes: roll forming, extrusion, pierce and draw processing and forging. The method that has proved to give the most reliable results in production of copper tubes is extrusion. Lids and bottoms are machined to specified dimensions from blanks that have been preformed by hot forging. The technology for fabricating lids and bottoms is applied in serial production.

Conclusions in RD&D 2001 and its review

The work is focused on showing that full-scale copper tubes can be fabricated by means of these methods and satisfying applicable requirements. Important aspects are optimizing material yield, process parameters and inspection methods.

Important aspects of the continued work of fabricating lids and bottoms are optimizing grain size in the forged blanks and optimizing material yield and inspection methods. In order to optimize material yield and grain size, different types of forging dies and different process parameters will be tried. Computer simulation and laboratory-scale trials of the fabrication methods in question, as well as material testing, will provide knowledge that can contribute to the desired optimization of material specifications and fabrication technology.

Figure 5-11. *Extruded and machined copper tube.*

According to SKI, SKB should in its continued work more clearly compare the advantages and disadvantages of different fabrication methods for producing seamless tubes, for example heating in several stages during pierce and draw processing and the effects on tubes (and bottoms) of pierce and draw processing with an integral bottom.

Newfound knowledge since RD&D 2001

Pierce and draw processing of tubes makes it possible to fabricate copper tubes with integral bottoms. Three tubes have been fabricated with this objective. Computer simulation has made it possible to study the degree of deformation in the different hot forming steps. The results have been used to design the tools that are used so that hot working of the bottom is sufficient. The most recently fabricated tube had a homogeneous bottom with an acceptable grain size. The technology will probably be able to be further improved. In connection with this development, a couple of detailed studies have been conducted of the large copper ingots that are needed. These studies have yielded greater knowledge of the solidification structure and the occurrence of defects such as centre cracks in the ingots. This has in turn led to measures being taken by the copper supplier to minimize the flaws. An approved fabrication of tubes with integral bottoms will require deliveries of sufficiently homogeneous copper ingots, optimized tool design and tested process parameters.

Even if pierce and draw processing of tubes with an integral bottom does not turn out to be a practical alternative, it will still be possible to use pierce and draw processing as a method for fabrication of copper tubes open at both ends, along with extrusion and probably forging.

Three copper tubes have been fabricated by forging at Scana Steel Björneborg AB. The results so far indicate that forging of copper tubes can probably be developed into a workable method. The results have been gradually improved, mainly by improvements in tool design.

Figure 5-12. *Fabrication of copper tube with integral bottom by pierce and draw processing.*

A method and equipment based on laser technology have been developed in cooperation with the Royal Institute of Technology in Stockholm for measuring the dimensions of the copper tubes. The equipment is mobile and can be transported to different suppliers of copper tubes to measure straightness, inside diameter and ovality along the entire length of the tube. The method provides much more accurate results than was previously possible.

The results obtained after computer simulations and tool optimization in forging of blanks for lids and bottoms have shown that this is now a workable method.

Programme

Fabrication of seamless copper tubes and blanks for lids and bottoms will continue in order to verify and further optimize tools, process parameters, inspection methods and technical specifications. Seamless copper tubes will be fabricated by means of extrusion in order to verify this method. Continued fabrication trials will be done with pierce and draw processing and forging. The development work on fabrication of copper tubes with integral bottoms by pierce and draw processing will continue.

Fabrication will be carried out primarily for a wall thickness of five centimetres, but also on a limited scope for four centimetres in order to gain experience and gather data as a basis for a possible later decision on a change.

In the continued work on tube fabrication, the advantages and disadvantages of the different methods will be compared. It is likely that more than one of these methods will be able to be used for future serial production.

Development of laser technology for dimension measurement of copper tubes will continue.

Methodology and equipment for nondestructive testing by means of ultrasound as an inspection method will be developed. Besides detection of discontinuities in the casting, the possibilities of using ultrasound to determine the grain size in the fabricated copper components will be examined, see also section 5.5.

5.5 Nondestructive testing of canister components

The different parts of the canister will be examined by means of different methods for nondestructive testing (NDT) in order to show that they fulfil the fabrication requirements.

Conclusions in RD&D 2001 and its review

The lessons learned from the trial fabrication of all canister parts will be applied to and influence the further development of the fabrication technology. The work of investigating and establishing acceptance criteria and testing methods will make it possible to specify equipment for NDT and other quality inspection more precisely. A more thorough evaluation of modified machinery and testing equipment for the canister factory will be carried out in cooperation with potential suppliers.

The viewpoints of the regulatory authorities are presented in section 7.2.

Newfound knowledge since RD&D 2001

See also section 7.2.

The methods used by the fabricators to test the components have been surveyed. Furthermore, the methods used by the suppliers to test similar items in their production have also been studied.

One of SKI's comments on RD&D 2001 was that coherent documentation of results and experience obtained from nondestructive testing was lacking. A report presenting results up to and including 2002 has been compiled /5-10/.

Efforts have been aimed at gathering knowledge and evaluating the potential of these methods. An important goal is to determine the reliability of the NDT methods. Efforts have been concentrated on the most critical and largest objects.

Nodular iron inserts

The outer parts of the insert are ultrasonically tested by the suppliers. The testing is carried out in two stages with different probes designed for this purpose. Through-transmission ultrasonic testing has been used to test the cast material between the channel tubes. The first tests show that there are good prospects for developing the method. Figure 5-13 shows the results of a test performed with this method. The figure is based on the signal obtained from through-transmission testing through all channel positions at a given length position. The signal has then been compiled for the six tests and a mean value has been calculated. This gives a picture over the entire cross-section through this position on the insert. The figure clearly shows that an area around 270 centimetres from the bottom of the insert had indications of defects between the channels. On closer examination it turned out that there really was a defect within this area. Figure 5-14 shows the area when the insert has been cut up about 270 centimetres from the bottom.

The results of the tests indicate that there are good prospects for detecting defects in different parts of the insert. It also proved to be possible to detect the areas for the spacer plates with poor bonding between the plate and the nodular iron.

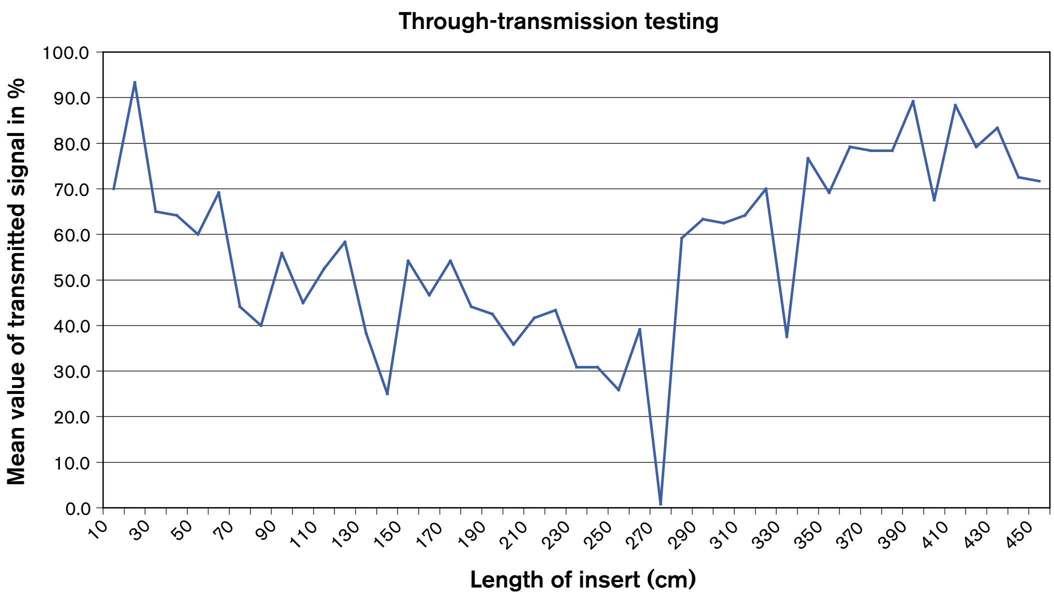


Figure 5-13. *Mean value of transmitted signal in percent for a given position.*

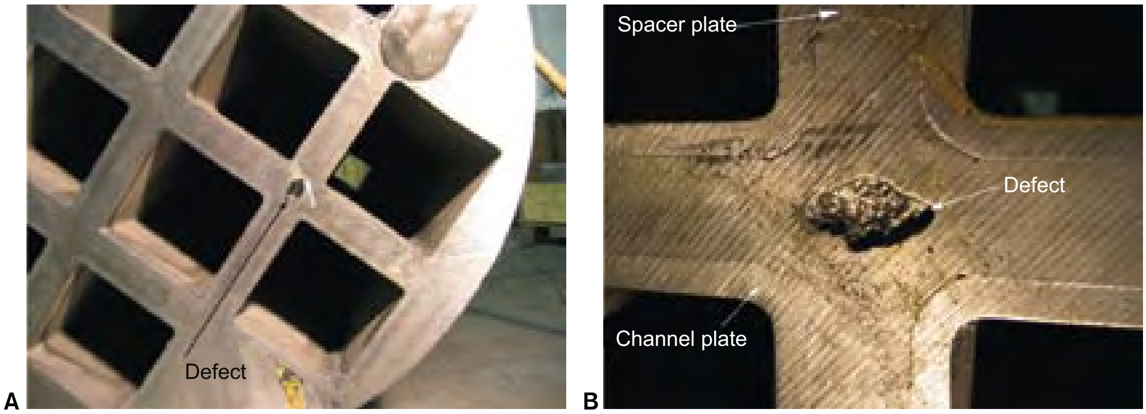


Figure 5-14. Cut area 270 centimetres from bottom of insert I25.

Lids and bottoms of copper

No new knowledge has been forthcoming.

Copper tubes

A reference ring with artificial defects has been developed. It has been used to ensure that the automatic ultrasonic systems that have been used are able to detect certain types of defects. The defects in the reference ring are grooves at different depths. The method can detect faults situated radially in the cylinder, but cannot determine their size. Axial defects can also be detected and size-determined to some extent. Experience from the Canister Laboratory shows that testing of copper tubes can be developed and improved, from the viewpoint of both detection and evaluation.

Steel lids

No new knowledge has been forthcoming.

Miscellaneous

Tests have been conducted to investigate the possibility of determining the grain size of the copper material with ultrasound. The method uses sound attenuation as a measurement parameter. The results show that the method has potential for providing the desired data.

Programme

Plans call for experience accumulation and method development to take place during the period 2004–2005.

Preliminary NDT procedures are planned to be established during 2005. As a part of this work, suitable reference bodies will be developed.

Continued experience accumulation and evaluation of reliability is planned during the period 2006–2007. This work will be pursued in close cooperation with the Canister Laboratory.

Further investigations are planned to determine material parameters by means of ultrasound in both copper and nodular iron. In copper the grain size is of interest, and in nodular iron the nodularity of the graphite.

The occurrence of different defect types in nodular iron is being investigated in the project concerning probabilistic analysis of the strength of the insert, see section 5.3.1. These will be characterized from an NDT perspective and catalogued.

Studies of possible defect types that can arise during the different fabrication processes in copper and nodular iron are planned.

5.6 Canister factory

SKB needs to have very good control of the empty canisters that are delivered to the encapsulation plant. For this reason, SKB is planning to build its own canister factory. The most recent planning report /5-8/ describes a reference design where blanks for all canister components are delivered to the factory from different subcontractors. In the factory, the components will be finish-machined, inspected and assembled to finished empty canisters, which will be transported to the encapsulation plant.

The fundamental principle for the factory is still that handling of copper and nodular iron are separated all the way up until the insert is lowered into the copper tube. The factory will therefore contain two machining lines: one for machining of copper and one for machining of nodular iron inserts and steel lids for inserts. Seamless, probably rough-machined hollow copper billets are delivered to the factory from subcontractors. The tubes are fabricated by means of one or more of the methods extrusion, pierce and draw processing and forging. Forged and probably rough-machined blanks of copper for lids and bottoms are also delivered to the factory from subcontractors. In the factory, the tubes, lids and bottoms are machined to specified dimensions. After measurement, bottoms are welded onto the canister tubes and inspected by nondestructive testing methods such as ultrasound and radiography. The step involving welding of bottoms may become superfluous if the development of pierce and draw processing of tubes with integral bottoms is successful.

In the other machining line, inserts and insert lids are turned. The inserts are delivered in the cast and rough-machined state from various foundries. The insert lids are fabricated from rolled steel plate. After measurements and cleaning of all parts, the insert is lifted down into the copper tube. The finished canister is then placed in a special transport frame and delivered along with an insert lid and a copper lid to the encapsulation plant.

The reliability of deliveries from various subcontractors is of fundamental importance for future production in the canister factory. All components to be delivered to the canister factory must meet SKB's quality requirements. These are specified in an existing quality system for canister fabrication which is certified to ISO 9001 and ISO 14001 and is progressively developed. One step in the ongoing work of development of the quality system for canister fabrication is finding the necessary network of suitable subcontractors and creating a long-term and businesslike relationship with them. In conjunction with ongoing trial fabrication, suppliers are continuously assessed by means of regular quality audits and analysis of pricing, delivery reliability and probable future development.

Where the canister factory will be located has not yet been decided. Questions that must be taken into consideration in the siting of the factory concern e.g. shipments to and from the factory and societal aspects, such as availability of labour and industrial environment. Alternatives to be studied include a siting in the same region as the encapsulation plant or the deep repository, but other alternatives entirely may also be considered.

Conclusions in RD&D 2001 and its review

The design of the canister factory must be updated in the event of changes in fabrication technology or canister design. SKI recommends that SKB continue to study whether possible changes in the technology for machining of copper tubes and blasting of inserts, as well as the allocation of what is done by suppliers and what is done in the canister factory, can improve the quality of the delivered canisters. SKI has conducted its own analysis and assessment of SKB's investigation and planning of the canister factory /5-12/. The results indicate that SKB's proposed fabrication methods, choice of equipment and organization should result in a workable system for canister fabrication. Further studies are recommended in some cases, however.

Newfound knowledge since RD&D 2001

Experience within the framework of the conclusions in RD&D 2001 is being documented. No new separate analysis of the canister factory has been done.

Programme

The lessons learned from the trial fabrication of all canister parts will be applied to and influence the further development of the factory. The work of investigating and establishing acceptance criteria and testing methods will make it possible to specify modified equipment for NDT and other quality inspection more precisely. A more thorough evaluation of modified machinery and testing equipment will be done in cooperation with potential suppliers. This will provide opportunities for a more precise analysis of the factory's layout and investment costs.

If the development of friction stir welding shows that the technique may be suitable for sealing the canisters, the consequences of this need to be examined and weighed into factory layout and investment costs.

In order to get a complete picture of potential uncertainties, a risk analysis will be conducted of operations in the planned canister factory.

A detailed timetable coordinated with SKB's main timetable will be prepared.

A technical description of the canister factory will be appended to the permit application for the encapsulation plant. However, the siting work for the canister factory is not expected to be finished at the time of the permit application for the deep repository.

6 Canister – sealing

Two different methods are being considered for sealing the canister: friction stir welding (FSW) and electron beam welding (EBW). SKB is studying the methods in parallel. The results obtained to date show that both methods provide welds of sufficiently good quality. Our intention is to choose a reference method for sealing in March 2005. This will give us enough time to finish designing the encapsulation plant prior to applying for a permit. Section 6.1 deals with the overall planning prior to an application. The programmes for electron beam welding and friction stir welding are described in sections 6.2 and 6.3, respectively. A more detailed description of strategy and methodology for choosing a welding method is presented in Chapter 7.

When the canisters have been sealed, they have to be inspected by means of different methods for nondestructive testing (NDT), for example radiographic and ultrasonic inspection. The application of the NDT methods differs depending on which welding method is used. Thus, it is not possible to detect discontinuities by means of ultrasound in an FSW weld using the same procedure as for an EBW weld. SKB's work with nondestructive testing of the sealed canisters is aimed at:

- Developing existing methods.
- Testing new methods.
- Verifying the reliability of the methods.

The programme for nondestructive testing is presented in section 6.4.

6.1 Planning

At the time of an application for a permit to build the encapsulation plant, SKB must have chosen methods for sealing and testing. The reason for this is that the methods influence the design of the encapsulation plant. At this time, a programme for qualification of the methods must also exist. The overall milestones for the work on sealing technology and nondestructive testing are:

- Verifying of the welding processes, i.e. confirming that the important process parameters that determine weld quality are identified and establishing the limits within which they can be allowed to vary. This programme will be carried out during 2004. Further information is found under the relevant welding method in sections 6.2 and 6.3.
- Demonstrating the welding processes, i.e. showing the weld quality that is achieved under production-like forms and showing that the different welding processes can be used under industrial conditions. This programme will be carried out during 2004 and early 2005.
- Establishing how reliable the nondestructive testing is, i.e. determining the probability that we can detect discontinuities of different types and sizes. This programme will be carried out during 2004–2005. Since the welding methods are based on different principles, the NDT methods that are applied are tailored to the particular welding methods, see section 6.4.
- Choosing a reference method for welding the canister. The time for choosing a reference method is linked to the timetable for designing the encapsulation plant. For further information on choice of welding methods see Chapter 7.
- Obtaining data for the safety assessment SR-Can. A programme aimed at determining the probability that canisters containing critical defects are delivered from the encapsulation process has been started, see further section 7.1. Other research on the canister's long-term safety is dealt with in Chapter 16.

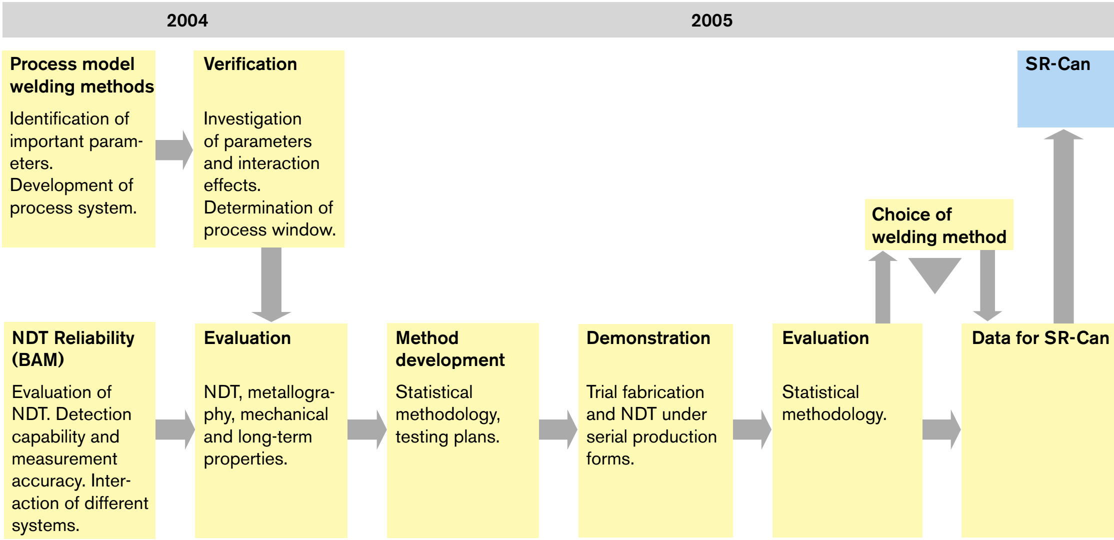


Figure 6-1. *Logical connections and time sequence between the milestones in sealing technology.*

For the first two points (verification and demonstration of the welding methods), statistical methodology will be used for test planning and evaluation, and data from the programmes will be used in the safety assessment. For more detailed information, see sections 6.2 and 6.3 /6-1/. The logical connections and time sequence between the milestones are shown in Figure 6-1.

6.2 Electron beam welding

During the past two decades, SKB has developed the technology for electron beam welding at The Welding Institute (TWI) in Cambridge, UK /6-2/. The development work at the Canister Laboratory began in 1999. Technical details regarding this system and process development have been reported through 2001 /6-3/ and 2003 /6-4/.

An important part of the development work is determining how often discontinuities occur in the welds and under what conditions they are formed. The goal is to design the welding process in such a manner that the risk of getting defects in the weld is very small. As mentioned in SKB's plan of action, see Appendix A, the preparatory work for an application for a permit to erect an encapsulation plant is focused on a copper canister with a wall thickness of five centimetres.

6.2.1 Welding equipment

In electron beam welding, a gun is used to generate the electron beam. The gun was developed by TWI and is designed for use at reduced pressure. The design is unique and consists of an indirectly heated diode gun and a switch mode power source. Table 6-1 shows technical data for the welding machine. Figure 6-2 shows a schematic drawing of the electron gun.

The cathode is heated and starts to emit electrons. The electrons are accelerated to about 2/3 of the speed of light by a high acceleration voltage. The electrons pass through a hole in the anode and on through the gun. The electron beam is focused by the upper lens coil and passes through the nozzles N1 and N2, after which it is focused on the workpiece by the lower lens coil. The upper alignment coils and the lower alignment coils centre the beam exactly in the centre of the small bores in nozzles N1 and N2. Thermocouples monitor the temperature of the nozzles N1, N2 and N3. The signal from each thermocouple has two limits: one for alarm and one for system trip /6-4/.

Table 6-1. Technical data for the EBW machine.

Developed by	TWI
Delivered to SKB	1997
Commissioned	1998
Beam power	100 kW
Acceleration voltage	200 kV
Beam current	500 mA
Cathode heating by	RF 84 MHz, 250 W
Cathode material	Ceramic LaB_6
Filament material	Tungsten alloy
Chamber size	180 m^3
Chamber pressure	0.1 mbar
CNC system	Siemens 840C
Control system	TWI
Monitoring system	NI Labview 4.0/TWI

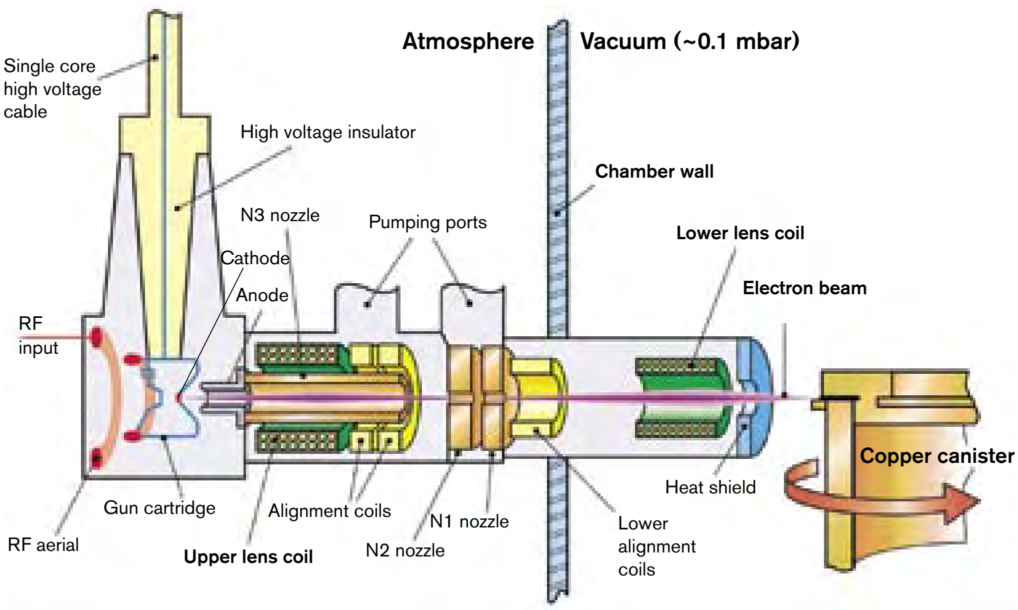


Figure 6-2. *Schematic drawing of gun.*

The welding system is being developed at TWI and the Canister Laboratory. So far the work has concerned the following areas:

- New type of cathode (TWI).
- Equipment for measurement and oscillation of the electron beam (TWI).
- Reduced pressure in the welding chamber (Canister Laboratory).
- Welding parameters after installation of a new cathode (Canister Laboratory).
- Study of the shape of the electron beam (Canister Laboratory).
- Welding trials with oscillating electron beam on copper blocks and copper lids (Canister Laboratory).

Conclusions in RD&D 2001 and its review

Kasam says in its review that a great deal of work remains to be done on sealing of the canister. Further studies should be conducted of FSW and EBW until one of the methods gives completely satisfactory results. A thorough understanding of the mechanisms that give rise to defects in the canister must be built up.

SKI says that the documentation of the welding technique for EBW, with regard to both achieved progress and planned work, is far too scanty and recommends that SKB compile the results achieved as soon as possible.

Newfound knowledge since RD&D 2001

The results of the development work on EBW have been described in two reports /6-3, 6-4/. Since 2001, SKB has been working to investigate the mechanisms that give rise to defects in the weld. This has been done in close cooperation with TWI. Several technical breakthroughs have been made with regard to generation and control of electron beams as well as process control. The most important aspects have been development of technology for controlling the electron beam's energy distribution, and installation and use of a system to measure and oscillate the beam.

Due to the parallel development of process and welding systems, the pace of development has been inhibited by the implementation of untested solutions in the system. This has in turn led to problems with availability. A programme has been initiated to tackle these problems.

A new type of cathode was developed by TWI in 2002. The goal of the development work on this cathode was to achieve an electron beam that provides a round weld profile in the root (the bottom of the beam) and that has a root radius greater than 2.5 millimetres. The risk of root defects is then minimal. The cathode produced a much better weld profile in tests than before. The root radius was greater than two millimetres in most cases. Although the goal was not reached in terms of root radius, the cathode was nevertheless considered to be good enough. Details concerning cathode design and beam shape cannot be revealed at this time, since TWI is exploring the possibility of applying for a patent.

TWI has developed equipment for measurement and oscillation of the beam. The equipment was installed and commissioned in the Canister Laboratory in September 2003. It consists of a coil for oscillating the beam, a measurement probe, two computers (one for control of the process and one for collection of welding data), software for control and data collection, plus a control console, electronics cabinet and cabling between the units. When the shape of the beam is to be measured, a holder, including a measurement probe on three bars, is mounted on the coil's extension into the welding chamber, see Figure 6-3. The control console (see Figure 6-4) has been replaced with a new, bigger console that has been modified to suit the new equipment.

Figure 6-3. *Coil with holder for beam defection.*

Figure 6-4. *Control console for EBW system.*

When the welding chamber was built, the recommended maximum pressure was 0.5 millibar. During testing it was found that the pressure had to be less than 0.2 millibar in order for the welding process to be stable. If the pressure exceeds 0.25 millibar at maximum welding power, extensive plasma formation occurs in the area around the weld pool. The plasma disturbs the beam, resulting in poorer weld quality. An additional vacuum pump was installed. Along with other measures, such as leak detection and sealing of the welding chamber, plus a minor rebuild, this improved the vacuum level in the welding chamber to about 0.05 millibar.

The beam's electron distribution has been measured regularly to determine the relationship between electron distribution and weld quality and to assess the condition of the cathode, see Figure 6-5.

Programme

Standard EBW machines are normally reliable. The equipment at the Canister Laboratory is much more complicated than a standard machine. It is more like a prototype, and its reliability has therefore been less than desirable. A number of measures are planned during the autumn of 2004 to improve reliability:

- Develop and improve the manufacture of cathodes. The goal of the work under way at TWI is enable cathodes to be precision-made so that they generate uniform beams and welding results at identical parameter settings. It must also be possible to mount the cathodes in the welding machine without individual adjustment.
- Develop, test and rebuild the high-voltage cable's connection to the gun to minimize the risk of flashover.
- Rebuild the beam generation system so that the beam bore in the gun is simplified and the risk of flashover is minimized. This work is expected to be finished during the autumn of 2005 so that the demonstration series of 20 lid welds is not delayed.

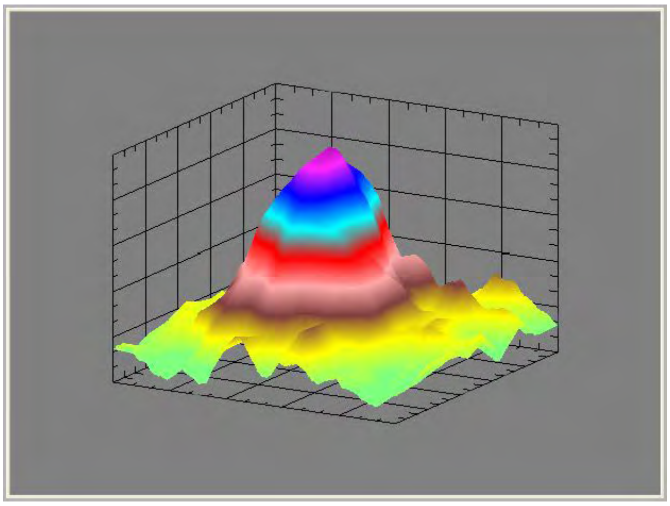


Figure 6-5. *Electron density in beam focus. Green indicates low density and violet high density.*

6.2.2 The welding process

In parallel with development of the equipment for electron beam welding we have also developed the actual welding process. It was not until 2003 that all important process parameters could be identified and controlled, so that the occurrence of unacceptable defects in the weld can be prevented. An important part of the work has been to systematically try different combinations of process parameters.

Conclusions in RD&D 2001 and its review

Kasam says in its review that a great deal of work remains to be done on sealing of the canister. Further studies should be conducted of FSW and EBW until one of the methods gives completely satisfactory results. A thorough understanding of the mechanisms that give rise to defects in the canister must be built up.

Newfound knowledge since RD&D 2001

The welding process has been developed by means of trial weldings, where full-scale lids are joined to shortened cylinders. Trial weldings have also been performed in copper blocks in connection with the development and testing of new welding parameters. Through the end of February 2004, 29 lids and 172 copper blocks had been welded. All welds have been examined by means of NDT in the form of radiographic, ultrasonic and visual inspection. Furthermore, the microstructure of the weld has been examined in etched macrospecimens from selected parts. Test bars from two lid welds have also been tensile tested (L026 and L028).

New welding parameters have been tried after installation of the new type of cathode. This has made it possible to weld at high beam powers and high welding speeds. Under such conditions the weld pool solidifies faster. At welding speeds higher than 300 millimetres per minute, the problems with run-out of the weld pool and internal cavities virtually disappeared. The internal weld quality is now very homogeneous. After installation of the new equipment for oscillating the beam, a number of different beam patterns have been tried. The purpose is to control how the surface of the weld solidifies, see further below.

Trial welding with an oscillating beam has been done in a number of copper blocks. The trials were performed with a portable machine from TWI that was connected to SKB's welding machine. After a number of different parameter settings were tried, good weld quality was achieved. The weld was homogeneous and the weld surface was smooth with a concave contour, see Figures 6-6 to 6-8.

By using an oscillating beam we can obtain a homogeneous weld metal. The weld surface is treated during the process by remelting, which results in a smoother surface. Four different beam patterns have been tried with an energy distribution of about 91 percent for welding and

Figure 6-6. *Weld TB 122. Welding test with oscillating beam.*

***Figure 6-7.** Macrospecimen from weld TB 122. Welding test with oscillating beam.*

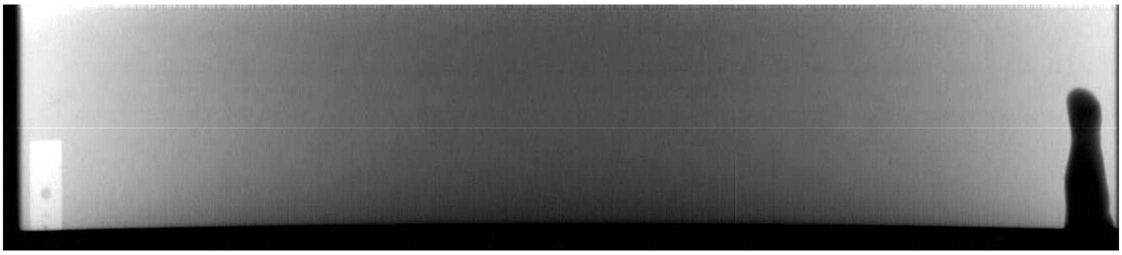


***Figure 6-8.** Radiograph of weld TB 122. If welding is interrupted, the cavity (key hole) in the material that constantly surrounds the beam during welding is retained. This provides an image of the shape of the beam. The round shape is important for avoiding root defects.*

9 percent for surface treatment. Trials with an oscillating beam have been carried out in two lid welds (L028 and L029). Lid weld L028 was welded both with and without an oscillating beam at welding speeds of 250, 275, 300 and 325 millimetres per minute, see Figure 6-9 and Figure 6-10. The surface of the weld is smooth in the oscillated area. However, it is rough in the area welded without oscillation. A smaller quantity of near-surface incomplete penetration flaws were also formed when the welding speed was 325 millimetres per minute. The internal quality of the weld is good as a whole, although there are a few discontinuities in the area with rotation speeds of 250 and 275 millimetres per minute. The other lid weld (L029) was welded with a welding speed of 300 millimetres per minute. Both the homogeneity of the weld and the weld surface are excellent on the whole, see Figure 6-11.

The results of these tests show that it is now possible to achieve welds of very high quality with homogeneous weld metal and a good weld surface. The occasional flaws that occur are mostly due to mechanical faults.

All weld specimens in copper lids were examined by means of nondestructive testing. The typical discontinuities that were found were root defects, internal cavities, cavities associated with the surface and near-surface pores. After the introduction of the new cathode and oscillating beam welding at a high welding speed, the weld metal is now very homogeneous. An example of good homogeneity can be seen in Figure 6-8, where the weld metal is completely free of discontinuities. The shape of the electron beam can also be studied by means of radiography. If welding is interrupted, the cavity in the material that constantly surrounds the beam during welding is retained, which is a useful technique for understanding the relationship between beam shape and weld quality.

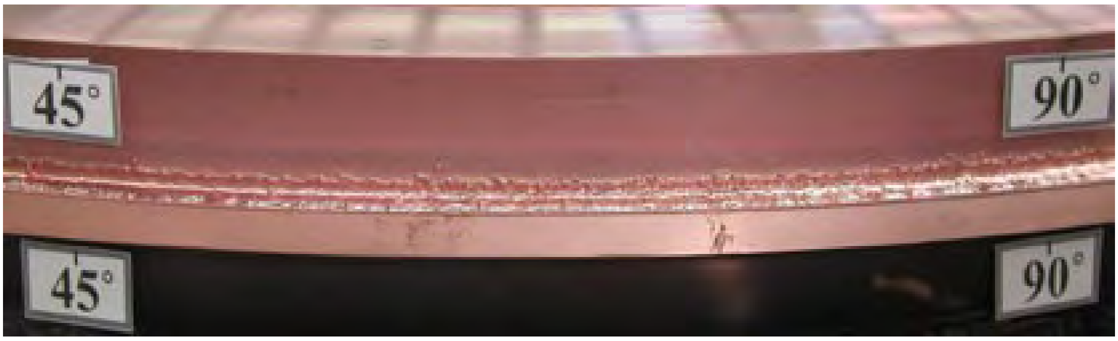


Figure 6-9. Lid weld L028. Section welded with oscillating beam.

Figure 6-10. Lid weld L028. Section welded without oscillating beam.

Figure 6-11. Lid weld L029, welded with oscillating beam.

All weld specimens are inspected visually before and after machining so that we can discover surface-breaking defects. The weld surfaces are also photographed digitally so that we can judge the shape and appearance of the welds. After the introduction of oscillating beam welding, the weld surfaces are now relatively smooth prior to machining. The working allowance for achieving finish-machined canister surfaces is more than sufficient, see Figure 6-11. After finish machining, occasional small pores (< 1 millimetre) have been observed on the surface of the weld.

Macrospecimens in the cross-section of the weld are taken out of each trial weld in order to analyze the relationship between parameter setting and weld shape and to study any discontinuities, see Figure 6-12. A longitudinal section has been removed to study any variations in weld depth. The shape, depth, width and root radius of the weld, based on the parameter settings, has been studied and can be predetermined with high certainty. The root radius is also affected by the design and wear of the cathode.

Macrospecimens in a longitudinal section from the weld show that the weld depth varies by four millimetres from the unmachined surface, see Figure 6-13. The weld metal is very homogeneous with microrpores with a diameter of less than 0.2 millimetres. The micropores are mainly located in the root area.

Figure 6-12. *Lid weld L027. Cross-section of weld. The macrospecimen shows a weld depth of 66 millimetres and the weld has a root radius of 1.5 millimetres, which minimizes the risk of root defects.*

Figure 6-13. *Lid weld L026. Longitudinal section in weld, length approximately 200 millimetres. The coarse structure shows the penetration of the weld.*

Tensile test bars have been taken out of two lid welds (L026 and L028). L026 was welded without oscillation and L028 with oscillation. Different rotation speeds have also been tried. No significant difference has been found in strength properties related to welding speed or beam oscillation. The tensile specimens from lid weld L028 (see Figure 6-14 and Table 6-2) exhibited a slightly higher tensile strength and elongation limit compared with lid weld L026.

The conclusions from the tensile tests are:

- The fracture occurred in the weld metal.
- The strength level of the weld metal is shown in Table 6-2.
- The strength of the weld metal is uniform at welding speeds between 250 and 325 millimetres per minute.
- The strength of the weld metal in the overlap area is roughly the same as that of the rest of the weld metal.

Programme

Electron beam welding as a method is known for its good repeatability and reliability once the process parameters have been determined. The welding trials performed confirm the good repeatability of EBW, despite a lack of precision in the manufacture of different cathodes. In the planned demonstration phase, the potential of the method as a production method will be demonstrated on roughly 20 welds. The resulting weld quality will be investigated for further statistical processing for the purpose of gathering input data for the safety assessment prior to the application for a permit to build the encapsulation plant. According to plans, the demonstration phase will be carried out during 2004 and early 2005.

Figure 6-14. *Tensile specimen from lid weld L028. Rotational position 310°.*

Table 6-2. Tensile specimen from lid weld no L028 welded with an oscillating beam.

Specimen no/ position in lid weld	Welding speed mm/min	Tensile strength R_m MPa	Elongation limit $R_{p0.2}$ MPa	Elongation at rupture A_5 %
S3/12.5° Slope-out zone	250/325	185	70	26
S1A/40°	250	189	65	29
S1B/40°	250	190	64	30
S2A/310°	325	191	67	29
S2B/310°	325	188	66	29
Reference specimen in parent metal near weld area:				
L1/40° lid	–	203	85	68
L2/310° lid	–	205	82	52

A programme has been devised for optimizing the welding parameters and establishing tolerances for parameter setting. The programme comprises a test series with two levels (high and low). The difference from the normal parameter level will be set at about five percent. Permissible deviations from specified parameters can then be determined and serve as a basis for the preparation of a WPS (Welding Procedure Specification).

6.3 Friction Stir Welding (FSW)

SKB has been developing friction stir welding for sealing copper canisters for spent nuclear fuel in cooperation with TWI since 1997. FSW was invented in 1991 at TWI and is a thermo-mechanical solid-state process, i.e. not a fusion welding method. This means that the problems encountered in fusion welding, for example unfavourable grain structure and size and segregation phenomena, can be avoided. The microstructure in copper resulting from FSW resembles the microstructure resulting from hot forming of the copper components in the canister. FSW can also be used to join bottoms to the copper canisters.

One reason for the rapidly increasing use of FSW in industry is that the method has few process parameters. This means that the welding process is simple to control. The welding tool rotates at a specific number of revolutions per minute and moves along the joint at a constant speed. The tool also has a constant angle to the workpiece. The leading side of the tool shoulder is located above the canister surface, so that the tool shoulder "surfs" on the surface. The position of the tool shoulder in relation to the canister surface is then controlled with a specific downward force, as shown in Figure 6-15.

6.3.1 Tool

The FSW tool consists of two parts: a tapered pin (or probe) and a shoulder, see Figure 6-16. The function of the probe is to heat up the material by means of friction and, by virtue of its shape, force the material to flow around it and create a joint. The function of the shoulder is to heat up the material by means of friction and prevent it from being squeezed out of the joint. There is no doubt that the tool is the most important part of the FSW process. The parts of the tool must be able to withstand the high process temperature (800–900°C) as well as the complex forces to which they are subjected when a weld of up to four metres is produced in approximately 45 minutes.

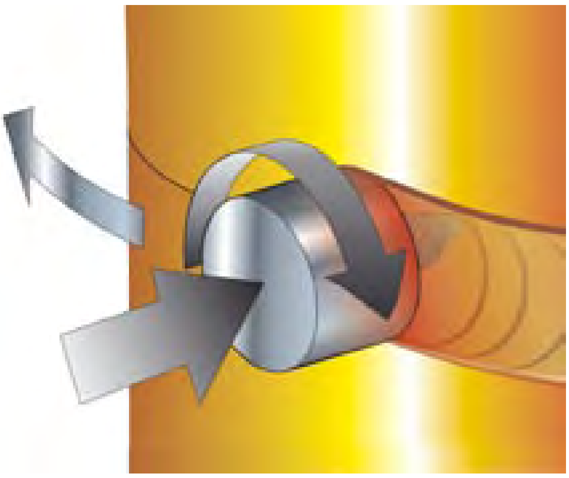


Figure 6-15. *Schematic drawing of the FSW process.*

Figure 6-16. *The FSW tool.*

Conclusions in RD&D 2001 and its review

The development of the alternative method for sealing copper canisters by joining copper by means of friction stir welding and SKB's cooperation with TWI were described in detail in RD&D 2001. In its review, SKI emphasized the importance of examining the joint, see sections 6.3.3 and 6.4.

Newfound knowledge since RD&D 2001

The design and manufacture of a probe, in accordance with the stipulated requirements, was the subject of an intensive development programme during the period 2001–2003. The technical breakthrough came with the development of a probe capable of welding 50 millimetres thick copper. The probe is a variant of MX-Triflute™. The effectiveness and reliability of the probe is the basis of a granted patent (SKB/TWI) /6-5/.

The choice of suitable materials for the manufacture of the FSW tool proved to be a challenge. A large number of materials with sufficient strength at high temperatures have been evaluated as the material in the probe. A nickel-based superalloy (Nimonic 105) was chosen, since it proved capable of producing canister welds without traces of abrasion or rupture.

Programme

Nimonic 105 will be used in SKB's development programme during 2004. There are, however, other materials that have certain physical properties that are superior to those of Nimonic 105. The evaluation of alternative materials will therefore continue. A surface treatment method has been used with some success to increase the surface hardness of probes made of the alloy Nimonic 105. Other surface treatment methods will be evaluated with respect to their ability to increase the service life of the FSW probe and thereby reduce the risk of defects in the process.

The geometry developed for the probe permits the production of welds with excellent properties. The work of improving the durability, geometry and size of the probe continues. No great changes in the probe are expected during 2004–2005, however.

The tool shoulder is made of a machined tungsten alloy with a high melting point that rapidly reaches high temperature. The tool shoulder generates most of the friction heat, and it is unlikely that the shape or dimensions of the shoulder will be significantly changed in the near future.

6.3.2 Welding equipment

Two welding machines have been used in the development of friction stir welding since RD&D 2001: One development machine at TWI was used in 2001–2002 and was phased out in January 2003, and one production-adapted machine was commissioned in April 2003 in the Canister Laboratory.

The specifications for the welding machine that was described in RD&D 2001 and was developed by TWI were determined in conjunction with early attempts to weld together 50 millimetres thick copper plates with a rebuilt milling machine. Important design parameters were adequate strength and stiffness to counteract the forces that arise in the FSW process without the machine being deformed.

During the development programme conducted with the welding machine at TWI, 100 millimetres high rings (taken from a canister) were mounted two by two on top of each other and welded together. A milestone for the programme was when a real lid was welded to a ring in January 2003.

Conclusions in RD&D 2001 and its review

It is stated in RD&D 2001 that it is possible to join 50 millimetres thick copper with FSW and that the process can probably be developed into an alternative production method for welding of copper canisters. The work, which was performed on a development machine developed at TWI, was focused on continued development of tool and process parameters. Welding tests were planned in both 50 and 30 millimetres thick copper tubes. At this time there was no solution for how to handle the exit hole left by the tool at the end of the weld. There were plans to build a completely new FSW machine specially designed for the purpose at the Canister Laboratory. Investigations of the strength properties of the FSW material were under way.

Newfound knowledge since RD&D 2001

It was shown in 2001 that friction stir welding is a promising technique for sealing copper canisters in serial production as well. The technique had been presented to SKI, which gave its support to continued development. A decision was made to transfer the FSW technology to the Canister Laboratory for further development. The information that was gathered from the welding of rings at TWI was used to formulate operating specifications for a new FSW machine. The new machine was developed and built by Esab during 2002. The welding machine has been in operation at the Canister Laboratory since April 2003. It has performed outstandingly, and the transfer of the technology from the experimental machine to a production-adapted machine has gone well.

The FSW machine has a unique design with respect to strength and stiffness which makes it suitable for production welding. The welding machine, which is shown in Figure 6-17, has a spindle power of 110 kW, making it one of the most powerful welding machines in the world. Only 35 kW is used in operation, since the heat input must be limited.

Programme

The FSW machine's potential as a production machine will be demonstrated in a test series of about 20 welds under operation-like conditions. The work entails:

- Development and improvement of software for controlling and monitoring the process.
- Improvements of the system for process monitoring.
- Improvement to enable the constant welding angle to be adapted to the welding direction.

Figure 6-17. *The FSW machine in the Canister Laboratory.*

6.3.3 The welding process

The parameters that are controlled are:

- The downward force of the tool (welding force).
- Spindle speed.
- Welding speed.

In addition to the process parameters, the important resultants are also measured. These process indicators are:

- The temperature of the tool probe.
- The torque of the rotating spindle.
- The force on the tool in the travel direction.
- The position (depth) of the tool shoulder in relation to the canister surface.

One goal in the development work has been to keep the parameters constant throughout the welding process. Important points in the development work have been to:

- Reduce the risk that the FSW probe is exposed to high temperatures that could reduce its life.
- Achieve even weld quality and grain size in the weld metal.
- Develop a simple and robust method for monitoring the process.

Following is a description of the different sequences in the welding process and how they are controlled:

- **Positioning and heating.** A pilot hole is drilled above the joint line to facilitate the positioning of the FSW tool and reduce the risk that the probe will be damaged. The tool is rotated and pushed into the pilot hole until the welding force is reached. The welding force is maintained throughout the heating sequence.
- **Start and acceleration.** When a given welding temperature has been reached the acceleration sequence starts. The welding speed is a function of the welding temperature.
- **Steady state.** The welding temperature is controlled by maintaining a constant heat input (spindle torque x spindle speed), which is achieved by small variations in the welding force.
- **Termination**. When welding is terminated and the tool is removed from the canister, an exit hole is formed. Since the exit hole may not remain in the joint, the tool is parked above the joint line, see Figure 6-18. This area is machined away, along with the start area, after welding.

Figure 6-18. *The start area (at right) and the exit hole (at left) above the joint line.*

Conclusions in RD&D 2001 and its review

SKI pointed out the importance of investigating the joint after FSW in order to establish whether foreign particles from the tools or oxidation occur. Investigations of the material's composition and the occurrence of impurities in the weld joint were also recommended.

Newfound knowledge since RD&D 2001

As a result of development work during the period from March 2003 at the Canister Laboratory, further experience has been accumulated with full-scale welding by FSW. Thanks to the new welding machine and the availability of resources for nondestructive testing, it has been possible to conduct the project under rational forms with regard to both execution and evaluation of welding trials.

An important milestone has been reached in the development of the encapsulation technology with the fabrication and sealing of a full-scale canister according to the quality plan. The constituent components have thus met SKB's current quality requirements. Furthermore, the FSW technology has been demonstrated as a welding method for the canister bottom, see Figure 6-19. No significant discontinuities have been detected in the lid and bottom welds.

Tests have shown that a two millimetre wide gap with a depth of 32 millimetres in the joint line does not affect the quality of the weld. This shows that the process works with large tolerances and that it is possible to repair volumetric defects.

The risk of causing defects during welding is elevated during the start sequence. Once the process is in the parameter window (steady state) and no disturbances occur, no risk of defect formation has been observed.

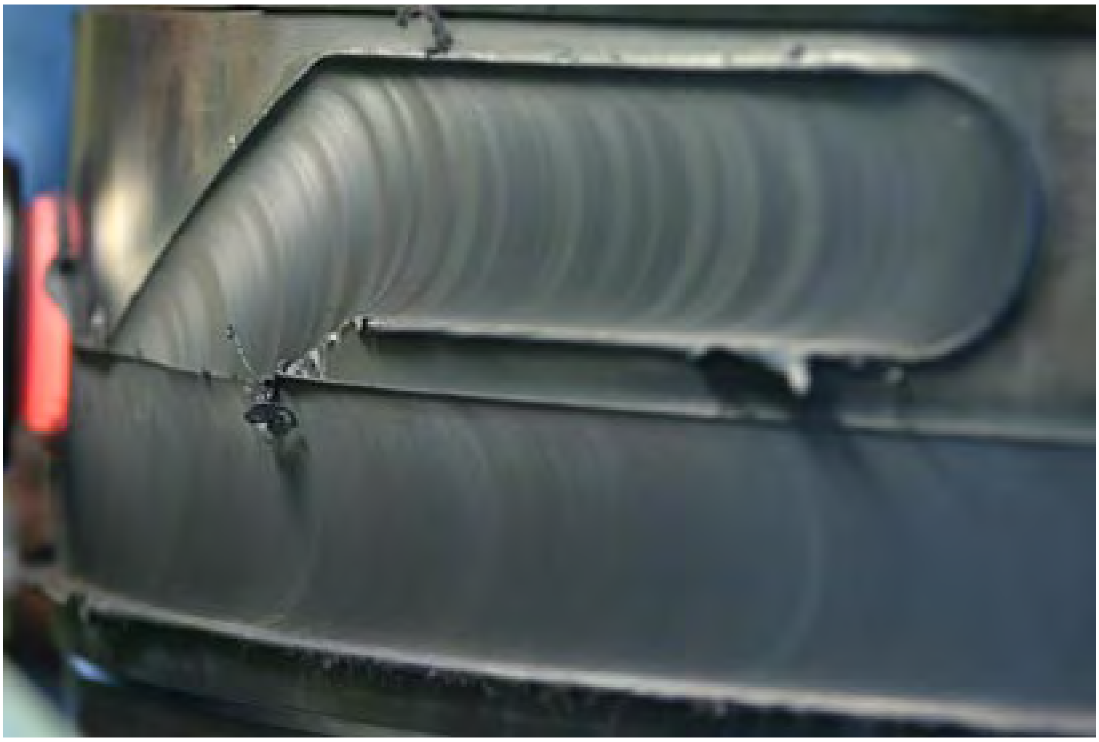


Figure 6-19. *Start sequence and FSW tool on the way up to the parking position at the bottom weld.*

A limitation in the evaluation of the welds up to 2004 has been that it was only possible to detect the presence of volumetric defects by means of nondestructive testing (radiography), since the technology for ultrasonic testing was not fully developed. Ultrasonic testing of the welds has been possible since the beginning of 2004. Destructive testing (macrosection, see Figure 6-20) is used, but since a lid weld is more than three metres long only random samples can be taken. Additional destructive testing has been carried out. Tensile specimens (45 millimetres wide) from lid welds show no reduction in tensile strength compared with the parent metal. The test bars rupture in an area outside the weld zone in the heat-affected zone, see Figure 6-21. The tensile test results for the lid welds confirm the good quality of the welds.

One problem that arose when real lids and not rings were to be welded was too much flash on the canister side. This was a result of the large mass of copper in the lid, the high thermal conductivity of copper and the lid clamping/cooling unit. Together, they caused the canister to be hotter than the lid. Since copper has a relatively high coefficient of thermal expansion ($17.7 \cdot 10^{-6}$ per °C), the canister expanded more than the lid. The extra flash gave rise to surplus heat, which had an adverse effect on the stability of the welding process. This problem was solved by mechanically locking the lid and the canister with a male-female rebate. This modification is now used with success at the Canister Laboratory. The joint line was also moved to a position equivalent to that used in electron beam welding, i.e. higher up in the lid. This reduces the asymmetric heating and expansion of the lid and canister, resulting in a more stable process. The procedure also improves the possibilities for inspection by nondestructive testing.

As mentioned previously, the exit hole is positioned at a distance from the weld line. This concept was transferred to the Canister Laboratory during 2003 and entails that welding starts above the joint line, see Figure 6-18, for the purpose of isolating welding defects, but also to enable the process to be interrupted at an early stage if it does not converge towards a stable process. It is possible to start a new weld in a new start point without discarding the piece, since the affected area is machined away after welding when the lid is machined to its final dimensions.

Figure 6-20. *Macrosection of FSW weld showing the fine-grained microstructure that is obtained.*

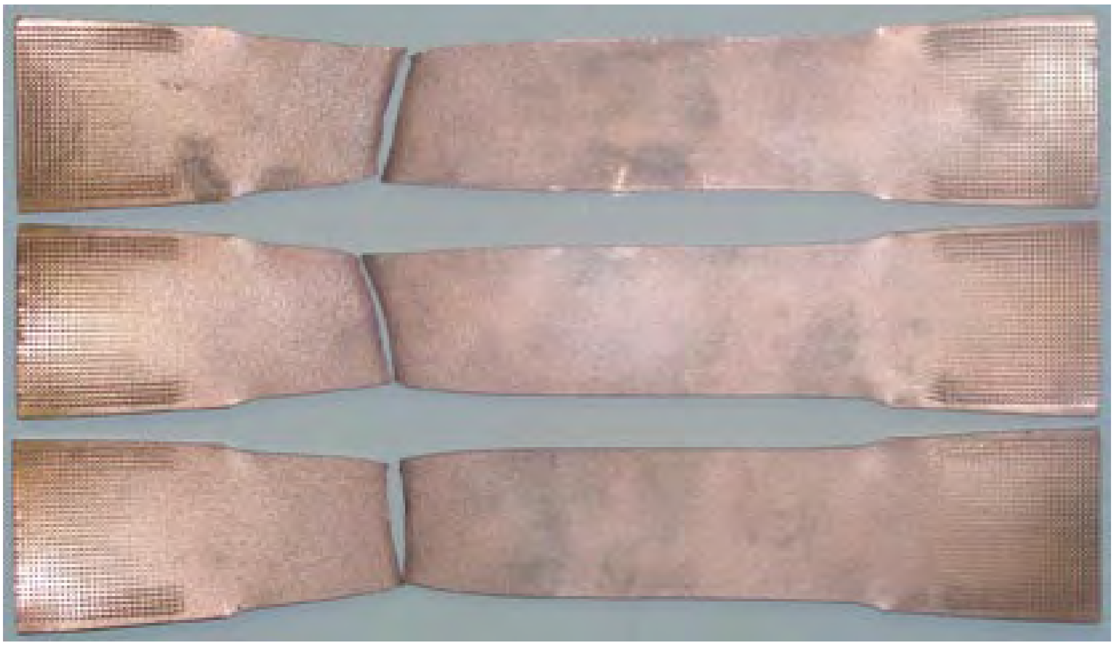


Figure 6-21. *Tensile specimens from lid weld.*

After one lid weld at TWI and eleven lid welds in the Canister Laboratory's new welding machine, the FSW process can be summarized as robust and stable. However, it is not fully developed in the sense of full automation of the process to eliminate the human factor. But experience has shown that it is possible to weld with high repeatability and reliability despite this limitation. The reason is that the only parameter that is changed during a welding cycle is the downward force, and it has a relatively high tolerance.

The problem with the exit hole has been solved by parking the tool above the joint line, which means the hole is machined away when the lid is machined to its final dimensions. The start sequence also takes place at this height above the joint line, which means that any start defects are machined away.

Programme

An important phase of the development programme is optimizing the welding parameters and establishing tolerances for parameter setting. A programme for this has been devised that includes a test series with three levels of selected parameters. Permissible deviations from specified parameters can then be determined and serve as a basis for the preparation of a WPS (Welding Procedure Specification). This part of the programme is expected to be carried out during 2004, see also /7-1/.

In the subsequent demonstration phase, which will take place under production-like forms, the method's potential as a production method will be demonstrated on approximately 20 welds and the resulting weld quality will be investigated for further statistical processing to provide input data for the safety assessment SR-Can.

Material evaluation including nondestructive and destructive testing will be carried out to fully evaluate the integrity of FSW lid welds. Metallurgical investigations will be performed in a structured manner so that the integrity of the welds can be related to the welding conditions. Much of this evaluation will be carried out by Swedish research and development centres and Swedish universities. In parallel with these studies, mechanical tests, corrosion tests, creep tests and chemical analyses of the weld will be performed.

Nondestructive testing methods such as radiographic and ultrasonic inspection will be developed so they can detect both volumetric and other defects in the weld. The results of this work will be regularly compared with metallurgical investigations to obtain defect descriptions for the FSW process. The information will be collected in a catalogue of physical properties of FSW welds.

6.4 Nondestructive testing of the sealing weld

The work on nondestructive testing at the Canister Laboratory is focused on testing of the canister's sealing weld. During 2003 the scope of the work has been broadened from testing of EBW welds only to testing of FSW welds as well.

The work being done on nondestructive testing at the Canister Laboratory can be described as follows:

1. Development of existing methods and trials of new methods for nondestructive testing of the sealing weld.
2. Application of nondestructive testing according to established procedures for evaluation of welding trials.
3. Verification of the reliability of the testing methods.

The methods used at the Canister Laboratory are digital radiographic testing (RT), ultrasonic testing using the phased array technique (UT), and eddy current testing (ET).

Conclusions in RD&D 2001 and its review

Development of methods and equipment for NDT of canisters sealed by EBW is under way at the Canister Laboratory. The project is planned to be concluded in early 2004. The development work is now finished with the exception of eddy current testing, which is expected to be implemented gradually during 2004.

In addition, it is noted from RD&D 2001 that a project was to be started for development of methods and equipment for NDT of canisters sealed by FSW. The development work is under way and is planned to be concluded during 2004.

Furthermore, it was observed that a research project has been under way at Uppsala University for the past five years concerned with ultrasonic testing of EBW-welded copper canisters. The results obtained in the project will be used at the Copper Laboratory. Implementation of signal processing algorithms for ultrasonic testing is currently under way at the Canister Laboratory.

A development project was initiated during 2000 in which Uppsala University, the University of Magdeburg and the Canister Laboratory are jointly developing the technology for detection of near-surface discontinuities in copper by eddy current testing. The development work has continued during the period, and the results are being implemented at the Canister Laboratory.

SKI has pointed out the lack of coherent documentation of results and experience obtained from nondestructive testing. SKB has presented such results in Project Memorandum TI-03-04, which was published in May 2003. The report covers the work with nondestructive testing of the canister through 2002. This memorandum has also been published as an SKB report /6-6/.

Newfound knowledge since RD&D 2001

A milestone that has been reached is that testing procedures have been established for radiographic and ultrasonic testing of EBW sealing welds. In order to investigate the detection capability of the NDT methods, a study has been conducted where some 40 indications from radiographic and ultrasonic testing have been studied with respect to the actual character of the discontinuities. The study shows a good correlation between indications obtained from NDT and actual defect sizes. Furthermore, the results of the investigations are also useful in describing defects obtained in EBW welds. Another conclusion of the investigation was that a more detailed study should be conducted to determine the detection capability of the NDT methods. There is also reason to further study the technology for digital radiography, in view of the fact that research and development to date has mainly focused on ultrasonic testing.

Based on the above, a project was initiated in 2003 at BAM (Bundesanstalt für Materialforschung und -prüfung) entitled “NDT Reliability”. The 3-year project is focusing on inspection of welds made by means of both EBW and FSW. The programme is described in greater detail under the heading “Programme” below.

Within digital radiography, a similar methodology will initially be used for testing of FSW welds as that used for testing of EBW welds. However, a review will be made of possible development needs within the project “NDT Reliability”, which also deals with other development work on digital radiography.

Development efforts within ultrasonic testing have been aimed at developing methods for inspection of FSW sealing welds. For development of the testing methodology, a new phased array ultrasonic system was procured at the end of 2002. The system meets the requirements for FSW testing with regard to frequency range and greatly simplified programming compared with the previous system. It is easier to control and focus the sound beam with the new system.

In order to enable a suitable testing frequency to be specified in the ultrasonic testing of FSW welds, the sound attenuation and propagation properties of the structure have been studied. Similar tests have also been conducted on material from copper lids and cylinders. Testing methods have been defined on the basis of heretofore known types of defects that can occur in FSW welds in copper. Furthermore, theoretically possible defect formations have been posited and testing methods have been devised to cover these hypothetical cases as well.

The testing methods are being progressively improved by evaluation of the indications obtained and comparison with the results from destructive tests.

The methods that are currently being developed and evaluated are all based on phased array ultrasonic technology and can be described in brief as follows:

- Testing of discontinuities with principal extent in the radial-tangential direction. This testing is currently being done from the top side of the lid with a 5 MHz probe that focuses in the middle of the weld, see Figure 6-22a.
- Testing of discontinuities with principal extent in the axial-tangential direction. Two methods are currently being tried with testing from the outer surface:
  - Method 1 focuses on the area 2–10 millimetres from the surface and is performed with a 10 MHz array probe that is controlled so that it simulates a double crystal probe, see Figure 6-22b.
  - Method 2 focuses on the internal part of the weld and is performed with a 5 or 10 MHz phased array probe that is focused centrally in the weld, see Figure 6-22c.
- Testing of discontinuities with principal extent in the radial-axial direction. Two configurations are currently being tried with 5 MHz phased array probes:
  - Most of the welding volume is examined by one probe on the outer surface and one on the inside of the lid. The probes scan at a 45 degree incident angle with direct through-transmission and with reflection against any discontinuities, see Figure 6-22d.
  - For the lower part of the weld, the inside of the pipe is used as a reflector for two phased array probes on the outer surface. The location of the receiver is varied depending on whether the discontinuities are to be detected by defect echo reflection or back-wall echo reduction, see Figure 6-22e.

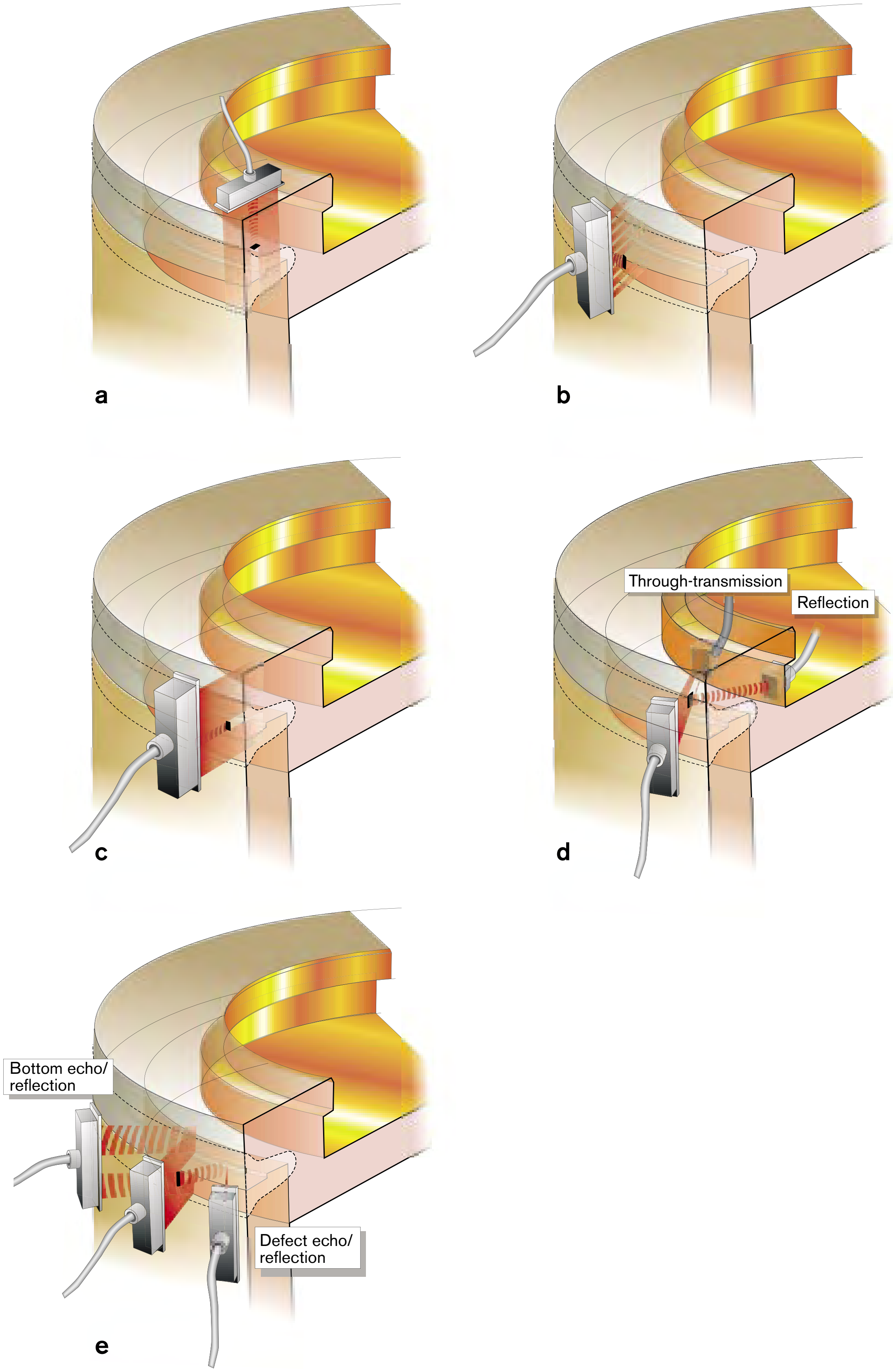


***Figure 6-22.** Methods for ultrasonic testing of FSW sealing weld.*

Within eddy current testing, the project at Uppsala University has been concluded with good results /6-7/. The results show that the testing results are not dependent on the material's microstructure, i.e. welds and parent metal give equivalent results. The distance from the surface to the discontinuity can be determined by means of the signals' phase angle, regardless of the shape of the discontinuities. At the Canister Laboratory, equipment for eddy current testing (ET instrument with probe and data collection system) has been acquired, and evaluation of full-scale welds is currently under way.

Programme

Development of methodology and equipment for nondestructive testing (NDT) of FSW is under way at the Canister Laboratory and is expected to be completed during 2004.

As a part of the programme for determining the reliability of the NDT methods (NDT Reliability), we will study radiographic inspection of welds. The basis for this is that SKB has not conducted any studies on radiographic testing, something which SKI has emphasized is important. A 35 degree incident angle to the weld is used in radiographic testing of EBW welds, which gives good results. One question is whether we should use other and multiple beam directions in order, for example, to be able to determine defect position. These questions are of interest for FSW welds in particular. Practical radiographic tests are time-consuming and expensive and not possible in a reasonable time perspective, since possible beam directions are limited by the X-ray chamber.

This part of the project includes the following:

- Measurement of the spectrum of the radiation source and the detector at the Canister Laboratory. This survey is focused on the linear accelerator's characteristics, the detector's sensitivity and spatial resolution, and a comparison of system performance with standards for traditional film-based radiography.
- Adaptation of BAM's simulation model with the aid of the above-measured parameters.
- Simulation tests to study the detection possibilities at different configurations. Reconstructions of actual defects imaged by means of high-resolution microfocus computer tomography and placed in a CAD model of the weld are used as input data in the simulation. The simulations are validated by comparing simulated images with real images obtained in SKB's system.
- Evaluation of alternative radiographic methods and detectors.

A second part of the project concerns determination of the reliability of the NDT methods. In an initial stage, test objects are being examined according to established testing procedures at the Canister Laboratory and the results are being carefully documented. The test objects consist of lid welds with a large number of discontinuities created by varying important parameters beyond the process window for the particular welding method. The purpose of this approach is to ensure that different types of possible discontinuities are present in the test objects. In the next stage the incidence of defects is investigated in detail by computer tomography complemented by high-resolution microfocus computer tomography. In addition, investigations are also conducted by means of other NDT methods and destructive tests on metallographic sections and tensile specimens. These data are then processed statistically. In order to describe the reliability of the NDT methods, POD (probability of detection) curves and ROC (risk of false calls) curves are used in accordance with relevant recommendations in the standard MIL-HDBK-1823 /6-8/. The statistical processing of the data will shed light on the reliability of the NDT methods both individually and in combination. Simulation tests will also be performed in the project in order to determine POD in the use of radiographic technique. Initially, the information that exists on the real defects with respect to such important parameters as orientation, size, shape factors, gap width etc will be processed. The next step is to statistically determine within what limits these parameters vary and randomly generate defects within this parameter window. The advantage is that a virtually unlimited number of relevant defects can be generated and imaged in the simulation program, and the body of statistics available for the analysis can thereby be increased considerably. The above process, which is described schematically in Figure 6-23, will take place along two parallel tracks that deal with sealing welds executed by EBW and FSW.

The project at BAM is expected to be concluded during 2005 and the final report published in 2006. Interim results from the study will be reported during this period.

We intend to publish experience and results from nondestructive testing during the first half of 2005.

After the choice of welding method, we intend to start a feasibility study regarding the requirements for and possible usefulness of ultrasonic modelling. Plans call for the feasibility study to start during the second half of 2005.

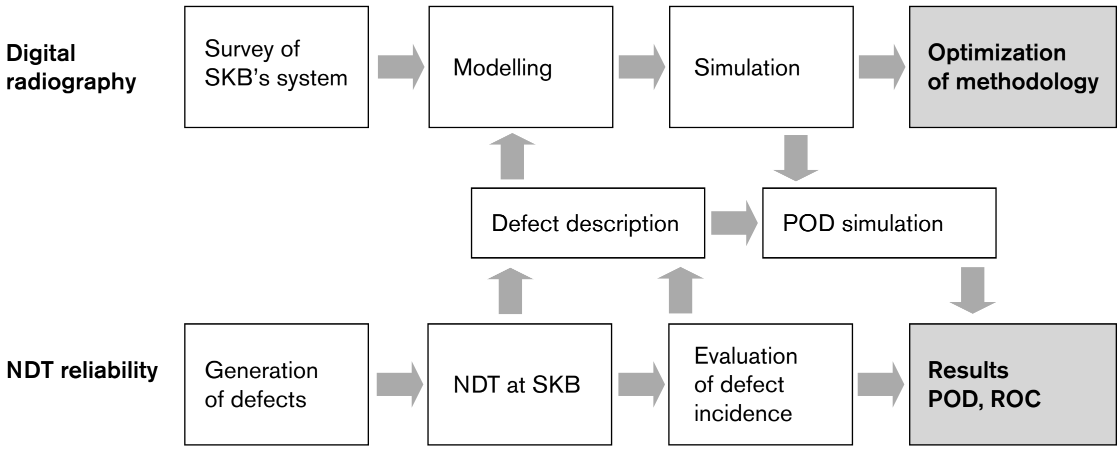


Figure 6-23. *Flow chart (project "NDT Reliability" at BAM).*

7 Canister – qualification

Before the encapsulation plant and the canister factory are taken into service, qualification of methods for fabrication, welding and nondestructive testing of canisters must be carried out.

Qualification of the processes consists of documented investigations that ensure that the finished canisters satisfy the ultimate requirement of being a reliable barrier in the deep repository. Requirements will be specified for each process, after which the process will be qualified to these requirements. A programme will be prepared for qualification and presented as a supporting document for the permit application for the encapsulation plant.

The qualification work can be divided into qualification of methods for fabrication and welding and qualification of methods for nondestructive testing. This is described in greater detail in sections 7.1 and 7.2.

7.1 Qualification of methods for fabrication and welding

As is evident from Chapter 6, SKB is working in parallel on the development of two welding methods at the Canister Laboratory: friction stir welding (FSW) and electron beam welding (EBW). Prior to an application for a permit to erect the encapsulation plant, the methods for sealing and nondestructive testing (NDT) must be determined.

The choice of reference welding method can be viewed as the first step of qualification. A number of criteria have been formulated for this. The methods must fulfil these criteria and be evaluated in reference to them. Some of the criteria are:

- **Reliability.** The risk that defects will arise that exceed the acceptance criteria for the sealing welds must be low. It must be possible to control the welding process by means of variable parameters.
- **Robustness.** The probability of disturbances that affect weld quality must be low. Small, unforeseen or normal changes in welding parameters, equipment or the surrounding environment must not affect the quality of the weld. The process window, i.e. the interval within which the welding parameters must lie in order for the quality of the weld to be acceptable, must be large in comparison with the tolerances of the process parameters.
- **Repeatability.** The same welding parameters and surrounding environment must give the same weld quality. Changes in weld quality must be able to be attributed to changes in parameters and the surrounding environment. After service and maintenance of the welding equipment, the same welding parameters must give undiminished weld quality.
- **Testability.** The discontinuities that can arise in the process must be detectable with sufficient probability by means of NDT. The forms for this evaluation are described in greater detail in section 7.2.

SKB's task is now to finish the development of the welding processes and equipment and verify that the above criteria are fulfilled. Much of the fundamental development of the welding processes and equipment has already been done. What remains to be done is to better quantify some of the important variables and how they affect each other, and establish the optimal settings for stable operation. Furthermore, SKB must demonstrate that it is possible to weld with sufficiently high quality under conditions similar to those of serial production sealing in the encapsulation plant.

SKB has devised a quality system for the different fabrication processes used in canister fabrication. This system includes procedures that describe how qualification of both suppliers and fabrication processes is done.

Conclusions in RD&D 2001 and its review

The choice of methods for sealing and testing the canister influence the design of the encapsulation plant and should also have been made at the time of the application for a permit to build the plant. At that time there will also be a programme for qualification of the methods. Qualification of the methods will be done at a later stage, prior to encapsulation of the spent fuel.

SKI's viewpoints on qualification of the sealing method are largely the same as their viewpoints on nondestructive testing (see below).

Newfound knowledge since RD&D 2001

A strategy has been devised for establishing the reliability, robustness and repeatability of the welding methods for canister sealing. This strategy is based on statistical methods. Such methods have been used with great success since the 1950s to develop and design industrial processes. Experiments based on a statistical approach are often used to model and optimize the response of a system, but the focus may also be on studying the system's stability (the variance of the response). The choice of a suitable experimental plan for a given welding method has been made on the basis of the number of factors involved and the degree of detail with which the studied domain is to be described. A more detailed description of the programme has been published and is presented in Chapter 6 under the relevant welding method.

Programme

Welding trials and testing of welds will, according to plans, be conducted during 2004. Evaluation of the results will take place during 2005. The results are important both for the choice of welding method and for obtaining input data regarding the encapsulation process for the deep repository's safety assessment.

SKB plans to carry out a project during 2004 aimed at studying the prerequisites and the overall forms for qualification of fabrication and welding methods. SKB intends to present a programme for this at the time of the permit application. SKB will keep SKI informed of the preparation of this programme.

A milestone that can already be defined now is the preparation of a programme by mid-2006 for determining the reliability of the fabrication methods. The programme will be carried out in preparation for the planned safety assessment for the deep repository, SR-Site.

The connection between qualification and safety assessment is important, since the qualification goals for fabrication and welding processes as well as nondestructive testing must be set so that safety in the deep repository is guaranteed. Figure 7-1 shows the timetable for compiling supporting material for the various safety assessments. Data from the probabilistic safety assessment are also expected to be available prior to SR-Can, see section 14.2.

As is evident from the timetable, efforts during the period 2005–2008 will be aimed at gathering data on the reliability of the fabrication processes for SR-Site.

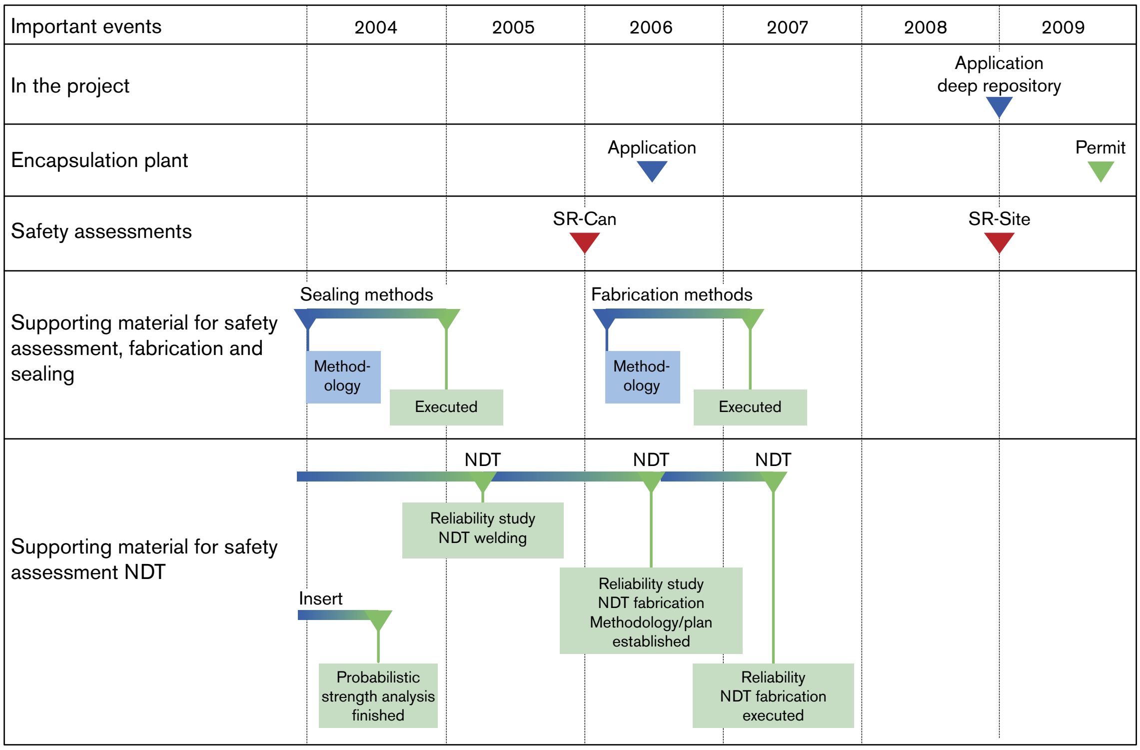


Figure 7-1. *Timetables for compiling supporting material for the various safety assessments.*

7.2 Qualification of NDT methods

The canisters with spent nuclear fuel will undergo NDT by means of e.g. radiography and ultrasonics before being emplaced in the repository. Like the fabrication and sealing methods, the NDT methods planned to be used will also undergo qualification.

Conclusions in RD&D 2001 and its review

Two milestones can be distinguished in qualification. The first will be reached when SKB plans to apply for a permit to build an encapsulation plant. At this point, qualification will be focused on so-called technical justification. What technical justification entails is laid down in ENIQ (European Network for Inspection Qualification) Recommended Practice 2 /7-2/. SKB intends to apply this recommendation in the documentation of its NDT methods. The second milestone will be reached when the encapsulation plant is commissioned. Then SKB intends to qualify the NDT methods based on ENIQ Recommended Practice 4 /7-3/.

SKI recommends that SKB more clearly describe who is to carry out the qualification of non-destructive testing and what the infrastructure for qualifications should look like. SKI believes that SKB underestimates the time required for qualification and that the results of qualification can, at a late stage, influence the design of the encapsulation plant, for example if an NDT method does not have the desired result.

Furthermore, the Inspectorate points out that the qualification methodology described in ENIQ's document must be adapted for the nondestructive testing of canisters, since it has actually been developed for the recurrent testing of mechanical devices in nuclear power plants. The development of the methodology should take place towards clearly defined qualification goals. A necessary condition for qualification is knowledge of possible defects as well as acceptance criteria. The work on acceptance criteria must be given high priority.

Newfound knowledge since RD&D 2001

SKB concurs with the viewpoints of the Inspectorate that the qualification process must be adapted to KBS-3. SKB has an ongoing dialogue with SKI regarding the general forms and the long-term timetable for qualification. SKB is holding a parallel dialogue with the independent qualification body SQC Kvalificeringscentrum AB (SQC) regarding the development of a qualification programme adapted to KBS-3. In preparation for the upcoming applications for the encapsulation plant and the deep repository, SKB is working on a plan for qualification of NDT methods. The discussions being held with SKI have shed light on the need for clarifying the different steps in the qualification programme, the logic in the underlying documentation, and links to the safety assessments prior to the application for a permit to build the encapsulation plant (SR-Can) and the deep repository (SR-Site).

The overall timetable SKB is working with to carry out qualification of nondestructive testing is shown in Figure 7-2.

"Principles for technical documentation" are to be described in conjunction with the application. By this is meant documentation that can be regarded as relevant for setting up the requirements for nondestructive testing. Work on defining relevant technical material is under way. The purpose of the milestone is to compile the supporting material in a coherent fashion and, if necessary, present action plans for ensuring that the compilation is complete when it is presented in its final form in mid-2011. A suitable structure for this supporting material is:

- **Design premises.** Analysis and development of requirements derived from the overall design premises for the deep repository. The analysis results in detailed design premises for the canister and supporting material for the choice of canister material.
- **Load data.** The different loads on the canister such as handling loads, compressive loads in the deep repository and the various chemical processes that affect the canister on different time scales.
- **Strength analyses.** Determination of the material properties of the canister, strength calculations and their premises. Dimensional design of the canister.
- **Fabrication, sealing and inspection.** Fabrication and welding processes as well as description of the defects that can arise during them. The inspection processes intended to be applied and acceptance criteria. Qualification requirements and detection goals for the inspection processes.

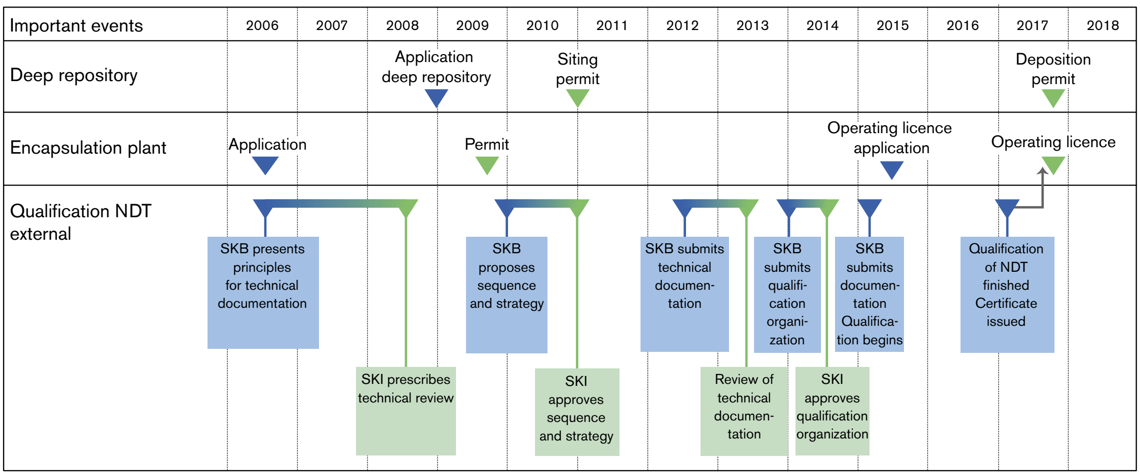


Figure 7-2. General timetable for carrying out qualification of nondestructive testing.

Another important milestone will be reached at the end of 2009, when SKB proposes the qualification sequence. SKB's main line is that a qualification body should carry out the qualifications. To prepare this point, SKB has initiated a project together with SQC to adapt the prevailing qualification process to obtain a relevant qualification programme for the fabrication and encapsulation processes. An important prerequisite for the programme to be implemented is that the qualification body is approved by SKI. The qualification body must therefore acquire expertise and the necessary instructions. SQC has been assigned the task of developing a programme for the necessary preparations.

SKB also concurs with the authorities' viewpoint that it is important to guarantee that the reliability of the NDT methods meets the requirements at an early stage in order to avoid complications in the encapsulation plant. We have therefore initiated a programme for determining these requirements. In the first part of the programme, the NDT processes that have been developed at the Canister Laboratory and that are planned to be used for inspection of the sealing process are being evaluated. The programme is being carried out in cooperation with external expertise at BAM, Bundesanstalt für Materialforschung und -prüfung in Berlin, and is presented in section 6.4.

Programme

A report that describes the programme for qualification of NDT methods will be issued. Based on a general structure (see Figure 7-2), the milestones in the project will be defined and requisite activities described. According to plans, the report will be completed during 2004. A status report will be submitted at the time of the application.

The reliability study for nondestructive testing of the sealing weld will, according to plans, be completed during 2005. Reports describing execution, results and conclusions will be published. A summarizing report will be issued no later than at the time of the application.

8 Canister – encapsulation

The design of the encapsulation plant depends on where it is sited. SKB's main alternative is to build the encapsulation plant connected to Clab. The work of designing such a facility was begun in 1993. Since then the facility has been further developed and modified. SKB has also studied the possibility of building an encapsulation plant adjacent to the deep repository in Forsmark.

In this chapter, an encapsulation plant connected to Clab is dealt with in section 8.1 and an encapsulation plant in Forsmark in section 8.2. Sections 8.3 and 8.4 describe the measures that will be required with regard to physical protection and safeguards.

8.1 Encapsulation plant at Clab

The general production requirements on the encapsulation plant are that it must have a capacity of one canister per day and a lifetime of at least 60 years, and that all types of spent fuel that are stored in Clab must be able to be handled and encapsulated. To protect personnel and nearby residents, high standards of safety must be met in the operation of the plant. The safety standards cover radiation protection and fire protection, among other things. The spent fuel must always be able to be handled without risk of criticality.

For the licensing work the plant is dealt with separately from Clab with its own preliminary safety report. When the plant is ready to take into operation, the safety analysis report will be integrated with the one for Clab.

Different siting alternatives have previously been compared and presented /8-1/. There are several advantages to a siting adjacent to Clab. For one thing, the experience of fuel handling that exists at Clab can be taken advantage of. Several of the existing systems and facility sections in Clab can also be utilized for both facilities.

8.1.1 The plant

Besides fuel from today's energy-generating nuclear power plants, certain other fuel types are also stored in Clab's storage pools. The intention is that this fuel can also be encapsulated in the copper canisters without the canister design having to be modified. In the same way as spacers are used in the transport casks for fuel shipments to Clab, the space in the channels in the inserts can be modified to suit all fuel types by means of spacers in the canisters.

Damaged fuel is transported to Clab in special cans for leaking fuel. After arrival at Clab, the damaged fuel has previously been lifted out of the cans and stored in the same way as other fuel, i.e. in storage canisters in the storage pools. In the future, damaged fuel may be stored in Clab in cans for leaking fuel. Prior to encapsulation of the damaged fuel, however, this fuel must also be lifted out of the cans to be placed in the copper canisters. The experience that exists of transporting damaged fuel and handling and storing it in Clab suggests that no further degeneration of the fuel take places during storage.

A limiting factor for the fuel content in a copper canister is the canister shell's outer temperature in the deep repository. In designing the encapsulation plant the maximum permissible heat output of each canister is assumed to be about 1.7 kW. Since burnup and cooling times vary for the spent fuel, this means that the contents of each individual copper canister must be planned carefully to permit maximum utilization of the canisters. Towards the end of the encapsulation period, it may nevertheless be decided not to fill the canisters completely rather than to wait for them to cool sufficiently.

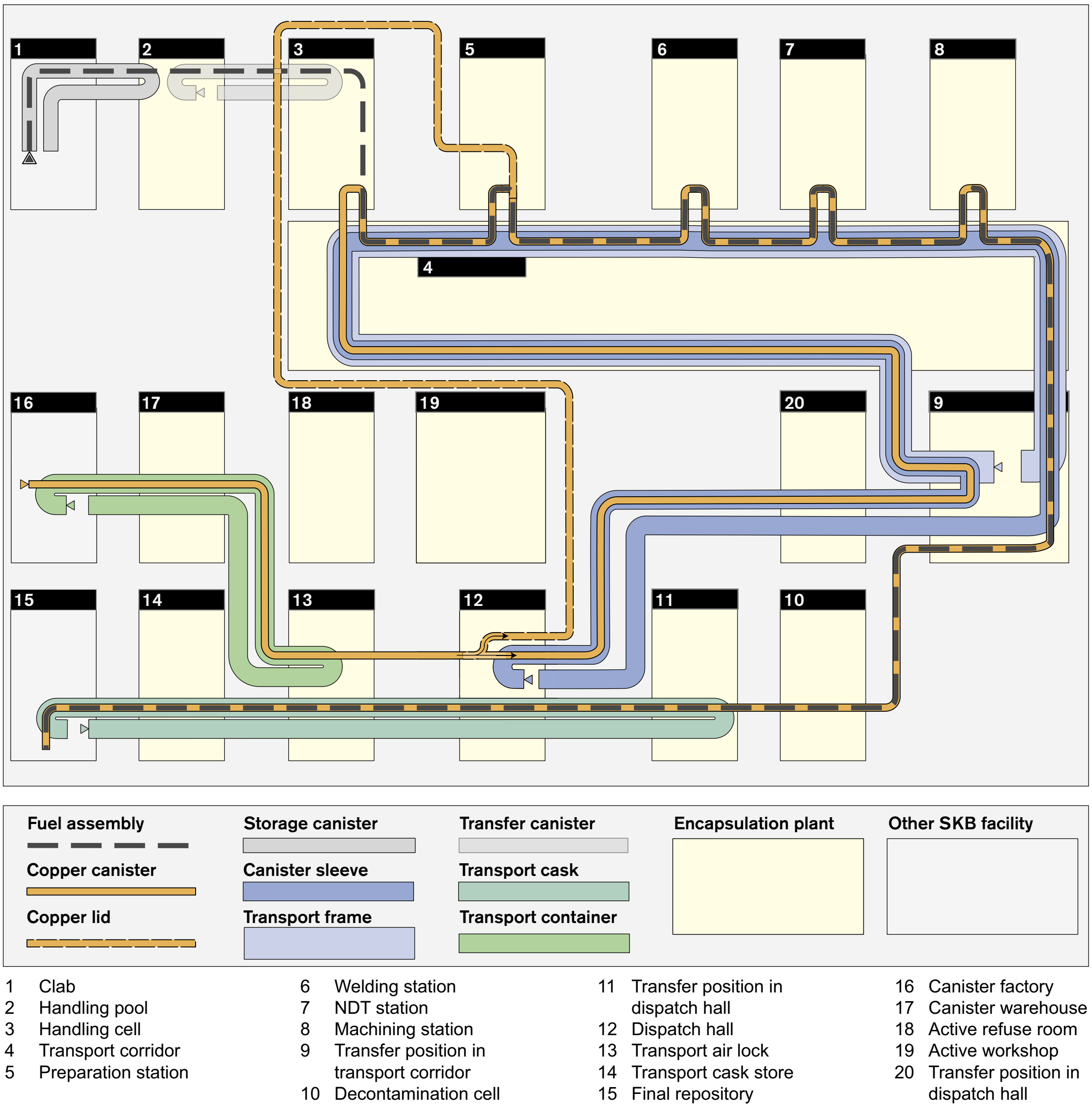


Figure 8-1. *Main process diagram for the encapsulation plant.*

References are made in the following text to items 1 to 13 in Figure 8-1. An illustration of the encapsulation plant is shown in Figure 8-2.

The fuel assemblies, which are stored in storage canisters, are moved to the encapsulation plant via the existing fuel elevator in Clab (1). The storage canister is placed in the fuel elevator's water-filled elevator cage and lifted up from the storage section. The storage canister is then taken to the encapsulation plant's pools, which are situated directly adjacent to the fuel elevator.

In the handling pool (2), the fuel assemblies are moved from the storage canister to a transfer canister, which is intended for internal fuel handling in the encapsulation plant. This transfer is made for several reasons. The storage canisters contain more assemblies than fit in a copper canister, while the transfer canister has the same number of positions as a copper canister. Furthermore, the total decay heat in a canister may not exceed 1.7 kW. An attempt will be made to have a uniform distribution of decay heat in the canisters. Since the safeguards system in Clab contains all the necessary information regarding position, history, origin and physical data for each stored fuel assembly, the selection to each copper canister can be made in good time. In conjunction with the transfer to transfer canisters, the identity (marking) and decay heat output of each assembly is checked. The verifying measurement of decay heat is done by a gamma scanning equipment. Transfer of fuel assemblies is controlled by an operating order in the same way as in Clab today.

Figure 8-2. *Work stations in the encapsulation plant.*

The transfer canister is lifted out of the pool in the encapsulation plant into the radiation-shielded handling cell (3) by means of the remote-controlled handling machine in the cell. The transfer canister is drained of water and placed in one of the two positions where the fuel is dried. When the fuel has dried, the assemblies are lifted one at a time over to a copper canister. The copper canister with canister sleeve stands in a radiation-shielded transport frame which is docked from beneath to another part of the cell. During loading of the fuel, the copper canister is fitted with a protective cover so that the copper shell's joint surface will not be damaged. Damage could cause problems during welding of the copper lid. When the canister is filled, the steel lid is screwed onto the cast iron insert. The empty transfer canister is taken back to the handling pool. Handling is done by remote control from a work station outside the handling cell.

The connection between the copper canister and the handling cell is airtight to prevent the outside of the canister from being contaminated and to prevent air from escaping from the cell and spreading radioactivity to other parts of the plant.

The transport corridor (4) constitutes the connecting space between (and beneath) the different cells where copper canisters are handled. The copper canister and the canister sleeve are moved standing in a transport frame by an air cushion transporter. The transporter consists of a pallet supported by a number of air cushions. The air cushions are supplied with air via a hose and powered by batteries on board the transporter. The transport frame consists of a stand with a radiation shield. The canister sleeve, in which the copper canister is placed, fits inside the radiation shield. The radiation shield has two telescopic parts. The upper part is fixed and fitted with a movable radiation-shielding hatch on top. The lower part can move vertically so that the canister can be raised and lowered. At the bottom is a turntable that can rotate the canister, which is required for electron beam welding, machining and nondestructive testing. The canister is prepared for welding in the preparation station (5). The canister is docked from beneath in a similar manner as at the handling cell. (Applies to the following work stations as well.)

The atmosphere in the canister is changed via a valve in the steel lid, the air is evacuated and the canister is filled with argon. The steel lid is then leak-tested. In the cell, the canister's joint surface is also inspected and cleaned if necessary, after which the copper lid is lifted down onto the canister.

Electron beam welding: At the welding station (6), the copper canister is docked to a vacuum chamber inside the station. After docking, the copper lid is lifted up and the chamber is vacuum-pumped, as is the gap between the insert and the copper shell. The copper lid is then put back and the copper canister is sealed by EBW. During welding the canister is rotated around its axis on the turntable in the transport frame.

Friction stir welding: At the welding station (6), the canister is docked from beneath in a similar manner as at the handling cell. The copper canister is sealed by FSW. During welding, a clamping system holds the canister and the lid while the welding head rotates around the canister.

In the Non Destruction Testing (NDT) station (7), the weld joint is tested with respect to the quality of the weld. The methods used are radiographic and ultrasonic testing. Depending on what the final quality requirements on the welds are, eddy current testing may also be used.

If the weld fails NDT but contains reparable defects, the canister is taken back to the welding station, where it is repaired. Then the quality of the weld is checked once again. In cases where the weld cannot be repaired, the transport frame with the rejected weld is put aside so that it does not obstruct normal production. At a suitable opportunity, the canister is transported back to the station for machining, where the copper lid is cut open by means of the milling machine. The copper lid is then lifted off, after which the canister is transported to the handling cell. There the fuel is transferred to an empty transfer canister standing in one of the drying positions. The copper canister is decontaminated in the active workshop (19) and the copper shell is sent to recycling. The insert is reused in a new canister. The unloaded fuel assemblies in the handling cell are transferred to a new canister.

If the canister meets the quality requirements, it is transported to the machining station (8), where the weld joint and the area around it are machined to a smooth finish in accordance with the canister's other shape and dimensional requirements. In the transfer position in the transport corridor (9), the canister is lifted out of the canister sleeve, after which the canister sleeve is lifted out of the transport frame. In the decontamination cell (10), smear tests are performed on the canister to make sure it is free of surface contamination. If decontamination is necessary, a high-pressure water jet is used, after which new smear tests are performed. The surface dose rate is also measured before the canister leaves the cell.

In the transfer position in the dispatch hall (11), the canister is loaded into the transport cask, after which the transport cask lid is fitted. Via the dispatch hall (12), the canister transport cask is moved to the transport air lock (13), where it is lifted down onto a transport frame and secured in the horizontal position. In the transport air lock the cask is inspected, after which it is removed by a terminal vehicle. If transport to the deep repository does not begin immediately, the cask is placed in a store awaiting transport. The store is also a temporary holding site for empty canister transport casks.

The filled canister transport casks are transported to and received at the deep repository. There the canisters are unloaded, after which the empty casks are transported back to the encapsulation plant.

Conclusions in RD&D 2001 and its review

In its review comments on RD&D 2001, SKI pointed out the importance of flexibility in the encapsulation plant, since many steps in the process have not been finalized. Furthermore, SKI pointed out that it is important to incorporate experience from the Canister Laboratory in designing the encapsulation plant, and that a more detailed description is needed of how damaged fuel, fuel debrish, MOX fuel etc affect handling in the plant and plant design. The impact on the encapsulation plant of a possible switch to horizontal deposition should also be examined.

Newfound knowledge since RD&D 2001

Experience feedback from the Canister Laboratory to the design of the encapsulation plant takes place continuously, for example due to the fact that personnel from the Canister Laboratory also work with the encapsulation plant project.

The new welding machine for friction stir welding was installed and commissioned in the Canister Laboratory during 2003. The FSW equipment offers an alternative to electron beam welding. Experience from the development of the welding methods provides important information for the design of the encapsulation plant. This also applies to the development of the methods for nondestructive testing and other activities at the Canister Laboratory.

The change of atmosphere in the canister's cast insert is not necessary, providing a certain quantity of water can be accepted in the canister. Even after the fuel has undergone the drying process, there might theoretically be water left in a damaged fuel rod. At present it is not possible to determine how many damaged fuel rods might end up in the same canister. It is therefore not possible to determine the exact amount of water there might be in the canister. As a result, the plant is currently designed for a change of atmosphere in the canister insert. The atmosphere change results in acceptable chemical conditions inside the canister, but entails an extra step in the encapsulation process.

The encapsulation plant is being designed solely for the encapsulation of spent fuel. It will not be possible at a later point in time to add equipment for handling of low- and intermediate-level waste without re-designing the whole plant.

A possible switch to horizontal deposition will not, according to current plans, affect the design of the encapsulation plant, since the preparation of the canister prior to deposition is planned to take place in the deep repository.

The new decay heat measurement equipment was installed at Clab in 2003. It is designed for accurate determination of the fuel's decay heat. The equipment consists of a calorimeter, along with gamma probes to measure the heat losses in the calorimeter caused by gamma radiation that has not been absorbed. The more accurate the determination of the decay heat is, the better the deep repository's layout can be designed, since the surface temperature of the canisters determines how closely they can be spaced. High decay heat, or high uncertainty regarding the amount of decay heat, means that the canisters must be spaced at greater distances. This in turn means that the deep repository's underground part will be bigger.

Programme

Decay heat measurements with the new measurement equipment will be conducted in campaigns. The first measurement campaign on Clab fuel has been initiated. A special database has been established for storage and handling of the large quantities of measurement data. An estimated 15–20 fuel assemblies will be measured each year at Clab. In parallel with the calorimetric measurements, gamma measurements will be performed on the same fuel assemblies. The intention is that the calculated decay heat output can be verified by gamma measurement alone at the time of encapsulation, since calorimetric measurement is a time-consuming and complicated process.

The results from each campaign will be evaluated carefully, in close cooperation with both Swedish companies and Oak Ridge National Laboratory (ORNL) in the USA. Since November 2000, SKB has had a cooperation agreement in this area with UT-Battelle, which operates ORNL.

An action plan will be prepared to describe what it would entail for the encapsulation process if the verifying measurement of fuel done just before encapsulation were to show large discrepancies in relation to the figures submitted by the nuclear power plant when the fuel was transferred to Clab. It should be noted that encapsulation will continue for a long time after the nuclear power plants have been shut down.

The plans of the nuclear power utilities include changes that may affect the fuel's geometry and source terms. This may affect the facilities and the transportation system. An inquiry has been initiated to develop a long-term strategy for SKB.

8.1.2 Design and application

Design of the encapsulation plant is proceeding in steps. The ongoing design step corresponds to the level of detail required in an application for a permit to build a plant. The design of an encapsulation plant at Clab has previously been carried out to this stage /8-2/. The ongoing design process is thus a revision where experience from the Canister Laboratory, changes in the regulatory framework and technical progress are being incorporated in the design. Design is taking place in close cooperation with SKB's Finnish counterpart Posiva.

In order to design the plant, SKB has started a project and contracted a consultant for plant and process design. Design is supplying supporting material for the system part in the preliminary safety report as well as certain references to the report's general section. Work on the general section is being pursued separately. All safety-related supporting material will also be reviewed independently by an organization with experience from similar nuclear assignments.

In parallel with the design of the encapsulation plant, an environmental impact statement (EIS) is being prepared in a process called environmental impact assessment (EIA), an important part of which is consultation with affected parties.

In addition to a preliminary safety report and an environmental impact statement, a safety assessment of the long-term safety of the deep repository and a system analysis of KBS-3 will also be appended to the application for a permit to build the encapsulation plant. This is shown in Figure 8-3.

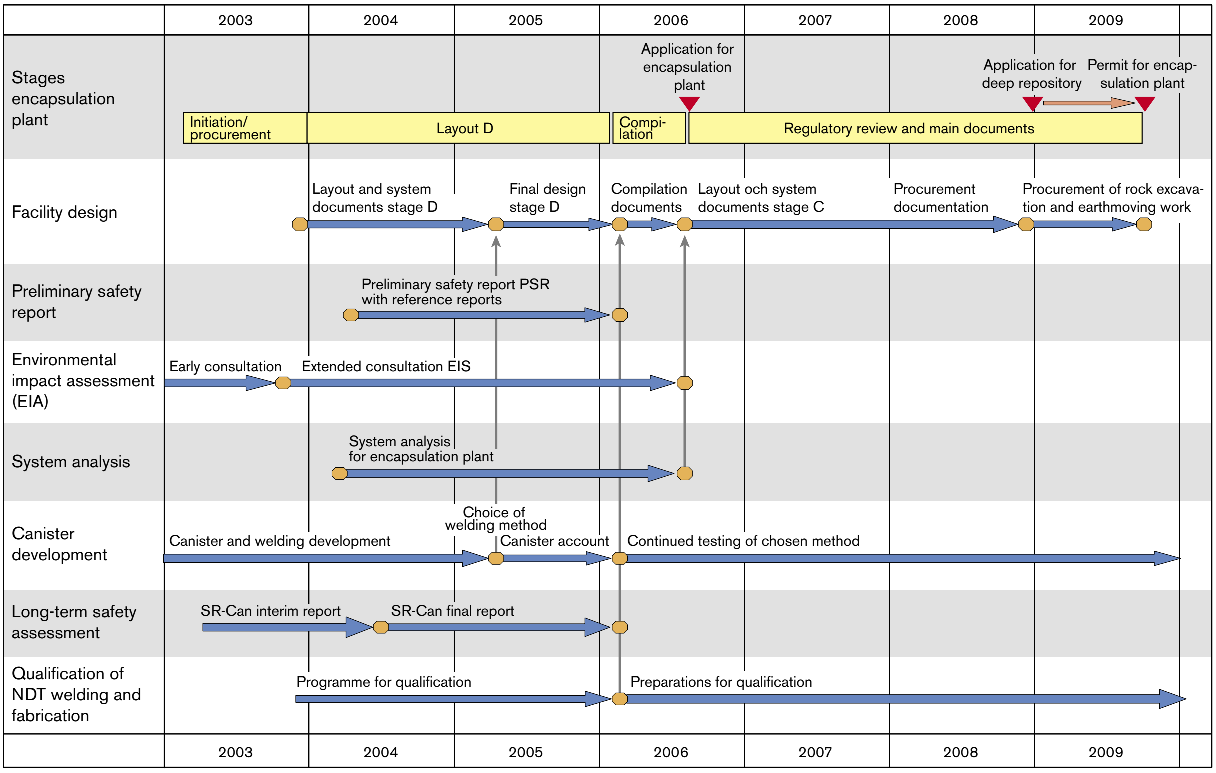


***Figure 8-3.** Timetable for encapsulation plant.*

8.2 Encapsulation plant at deep repository

SKB has previously conducted a feasibility study of a standalone encapsulation plant, separate from Clab /8-3/. The plant was then assumed to be situated near the surface part of the deep repository. A prerequisite for siting the encapsulation plant at Forsmark is naturally that the deep repository is also sited there.

The primary technical difference between the planned encapsulation plant at Clab and a standalone plant at the deep repository is the way in which the fuel is handled and prepared prior to encapsulation. Fuel reception at the encapsulation plant at the deep repository takes place dry, i.e. no pools are used. The technical solution for fuel reception has been reviewed by two independent international companies with experience of dry handling of fuel assemblies.

The existing Clab facility is used for verification measurements, sorting and drying of the fuel before it is transported to the encapsulation plant. This means that parts of Clab must be rebuilt and provided with new equipment.

The technical prospects for being able to build an encapsulation plant co-sited with the deep repository are good. Following is a short process description for this siting.

The fuel assemblies to be encapsulated are moved from the storage pools via the fuel elevator into Clab's component pool, where a verifying gamma measurement can be performed. The fuel assemblies have to pass a number of detectors that measure the radiation from the fuel. The fuel is then placed in a transfer canister which, when full, is moved to the service pool. From there the fuel is lifted over to a transport cask.

When the cask is filled the lid is fitted and the cask is lifted up from the pool and transferred to a cooling cell. The water is drained out and a drying system is connected to the cask. After drying the transport cask is checked to make sure it is dry and the surface is clean. Finally, shock absorbers are fitted, after which the cask is transported to the encapsulation plant at the deep repository.

The fuel arrives at the encapsulation plant sorted and dry, which is a prerequisite since there are no pools in the plant. Four fuel transport casks are received every week. The cask's shock absorbers are removed and a bottom adapter is screwed on. The cask is moved by the main overhead crane either to the holding area for transport casks or to one of the preparation cells in the handling hall.

In the preparation cell, a ventilation system is connected to ventilate the cask and detect any damaged fuel. A negative pressure is maintained to prevent airborne activity from being spread in the plant. Then the outer lid is removed. When the preparations are completed, the cask is moved by the main overhead crane to a rail-borne carriage.

The carriage is moved to a position directly beneath the handling cell. A ventilation system is connected and normal air pressure is established in the transport cask. The carriage and cask are now lifted by hydraulic motors up to the handling cell's floor passage sleeve. Docking is concluded with the inflation of a rubber seal.

The floor plug in the handling cell is removed by the overhead crane. The cask's inner lid is lifted up, enabling the fuel in the cask to be lifted over to a copper canister or placed in the handling cell's buffer store. When the fuel is to be moved to a copper canister, the canister insert's steel lid is first removed by a lifting device fitted with magnets, after which the fuel assemblies can be placed in the canister.

When the canister is filled, the insert's steel lid is fitted. The subsequent operations – including lid welding NDT and machining – are similar to those for the encapsulation plant at Clab, see section 8.1.1.

Conclusions in RD&D 2001 and its review

The review of RD&D 2001 did not give rise to any special viewpoints on the encapsulation plant co-sited with the deep repository.

Newfound knowledge since RD&D 2001

A possible location of a standalone encapsulation plant in the Forsmark area is between the operations area for the Forsmark 3 reactor and the operations area for Forsmark 1 and 2. This location is shown in Figure 8-4.

Programme

The consultation process for a deep repository in Forsmark will also consider the alternative of an encapsulation plant co-sited there. The environmental consequences of this will be analyzed. Design of this plant is not planned.

A decision to site the encapsulation plant at Forsmark would have a great impact on SKB's main timetable and costs. Certain parts or functions of the planned encapsulation plant at Clab could be transferred to the standalone plant, but the whole construction layout would have to be entirely redone. Since the prerequisite for the plant is dry handling of fuel, a thorough study must be conducted for the operation at Clab, since sorting, verifying measurements and drying of the fuel must then take place in the existing facility. The feasibility study that has been done shows that Clab can be used, but a revision may be necessary that takes into account the expansion of Clab.

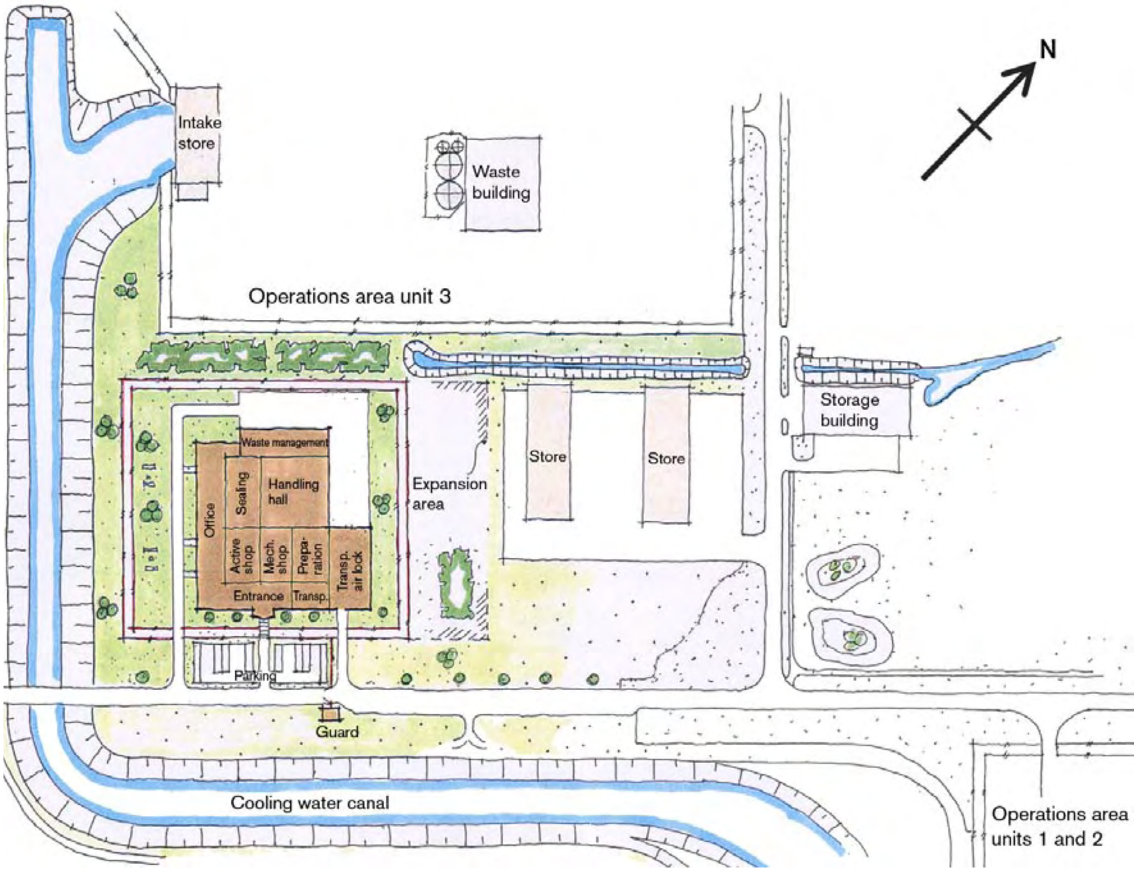


__Figure 8-4.__ Possible location of a standalone encapsulation plant in the Forsmark area.

8.3 Physical protection

The term "physical protection" refers to guarding and other measures that are adopted to prevent theft, sabotage or other unauthorized access to nuclear waste or nuclear material. Physical protection is designed to comply with legislation and regulations.

SKI's regulation for physical protection is included as a design premise for the encapsulation plant. There is a well-functioning system for physical protection during handling and transport. The plant's guarded area will be fenced-in and other surveillance equipment will be installed similar to what is required for nuclear installations. Access to the area will be controlled and checked in a manner similar to what is done at the nuclear installations in operation today. The encapsulation plant's buildings will be integrated with Clab's protection area and the perimeter protection.

8.4 Safeguards

Through international treaties such as the Nuclear Non-Proliferation Treaty, the Euratom Treaty and other bilateral agreements, Sweden has undertaken to use nuclear materials for peaceful purposes only as well as to keep records of all handling of nuclear materials, including spent nuclear fuel. Sweden has also agreed to subject all material of this type to international verification. These so-called safeguards are administered by Euratom and the IAEA, and on a national level by SKI. The purpose of the safeguards is that the inspection bodies should discover in a timely manner if nuclear materials are diverted from the system.

The requirements on safeguards issued by both Swedish and international inspection authorities must be met in the encapsulation plant. This is provided for during the engineering phase by setting aside space in the layout for apparatus rooms, fuel measurement equipment, cameras and surveillance instruments. The plant will be designed so that several Key Measuring Points (KMPs) can be established, for example at the fuel handling pool, in the handling cell after the fuel has been placed in the canister before the lid is put on, and in the transport air lock before the canister is dispatched from the plant. The canister components are individually marked and can be followed through the various handling steps. In designing the plant's layout, steps are also taken to prevent "diversion routes" for nuclear materials in order to facilitate surveillance. The smallest unit that will be able to be handled is a fuel assembly.

Information on the fuel's nuclear material content and other safeguards-related information is that which is available for the fuel stored in Clab. The fuel's decay heat will be verified by means of gamma measurements, which are planned to be performed in the encapsulation plant. This measurement position can also be used by the supervisory bodies for their own measurements. It is also possible to "share" the signal from the measurement probes.

Each canister will have a unique identity that can be checked visually. The administrative safeguards system keeps track of which fuel assemblies are contained in each canister. Visual verification of the fuel's identify can be performed before the canisters are sealed. This information can be recorded by a TV camera and stored in digital form. After sealing and inspection, the canisters are placed in transport casks. The casks also have a unique identity which is administratively linked to the contents and permits verification. The transport casks are placed in a supervised store and kept under surveillance awaiting transport to the deep repository. The total number of casks needed for spent fuel transport depends on the geographic location of the repository. The transport casks will be handled in keeping with the same principles as those that apply to transport of spent fuel from the nuclear power plants to Clab.

In the event the encapsulation plant is built connected to Clab, it will belong to the same Material Balance Area (MBA) as Clab. This facilitates administration for both the operator and the supervisory bodies.

Through SKB's participation in international working groups in the area of safeguards for final disposal, where encapsulation is one aspect, groups from the EU (Esarda) and the IAEA have studied the Canister Laboratory and deposition of canisters at Äspö. This has led to a greater understanding of the whole process of handling of spent fuel from Clab to the deep repository. Both Euratom and the IAEA share the view that SKB should have an MBA for the encapsulation plant and Clab in the event the encapsulation plant is built connected to Clab. In the event of a standalone encapsulation plant, this will comprise its own MBA.

The trend within safeguards to supplement or partially replace traditional safeguards (seal, camera inspections, etc) with indirect controls such as measurements in the surrounding environment and gathering of open information, unannounced inspections etc, will naturally affect the design of the safeguards system at the time of the permit application /8-4/.

9 Transportation of encapsulated fuel

9.1 Introduction

The shipments of canisters from the encapsulation plant to the deep repository's reception building are described in this chapter. It is assumed that the encapsulation plant is situated adjacent to Clab in Simpevarp, while the deep repository is situated on one of the sites that are undergoing site investigations.

Conclusions in RD&D 2001 and its review

Compared with the account of canister shipments in RD&D 2001, there have been no major changes. The reviewers made few comments, but their main point was that the description was too cursory. Transportation of encapsulated fuel is therefore described in a separate chapter in RD&D 2004.

SKI found in its review that the current transportation system for spent nuclear fuel and nuclear waste has worked well and is practical.

Alternative modes of transport (rail) for the canisters are not of interest as long as the deep repository is assumed to be situated near either Simpevarp or Forsmark. If another location should be considered at a later time, alternative modes will be re-examined.

An exchange of experience is taking place in the field of transportation with other countries, both in the context of the IAEA's activities and in other contexts. SKB will continue to participate actively in this work.

9.2 Transportation need

The operation of the deep repository and the encapsulation plant is based on a more or less continuous circulation of canisters between the two facilities, see Figure 9-1.

Each transport cask (see section 9.3.3) holds one canister and weighs 70–75 tonnes, including load, when it is transported. This is slightly less than the weight of the cask used to transport fuel to Clab. The empty casks are returned and can be used over and over.

Since the encapsulation plant is designed for a production capacity of 200 canisters per year, the transportation system must be able to transport approximately 200 transport casks per year back and forth between the facilities.

9.2.1 Sea transport

If the deep repository is located in Forsmark, canisters will be transported by sea, with up to ten or so canisters in each shipment.

The ship m/s Sigyn travels between Forsmark and Simpevarp today, carrying spent fuel to Clab and waste To SFR. The trip is 250 nautical miles and takes about 20 hours. A future ship can be expected to have roughly the same size and payload capacity.

If ten casks with canisters are carried per trip, 20 trips are required to transport the nominal annual output. There is no obstacle to consolidation with waste or fuel transport casks and containers during the period such shipments occur.

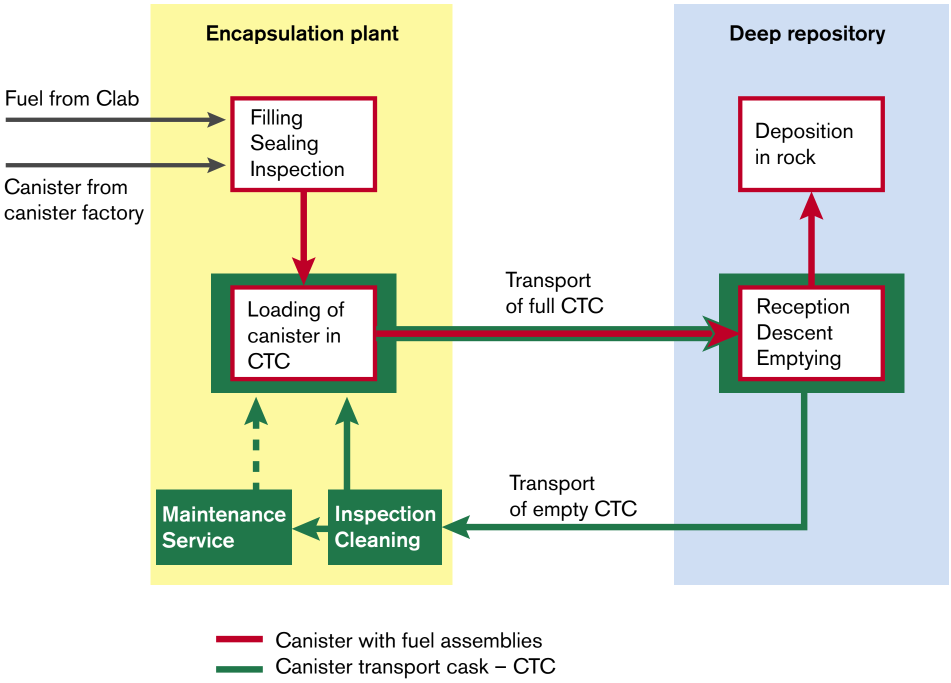


Figure 9-1. *Flow chart for shipments from encapsulation plant to deep repository.*

If both the encapsulation plant and the deep repository are located in the Simpevarp area, only overland transport will be necessary.

9.2.2 Overland transport

If the deep repository is located near Clab, the canister transport casks will be transported by a terminal vehicle from the encapsulation plant's dispatch air lock to the deep repository's reception building.

In Forsmark, the canister transport casks are transported from the ship in the harbour, which is situated next to SFR, to the deep repository's reception building. Canister transport casks are transported one by one by a terminal vehicle that picks up the cask inside the cargo hold and drops it off inside the reception building.

9.2.3 Alternatives for canister transport

Based on the ongoing site investigations, it can be assumed that the transport route to the deep repository will in both cases be a few kilometres. Rail shipments are therefore ruled out.

If the encapsulation plant is located adjacent to a deep repository in Forsmark, two types of transport are needed:

- *Transport of fuel assemblies*, which is similar to transportation to Clab from the various nuclear power plants. The design of Clab permits fuel to be dispatched from the receiving section, after additional equipment is acquired.
- *Transport of canisters* a short distance to the deep repository.

9.3 SKB's transportation system – equipment and function

The transportation system was commissioned partially in 1983 and fully in 1985. Its primary task is to transport spent nuclear fuel to Clab and radioactive waste To SFR. SKB is responsible for the operation of the transportation system and owns the equipment in the system. The most important components are the ship m/s Sigyn, the transport casks and containers, and the terminal vehicles. Transportation is planned by the operations department at SKB and is carried out in collaboration between many organizations. The contract for the operation of Sigyn is written with Rederi AB Gotland, whose subsidiary Destination Gotland crews and operates the ship.

9.3.1 Today's transportation system for spent nuclear fuel and operational waste

Each year Sigyn carries an average of 20 shiploads of casks containing spent nuclear fuel and spent core components to Clab and about ten shiploads of operational waste to SFR in Forsmark. Waste is also shipped from Studsvik to SFR. The waste packages are transported either in heavy casks (ATB) or in freight containers, depending on how radioactive the waste is.

Spent fuel and core components from the Oskarshamn Nuclear Power Plant are transported locally overland to Clab in the same transport casks as from other power plants. A special waste transport container is used for local waste transport in Forsmark to SFR.

9.3.2 Operational experience

Experience from approximately 20 years of operation shows that the transportation system is reliable and works well and has the necessary capacity for the planned shipments.

The quantities of spent fuel that are transported annually to Clab from the nuclear power plants have stabilized in recent years at around 230 tonnes, which is equivalent to about 75 transport casks per year. The number of waste shipments from all the nuclear power plants to SFR has decreased, and the trend continues downward.

Sigyn

The ship, which was commissioned in 1982, has undergone extensive modernizations and modifications over the years. Besides normal maintenance, the following changes have been made: switch to low-sulphur oil, replacement of heating system, replacement of monitoring equipment for hold and engine room, new fire extinguishing and monitoring system, double hull for fuel tanks, and installation of catalytic converters, which has reduced nitrogen oxide emissions by over 80 percent.

Inspections of hull and tanks are performed regularly. In a thorough going-over by experts from Chalmers University of Technology in 1999, it was found that the ship is in good shape and should be able to be used at least until 2010. The navigation equipment with electronic sea charts and the recently replaced radar system are modern and of high standard.

The harbours at the nuclear power plants visited by the ship are tailored to the ship and have good mooring arrangements. Ringhals's entrance channel and harbour basin were dredged in 2002, which has led to improved manoeuvring conditions.

There are standard procedures for reporting incidents and nonconformances to SKB and the shipping line. Only a few incidents involving material damage have been reported, and no personal injuries.

Transport casks for spent nuclear fuel (Type B packages)

SKB owns ten transport casks for spent fuel assemblies of model TN17-2 and two casks for core components of model TN17-CC. The casks were made in 1982–84.

Up to and including 2003, the fuel transport casks had been used 130 to 150 times and the casks for core components some 60 or so times each. The casks have served their purpose well. Other equipment in the transport chain has also proved to be reliable. Consumption of spare parts has not exhibited an appreciable increase over time.

Terminal vehicles

SKB owns five terminal vehicles. One is at SFR in Forsmark and the others stationed at Clab. The terminals vehicles are usually carried by m/s Sigyn to the nuclear power plants to be used for local overland transport of fuel and waste transport casks and containers.

The terminal vehicles at Clab underwent a total renovation in 1997–2001, when diesel engines and cabs were replaced, among other things. The fifth vehicle is being renovated to the same standard as the others during 2004. The vehicles work well and are expected to be able to be used for another ten years or so without the need for any major modifications.

9.3.3 Transport of encapsulated fuel

Canister transport casks

A feasibility study was carried out in the mid-1990s regarding a transport cask for canisters. A more detailed design of a canister transport cask is being carried out during 2004. The basic features are not expected to deviate from those proposed previously, which are described in brief below.

The main function of the cask is to comprise a radiation shield for the enclosed canister so that it can be handled during transport without any additional radiation shielding. It must also satisfy the other requirements for Type B packages in accordance with the IAEA's transport recommendations, see section 9.4, regarding for example strength and heat resistance, and must be able to dissipate the emitted decay heat so that neither the canister nor the surface of the cask get too hot. A transport cask with canister is shown in cross-section in Figure 9-2.

The planned cask, which will have a diameter of about 1.6 metres, is made of cast iron with a thickness of between 250 and 300 millimetres. The wall thickness is determined by the required radiation shielding. Iron does not attenuate neutron radiation as well as gamma radiation, so the cask shell is provided with a number of channels that are filled with a plastic material that

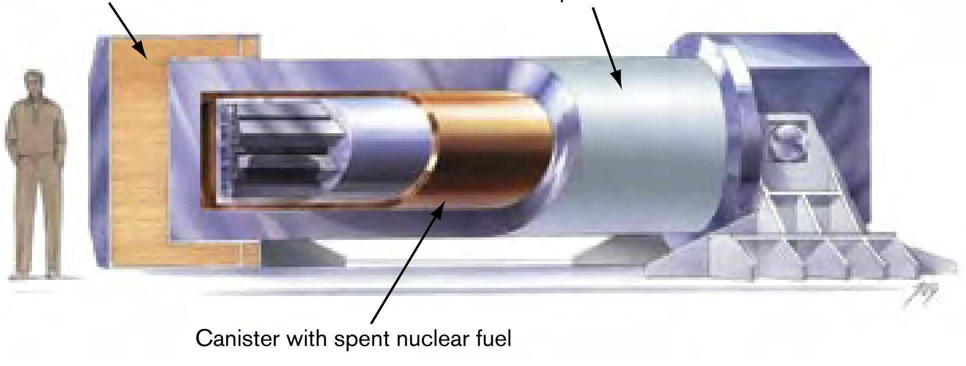


Figure 9-2. *Canister transport cask in cross-section.*

absorbs neutron radiation. The lid and bottom contain a neutron-absorbing mat, which also acts as an extra shock cushion for the canister inside the cask. The lid, which seals against the cask shell, may be either bolted or threaded. The weight of the cask, including lid, will be around 40 tonnes, total weight with canister and transport frame about 75 tonnes. The weight of the lid is 1.5–2 tonnes. The cask has lifting trunnions at both ends, bolted to the shell. The lifting trunnions are used to lift the cask and to fix it in a horizontal position.

Ship, transport frame and terminal vehicle

Eventually a new ship will have to be procured to succeed m/s Sigyn. Even though this will not be in the near future, the ship will probably have been in operation for a long time before the canister shipments commence. These will not affect the operation of the ship at all if the deep repository is located in Oskarshamn. The new ship will be designed for continued fuel and waste shipments and will serve the same purpose as the present ship.

During and awaiting transport, the cask rests on a transport frame with supports for the lifting pins. The transport frame will be comparable to those used today, i.e. it will be able to be handled by the terminal vehicle. Figure 9-3 shows a transport frame with a core component cask.

The vehicles used today will eventually fall victim to age, see section 9.3.2, but otherwise no dramatic changes are planned in the technology of overland transport. The heavy units require large vehicles with many axles.

Roads

Existing roads will have to be strengthened and some new roads built in conjunction with the construction of the deep repository, not least to accommodate all other transport during the construction and operating phases.

According to the ongoing site investigations, we can assume for the time being that the transport route to the deep repository's reception building will be relatively short. This means that transport at low speed does not entail any major problems. The overland transport can therefore be compared to today's overland transport between harbours and facilities. Planning of roads and choice of exact route are included in the work during the site investigation phase.

Figure 9-3. *Transport frame with transport cask for core components.*

9.3.4 Coordination with today's transportation system

When shipments of transport casks are to begin, routine shipments to Clab and SFR will still be in progress. Casks of the new type will be handled and administered in the same way as the previous ones. The canister shipments will therefore be integrated into the transportation system's scheduling, pre-notifications (consignment notifications) will be issued, and the procedures surrounding the shipments will be similar to those that exist now.

The start of canister shipments entail that another kind of cask will also be handled by the system. These shipments do not entail any technical or organization difference compared with today. The capacity of the system will depend on the number of canister transport casks and available manpower and time resources. These resources will be adjusted so that sufficient transport capacity is achieved for the needs of the encapsulation plant and the deep repository.

Since many years still remain until the canister shipments get under way, it is likely that technical and organizational changes will have occurred in the meantime for other reasons than the commencement of canister shipments.

9.4 Requirements and other conditions for transport

Both international recommendations and agreements and national laws and regulations govern the transport of dangerous goods such as radioactive materials.

9.4.1 Transport regulations

The UN International Atomic Energy Agency, IAEA, has issued transport recommendations /9-1/, which have been developed in consultation with and approved by the member states, including Sweden. The IAEA's recommendations have then served as a basis for international rules governing transport by sea, land, rail and air, as well as their Swedish equivalents. These regulatory codes (see box) cover all types of dangerous goods, but in the case of radioactive materials the regulations are based on the IAEA's recommendations and are largely the same in all the regulatory codes.

The rules cover different modes of transport, and both carriage within a country and carriage between and through different countries. The main rules governing transport of radioactive material are as follows:

- Minimum requirements on type of transport package depending on the nature of the goods, i.e. physical form, chemical composition and radioactive content.
- Rules regarding maximum permissible radiation levels on the outside of packages or vehicles.
- Marking and classification with regard to radiation level.
- Rules governing handling, stowage and consolidation with other goods.
- Checklists of measures in the event of an accident (for transport and rescue personnel).
- Requirements regarding contents of transport documents.

Applicable international and Swedish regulations:

- IMDG Code – International Maritime Dangerous Goods Code.
- SJÖFS 2003:15 – The IMDG code. The competent authority is the Swedish Maritime Administration.
- ADR – Accord européen rélatif au transport internationel des marchandises dangereuses par route (European Agreement concerning the International Carriage of Dangerous Goods by Road).
- ADR-S – The Swedish Rescue Services Agency's regulations concerning the domestic transport of dangerous goods on and off road.
- RID – Réglement concernant le transport internationel des marchandises dangereuses par chemin de fer (Regulations concerning the international carriage of dangerous goods by rail).
- RID-S – The Swedish Rescue Services Agency's regulations concerning the domestic transport of dangerous goods by rail.

Transport casks

Due to its content of radioactive substances, spent nuclear fuel, whether encapsulated or non-encapsulated, must be transported in Type B packages, according to the IAEA's recommendations.

A cask that has been approved according to the requirements for Type B packages has a very great ability to withstand stresses even in connection with serious accidents without losing its integrity or radiation-shielding capacity. This is verified both by calculations and by specified tests performed with a prototype cask. The tests include a drop from nine metres onto an unyielding surface, a drop onto a pointed test object, a heat test equivalent to a fire of 800°C for 30 minutes, and a pressure test equivalent to the water pressure at a depth of 200 metres. In general, transport casks for fuel more than meet these requirements, since the radiation shielding makes the cask very strong.

The cask's design is reviewed by the competent authority, which issues a cask licence specifying what the cask may hold. A licence for use in Sweden is issued by the Swedish Nuclear Power Inspectorate (SKI) or the Swedish Radiation Protection Authority (SSI).

9.4.2 Permits

The general Swedish provisions governing handling and transport of radioactive materials are to be found in the Nuclear Activities Act, the Radiation Protection Act and Transport of Dangerous Goods Act. The permit-issuing authorities are SKI and SSI.

The permits needed to transport nuclear material or nuclear waste are of two types:

- Permit to transport nuclear material or nuclear waste with a particular transportation system (equipment and organization).
- Approval that a certain kind of goods, for example transport packages for a certain waste type, may be transported.

The permits are subject to different conditions, such as:

- Transport regulations must be complied with.
- Pre-notification must be made of planned shipments.
- Data on the waste to be transported must lie within certain limits.

An application is made for a permit for the transport of a specific kind of goods. If another kind of goods is then to be transported, a new permit must be applied for.

Each company and organization that carries out transport of what is defined as dangerous goods must have a safety adviser within the organization. This person must be familiar with the applicable rules and be the company's resident expert on related matters. In SKB, this position is currently held by the same person who has overall operational responsibility for transport to Clab and SFR.

9.4.3 Application to coming shipments

If shipments of canisters were to commence today, SKB would thus have to apply for a permit to transport a new kind of cask with the existing transportation system in addition to those for which today's permits apply.

Transport from the encapsulation plant to the deep repository must naturally comply with applicable transport rules. This is simplified by the fact that all transport takes place under SKB's own auspices. We will have our own handling instructions and standardized shipping documents and computer files.

Shipments of canisters must comply with the same principles regarding division of responsibilities, scheduling, pre-notification, hand-over and physical protection as fuel shipments to Clab.

The contents of each canister are determined long before encapsulation. The pre-notification (consignment notification) specifies which canisters are to be transported. A canister that is approved for sealing in the encapsulation plant is simultaneously approved for transport to deposition. The transport casks for canisters are designed for a canister with design-basis contents (activity content, decay heat, etc). The detailed documentation on each canister and its contents is carefully registered, but is of no interest during transport.

9.4.4 Safeguards

The requirements on safeguards entail that detailed records must be kept of all nuclear materials. After encapsulation the canister is the smallest unit. The record-keeping is based on the registers that exist today in Clab in SKB's computerized fuel registers.

From a safeguards viewpoint, transport of copper canisters will take place in the same manner as today's shipments of spent nuclear fuel from the nuclear power plants to Clab. The documents required for safeguards will be issued and sent from the encapsulation plant/Clab (common MBA) to the recipient, which is the deep repository (own MBA) and to the competent bodies, SKI and Euratom. Transport plans and pre-notifications for shipments of canisters to the deep repository will also be reported to SKI and Euratom in good time before transport.

The administrative measures needed for safeguards take place before and after the shipment between the encapsulation plant and the deep repository.

9.5 Programme

9.5.1 Transportation system in operation

SKB's transportation system, which is used today for transport of spent nuclear fuel and spent core components from the nuclear power plants to Clab and of waste from the nuclear power plants and Studsvik to SFR, will continue with this as long as spent fuel and waste are produced. A temporary interruption in the fuel shipments is being made during the second and third quarters of 2004 while Clab stage 2 is being commissioned.

The equipment in the transportation system is maintained regularly and modernized as needed. M/s Sigyn is maintained so that the ship can be in full operation at least until 2010. Plans call for the replacement of m/s Sigyn with another ship. The requirements on the new ship have not been specified yet. Since the size of the harbours and the needs of the transportation system will not be different than they are today, m/s Sigyn can, in terms of size and characteristics, be used for the time being as a point of departure in the planning of the shipments to the deep repository as well, assuming the latter is located in Forsmark.

The terminal vehicles will eventually have to be replaced as well for reasons of age. Old and new vehicles will be able to work side by side during a transition period.

Any proposed changes in cargo handling will first be studied to make sure that today's shipments can also be performed.

9.5.2 Equipment for canister transport

A transport cask for canisters is being designed, see section 9.3.3. Transport frames that can be handled in the encapsulation plant and in the deep repository, as well as together with the transportation system's vehicles and ship, are needed for the new transport casks. The transport frames will be designed together with the casks.

The planning of shipments to the deep repository is being coordinated with the encapsulation plant and with the deep repository project, above all when it comes to the equipment for handling canister transport casks and associated transport equipment.

In addition to technical data concerning size, weight, design of transport frame and the like, such questions as maintenance of casks, temporary storage of empty or full casks and other logistics questions for the canister transport casks must be dealt with jointly.

9.5.3 Accounts

A relatively comprehensive account of canister transport forms a part of the account of the deep repository and will be included in the permit application for the deep repository. A status report will be included as supporting material with the permit application for the encapsulation plant.

The material will be produced gradually. However, there will not be any extensive investigations, since a functioning transportation system has been in operation for a long time. The changes in SKB's transportation system that will be made up to the time the deep repository is taken into operation will for the most part be such changes that would have been made anyway due to the need for modernization and new regulations, agreements or the like.

10 Deep repository – technology

Developing and demonstrating methods and technology for construction, operation and closure of the deep repository is an important part of SKB's work. This development work is aimed at ensuring that methods and materials, as well as the technology needed to build the deep repository, are available and that they meet stipulated requirements. It is also an important basis for planning. The choice of materials, deposition technology etc is dependent on the requirements that are made on the facility during different phases, for example with regard to reliability and long-term safety. SKB is also investigating the possibilities of modifying the reference method by depositing the canisters horizontally.

SKB conducts its own technology development, participates actively in various joint European projects and follows others' work in the field. Development, testing and demonstration in preparation for the construction and operation of the deep repository are being conducted at the Äspö HRL. Various technical solutions are being applied there on a full scale and in a realistic environment.

10.1 Rock excavation technology

10.1.1 Requirements and premises

The choice of rock excavation technology will be made in the light of the following requirements:

- Construction and operation shall have a limited impact on the safety functions of the rock and the other barriers.
- Technical properties relating to loadbearing capacity and strength, fire protection, health and environment, and accident prevention shall ensure safety for users and visitors.
- Rock investigations, rock works and deposition operation shall be possible simultaneously, but in separate areas.
- Extention of the underground area shall be able to proceed at the desired pace and in a cost-effective manner.
- Environmental impact shall be limited.
- Nearby residents shall be disturbed as little as possible.

The requirements influence both system and material choice and choice of methods for execution. The choices can be influenced by information obtained from the site investigations.

10.1.2 Technology for rock extraction

As the deep repository is built out, large volumes of rock will be extracted during the excavation of ramp, shaft, central area, main tunnels, deposition tunnels and deposition holes. Stress redistributions and deformations will occur around the cavities that are created in the rock.

Conclusions in RD&D 2001 and its review

In RD&D 2001, SKB concluded that:

- Tunnelling can be done by conventional drill-and-blast or by mechanical excavation. Both methods have been used with good results in tunnelling at the Äspö HRL.
- The damaged zone created during rock excavation by means of the two methods was investigated, and the conclusion was that mechanical excavation created a smaller damaged zone.

- Methods exist for full-face drilling of the deposition holes. Such drilling of deposition holes has been demonstrated at the Äspö HRL.

Based mainly on existing information and knowledge, selection and further development of excavation methods, machinery and equipment can take place in parallel with the gathering of design-basis data for construction and detailed characterization of the underground part of the deep repository facility. Freedom of choice with regard to methods for excavation of deposition tunnels and holes will remain even after deposition has begun.

Newfound knowledge since RD&D 2001

A new tunnel, The Apse tunnel, was built at the Äspö HRL at a depth of 450 metres during the spring and summer of 2003, see Figure 10-1. The tunnel is about 70 metres long and was excavated by drilling and cautious blasting.

The blast-damaged zone around the new tunnel has so far been preliminarily investigated in the tunnel floor. The results of these investigations indicate that:

- Drilling procedure is of importance for the damaged zone.
- Modern alignment instruments on the drilling rig provide a satisfactory means for controlling drilling precision and thereby indirectly also the blast-damaged zone.
- Of 13 cored boreholes in the tunnel floor, macroscopic fractures with a depth of about 10 centimetres were observed in 12 of the holes, and 30 centimetres in one of the holes.
- In three holes bored in the tunnel floor (diameter 1.75 metres), the picture from the cored holes is confirmed as regards the depth of the fractures. The macroscopic fractures are natural fractures sheared or opened by blasting and/or stress redistributions. Since the induced fractures are only partially plane-parallel with the tunnel contour, the extent of the damaged zone appears to be heterogeneous.

Figure 10-1. *The new Apse tunnel at the Äspö HRL excavated during the summer of 2003 by controlled drill-and-blast.*

The methods deemed possible for excavation of the deposition holes today are: full-face boring with a shaft boring machine (SBM) or drilling of a pilot hole followed by reaming with a larger drill bit as shown in Figure 10-2 (a and b). Core drilling and percussion drilling have been discussed for making deposition holes but judged not to be competitive alternatives.

Full-scale full-face boring of deposition holes has been demonstrated at the Äspö HRL, where a total of 17 deposition holes have been drilled with SBM. Posiva has made two full-sized deposition holes by pilot hole drilling followed by reaming to full diameter in one step /10-1/.

A variant of reaming is called raise boring, and this technique is being discussed for excavation of deposition tunnels and other chambers. The technique is normally used for excavating shafts between two chambers in a mine. Figure 10-2 describes the principle of the technique. First a pilot hole (a) is drilled and then a drill bit is attached to the drill string and a shaft or tunnel is created by pulling and rotating the bit (back reaming) (c). Shafts with a diameter of about six metres can be created by means of back reaming. If larger diameters are desired, reaming can be done in stages by changing after the first stage to a bit with a larger diameter. It is also possible to push and rotate the bit (down reaming) instead of pulling it so that a shaft or tunnel is created.

Horizontal deposition of the canisters is currently being studied by SKB and Posiva in cooperation and a demonstration of the KBS-3H method is planned at the Äspö HRL. In the KBS-3H method, the canisters with buffer are deposited in a perforated steel container one after the other in long deposition drifts 1.85 metres in diameter, see section 10.7. The deposition drifts that will be drilled for the demonstration must be straight and must meet narrow tolerances on e.g. diameter. A drilling rig based on water hammer technology was built and tested in the autumn of 2003. Alternative methods exist for boring horizontal deposition drifts for KBS-3H, and one alternative that is being discussed is drilling of a pilot hole followed by down or back reaming to the desired diameter of the deposition drifts.

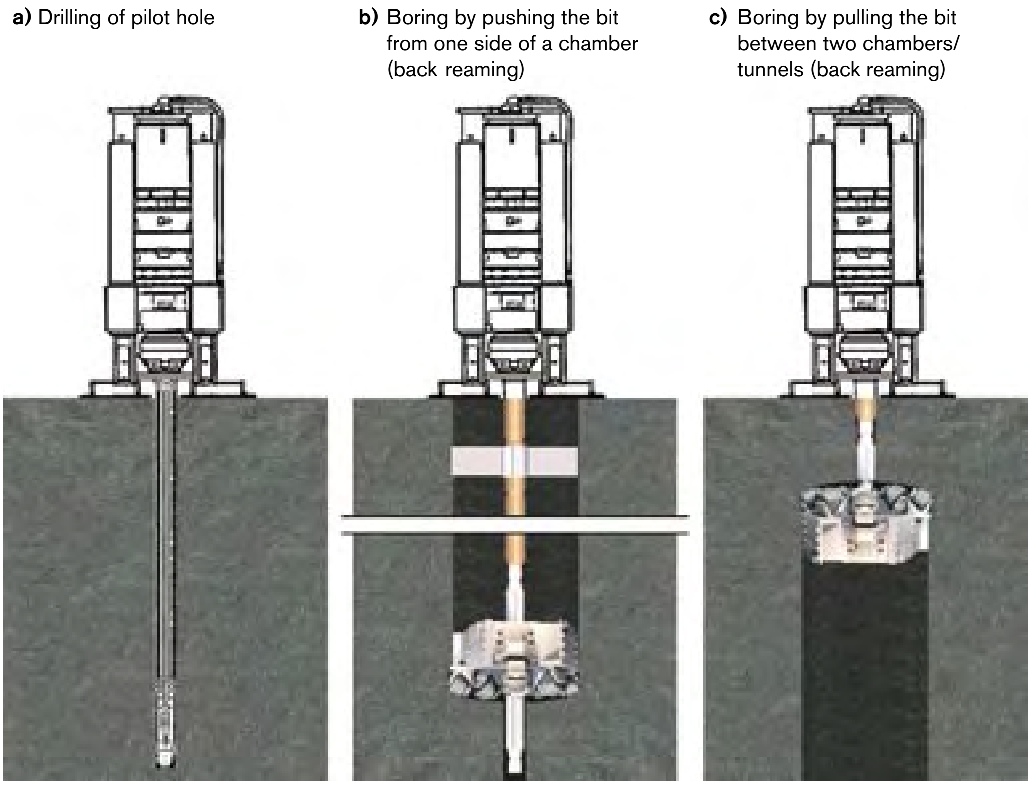


Figure 10-2. *Sequence of operations in down and back reaming.*

Programme

SKB keeps track of current research and development in the field of rock construction and civil engineering to keep its know-how and knowledge in the field up-to-date.

In the autumn of 2003, SKB started an investigation aimed at clarifying which methods and technologies are available for creating various chambers in the rock i.e. ramp, shaft, central area, main tunnels, deposition tunnels and deposition holes. For the deposition tunnels in particular, it is important that rock damage be limited. In the project, which is expected to last until 2007, in addition to an inventory of available methods and technologies, assessments will be made of possible development of drill-and-blast techniques and mechanical excavation up until the time when rock extraction in the deep repository is to be done. The project will be carried out in two stages where the first stage, which will be concluded in 2004, will serve as a basis for the preliminary choice of methods and technologies for rock extraction presented in Layout D1 for the deep repository. The second stage in the project, which will be concluded in 2007, will comprise the final choice of methods and technologies on which Layout D2 will be based.

Possible methods for rock excavation and which methods should be studied further have been specified for different type of openings, see Table 10-1. Preliminary reference methods in Layout D1 have been marked in the table. Among the alternatives chosen for further studies are e.g. conventional drill-and-blast, TBM boring and reaming. Controlled blasting will limit the damaged zone created around excavated rock chambers. Boring of horizontal demonstration drifts at the Äspö HRL is planned to be done during 2004.

Different studies for follow-up of the blast-damaged zone are planned, for example by slot sawing in the Aspe tunnel at the Äspö HRL or other verifying tests. Studies and inspection of the blast-damaged zone in connection with drilling and controlled blasting of the ramp in Onkalo in Finland are being discussed with Posiva.

Table 10-1. Possible methods for rock extraction of the different openings in the deep repository.

Type of openings in deep repository	Possible methods	Methods that will be studied further
Ramp	Drill-and-blast TBM (tunnel boring machine)	Controlled blasting[1] TBM
Skip shaft (blind)	Drill-and-blast SBM (shaft boring machine)	Controlled blasting with work platform and drilling equipment in sunk shaft[1]
Ventilation and elevator shaft	RBM (full-face boring of shaft by raise boring)	Back reaming[1]
Central area and other rock caverns	Drill-and-blast Mechanical milling	Controlled blasting[1]
Main tunnel	Drill-and-blast Mechanical milling TBM	Controlled blasting[1] TBM
Deposition tunnels, KBS-3V	Drill-and-blast Back reaming Mechanical milling TBM	Controlled blasting[1] TBM (with improved design) Back reaming with service tunnel
Deposition holes	SBM Down reaming	SBM[1] Down reaming
KBS-3H, horizontal deposition holes	Water hammers in cluster Small TBM Back reaming Back reaming with service tunnel	Water hammers in cluster formation Down reaming without service tunnel Down reaming with service tunnel

[1] Preliminary reference method in Layout D1.

10.1.3 Sealing of the rock by grouting

The host rock must be sealed to reduce groundwater inflow for construction and operation, but the KBS-3 system does not require any long-term permanent sealing measures. Heavy inflow causes poorer working conditions and environmental impact. Groundwater drawdown increases the risk of intrusion of deep groundwater with high salinity (upconing), which can affect the performance of the repository. Furthermore, local seepage must be limited to permit buffer and backfill to be emplaced under controlled conditions. It is assumed that the deep repository will be sealed primarily by injection grouting of fractures. The design work includes determining how much grouting work is needed and estimating the quantity of grouting material needed. The high water pressure prevailing at repository depth creates different conditions from those that are normal in the excavation of Swedish road tunnels. Even small fractures can conduct a great deal of water, and SKB's work is therefore focused on improving the means for sealing small fractures. Furthermore, requirements regarding the chemical environment in the deep repository, for example the pH of the groundwater, may require adaption of the grout. For example, grouts that give rise to leachate with a pH of less than 11 may be required.

Conclusions in RD&D 2001 and its review

In the mid-1990s, SKB initiated research and development concerning rock grouting based on an expert assessment of the state of knowledge and development needs /10-2/. Among other things, work was begun on development of models to describe the rock and the grouting process and to characterize grouting materials, as well as to develop materials for various situations. The possible need for a cementitious material in the deep repository that would give leachates with a pH below 11 led to the start of a special project aimed at developing and qualifying low-pH grouts.

Kasam suggests that SKB should study various methods for grouting of fractures aimed at achieving a permanent reduction of permeability in the rock surrounding a deep repository, without adversely affecting the chemical environment in the repository.

A permanent reduction of permeability is not required in the KBS-3 system, nor is it possible to prove a permanent reduction in permeability, since methods are not even available for proving a durability of 100 years for available grouting materials. Accordingly, SKB does not share Kasam's view.

Newfound knowledge since RD&D 2001

A pre-study, followed up by a feasibility study, was conducted in cooperation with Posiva and Numo in Japan to develop and qualify low-pH cement for various purposes in the deep repository, including grouting fractures in the rock. The goal of the development work is to develop materials that produce leachates with a pH lower than 11, see Figure 10-3. The studies have so far not resulted in a formulation for a low-pH injection grout that will also penetrate into small fractures. The conclusion was that alternative, non-cementitious materials should also be investigated, at the same time as the development work on cementitious grout continues. In the project that has been under way since 2003, efforts are being focused on development of formulations in which Portland cement, slag cement, silica, high alumina cement and gypsum are principal components. A non-cementitious material that is being investigated is silica sol.

Since RD&D 2001, two doctoral theses have been published dealing with a methodology for rock characterization prior to grouting /10-3/ linked to models for grout spread /10-4/. The methodology was tested during the construction of the Apse tunnel at the Äspö HRL. This meant that systematic pre-grouting could be avoided thanks to the fact that detailed rock characterization and early assessment of a suitable grouting method could be performed. Even though investigations led to changes in the scope of grouting along a portion of the tunnel, a combination of inflow measurements and pressure build-up tests provided a good basis for the choice of grout and a preparedness for handling more extreme conditions. The quantity of grout used could be limited while the sealing effect was good /10-5/.

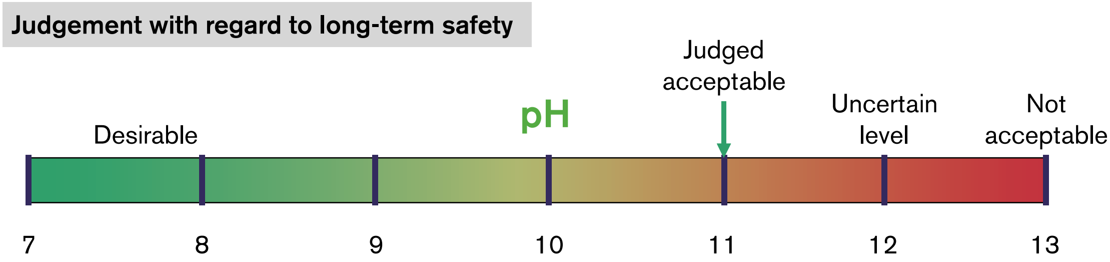


***Figure 10-3.** Judgement of accepted pH in leachates from material in deep repository with regard to long-term safety.*

Programme

The overall goal of the grouting research is to make sure that the necessary knowledge, methods, grouting materials and equipment are available to deal with the sealing situations that arise due to the special requirements that are made on the deep repository. Knowledge concerning grouting has long been experience-based, while SKB's programme is aimed at acquiring a better scientific understanding of how the system consisting of rock, grout and grouting technology works. Such knowledge is necessary to be able to control the grouting process. SKB's funding of doctoral projects is also aimed at ensuring that grouting will continue to be a living discipline where new knowledge is acquired, disseminated and discussed in broad circles to be used on a regular basis in civil engineering projects. SKB has also taken an initiative to develop a training programme for grouters and design engineers. Swedish Rock Engineering Research (SveBeFo) is responsible for the program.

The work of developing injection grouts that meet fundamental requirements and optimizing them for use in the field is vital to the development of sealing systems. Our understanding of grouting as a system needs to be improved, and SKB will continue to pursue independent and joint projects in order to:

- Qualify cementitious grouting materials for sealing of large fractures and non-cementitious materials for sealing of smaller fractures (< 100 µm) that produce leachates with a pH of less than 11. This work is being pursued in cooperation with Posiva and Numo and includes research and development in the laboratory and tests to check that it works in the field.
- Investigate and measure the mechanisms that control filtration stability, i.e. the ability of the grout to pass constrictions without clogging. These properties are essential for penetration and thereby also for the sealing results. The work, whose results to date have been published in a licentiate report /10-6/, is being done as a doctoral project and is being co-financed with SveBeFo, Elforsk and Cementa.
- Develop methods for characterizing rock and predicting grout penetration. The goal is to further develop the methodology for characterization of the rock in such a manner that it can be used to predict grout spread and grout consumption and thereby also to determine a suitable grouting procedure. SKB is funding two postgraduate students for this work as a continuation of previous doctoral projects.

10.1.4 Rock support

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 main rock support methods that will be used are conventional support elements such as rock bolts, shotcrete and wire mesh.

Conclusions in RD&D 2001 and its review

No description of rock support methods was presented in RD&D 2001. Mention was made of SKB's cooperation with Posiva, which is aimed at investigating and testing low-pH cementitious materials.

Newfound knowledge since RD&D 2001

Formulations for bolt anchoring grouts have been developed within the framework of SKB's ongoing research programme for development and qualification of cementitious grouts that produce leachate with a pH lower than 11. Silica fume and cement have been used and ground together by different methods. The grouts have not yet been tested in the laboratory or under realistic conditions in the field, and they have not been checked against requirements for shrinkage and corrosion protection. The chances of developing structural concrete are deemed to be good, but further studies and development are needed to obtain shotcrete with a low pH and good adhesion.

In October 2003, SKB held an international workshop in Stockholm on the topic of qualification of low-pH cements for use in geological final repositories. Participants from Belgium, Finland, France, Japan, Spain, Sweden, Switzerland and the UK presented study results and plans for the future. The participants also discussed and compared their views on low-pH cementitious materials with respect to technology and long-term safety. The workshop provided a good overall picture of the European research front in the field.

Requirements on the lifetime of different underground repository parts have been preliminary determined via design premises for the deep repository's underground part /10-7/. With a view towards construction, deposition and backfilling, the lifetime of deposition tunnels has been set at about five years. Underground accesses, operating caverns and transport tunnels have a much longer lifetime. Their lifetime has been set at about 100 years, which is judged to be conservative while at the same time permitting utilization of references regarding lifetime that have been agreed on for facility construction in Sweden.

Supervisory procedures currently applied to SKB's underground facilities (Clab, SFR, Äspö HRL) should also be applicable to the deep repository, since similar design solutions and materials will be used.

Programme

In cooperation with Posiva and Numo, studies are being conducted to investigate and test whether low-pH cementitious materials in the form of bolt anchoring grouts and shotcrete can be used for rock support.

SKB is participating in an integrated project within the EU's Sixth Framework Programme for research, technological development and demonstration (Engineering Studies and Demonstrations of Repository Designs, Esdred) /10-8/ which includes development of low-pH concrete that can be used as shotcrete for rock support.

10.2 Buffer

The buffer material being considered is swelling bentonite clay.

10.2.1 Requirements and premises

The buffer's most important safety function is to retard transport between canister and rock. For this reason it should have such low hydraulic conductivity that any transport of corrodants and radionuclides will take place solely by diffusion. The buffer should also filter colloidal particles.

Furthermore, it must not have an adverse effect on canister and rock, and it must retain its safety functions for a long time.

In order to retain its safety functions, the buffer must have sufficient density and interact with the backfill in such a manner that the canister is always surrounded by buffer material. The buffer must also possess such properties that minor rock movements can be absorbed without the canister being damaged, and it must be able to dissipate heat from the canister so that the temperature on the canister surface and in the buffer does not get too high.

The requirements on the buffer for KBS-3H (see section 10.7) are the same as for KBS-3V. However, the detailed design of the buffer may differ depending on such circumstances as deposition method and diameter of deposition tunnel.

Furthermore, it must be possible to fabricate, handle and deposite the buffer with acceptable environmental impact and so that requirements on capacity and quality can be met.

10.2.2 Fabrication technology

Conclusions in RD&D 2001 and its review

In RD&D 2001, SKB concluded that:

- There are primarily two methods available for fabrication of bentonite blocks and rings: uniaxial pressing and isostatic pressing.
- Blocks have been pressed to both a natural water ratio (10 percent) and an elevated water ratio (17 percent). Bentonite blocks and rings have been produced for experiments in the Äspö HRL. They have been fabricated from sodium bentonite (MX-80) by uniaxial pressing.
- Blocks and rings thicker than 0.5–1.0 metre cannot be easily produced by uniaxial pressing. Thicker buffer units have advantages in connection with handling and emplacement in the deposition holes.

In its review, SKI finds it laudable that SKB is investigating alternative fabrication methods for bentonite blocks, since isostatically pressed blocks will probably be more homogeneous in structure than uniaxially pressed blocks and rings and thereby more likely to meet strict quality demands.

Newfound knowledge since RD&D 2001

Blocks and rings for nine full-sized deposition holes have been fabricated from sodium bentonite (MX-80) by uniaxial pressing for use in the Prototype Repository and the Lasgit test at the Äspö HRL. The blocks and rings pressed for the Lasgit test had a very high initial degree of water saturation.

There is no isostatic press in Sweden today where full-scale blocks and rings can be fabricated. No equipment for isostatic pressing of large blocks and rings has been developed during the period. Twelve blocks on a scale of 1:4 were pressed in a press at Ifö Ceramics in 2000 /10-9/. The results show that the technique should also be suitable on a larger scale.

In the KBS-3 variant with horizontal deposition (see section 10.7), the bentonite rings and blocks are the same as in the reference variant, except that they are a few centimetres thicker and thereby have a lightly larger diameter.

Programme

SKB will study fabrication of the buffer by means of isostatic pressing. The goals of the study are to specify processes and equipment for material handling, pressing, handling of pressed blocks, post-press machining and interim storage of blocks and rings prior to deposition.

10.3 Deposition technology

By "deposition technology" is meant the equipment and machines required for reception, handling, transport and deposition of canisters and buffer in the deep repository.

10.3.1 Requirements and premises

Operation of the deep repository may have only a limited impact on the safety performance of the rock and the other barriers. Equipment and procedures for handling and deposition of 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. It must be possible to carry out deposition in parallel with rock investigations, construction and operation.

10.3.2 Handling and deposition

Conclusions in RD&D 2001 and its review

In RD&D 2001, SKB concluded that:

- A full-scale prototype of a deposition machine has been manufactured to permit testing and demonstration of the technology for deposition of canisters and buffer in the deep repository.
- The peripheral functions that will be required for transporting transport casks from the encapsulation plant down to repository level and transferring the canister from the transport cask to the deposition machine's radiation shielding tube have so far only been superficially studied.

In its review of RD&D 2001, SKI considers that if SKB encounters problems in connection with a separate deposition of bentonite and canister, they should prepare to develop a technique and technology for simultaneous deposition.

Newfound knowledge since RD&D 2001

The execution of the installations in the Prototype Repository required the development of full-scale equipment for handling and deposition of buffer and canister. This has entailed studies of different tools for handling of blocks and rings of compacted bentonite. Altogether, more than 130 buffer units have been handled without mishap in the experiments conducted at the Äspö HRL. This experience will be very useful in the continued work of developing the equipment for the buffer units that will be used in the future deep repository.

Similarly, the deposition of the seven canisters in the Prototype Repository and the Canister Retrieval Test at the Äspö HRL have yielded valuable experience for the choice of the final design of a deposition machine.

Moreover, development of deposition technology and machines for the KBS-3 variant with horizontal deposition is also under way, see section 10.7.

Programme

The design of the deposition machine determines the dimensions of the deposition tunnels. It is therefore important to be able to limit the size of the machine while meeting the stringent requirements made with regard to radiation protection, reliability and a low risk of mishaps in conjunction with the handling of canisters with spent nuclear fuel. The equipment for handling and emplacement of the buffer units will not determine the layout of the deposition tunnels, but it is important to design the equipment for safe and rational handling. The continued programme will be carried out partially in cooperation with Posiva, since they intend to handle similar canisters and buffer units.

Studies of equipment will be conducted in stages to provide support for Layout D1 and Layout D2 for the underground part of the deep repository. The studies will also provide the necessary background material for the preparation of preliminary operational safety reports with associated analyses.

What is currently being discussed and planned is:

- The scope of radiation protection during the deposition process, which directly influences the size of the deposition machine.
- The deposition machine – a conceptual study is planned of a wheeled deposition machine instead of the rail-bound machine currently used at the Äspö HRL. The study will give answers regarding feasibility, requirements on roadway and whether sufficient accuracy can be achieved for positioning.
- Handling and emplacement of buffer, which is linked to the choice of technology for compaction of the buffer units and how they will be transported to the repository level. The reference alternative for transport of the buffer units is that they will be transported on the ramp to the repository level.
- Demonstration may be necessary to verify that the chosen method and equipment for handling will work in the deep repository.

10.4 Backfilling and closure

The purpose of ongoing studies is to develop concepts for backfilling of deposition tunnels and other rock caverns and closure of the deep repository.

10.4.1 Requirements and premises

The purpose of backfilling deposition tunnels and other rock caverns is that the barrier functions of the rock will be retained. The backfill is therefore not a barrier in itself. The following requirements are therefore made on the backfill:

- In order that the deposition tunnels should not constitute conductive pathways that affect the water flux in the repository, the backfill, over the entire cross-section and length of the tunnel, shall have a hydraulic conductivity that is comparable to that in the surrounding rock, or is so low that the dominant water transport mechanism is diffusion.
- In order that the density of the buffer should be preserved, the backfill shall have a compressibility that limits the upward expansion of the buffer so that the function of the buffer is retained.
- The backfill shall be durable so that its functions are retained in the environment expected in the deep repository.
- Technical and financial feasibility.

Furthermore, backfilled deposition tunnels must not have an adverse impact on the barriers in the repository. Materials and backfilling technique shall be chosen so that they do not lead to an unacceptable impact on the environment.

10.4.2 Materials and compaction technology

Conclusions in RD&D 2001 and its review

Different materials and methods for backfilling of tunnels, rock caverns and shafts in a deep repository have been considered in SKB's development work through the years, for example bentonite and crushed rock, bentonite and quartz sand and crushed rock alone have been investigated. SKB is developing and testing compaction technology and materials for backfilling.

At the Äspö HRL, full-sized tunnels have been backfilled with a mixture of bentonite and crushed rock in the Backfill and Plug Test and the Prototype Repository experiment.

Newfound knowledge since RD&D 2001

There are reasons to further study and develop concepts for backfilling of tunnels, for example to assure the function of the backfill even if the groundwater has high salinity at repository depth, to satisfy the need for backfilling concepts for other rock caverns, and to develop technology for backfilling with sufficient efficiency.

In cooperation with Posiva, within the framework of an ongoing research programme, SKB has conducted theoretical studies to identify backfill concepts deemed to be capable of satisfying requirements on both deposition tunnels and other rock caverns. The studies cover the following materials: bentonite, other swelling clays, non-swelling clay, crushed rock and till, see section 18.1.6. Two different backfilling methods have been studied for the different materials: compaction in the tunnel and emplacement of pre-compacted blocks.

Programme

SKB and Posiva will continue the ongoing research programme and three backfilling concepts will be further studied /10-10/. The three concepts are:

- Compaction of a mixture of bentonite and crushed rock in the tunnel.
- Compaction of swelling clay in the tunnel.
- Emplacement of pre-compacted blocks in the tunnel.

The research programme comprises four stages in all. The first stage has been completed and included technical studies for describing the prospects of the proposed backfilling concepts for meeting SKB’s requirements.

In the second stage, geotechnical laboratory tests and a deeper analysis of the three concepts will be performed. Fabrication of pre-compacted blocks with desired properties as regards e.g. density and handleability is planned during this stage. Pressing of blocks of swelling clay and a mixture of bentonite and crushed rock will be done on a laboratory scale. In addition, the already developed technique for in-situ compaction with vibrating plates /10-11/ will be optimized with respect to e.g. compaction technique and material properties such as grain size.

In the third stage the importance of scaling-up will be investigated. This entails technology development plus tests to verify that the backfilling concept is technically feasible. The tests will be performed with prototype equipment. Stage four involves full-scale tests to verify the performance of the backfill.

10.4.3 Plugging of deposition tunnels

When all canisters in a deposition tunnel have been deposited, the tunnel is backfilled and plugged pending the backfilling of all openings in the underground part. The temporary plug consists of a concrete plug in the entrance of each deposition tunnel. The plug is designed to withstand the water pressure at repository depth and the swelling pressure in the backfill. The plugs do not have any long-term function, but will be left in place when all other openings are backfilled.

The need for seals with permanent functions in the underground part, for example between different deposition areas, will be studied in site-specific preliminary safety evaluations during 2005. This type of seal is foreseen to be some form of bentonite plug with long-term durability. Performance requirements and detailed technical solutions for this type of plug will be determined later.

A third type of seal is intended to prevent or hinder intrusion in the underground facility after it has been backfilled and sealed. SKB judges that detailed technical solutions for this can wait.

Conclusions in RD&D 2001 and its review

SKB's judgement in RD&D 2001 was that sufficient knowledge will exist regarding the design and construction of temporary seals once planned experiments are completed. Temporary seals in the form of plugs are included in the full-scale Backfill and Plug test and the Prototype Repository experiment at the Äspö HRL.

Newfound knowledge since RD&D 2001

Temporary seals in the deposition tunnels can be designed in different ways. The type of plug that has been installed in the Backfill and Plug test and the Prototype Repository experiment is a reinforced plug anchored in a slot in the rock around the tunnel. Another type is a friction plug which is held in place by the friction between the rock wall and the plug.

The design of the two reinforced plugs installed in the Prototype Repository differs somewhat from the plug in the Backfill and Plug Test in that they lack a sealing ring of bentonite and have been cast in self-compacting concrete certified by the supplier. Friction plugs have not yet been tested in the Äspö HRL.

Programme

Establishing performance requirements, technical solutions and a fabrication method for plugs is part of the development programme being conducted by SKB with regard to backfilling and closure of the deep repository. In a completed feasibility study within the framework of this programme, it was concluded that there is a need to conduct an inventory and evaluation of possible concepts for seals, both with temporary and permanent function. The choice of concept for seals is dependent on, among other things, which method is used for excavation of the rock and which backfilling concept is used.

SKB is participating in an integrated project within the EU's Sixth Framework Programme for research, technological development and demonstration (Engineering Studies and Demonstrations of Repository Designs, Esdred) /10-8/. A part of the project deals with development and validation of technology for development of temporary seals made of low-pH cementitious materials. For example, the programme includes application and qualification of a temporary seal made of low-pH shotcrete.

A technical solution for sealing of horizontal deposition tunnels will be arrived at prior to the demonstration of KBS-3H, with horizontal deposition of the canisters, that is planned at the Äspö HRL in 2006. According to current plans, at least one of the deposition tunnels will be sealed with a friction plug made of shotcrete based on low-pH cement. The KBS-3H method is described in greater detail in section 10.7.

10.5 Sealing of investigation boreholes

10.5.1 Requirements and premises

Rock excavation and operation of the underground part of the deep repository facility will have only a limited impact on the safety performance of the rock and the other barriers. Investigation holes from the surface and from tunnels in the deep repository must therefore be cleaned and sealed no later than at the closure of the deep repository.

10.5.2 Technology for sealing of boreholes

Conclusions in RD&D 2001 and its review

Technology for sealing of boreholes was previously developed and tested within the framework of the Stripa Project /10-12/ and applied to boreholes in the seabed near SFR. Two different techniques were used to insert highly compacted bentonite blocks into boreholes up to 200 metres long. Another sealing technique has been tested by Nagra involving blowing in bentonite pellets through a hose.

SKI points out in its review that the possibility of a failure of a borehole seal or the opening of flow paths in old borehole locations cannot be completely ruled out. SKI therefore believes that some kind of respect distance between boreholes and deposition holes is needed. SKB is developing a concept for sealing of boreholes and dealing with the question of a respect distance between boreholes and deposition holes in safety assessment and design.

Newfound knowledge since RD&D 2001

A programme for identifying and demonstrating the best available technique for cleaning and sealing investigation holes is being carried out by SKB and Posiva in cooperation. The first stage of the programme, which was concluded during 2003, comprises a feasibility study in which available techniques for sealing of long borehole were identified. In the feasibility study, clay was identified as a suitable material for sealing most of a borehole. The top part, if the hole is drilled from the surface, must be sealed so that erosion, glaciation and sabotage will not lead to a deterioration of the function of the seal in the deeper parts of the hole. Two concepts for applying clay plugs in boreholes have been identified that should be further investigated: sealing with pre-compacted blocks and sealing with compacted pellets.

Programme

Additional stages of the ongoing research programme will be carried out during the coming RD&D period. To start with, stage two will be carried out, including:

- Establishment of performance requirements.
- Formulation of a complete concept for sealing of investigation holes.
- Laboratory studies of potential materials and combinations of different materials.
- Cleaning of the boreholes that will be used in full-scale tests of material and equipment in the field.
- Planning of and preparations for field tests.

The programme for subsequent stages will be specified when experience is available from the initial stages.

10.6 Canister retrieval

How retrieval of deposited canisters is accomplished depends on when it takes place. The more time that has passed after the deposition of a canister, the more work is required. If it is decided to retrieve the canister immediately after deposition and the deposition tunnel has not been backfilled, retrieval can be done with the same machine used for deposition. If the deposition tunnel is backfilled and sealed, however, more work is required. If retrieval takes place several years after deposition and the bentonite has reached full swelling pressure, even more work 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.

10.6.1 Requirements and premises

In Sweden there is no formal requirement that retrieval of a deposited canister must be possible, and retrieval requires the permission of the authorities. The principle that retrieval should not be impossible is a logical consequence of the stepwise build-out of the repository with intervening evaluation that is planned. The design requirements are such that retrieval of canisters must be possible and that any measures adopted to facilitate retrieval may not affect the safety performance of the deep repository.

10.6.2 Freeing of canister

Conclusions in RD&D 2001 and its review

A number of methods for removing bentonite have been studied. They can be divided into four main categories: mechanical, hydrodynamic, thermal and electrotechnical. The hydrodynamic method has shown the best results and has been recommended for further study.

In RD&D 2001, SKB concludes that technology and methods for retrieval as well as a facility for interim storage of the fuel must be available if, on evaluation of the initial operating phase of the deep repository, it is found necessary to retrieve deposited canisters.

Newfound knowledge since RD&D 2001

Freeing of a full-sized canister surrounded by non-water-saturated bentonite has been demonstrated at the Äspö HRL. The purpose of the test, which was carried out with improvised equipment, was to clarify whether freeing of canisters is possible by slurrying of the buffer with salt solution and dewatering with a decanter in a continuous process /10-13/, see Figure 10-4. The tests show positive results and confirm that the hydrodynamic method used is a method which SKB should continue to develop and test.

Programme

Further demonstrations of technology and equipment for freeing of a deposited canister will be provided when the Canister Retrieval Test and the Prototype Repository at the Äspö HRL are dismantled. These demonstrations will only include parts of the buffer, since the buffer material will also be used and investigated in the framework of other studies.

Figure 10-4. *The photo at the left shows the experimental set-up used in the slurrying test – slurrying is done in the tank in the middle. The photo at the right shows how the bentonite is slurried by means of a salt solution.*

10.7 KBS-3 with horizontal deposition

The KBS-3 method is based on the multiple barrier principle. The possibility of modifying the reference method and depositing the canisters horizontally in a row in long horizontal deposition drifts instead of vertically in deposition holes with one canister in each has been discussed since the early 1990s /10-14 to 10-17/. The above-ground part, accesses and central area under ground can be designed independently of what the actual deposition area looks like. The fundamental difference between the reference method (KBS-3V) and a KBS-3 repository with horizontal deposition (KBS-3H) is shown in Figure 10-5. The canister and buffer are the same in both variants.

Conclusions in RD&D 2001 and its review

In RD&D 2001, SKB described the initiated work of devising a research, development and demonstration programme for KBS-3H, which was then termed Medium Long Holes.

In its review of RD&D 2001, SKI pointed out that it is gratifying that SKB presented an alternative with horizontal deposition, but that a decision regarding e.g. horizontal deposition may have to be made relatively soon. Further, SKI noted that a demonstration of the horizontal deposition technique is required.

Newfound knowledge since RD&D 2001

In 2001, SKB published a research, development and demonstration programme for a KBS-3 repository with horizontal deposition /10-18/. The programme, which is being carried out stepwise in cooperation with Posiva during the period 2002–2010, includes feasibility study, conceptual design, manufacture of equipment, demonstration and field tests at the Äspö HRL, plus an evaluation. The programme has been fitted as much as possible into SKB's reference timetable for the deep repository.

The feasibility study, which was conducted in 2002, mainly dealt with technical matters such as technology for rock excavation, handling equipment for deposition and design of a deposition container. The study showed that the concept is technically feasible. The work of devising a conceptual design was carried out during 2003. The purpose of this phase of the project was to identify critical points with regard to long-term safety in the programme. The work has involved three areas: technical development, preparations for a demonstration, and initial studies of

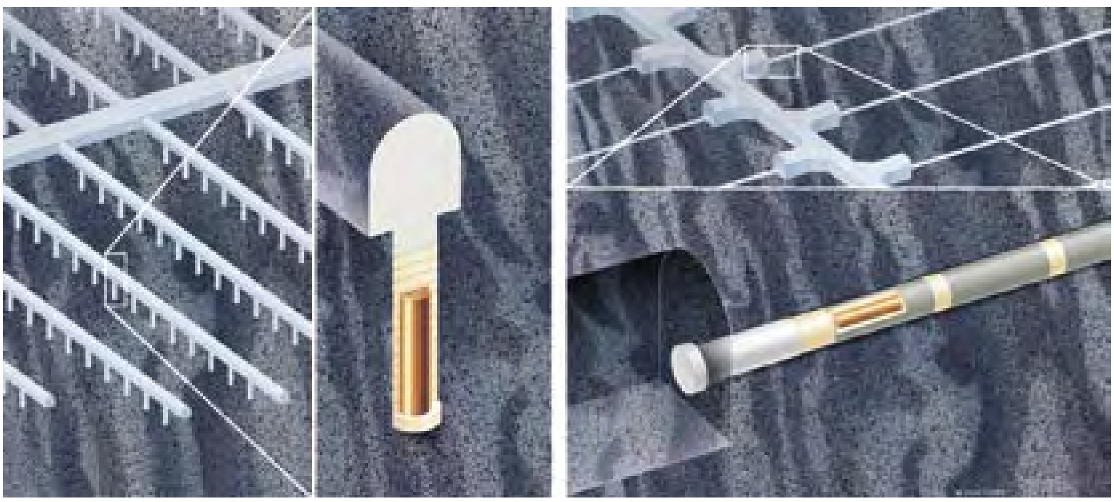


Figure 10-5. *Fundamental difference between the reference method KBS-3V (left) and KBS-3H (right).*

the long-term safety of the concept. The horizontal deposition drifts are planned to be up to 300 metres long and have a diameter of 1.85 metres, which is 10 centimetres more than the deposition holes in KBS-3V. The deposition drifts must be straight and meet narrow dimensional tolerances so that deposition will proceed smoothly. The feasibility study recommended that rock excavation using the cluster technique be further studied. Equipment for boring of the deposition drifts using this technique has been developed and tested, see section 10.1. The copper canister and the buffer will be placed in a deposition container of steel and the whole parcel, which weighs about 50 tonnes, will be emplaced in the horizontal deposition drifts. A spacer block of bentonite clay is placed between the deposition containers.

Development of deposition technology and machinery for this is under way. According to the plans, the remote-controlled deposition machine will utilize water cushions to reduce friction during transport along the deposition drifts. Studies of the function of the bentonite showed that about 60 percent of the surface area of the deposition containers should be perforated so that the bentonite will swell out and seal the deposition drift. The function of the spacer blocks in sealing and preventing erosion of the bentonite buffer has been studied in laboratory tests on different scales. The tests show that there is a risk of erosion and piping if there is a large hydraulic gradient, so studies of these matters continue, see section 17.2.19. A site at a depth of 220 metres in the Äspö HRL has been selected to demonstrate the concept on a full scale. The preparations for demonstration began during the summer of 2003, when a niche was blasted out and three cored boreholes were drilled to characterize the rock.

The safety evaluation of the proposed concept has been reviewed by external experts from Enresa, Nagra and Numo. The conclusion of the review was that the concept is judged to be technically feasible and to meet the requirements on long-term safety. KBS-3H is thereby an alternative to the reference method.

Programme

The remaining points in the research, development and demonstration programme for KBS-3H will mostly be carried out during the period 2005–2007 in cooperation with Posiva and within the EU's Sixth Framework Programme and the Esdred project /10-8/. The principal remaining step is manufacture of the requisite equipment, demonstration of this equipment at the Äspö HRL, performance of a safety assessment and evaluation.

The principal technical activities planned during the period 2004–2007 are:

- Boring of two horizontal deposition drifts in the Äspö HRL.
- Detailed design and manufacture of deposition equipment.
- Demonstration of deposition equipment in the Äspö HRL.
- Execution of feasibility study and basic design of equipment for retrieval.

A full-scale test may also be carried out at the Äspö HRL in order to verify the function of the bentonite during the initial water saturation phase. A decision in this regard will be made during 2004. If the decision is positive, the field test will start during 2006.

A safety assessment for KBS-3H based on site data from Olkiluoto in Finland will be performed by Posiva (section 14.1). This will be preceded by studies and research on critical questions, modelling, preparation of a process report and analyses of radionuclide transport. Examples of questions are swelling-out of the bentonite through the perforated deposition container (section 17.2.7), pressure build-up as a consequence of corrosion of the deposition container (section 17.2.10) and piping and erosion of the bentonite (section 17.2.19).

The research, development and demonstration programme will be concluded with an evaluation of the concept and reporting of results in 2007.

11 Deep repository – design

Design is a comprehensive term for the activities where technical information is gathered, processed and analyzed so that it can then be translated into the facility descriptions, function descriptions, engineering drawings, descriptions of technical systems, operating and maintenance instructions, etc that are required for the deep repository to be built, operated, sealed and closed.

The goal of design is to design the deep repository, with associated infrastructure and activities, so that the stipulated requirements are satisfied. The deep repository facility is described in general terms in facility descriptions. They show the layout and placement of the surface and underground parts and the coordination between them. An account is also given of the vehicles, machines etc that are needed in the facility, including technical systems and installations required for construction and operation. Facility descriptions are important supporting documents for planning of the construction phase, reliability analysis, system analysis, safety assessment and environmental impact assessment (EIA). The facility descriptions that are prepared after the complete site investigation programme will serve as a basis for applications for permits for the deep repository facility under the Environmental Code and the Nuclear Activities Act. Preparation of main and engineering documents will begin during the application period and will then continue during the construction phase.

11.1 Design methodology

The methodologies for designing the two parts of the deep repository, the surface part and the underground part, are different. The surface part is more or less a conventional industrial facility and will comply with existing standards and regulations governing buildings and mechanical and electrical installations. The deep repository facility is also a nuclear installation, which will be taken into account in preparing the design-controlling documents for the technical systems and in designing, for example, the special access protection for the facility's underground part.

There are no equivalent standards and regulations governing the design of the underground part's rock caverns. SKB has therefore issued a document called "Deep repository, Underground Design Premises (UDP)" /11-1/. This document describes the methodology for design and includes descriptions of and/or references to:

- The premises on which design is to be based, the design premises.
- How design is to be carried out.
- How the results of design are to be verified.
- How the results of design are to be documented.

Which of the interim results of rock cavern design are to be checked and verified by SKB in order that the work can continue is also specified in UDP. UDP also includes a number of instructions for various parts of the design work. The instructions develop or explain design requirements and describe how the different design steps are to be carried out.

Conclusions in RD&D 2001 and its review

The methodology for the design of the underground part has been developed since the publication of RD&D 2001, so there are no specific conclusions or review comments.

Newfound knowledge since RD&D 2001

During 2003, the design methodology for the underground part, as presented above, was used in a pilot project that applied the site investigation data on which site model version 1.1 in Forsmark is based /11-2/, to prepare the layout for the underground part. Application of the methodology has led to proposals for changes and improvements in the site model with regard to prioritized information, presentation of interpreted data and definition of verifiable criteria. Furthermore, the methodology has been improved with respect to control, traceability against general design premises, and use of early and general information.

Programme

The methodology for design of the underground part that has been used and refined in a pilot project will be applied in the design work during the site investigation phase.

11.2 Premises

Design of the facility will be coordinated with site investigations, EIA, safety assessments and system analyses, and with technical developments. A prerequisite for being able to carry out design – and in a later phase construction, sealing and closure – with satisfactory results is therefore to establish procedures for how:

- Design premises are to be fulfilled.
- Design – and later construction, operation, sealing and closure – are to be controlled.
- Results are to be controlled and checked.
- Results are to be documented.

11.2.1 Design premises

Design premises constitute a necessary basis for design and construction. Design premises can be divided into requirements and engineered and natural conditions and features that control design. The requirements express conditions that have been stipulated for construction and approval of the deep repository. The engineered and natural conditions and features, which are termed prerequisites, provide the other premises for design. Design premises will be formulated for the different areas of the deep repository facility such as rock, buildings, vehicles, machines and technical systems.

The requirements can be broken down into stakeholder requirements, system requirements (subsystem requirements) and configuration requirements:

- Stakeholder requirements consist of the statements of different stakeholders regarding what the facility should accomplish and what capacities it should have.
- System requirements express what the facility should do, or what functions, capacities, properties or qualities it should have, to meet the stakeholder requirements.
- Configuration requirements express how the facility should be configured to meet the system requirements, with respect to prevailing engineered and natural conditions and features.

The engineered and natural conditions and features that control the design of the underground part of the deep repository facility are:

- The spent nuclear fuel – quantity and properties.
- The site – as it is described generically or in site descriptions.
- The facility – interfaces between different parts and technical systems as well as the activities it will accommodate.

- Processes in the evolution of the repository – those processes that affect the deep repository's long-term safety performance.

The spent nuclear fuel and its properties are described in the information on the fuel that exists where it is currently being stored, i.e. in Clab. The quantities of fuel expected to be generated by the Swedish nuclear power programme are estimated annually and published in a report /11-3/.

Site descriptions are currently being compiled within the site investigation project. It is the task of design to adapt the facility to the information on the site that has been gathered. Design also provides suggestions on how further site investigations should be carried out to meet the needs of design.

The design premises that comprise interpreted site data are constantly updated. Designing the underground part consists largely of adapting the configuration of the facility to the new information regarding the rock, for example its mechanical, hydraulic, chemical and thermal properties.

The facility will be designed with flexibility to allow for technical advances during the long period of time spanned by construction, operation and sealing and so that the facility will meet safety and capacity requirements for the activities conducted there. The facility will also be designed with regard to technical risks and costs in the construction and operating phases. Studies of which technical solutions are most advantageous from the viewpoints of safety, environment, performance and costs will be conducted and the results reported.

Processes in the evolution of the repository are compiled in preparation for each safety assessment. They include all processes that influence the long-term evolution of the repository. In many cases, for example, the processes that influence the repository's configuration requirements influence design loads.

Figure 11-1 shows the links between stakeholder, system and configuration requirements and how requirements and natural and engineered conditions that control design are related. The figure also shows the activities by means of which the design premises are updated.

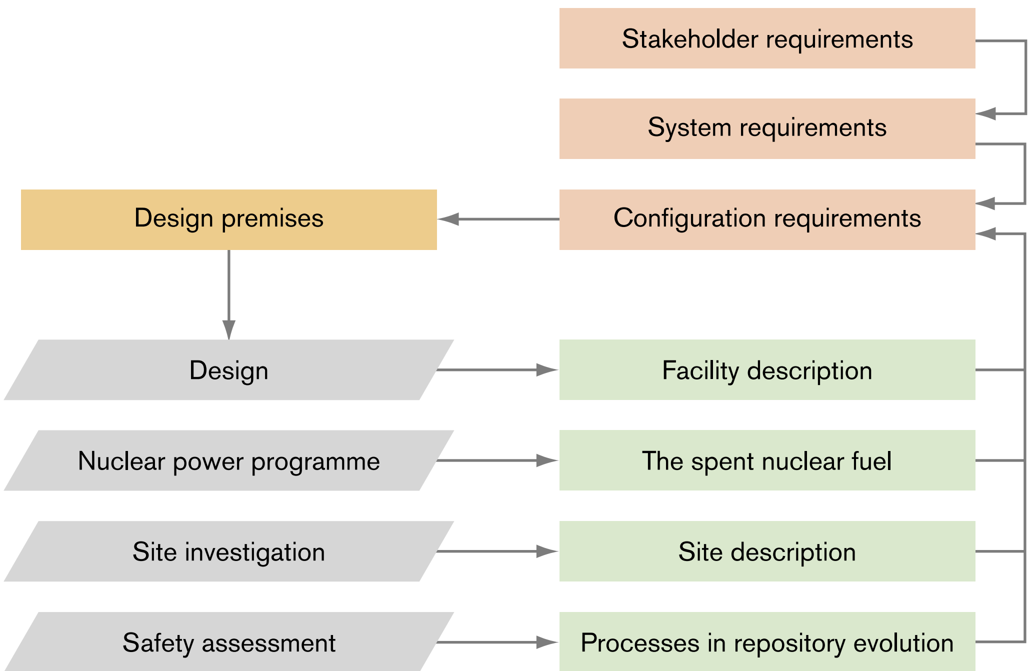


Figure 11-1. *Relationships between requirements, premises and features and how they influence each other. The figure also shows the activities by means of which the design premises are updated.*

Conclusions in RD&D 2001 and its review

In preparation for the design and engineering of the deep repository facility that began when the site investigations were initiated, a need was identified to compile all existing design premises in a single document. In RD&D 2001, the commenced work was presented by compiling and structuring the design premises for the deep repository.

SKI points out in its review of RD&D 2001 that the performance requirements that have not yet been determined must be complied with no later than when a permit application is submitted under the Nuclear Activities Act. It is then necessary that the permit allows for some range of variation and freedom of choice.

Newfound knowledge since RD&D 2001

SKB published general design premises for the deep repository in the KBS-3 system in 2002 /11-4/. The purpose of the document was to compile existing design-basis data in a single document and in this way present the requirements for the long-term safety of the deep repository on a general level. The idea was that the design management could use the document to check that general requirements are followed up in design and engineering. Another purpose was that regulatory authorities and stakeholders could use the document to follow up how their requirements are translated into the actual configuration of the deep repository facility.

In the work of compiling the general design premises, it was observed that these premises needed a far-reaching and thorough review and that this could be done when designers and engineers began to make use of the general design premises in their work. It was also observed that the information, due to the many connections and dependencies, was inaccessible and difficult to update in report form, and that it should be transferred to database format.

Available software for requirement management has been inventoried, and a tool has been purchased for testing and evaluation. Methodology and experience from systematic requirement management has been obtained via cooperation with Posiva in the KBS-3H project /11-5/. Review and checking of the contents of the requirements is carried out in parallel with the development of the methodology for design of the underground part of the deep repository. The purpose of the work is to check that general requirements are followed up in design, to identify which requirements are to be verified within design and which are to be verified in other contexts, to formulate the requirements so that they are unambiguous and easy to understand, and to identify any conflicts of interest and deal with them.

Programme

The general design premises that were reported in 2002 /11-4/ will be updated and transferred to database format. This work has been commenced, for example in conjunction with the preparation of the document "Deep repository, Underground Design Premises (UDP)" /11-1/. The work will result in an updated version of the general design premises and an evaluation of mode of working and database tools. UDP is being applied in practice during the design of the underground part in step D1. In the next step the design-basis material will be used for design of the underground part in D2.

11.2.2 Control and verification

A well-defined decision process established in procedures and plans for review and approval of different types of documents is needed for design.

Conclusions in RD&D 2001 and its review

Procedures for control and verification were not presented in RD&D 2001.

Newfound knowledge since RD&D 2001

Procedures and plans that establish the following are needed:

- Which design-basis information and which of the results of design must be approved before a decision can be made regarding continued design.
- How and by whom the design-basis material and results are to be reviewed and checked prior to a decision.
- Who is responsible for different types of decisions, who should participate in decisions and who should be notified of decisions.
- The meetings, consultations etc that must be held prior to different types of decisions.

Programme

The work of describing the application of SKB's management system and project model in the design work, with a view towards the specific needs and chosen organization of design, is under way and will continue during the RD&D period. The purpose is that design can be carried out with clear interfaces, efficiency and traceability.

11.2.3 Documentation

The deep repository project will last a long time and many people will be involved in the work of designing, reviewing, evaluating, building, operating, and finally closing the facility. It is important that all information of importance for the results of the project be documented and preserved.

Conclusions in RD&D 2001 and its review

Procedures for traceability in and documentation of the deep repository project were not presented in RD&D 2001.

Newfound knowledge since RD&D 2001

In order to achieve traceability in the work, all the premises, results, records and decisions that move the design process forward must be documented. This requires procedures for transferring and storing the information. This can be supported by a digital drawing and document management system.

Besides preserving information and making it traceable, a system for drawing and document management must be able to handle the necessary information flow. The system must also have validity and version management, which means that it must be capable of furnishing all those involved with correct and valid versions of the information. The information must be delivered in a format that can be applied by the user.

What is special about the deep repository project is its long duration. This will be taken into account in the choice of system for drawing and document management by having data preserved in such a manner that they can be entered into future systems efficiently.

Programme

The work of developing and establishing a system for documentation will continue during the coming RD&D period.

11.3 Execution – stepwise design

Siting, construction and operation of the deep repository facility has been divided into phases: the feasibility study phase, the site investigation phase, the construction phase and the operating phase with initial and regular operation and closure. In different phases of the deep repository project, design is supposed to deliver the documents that are required for a decision to be made prior to the next phase.

Design of the deep repository facility is proceeding stepwise. The following account focuses primarily on the design of the underground part. Prior to each new step in the design of the underground part, methodology and premises are updated based on the execution of the preceding step. In this way, the design of the underground part is progressively determined and detailed as investigations of the rock and safety assessment furnish new information, technology is developed and the facility is gradually built out. This stepwise information gathering, decision-making, detailing and build-out lead to a gradual narrowing-down of the freedom of action for changes.

Alternative non-site-adapted facility descriptions based on alternative layouts designated E were prepared in the feasibility study phase. These layouts were intended to provide a clear picture of what the construction of the deep repository facility entails and to serve as a basis for studying which of the alternative layouts is/are preferable from the viewpoint of safety, environment and effectiveness. Layout class E serves as the basis for the subsequent design step D.

Design step D was commenced when the site investigation phase began in 2002 and is intended to serve as a basis for permit applications for the encapsulation plant and the deep repository, and to proceed into the construction phase. The placement of the surface part of the facility and the design and placement of access roads are determined in this step. A decision on the layout of a part of the facility entails that the design of technical systems and installations in that part of the facility are also determined to a great extent. This means that possible future changes are limited.

The design continues during the construction phase with the preparation of main documents for planned parts of the deep repository. Based on the engineering documents, new site data, information from safety assessment and EIA and technology development, methodology and premises are updated. Design in the construction phase then continues with the preparation of a final layout and construction documents for the buildings and rock openings required for initial operation.

Conclusions in RD&D 2001 and its review

SKB's stepwise design model for the deep repository has been described in RD&D 98 and RD&D 2001. The configuration of the repository is refined and documented as more knowledge is obtained and the deep repository is progressively designed and controlling layout issues are dealt with. This stepwise detailing gradually narrows down the freedom of action for changes. It was observed that those parts that are built early should be configured so that sufficient freedom of choice is retained for the configuration of parts that are built later.

Newfound knowledge since RD&D 2001

A methodology for how the design steps are to be carried out has been devised and the connections between the documentation in each design phase have been established. The connections include feedbacks from the design work and finished layouts to the site investigations and different versions of the site models, as well as to safety assessment and EIA. The methodology also prescribes how uncertainties in early information and early functional solutions are to be estimated.

During the initial step E, which was concluded in 2002, a combined but non-site-adapted design of the deep repository facility's surface and underground parts was carried out and a reference design was devised for them. A facility description, Layout E, has been prepared with drawings showing the function, size and scope of the facility. The facility description has been published in three versions with alternative accesses: Straight ramp with two operating areas /11-6/, spiral ramp with one operating area /11-7/, and shaft alternative with one operating area /11-8/.

A study was conducted in 2003 as a basis for the different access alternatives ramp and/or shaft /11-9/. The result is a recommendation to build both ramp and shaft, and SKB has devised a schematic design of the deep repository, see Figure 11-2, that includes a ramp that is used for transporting heavy loads, a skip shaft for transport of rock much and backfill, and three ventilation shafts.

In designing the underground part, it is important to adapt it to the geological conditions on the site. Adaptation means that the layout and placement of tunnels, shafts and rock caverns and positions for canister deposition are adjusted as increasingly detailed and deeper knowledge concerning the conditions in the rock becomes available. The methodology is sometimes called information-based design and entails that the underground part is designed for the interpretation of the conditions in the rock that is judged to be most probable, but that variants are also devised for alternative interpretations. When the conditions have been determined with greater accuracy during the construction phase, the available information is used for e.g. final placement of deposition tunnels and individual deposition holes.

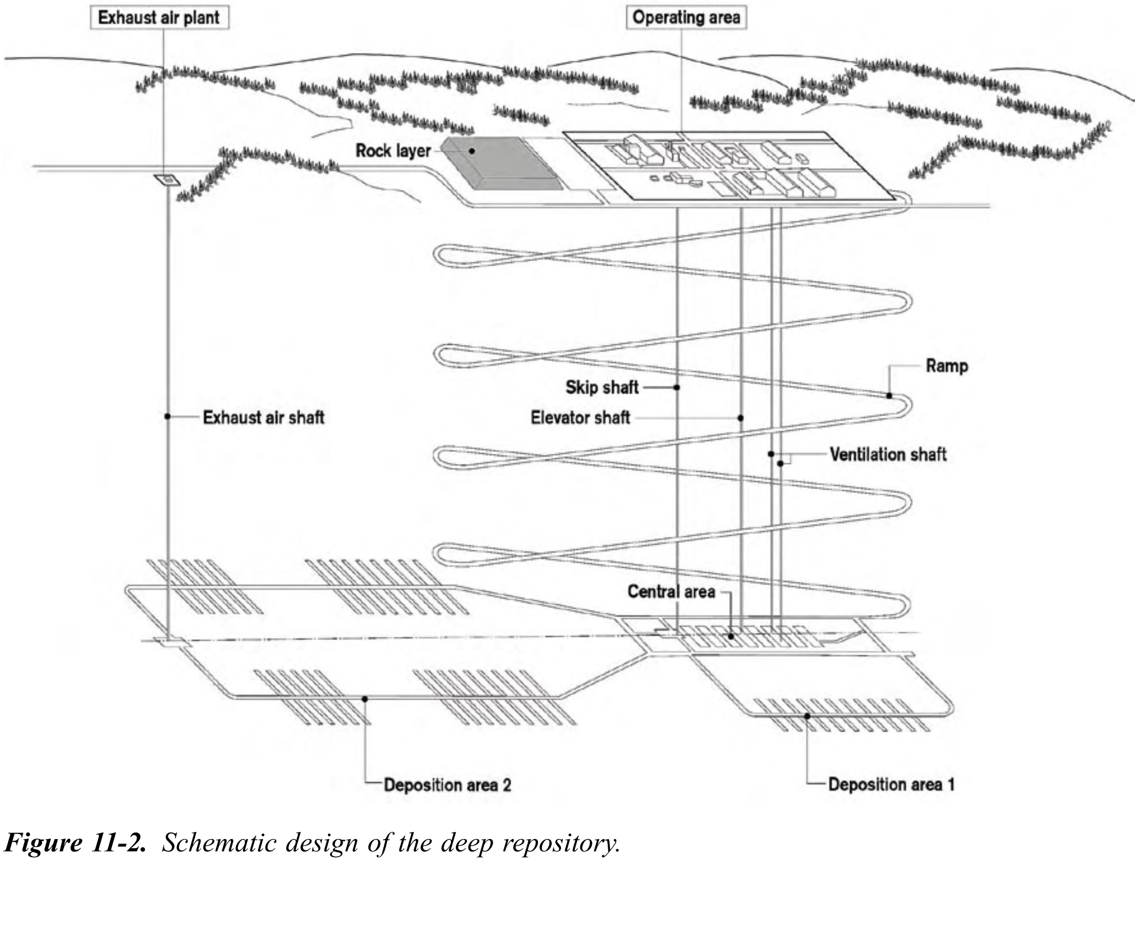


Figure 11-2. *Schematic design of the deep repository.*

Programme

Design step D, which includes design of the whole facility both above and below ground, has been divided into three substeps: D0, D1 and D2. The purpose is to include available information step by step. A summary of the scope and products of the steps is given in Table 11-1. Steps D0 and D1 are carried out in parallel with the initial site investigations (2002–2004) and step D2 is carried out in parallel with the complete site investigations (2005–2007).

Layout D0 entails the start of site adaptation of the surface part and preparation of preliminary proposals for alternative locations in Oskarshamn and Forsmark. Figure 11-3 illustrates an example of a proposed layout of the operating area.

In Layout D1, alternative functional solutions and technical solutions are further developed for e.g. operating areas and access alternatives for selected reference locations for the deep repository. In combination with this, a local site adaptation of the repository's underground part to available geological information takes place. Proposals are presented for alternative layouts of this part. The local adaptation also entails that the surface and underground parts are coordinated. One document is compiled per site. The level of detail is roughly the same as in Layout E, but site-adapted. The underground layout comprises a basis for the preliminary safety evaluation that is presented at the end of the initial site investigation phase. Studies of environmental and societal impact are conducted.

Layout D2, which is based on Layout D1 and the results of the site investigations, is more specific in that it describes various work and functional solutions for the surface and underground parts in detail. The placement of the underground part is verified by new available information, such as investigation results and site model version 2.2, updated reasons for choice of design, and updated engineering and design premises. Layout D2 will be described so that it serves as a basis for the safety assessment (SR-Site) that is included in the application for the deep repository.

The design during the site investigation phase also includes devising detailed design premises and programme for the next phase, the construction phase.

Table 11-1. Summary of the scope and products of the design steps.

Design step	Scope	Products
Layout E	Combined non-site-adapted design.	Facility description based on theoretical layouts for the surface and underground parts /11-6, 11-7, 11-8/.
Layout D0	Site-adapted design of the underground part.	Compilation of possible positions and layouts for the surface part.
Layout D1	Site-adapted design of the underground part based on data from ISI and completed consultations.	Layout for selected alternatives for surface and underground part. Facility descriptions based on alternative layouts. Basis for preliminary safety evaluation.
Layout D2	Continued site-adapted design of facility based on site data from CSI and taking into account safety assessment and EIA. Update of Layout D1 with respect to technical developments and result from design. Basis for execution of site preparation work and preparation of documents for construction of ramp and shaft.	Layout of proposed facility with final site plan for surface part and final placement of ramp and shaft. Facility description based on proposed or approved layout. Background material for SR-Site. Supporting material for deep repository application. Supporting material for preparation of main and construction documents for ramp and shaft.

Figure 11-3. *Deep repository operating area at the entrance to the Forsmark nuclear power plant during the Layout D0 step.*

Increasingly detailed design of the various rock openings in the underground part, the individual buildings in the surface part, earthmoving works, technical systems and installations is carried out during the construction phase. A programme for the construction phase will be prepared during this RD&D period, including design of the deep repository facility as one part. According to the overall timetable for this work, the first version of the programme will be prepared in 2005. This version will then be further detailed so that it can be presented in its entirety in conjunction with the permit application for the deep repository in 2008.

12 Deep repository – monitoring

SKB defines monitoring as "continuous or repeated observations or measurements of parameters to obtain a better scientific understanding of the site and the repository, to show compliance with requirements, or to adapt plans to the results". This definition covers monitoring programmes and surveillance, including observations to verify nuclear material supervision (safeguards) in the deep repository. SKB's definition of monitoring does not include single measurements or observations, and it is understood that the observations are repeated in the same points or areas.

Monitoring during the stepwise implementation of the deep repository has several purposes, but mainly to:

- Establish a primary baseline for the repository site.
- Develop and demonstrate an understanding of the repository site and the performance of the barriers.
- Provide data as a basis for the decision process.
- Show that requirements stipulated in international and national guidelines are met.

Specific rationales for monitoring are to:

- Obtain knowledge of undisturbed conditions in nature and their seasonal variations (baseline) in order to identify and evaluate the impact that the deep repository has during different phases.
- Obtain a better understanding of the function of the deep repository system to support the safety account and to test models and assumptions.
- Monitor the environmental impact of the repository.
- Provide evidence that the working environment is safe with regard to radiological and non-radiological effects.
- Show that requirements on safeguards are met.

12.1 Monitoring

Conclusions in RD&D 2001 and its review

In RD&D 2001, SKB identified a need to establish a policy for monitoring, and the possible need for continuous and periodic observations and measurements was preliminary listed. SKB also described the need to establish a monitoring programme for environmental impact and radiological control.

Newfound knowledge since RD&D 2001

As a result of RD&D 2001, SKB initiated a monitoring project for the deep repository and a framework has been established for such monitoring /12-1/.

The project included a review of definitions and nomenclature used and an international overview of the field. A presentation of SKB's previous experience of monitoring is also included. SKB's participation in the EU project "Thematic Network on the Role of Monitoring in a Phased Approach to Disposal" /12-2/ has been an important part of the project. The Thematic Network was started to obtain a better understanding of the role that can be played by monitoring and what monitoring alternatives are available. Within the Thematic Network, the contribution of monitoring to the decision process and safety during the operating and post-closure phases and its importance for confidence in this safety has been discussed.

The international and Swedish regulatory frameworks recommend monitoring during all steps of the implementation of the deep repository, with the limitation that the safety of the post-closure repository shall not be dependent on monitoring or future maintenance. The steps and measures that are adopted to carry out monitoring should have a minor or negligible impact on the safety of the repository, or should result in improved safety.

Over a number of years – not least during ongoing site investigations, ongoing activities and construction of the Äspö HRL, as well as the recently completed expansion of Clab – SKB has accumulated considerable experience from monitoring of nuclear and non-nuclear installations. The observations have, for example, concerned mechanical, geochemical and geohydrological conditions in the rock before and during construction as well as during operation of the facilities. The results of the observations have been utilized in the construction phase for detailed adaption of the facilities and to achieve high safety in construction and operation. Experience can also be gained from the monitoring of groundwater and barrier performance performed at the final repository for low- and intermediate-level waste (SFR) and at the Äspö HRL. Experience gained from monitoring concerns all aspects from design, installation, operation and maintenance to decommissioning of measurement systems.

Programme

The ongoing site investigations are an important part of the monitoring programme that will be prepared during the RD&D period.

During the site investigation phase, a primary baseline is established with data from the ground surface investigations. The purpose of the primary baseline is to create a reference so that changes caused by construction, operation and closure of the deep repository can be identified and distinguished from natural variations and variations caused by other human activities. Identified changes will also be compared with predictions of the changes obtained with the aid of models of the rock and the repository. The changes can also be used to adapt the repository to the geological conditions on the site. During the site investigations, information is gathered on e.g. land use, surface ecosystems, geology, hydrogeology, rock mechanics and hydrochemistry. Collection of primary baseline data takes place over a relatively long period of time and the measurement frequency is adjusted so that seasonal and annual variations are included.

An overview of possible features, processes and parameters included in primary baseline data for monitoring is published in /12-1/. The monitoring carried out during the site investigation phase largely follows the general execution programme /12-3/, where the investigation methods have been described, and the site-adapted programmes /12-4, 12-5/.

During the construction phase, detailed investigations of the rock from the surface will continue while the underground part is being built and the rock is being investigated. The monitoring performed during this phase focuses on an understanding of geohydrological, geochemical and rock mechanical processes and their impact on the long-term performance of the repository, but also includes documentation of the disturbances caused by repository construction and monitoring of environmental impact.

Planning for monitoring during the construction phase is under way, and it is predicted that the details will be presented in the overall programme for the construction phase, see section 11.3.

The monitoring programme should describe the following /12-1/:

- The goals of the monitoring programme.
- Criteria for selection of what is to be monitored.
- Identification of properties, processes, features and observable quantities to be monitored.
- Which methods are to be used.
- The duration and frequency of monitoring, including criteria for how monitoring can be terminated.
- Procedures for quality control and reporting of results.

- Trigger levels for action.
- Decision on action to be taken if trigger levels are exceeded.

Method and technology development take place continuously within the framework of planned activities.

Temperature, microseismic events, groundwater pressure etc can be monitored during the operating phase, along with resaturation and pressure build-up in the backfill. A safeguards system must also be implemented.

The safety of the closed repository is not dependent on surveillance or monitoring, but some institutional controls can be assumed to exist even after closure, for example safeguards (see section 12.2).

12.2 Safeguards and physical protection

In order to have a well-functioning safeguards system, it is important to adopt a holistic view of the entire fuel handling chain, which means that encapsulation, canister transport and deposition of fuel must be regarded as a whole. After encapsulation of the spent nuclear fuel, verification and measurement of the identity or contents of the canisters is more difficult (see Chapter 8 where safeguards for the encapsulation plant are presented). Good control of the flow of spent nuclear fuel to and from the deep repository facility is therefore required during transport and operation of the deep repository. This imposes demands on an inspection function.

Through international treaties such as the Nuclear Non-Proliferation Treaty, the Euratom Treaty /12-6/ and other bilateral agreements, Sweden has undertaken to use nuclear materials for peaceful purposes only as well as to keep records of all handling of nuclear materials, including spent nuclear fuel. Sweden has also agreed to subject all material of this type to international verification. These safeguards are administered by Euratom and the IAEA, and on a national level by SKI. The purpose of the safeguards is that the inspection bodies should discover if nuclear materials are diverted from the system.

The IAEA has also published a draft policy for safeguards for final disposal of spent nuclear fuel /12-7/, where it is recommended that safeguards be maintained even after the final repository has been backfilled and closed. The IAEA has concluded that a sealed repository needs to be under safeguards control as long as similar control is exercised in other areas.

Work is being pursued internationally to define the requirements on the post-closure safeguards system for a closed geological repository. There may be a need to develop new technology in certain respects. This can be done via individual states' support of the IAEA. The reason is that encapsulated fuel, like deposited fuel, cannot be checked by measurement to determine the fuel's content of fissionable material. It is therefore necessary to have a number of mutually independent components in the safeguards system that guarantee continuous knowledge of conditions in the deep repository.

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

Measurement equipment which senses whether the canister or other equipment contains spent fuel or not can be placed at the entrance to the deep repository. In this way it is possible to verify that no spent fuel is diverted from the deep repository.

An important component in the system of safeguards control of a deep repository is being able to verify that the facility has been built in accordance with the drawings presented, so that there are no ways out of the facility that have not been indicated, or spaces in which other activities take place than have been indicated. This means that the inspection bodies need to conduct inspections before and during construction and during operation and closure.

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 very durable. The same applies to the information on the canister's contents. Otherwise, the same principles can be applied to retrieval, transport and interim storage as to the various steps in deposition of the canisters.

Physical protection includes guarding and other measures that are undertaken to protect the fuel and other radioactive material from theft or sabotage. There is a well-functioning system for physical protection during handling and transport. At the deep repository facility, the operations area will be fenced-in and watched by surveillance equipment in a similar manner as at other nuclear installations. Access to the area will be controlled and checked in a manner similar to what is done at the nuclear installations in operation today. No physical protection is needed in a sealed repository. Instead, monitoring can be coordinated with safeguards supervision via for example satellite surveillance.

Conclusions in RD&D 2001 and its review

In its review of RD&D 2001, SKI stated its opinion that the areas of safeguards and physical protection of the deep repository were described in very general terms and SKI maintained that high demands must be made with respect to both safeguards for the fissile material and physical protection of the same. SKB does not fully concur with this objection, since it is the inspection bodies Euratom, IAEA and SKI who design safeguards for the deep repository. SKB has a great interest in cooperating with the inspection bodies at an early stage in order to be able to adapt the design of the deep repository facility so that safeguards are facilitated.

Newfound knowledge since RD&D 2001

The IAEA, Euratom and SKI collaborate in and organize international working groups for safeguards for both encapsulation and geological repositories for spent nuclear fuel. SKB believes that early cooperation with the inspection bodies on safeguards is important to ensure that the facilities are designed in such a way that safeguards are facilitated. By participating in the international working groups and "Esarda Working Group on the Back End of the Nuclear Fuel Cycle" and "IAEA Experts Group on Safeguards for Final Disposal of Spent Fuel in Geological Repositories", SKB wishes to ensure an early exchange of information and cooperation.

Among other things, the working groups have received information at the Äspö HRL about how handling of nuclear materials and deposition of canisters is planned to take place in the deep repository. SKB also informed the IAEA at a meeting in Oskarshamn /12-8/ how and what information is gathered during the site investigation phase. At the meeting, SKB also pointed out the opportunity which the collected information provides to the inspection bodies for obtaining Primary Baseline data, which may be needed in the future to identify changes that could indicate diversion of nuclear material.

The whole issue of safeguards will be taken into account when designing the deep repository. Spaces for monitoring equipment etc are being planned in keeping with the viewpoints of the inspection bodies, and the facility is being designed with as much transparency as possible.

The trend within safeguards is that traditional safeguards measures (seal, camera inspections, etc) will be supplemented or partially replaced by indirect controls such as measurements in the surrounding environment, gathering of open information and unannounced inspections. This trend will naturally influence the design of the safeguards system at the time of the permit application. An example of this trend is the so-called additional protocol /12-9/.

Programme

During the period 2005–2010, SKB will keep track of international developments in the field, but does not plan to conduct any development or demonstration of monitoring equipment or the like for the safeguards purposes of its own.

Part III
Safety assessment and research

13 Overview – safety assessment and research

The long-term safety of a deep repository for spent nuclear fuel is evaluated by means of safety assessments. These assessments essentially consist of first carefully describing the repository's initial state, for example at closure, then analyzing possible long-term changes, and finally describing the consequences for man and the environment. The safety assessment uses scientific methodology and obtains knowledge concerning long-term changes from research.

SKB's research on final disposal of spent nuclear fuel can be divided into three fields:

- Long-term safety
- Social science
- Alternative methods

These fields are described in general terms in this chapter and in greater detail in subsequent chapters. The greatest attention is given to research on long-term safety. The purpose of this research is to underpin SKB's safety assessments of the deep repository for spent fuel, and one purpose of the safety assessment is to establish priorities for the research. Processes of importance for long-term safety are discussed below and a rough estimate is made of the research need during the coming three-year period.

Social science research is a relatively new field for SKB, at least on the scale that is now planned. The focus is on questions that need to be addressed in conjunction with the environmental impact assessment, EIA.

When it comes to alternative methods for disposing of spent fuel, SKB keeps track of the results of research on two selected methods: Partitioning and Transmutation (P&T) and Very Deep Holes (VDH).

The research on low- and intermediate-level waste (LILW) is presented in Chapter 25.

13.1 Safety assessment

The most important safety assessment projects during the period are SR-Can and SR-Site. The purpose of these projects is to produce safety assessments for applications for permits to erect an encapsulation plant and a deep repository. SR-Can is currently under way. An important milestone is the interim report, which presents the methodology that will be used /13-1/.

Many of the models which the safety assessment needs to calculate e.g. groundwater flow, the chemical evolution of the buffer and the evolution of ice sheets etc. are arrived at by research on geosphere, buffer, climate and so on. A vital task of the safety assessment is to utilize these models, but also to develop modelling tools for integrated modelling. A system model has been developed consisting of submodels, each of which describes a process in the repository. In this way, different sets of input data can be quickly tested and probabilistic calculations can be performed if necessary, see section 14.2.1.

Numerical calculations of radionuclide transport are made with the aid of the software package Proper. In addition, development is under way of an alternative software package, Tensit, which can be run on a personal computer. The commercial codes Matlab and Simulink are used to a great extent within Tensit, which will greatly facilitate the future work of maintaining the codes and preserving knowledge about them. The near-field calculations and biosphere calculations are already fully implemented in Matlab and Simulink. The biosphere model included in Tensit has, incidentally, undergone considerable development, see section 14.2.2. Proper and Tensit will both be used for SR-Can.

As a complement to the numerical models, analytical simplified descriptions of near- and far-field models have been developed. They are extremely fast and can be used, for example, to make scoping calculations and supplementary probabilistic calculations in future safety assessments.

The work in the safety assessment is concentrated on the repository concept KBS-3V, but the KBS-3H variant with horizontal deposition of the canisters is also being studied. Long-term safety of KBS-3H will be analyzed under the leadership of Posiva, with the goal of presenting a safety assessment in 2007 with Olkiluoto as the reference site.

13.2 Research on long-term safety

The goal of the research on long-term safety which SKB is conducting is to understand the processes (long-term changes) that occur in a deep repository and how they affect the repository's ability to isolate the spent nuclear fuel.

Detailed accounts of the programmes for fuel, canister, buffer, backfill and geosphere follow in Chapters 15 to 19. Possible research and development needs for the initial state are discussed for each repository section. The time for the initial state may be different for different repository sections. Many analyses concern the evolution of conditions around individual deposition holes. All deposition holes will undergo more or less the same evolution from the time the canister and bentonite are deposited in them.

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. Biological processes – microbial – are included in the chemical processes (C). 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 characterized as integrated studies. One example is the hydro-mechanical-chemical (HMC) evolution of a damaged canister, another the thermo-hydro-mechanical (THM) evolution of an unsaturated buffer.

Chapters 20 and 21 discuss the research that is needed to chart the changes to which the evolution of the biosphere and the climate give rise.

There is no separate chapter on natural analogues this time, as there was in RD&D 2001. Activities in the field are now fully integrated in the research programmes for the different barriers. This is described in greater detail in section 13.2.8.

Table 13-1 shows all processes of importance for long-term safety that are dealt with in Chapters 15 to 19. The colour code provides a rough idea of the magnitude of the planned initiatives for the different processes during the upcoming three-year period. The scope of the planned research does not necessarily reflect the importance of the process for long-term safety. The corresponding information for the initial state is found in Table 13-2. The following sections provide a brief overview of the most important research areas for the different parts of the repository, the biosphere and the climate.

Table 13-1. Research on long-term safety.

Code: Major initiatives (red) | Moderate initiatives (yellow) | Minor initiatives/monitoring during coming three-year period

	Fuel	Canister	Buffer	Backfill	Geosphere
R	Radioactive decay 15.2.2				
	Radiation attenuation/heat generation 15.2.3	Radiation attenuation/heat generation 16.2.2	Radiation attenuation/heat generation 17.2.2	Radiation attenuation/heat generation 18.2.3	
	Induced fission (criticality) 15.2.4				
T	Heat transport 15.2.5	Heat transport 16.2.3	Heat transport 17.2.3	Heat transport 18.2.4	Heat transport 19.2.2
H	Water/gas transport 15.2.6		Water transport unsatur. 17.2.4	Water transport unsatur. 18.2.5	Groundwater flow 19.2.3
			Water transport satur. 17.2.5	Water transport satur. 18.2.6	
			Gas transport/dissolution 17.2.6	Gas transport/dissolution 18.2.7	Gas flow/dissolution 19.2.4
M		Deformation insert 16.2.4	Swelling 17.2.7	Swelling 18.2.8	Movements in intact rock 19.2.5
		External deformation Cu 16.2.5	Mech. inter. buffer/backfill 17.2.8	Mech. inter. backfill/rock 18.2.9	Reactivation (earthquakes) 19.2.7
		Inner deformation Cu 16.2.7	Mech. inter. buffer/canister 17.2.9		Fracturing 19.2.8
			Mech. inter. buffer/rock 17.2.10		Time-dependent deformations 19.2.9
	Thermal expansion/cladding failure 15.2.7	Thermal expansion 16.2.6	Thermal expansion 17.2.11	Thermal expansion 18.2.10	Thermal movement 19.2.6
					Erosion 19.2.10
C	Advection/diffusion 15.2.8		Advection 17.2.13	Advection 18.2.11	Advection/mixing 19.2.11
			Diffusion 17.2.14	Diffusion 18.2.12	Diffusion 19.2.13
	Resid. gas radiolysis/oxygen form. 15.2.9	Corrosion insert 16.2.8	Osmosis (salt effect) 17.2.15	Osmosis (salt effect) 18.2.13	Reactions with rock 19.2.15
	Water radiolysis 15.2.10	Galvanic corrosion 16.2.9	Ion exch./sorption 17.2.16	Ion exch./sorption 18.2.14	Dissol./precip. fract. minerals 19.2.16
	Metal corrosion 15.2.11	SCC insert 16.2.10	Montmorillonite transf. 17.2.17	Montmorillonite transf. 18.2.15	Microbial processes 19.2.18
	Fuel dissolution 15.2.12	Radiation effects 16.2.11	Dissolution/prec. impurities 17.2.18	Dissolution/prec. impurities 18.2.16	Inorganic decomp. 19.2.19
	Dissolution gap invent. 15.2.13	Copper corrosion 16.2.12	Colloid release/erosion 17.2.19	Colloid release/erosion 18.2.17	Colloid turnover 19.2.20
	Speciation radionuclides/colloid formation 15.2.14	SCC shell 16.2.13	Radiation-induced montmorillonite transf. 17.2.20	Radiation-induced transf. 18.2.13	Gas formation/dissolution 19.2.22
	Helium production 15.2.15	Grain growth copper 16.2.14	Radiolysis pore water 17.2.21	Radiolysis pore water 18.2.19	Methane ice formation 19.2.23
			Microbial processes 17.2.22	Microbial processes 18.2.20	Salt exclusion 19.2.24
Integration		HMC evolution damaged canister 16.2.16	THM evolution unsaturated 17.2.12		HC evolution 19.2.25
			THMC evolution saturated 17.2.23		
Radionuclide transport			Advection 17.2.24	Advection 18.2.21	Advection/mixing 19.2.12
			Diffusion 17.2.25	Diffusion 18.2.22	Diffusion 19.2.14
			Sorption 17.2.26	Sorption 18.2.23	Sorption 19.2.17
			Speciation 17.2.27	Speciation 18.2.24	Speciation 15.2.14
			Colloid transport 17.2.28		Colloid transport 19.2.21
					Gas phase transport 19.2.4
		RN transport near-field 16.2.15			RN transport geosphere 19.2.26

Table 13-2. Research on the initial state of the repository.

Fuel	Canister	Buffer	Backfill	Geosphere
Geometry 15.1.2	Geometry 16.1.2	Geometry 17.1.2	Geometry 18.1.2	
Radiation intensity 15.1.3	Radiation intensity 16.1.3	Pore geometry 17.1.3	Pore geometry 18.1.3	
Temperature 15.1.4	Temperature 16.1.4	Radiation intensity 17.1.4	Radiation intensity 18.1.4	
Hydrovariables 15.1.5	Mechanical stresses 16.1.5	Temperature 17.1.5	Temperature 18.1.5	
Mechanical stresses 15.1.6	Material composition 16.1.6	Smectite content 17.1.6	Smectite content 18.1.6	
Total radionuclide inventory 15.1.7		Water content 17.1.7	Water content 18.1.7	Site Investigations
Gap inventory 15.1.8		Gas contents 17.1.8	Gas contents 18.1.8	
Material composition 15.1.9		Hydrovariables 17.1.9	Hydrovariables 18.1.9	
Water composition 15.1.10		Swelling pressure 17.1.10	Swelling pressure 18.1.10	
Gas composition 15.1.11		Smectite composition 17.1.11	Smectite composition 18.1.11	
		Pore water composition 17.1.12	Pore water composition 18.1.12	
		Impurity levels 17.1.13	Impurity levels 18.1.13	

Code:	Major initiatives	Moderate initiatives	Minor initiatives/monitoring during coming three-year period

The point of departure for the detailed account of the research programme is the KBS-3V variant, i.e. vertical deposition holes bored from underground tunnels. But due to the fact that the KBS-3H variant is attracting increasing attention, studies that are specific for horizontal canisters surrounded by buffer and plugs in horizontal tunnels are also presented. The method is described in greater detail in section 10.7. Research, development and evaluation of KBS-3H are being carried out in close cooperation with Posiva of Finland. When it comes to research with respect to long-term safety, many processes are of course common to the two variants; but there are differences, especially with regard to the buffer. Various studies have been initiated, and the state of knowledge, as well as the future programme, is presented in Chapter 17, for example sections 17.2.7, 17.2.10 and 17.2.19. It can be expected that interest in the area will increase and more studies will be started when work on the safety assessment for KBS-3H, under the direction of Posiva, gets started in earnest.

13.2.1 Fuel

Dissolution of fuel, which occurs if it comes into contact with the groundwater via a breach in the canister, is an important process to address in the safety assessment. Research on fuel dissolution was prioritized in RD&D 2001, and some new results are presented in section 15.2.12, along with the programme for continued studies. The area remains prioritized, at least until the models for fuel dissolution have been examined in the SR-Can safety assessment.

13.2.2 Canister

For an intact canister in the repository, it is above all mechanical loads during glaciations and earthquakes that must be considered. Material data are being collected and tests conducted to enable the strength of the cast iron insert to be calculated. Newfound knowledge and the continued programme are described in section 16.2.4. Copper corrosion continues to be an important area in which different types of experiments are being conducted, sections 16.2.12 and 16.2.13.

For an intact canister, it is urgent to examine types and frequencies of defects that can occur in the canister's lid weld. Such information is being gathered from the trial weldings at the Canister Laboratory, see section 16.1.2.

If it is assumed that the canister is initially damaged so that groundwater enters, the iron in the insert can corrode. The scope and importance of this has been examined by means of various kinds of experiments. Further iron corrosion experiments remain to be conducted, see section 16.2.8.

13.2.3 Buffer

It is important to be able to predict the state of the buffer after full water saturation and complete homogenization, and roughly how much time this takes. When water is absorbed from the surrounding environment, the material is homogenized at the same time as the swelling pressure builds up and thermal conductivity is altered. The course of events is being studied both in the field and with models. The emphasis in the laboratory investigations has been on determining the material parameters that are needed for the model calculations, see section 17.2.12.

A water-saturated buffer is simpler to describe, but there are still a number of processes that need to be studied, not least in view of the long time spans that need to be considered. Processes where additional research is needed include gas transport, section 17.2.6, colloid release and erosion, section 17.2.19, and mechanical interaction between buffer and canister, section 17.2.9.

Some of the studies need to be broadened to take KBS-3H into consideration. An example is the progressive deposition of finished canister-buffer parcels, alternating with plugs between the parcels, creating a situation where erosion could occur, see section 17.2.19.

13.2.4 Backfill

Together with Posiva, SKB is studying a number of different concepts for tunnel backfilling. This, along with tests of different clay-based materials, continues to be a prioritized activity, see section 18.1.6. The long-term evolution of the backfill shares several issues with the buffer, and the same type of knowledge is required, although scope and relative importance may differ.

Processes that are still of importance to investigate are swelling, the subsequent long-term mechanical evolution, section 18.2.9, and factors that can affect it, including chemical action, section 18.2.13, and colloid formation and erosion, section 18.2.17.

13.2.5 Geosphere

The development of models for rock movements continues, with a focus on upcoming safety assessments, most immediately SR-Can. Model development is described in section 19.2.7. One question in particular that is being investigated in this context is postglacial faulting.

Models for groundwater flow are being developed, principally to obtain numerical models for calculations for the safety assessment. Further knowledge of groundwater flow has been gained from the supraregional simulations that have recently been carried out for Northern Uppland and Eastern Småland. From now on, special attention will be devoted to surface hydrology. Model development for groundwater flow is described in section 19.2.3.

A number of activities are under way aimed at gaining greater knowledge of the transport resistance and how it can be used to calculate the transport of radionuclides dissolved in the groundwater. The transport resistance retards this transport and is an important property of the rock. Processes that still need to be investigated include advection/mixing, section 19.2.12, diffusion in the rock matrix, section 19.2.14, colloids, section 19.2.20 and 19.2.21, and modelling of radionuclide transport, section 19.2.26.

Hydrogeochemical conditions are always investigated on the site. The task of the research programme is to supplement the geochemical investigations, shed light on the stability of prevailing conditions, and attempt to predict the changes that can occur, in the short term as a result of the fact that the repository is kept open, and in the long term due to the influence of foreign substances, see section 19.2.19. Processes that need to be studied are reactions with the rock, section 19.2.15, dissolution and precipitation of fracture-filling minerals, section 19.2.16, and microbial processes, section 19.2.18.

13.2.6 Biosphere

Describing the biosphere and its evolution is an important part of the safety assessment, since it is in the biosphere that any releases from the deep repository would have consequences. The biosphere is being thoroughly characterized in conjunction with the site investigations. Furthermore, it is necessary to predict what changes might occur in the future and what importance they might have for possible releases. The greatest attention will be devoted to the first 1,000 years. The subsequent period up until the next ice age can be dealt with in less detail.

In order to calculate the transport of radionuclides in the biosphere it is necessary to know the release points. In other words, a more coherent description is needed of hydrogeological and oceanographic processes all the way up to the release points, see section 20.5. Transport in the biosphere is described with compartment models where the biosphere is divided into units between which the transfer of radionuclides is calculated, see section 20.4.

Continued work will be devoted to further defining and describing the most important processes in different types of ecosystems, such as terrestrial, section 20.6, and aquatic, section 20.7. Long-term variations in climate, land uplift and salinity can have a great impact on the biosphere on a site, for example by changing the position of the shoreline, see section 20.8. Here there is a strong coupling to the next programme, which deals with the evolution of the climate, see below.

13.2.7 Climate

It is essential to describe what changes may occur in the future climate and see whether this may in any way affect the repository. Previous climate changes with permafrost and continental ice sheets will most likely occur in the future as well due to the earth's movement around the sun. But even though the earth's astronomical movement is predictable, it is more difficult to predict the exact course of climate change on earth. Many factors influence the climate. An additional complicating factor is the human influence, such as emissions of greenhouse gases. For the safety assessment it is important to be aware of the range of possible climates and their conceivable evolutionary pathways on the site for the deep repository. The climate research supported by SKB takes aim at this. The programme is described in Chapter 21.

13.2.8 Natural analogues

Nowadays studies of natural analogues do not comprise a separate programme, but are fully integrated with the research on long-term safety, divided into different concepts and barriers.

SKI asserted in its review of RD&D 2001 that natural analogues should continue to be given high priority, particularly material analogues. They further said that SKB should consider utilizing the information that is already available from completed projects and that the value of field experiments on previous sites should be considered. Anthropogenic material analogues were held up as something SKB should consider studying. Analogues could be used to judge the completeness of process descriptions, and it was recommended that SKB participate in EU projects aimed at further evaluating already finished projects.

Studies of material analogues are dealt with in sections 16.2.7 and 17.2.15. SKB has followed the work in the EU's thematic network Nanet (Network to review natural analogue studies and their applications to repository safety assessment and public communication). The network is collecting references to analogues that are relevant to various processes and barriers in a repository. Another, closer area for SKB is the Process Report. In the version that serves as a basis for the SR 97 safety assessment, reference is made to natural analogues for 14 of the processes that are dealt with /13-2/. The Process Report is being updated in preparation for SR-Can, and additional examples can be included /13-3/.

13.2.9 Research in the Äspö HRL

The Äspö HRL is SKB's facility for development, testing and demonstration of technology for underground deposition of spent fuel. Several of the projects being conducted there are concerned with 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 a barrier to the escape of radionuclides. There are also experiments that concern the function of the canister and tests aimed at the fuel. Table 13-3 gives a number of examples of Äspö projects that are completely or partially concerned with long-term safety. The table makes reference to sections in following chapters where more information is available on the importance of the experiments in understanding and modelling processes of importance of 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. Because long-term safety is naturally the aim of all development of deep repository technology. When new technology is being considered, a judgement must be made as to whether it meets the requirements of the safety assessment, or – as a first step in such a judgement – arguments must be advanced in support of this.

Table 13-3. Projects and experiments in the Äspö HRL, all or portions of which are focused on research regarding long-term safety.

Project/experiment	Section
RNR Experiment (includes experiments with the Chemlab probe)	15.2.12, 17.2.25, 19.2.17, 19.2.20
Corrosion tests	16.2.12, 16.2.16
Prototype Repository	17.2.3, 19.2.2
Lasgit	17.2.4, 17.2.6, 17.2.12
TBT	17.2.4, 17.2.12
Canister Retrieval Test	17.2.4, 19.2.2
Lot	17.2.18, 17.2.25
Colloid Project	17.2.19, 19.2.20, 19.2.21
KBS-3H	17.2.19
Backfill and Plug Test	18.2.2
Äspö models 2005	19.2.3
Apse (Äspö Pillar Stability Experiment)	19.2.5, 19.2.6, 19.2.7, 19.2.8
True	19.2.14, 19.2.26
LTDE	19.2.14
Matrix Fluid Chemistry Experiment	19.2.15
Microbe Project	19.2.18, 19.2.22

The references refer to sections in coming chapters where the particular process is dealt with, i.e. Chapter 15 Fuel, 16 Canister, 17 Buffer, 18 Backfill and 19 Geosphere.

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. In this respect, the special task forces have made a valuable contribution. They are composed 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 19.2.26. Hydrogeology, geochemistry and mass transport in crystalline rock are examples of areas where there are many different theories and opinions can differ. It is necessary to adopt a critical and questioning attitude in order to avoid overinterpreting results or too readily accepting prevailing theories and explanations.

Something new and important for the future in Äspö is the University of Kalmar's research school. Its research on mechanisms for transport and migration of pollutants in the transition between rock, soil layer and biosphere is of importance for SKB as well. Hopefully the school will also train researchers to meet SKB's future needs.

13.3 Social science research

SKB recently decided to support social science research. During 2003, a survey was conducted of what is of interest for the waste issue and the municipalities, an objective was defined and the four social science research areas were selected: socioeconomic effects, decision processes, psychosocial effects and global changes. A detailed account of the social science research programme is provided in Chapter 22.

13.3.1 Socioeconomic effects

The purpose of the research in the field of socioeconomic effects is to gain a greater understanding of how a community's economy and demographic composition is affected by the establishment of a new major enterprise in the community.

13.3.2 Decision processes

By gaining greater knowledge of political decision processes in complex issues, SKB hopes to obtain guidance on how to carry out consultations, conduct studies, plan and decide on the siting of a deep repository.

13.3.3 Psychosocial effects

The research on psychosocial effects will find out how public opinion and attitudes are created and changed in the different phases of the deep repository project. Such knowledge will hopefully increase understanding between the stakeholders and contribute positively to the consultations.

13.3.4 Global changes

Research on global changes is intended to increase our knowledge of what factors and changes in the world around us are of importance for the deep repository project and the community which is eventually chosen to host it. This knowledge can be valuable in making plans, conducting studies, carrying out consultations and making decisions leading up to an application for a permit to site a deep repository.

13.4 Alternative methods

SKB's research when it comes to alternatives to KBS-3 is concentrated on two methods: Partitioning and Transmutation (P&T) and Very Deep Holes (VDH). The programmes are described in greater detail in Chapter 23. The following sections provide only a brief sketch.

13.4.1 Partitioning and transmutation (P&T)

SKB continues to support research on P&T. 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. Sweden does not have the resources to pursue such development work on its own; international cooperation would be required, or the commitment of a major power. If P&T is implemented in the future and plants for it are built in some country, and if their services are made available, we must ask what it would cost and what waste products we would get back. But so far everything is in the basic research stage, and SKB's policy is to monitor international developments in the field. SKB supports research on Partitioning and Transmutation at the Royal Institute of Technology (KTH) in Stockholm, Uppsala University and Chalmers University of Technology (CTH) in Gothenburg. 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 participate in the international development work, competent partners must be provided as well as facilities in the country where research is conducted at an acceptable level. A detailed account of SKB's research programme in the field of Partitioning and Transmutation is provided in section 23.1.

13.4.2 Very Deep Holes (VDH)

The idea of disposing of high-level waste in very deep holes has been around for more than 20 years, and SKB looked into the possibility of disposing of spent fuel in this manner in the early 1990s. Further studies have been conducted since then without any obvious advantages being found – rather the contrary. The conclusion in RD&D 2001 was that there was no evidence to suggest that VDH would increase safety or reduce the cost of disposing of the spent nuclear fuel. It was nevertheless decided that SKB would continue to keep track of developments in the field. One reason for this was so that the results and experience gained would also provide valuable geoscientific knowledge for a KBS-3 repository at a depth of about 500 metres. Data from investigations in boreholes several kilometres deep that have been published since SKB's most recent literature reviews have been compiled and evaluated. The results are presented briefly in section 23.2. It can be concluded that nothing has emerged to change the judgement made in RD&D 2001, but it may nonetheless be worthwhile to continue to follow the geoscientific investigations of conditions at depths of several kilometres in the rock, for the same reason as before.

14 Safety assessment

14.1 Methodology for assessment of long-term safety of deep repository

An overview of the safety reporting during the site investigation phase is given in SKB's plan of action, see Appendix A. SKB's work with safety assessments for a deep repository and method and model development for them is being conducted during the site investigation phase almost exclusively within the framework of the projects aimed at producing safety reports for the applications for permits to build an encapsulation plant and a deep repository. The safety assessment projects are called SR-Can and SR-Site. Of special importance for RD&D-Programme 2004 is the interim report for SR-Can that was recently published /14-1/. The purpose of that report is to present the methodology for safety assessment prior to its use in the planned permit applications. The report demonstrates not only completed methodology development with examples, but also plans for how different problems are intended to be solved in the final report for SR-Can. The regulatory authorities are carrying out a thorough review of the interim report during the autumn of 2004 with the aid of a team of international experts.

Much of the relevant information on recent and planned development of safety assessment methodology and tools are therefore presented in the interim report and are not repeated in detail here.

Important method questions dealt with in the SR-Can Interim Report include:

- FEP processing and FEP database.
- Selection of scenarios.
- Handling of uncertainties.
- Sensitivity analyses.
- Risk calculations.
- Compliance with the regulatory authorities' regulations SSI FS 1998:1 and SKIFS 2002:1.

In addition to the needs identified by SKB, the methodology development has also been based on viewpoints on SKB's most recent safety report SR 97 /14-2/ and on RD&D-Programme 2001, as well as requirements in the authorities' regulations regarding safety reporting for a deep repository (SSI FS 1998:1 and SKIFS 2001:1).

The point of departure for this chapter is KBS-3V, but it should be noted that the variant KBS-3H with horizontal deposition of canisters is also being studied. SKB and Posiva are together carrying out a programme which includes research, development and demonstration of the variant KBS-3H with horizontal canisters, see section 10.7. Within the framework of the programme, an assessment is planned of the long-term safety of KBS-3H. This will be carried out under the leadership of Posiva, with the overall goal of presenting a safety assessment for KBS-3H with Olkiluoto as the reference site in the middle of 2007. The idea is to utilize as much as possible of the methodology that is being developed for the safety assessment SR-Can. The results of Posiva's own programme for research, development and demonstration will naturally also be used /14-3/. The planned assessment includes a process report focusing on processes that are specific for KBS-3H. Thermal, mechanical, gas-related and chemical processes will be analyzed and radionuclide transport calculations will be carried out. The planning report /14-4/ and the interim report /14-1/ that have been published within the SR-Can project, as well as the planning report which Posiva will publish for its safety assessment for KBS-3V, will be utilized in the planning of the safety assessment. Examples of steps included in the planning work are preparing a preliminary table of contents for the assessment, identifying the processes of importance for long-term safety that are common for the KBS-3H and KBS-3V concepts or whose descriptions require only minor modification, and identifying the processes that are specific for KBS-3H. The results and experience gained from the research, development and demonstration conducted within the programme will naturally be taken into consideration in the safety assessment.

14.2 Integrated modelling

The development of many of the modelling tools used in the safety assessment and results obtained with these tools are described in detail under the relevant sections in the coming chapters. This includes, for example, modelling of groundwater flow, of the chemical evolution of the buffer and of the evolution of continental ice sheets. Development of tools for integrated modelling of a number of processes that span a large part of the system is described below.

14.2.1 System development

The system of coupled processes that controls the long-term evolution of the repository is complex. In the mathematical modelling of the evolution of the deep repository, the process system is therefore studied with different process models, each of which illustrates a certain aspect of the total evolution. Often these models handle thermal, hydraulic, mechanical or chemical processes. Integration of all aspects of repository evolution therefore consists mainly of a discussion of the results of the process models within the framework of a safety account.

Recently a system model consisting of several integrated submodels has been developed, where each of the submodels mimics a process model /14-5/. The system of treated processes is necessarily simplified. For example, the short-duration saturation phase in the buffer, where the coupling between the processes is strong, is excluded, as is detailed hydromodelling of the heterogeneous fractured bedrock.

The first version of the system model does not deal with radionuclide transport. A simplified description is also provided of these phenomena (see section 14.2.2), and may be incorporated into future versions of the system model.

A principal reason for development of the system model is to obtain an integrated treatment of the most important processes in the long-term repository evolution, ensuring that a consistent input database is used in modelling all aspects of the evolution and that time-dependent output data from one submodel can be used directly as input data to another. Furthermore, this tool is controlled directly by the safety analyst, in contrast to the previous situation where a number of disparate expert groups handled their own process models. Several steps have been taken to speed up the calculations compared with underlying process models. This permits rapid evaluation of a number of different sets of input data as well as probabilistic calculations. The model can be executed probabilistically, but so far mainly deterministic results have been obtained, partly because the database for probabilistic calculations is incomplete, and partly because it is often not clear that probabilistic calculations are warranted.

Other reasons for developing the model are to gain insight into the relative importance of various processes at an overall level and to provide quality assurance in the form of an independent set of models for important aspects of the evolution of the deep repository. However, the ambition is not to replace the more detailed process models. They will always be needed to fully include all details in the mechanisms behind individual processes and as a necessary basis for the development of simplified models. Furthermore, the expertise behind the development of the process models will always be needed to describe and justify the common scientific basis for both types of models.

Figure 14-1 shows the set of process models that have been included as submodels in the system model, and how the submodels are linked to each other. Further description of different submodels, benchmarking results etc. are provided in /14-5/. The model will be used as one of several tools with which the general system evolution can be studied in the SR-Can project.

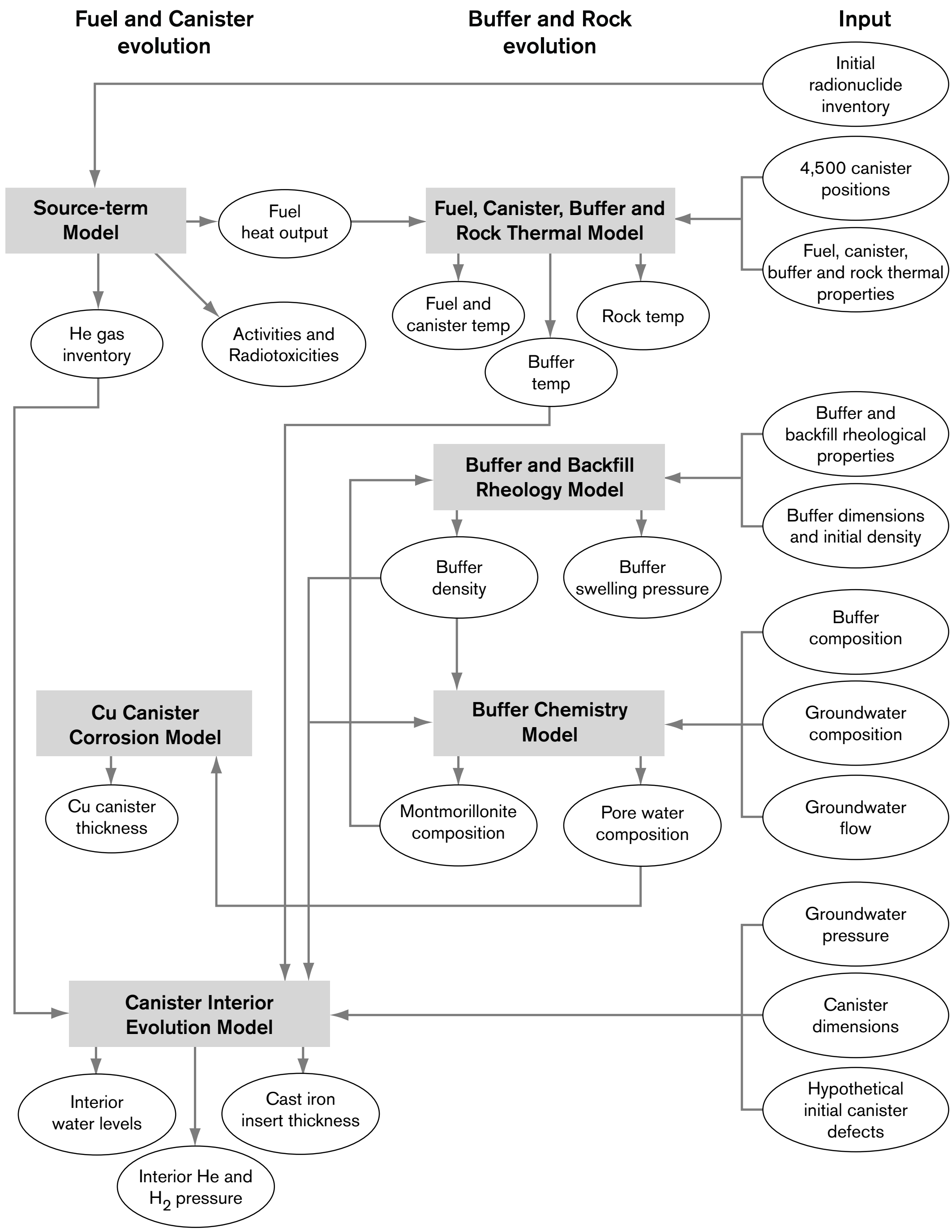


Figure 14-1. System model with submodels represented as rectangles. Input data and time-dependent calculation results are shown as ellipses.

14.2.2 Radionuclide transport and dose

Radionuclide transport calculations are performed in order to estimate the risk of environmental and health effects from a repository. Since many of the parameters in this type of calculation either have a natural variability or are incompletely known, probabilistic calculations are performed where the model parameters are permitted to vary in accordance with some kind of prescribed probability distribution. In SKB's previous safety assessments, transport calculations have been carried out with a probabilistic computational chain that includes transport through the near-field and far-field and dose calculations in the biosphere. These probabilistic calculations utilize the results of other simulations for parts of the input database. Figure 14-2 shows the interaction between the different models intended to be used in the SR-Can calculations, along with calculation modules for transport calculation (for near-field, far-field and biosphere). The figure also shows how these modules are linked to other calculation tools and what data the different models require. These data can be given as probability distributions for most input parameters. These probability distributions may be based on e.g. experimental data or on the result of a previously performed calculation which, for different reasons, may not be suitable to incorporate in the probabilistic transport calculation chain.

Time-consuming groundwater flow calculations based on interpretations and modellings of site-specific borehole data will be carried out in a separate code (Connectflow or DarcyTools) and used in different ways in the transport models. Correlated probability distributions from flow calculations are used as input data for the radionuclide transport models for the near-field, the far-field and the biosphere.

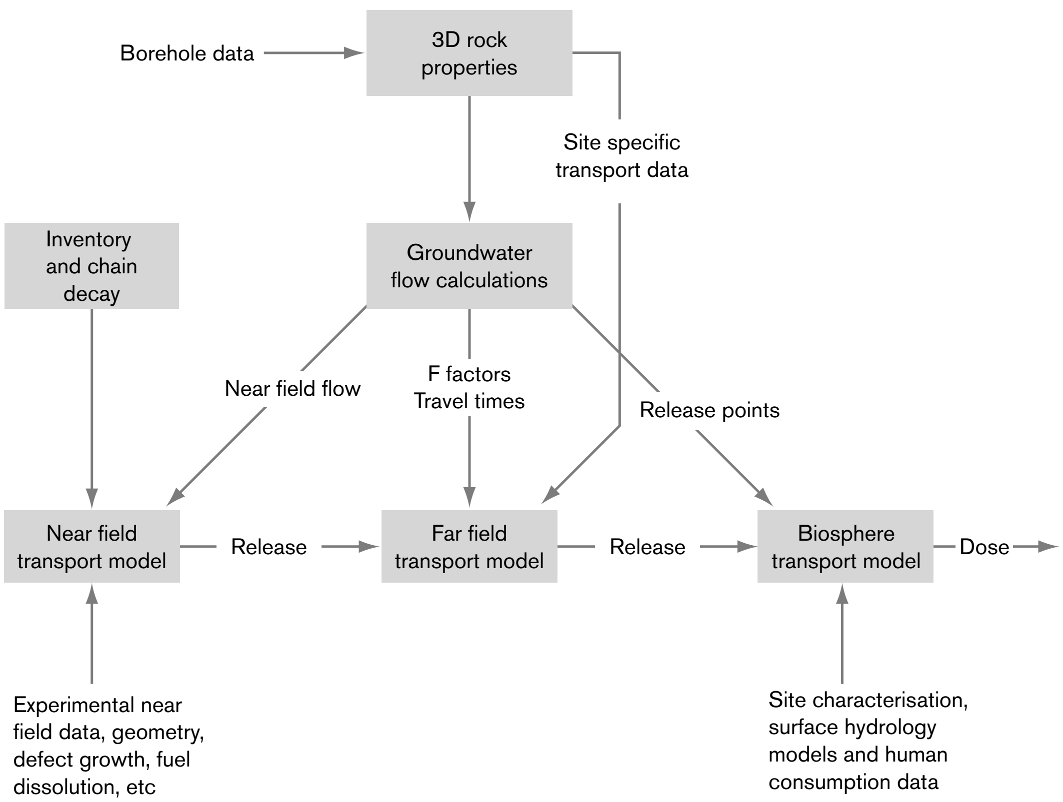


Figure 14-2. *Schematic illustration of different sub-models in the radionuclide transport calculation.*

Recently, simplified analytical versions of the near- and far-field transport models have been developed /14-6/. These models use the same input data as the corresponding numerical models and doses are calculated by means of ecosystem-specific dose conversion factors. The models can be executed probabilistically and yield results in good agreement with the deterministic and probabilistic calculation cases in SR 97. A single realisation with the analytical models runs in about 0.1 second on a 2 GHz personal computer, making them well suited for extensive probabilistic calculations. The analytical models will be used as a complement to the numerical models in coming safety assessments, in particular for early scoping calculations and for complementary probabilistic calculations.

The following sections briefly describe the platforms for the numerical radionuclide transport calculations and the numerical models of the near-field, the far-field and the biosphere.

Platforms for radionuclide transport calculations

Radionuclide transport calculations in SKB's safety assessments have been performed with the Proper package (SKB 91, SR 95 and SR 97). The Proper package, written in Fortran 77, consists of a number of sub-modules that handle the transport calculation, see Figure 14-2. The near-field transport calculation is handled by the Proper sub-module Comp23 /14-7/, the far field by Farf31 /14-8/ and the biosphere by Bio42. The Proper environment not only has centralized communication between the different modules, but also routines for performing deterministic simulations and libraries with tools for numerical calculations (Numlib). In addition, the environment contains sub-modules for communication with the groundwater flow model, weighting and summation of time series (Sum41) and communication with ASCII files outside Proper (TS01 and Pick51).

As a complement to the Proper package, an alternative software package, Tensit, that runs on a desktop PC is under development. Tensit can be used in parallel with the Fortran77/Unix version of Proper in the safety assessment calculations. The PC version, which is based on the same conceptual models as the Proper package, has been developed separately from the Fortran77/Unix version and is written as a Matlab program. Matlab is a widely used tool in numerical calculations and offers a wide selection of mathematical functions, a script language and a graphical environment, Simulink, where models can easily be built and where different sub-modules can be connected together in a simple and intuitive way. Both Matlab and Simulink are widely used, both in the university world and in industry, which is helpful since it means personnel with the necessary programming know-how and skills are trained and leads to continuous maintenance of the code. A large number of users should also increase the likelihood that any errors in the code's computational routines will be discovered. Simulink's graphical interface enables the total quantity of program code to be reduced. This, in combination with Matlab's built-in numerical calculation routines, simplifies review and development of the different models (especially for persons outside the development group).

At present the near-field calculation has been fully implemented in Matlab and Simulink, which means that calculations equivalent to those handled by the Comp23 sub-module can be run in Tensit. A ported version of the Fortran77 code that is used in Proper, with an interface that enables the code to be used as a Matlab function, is used for migration calculations in the far-field. The biosphere module has been developed into a considerably more versatile tool. While the Proper module uses dose conversion factors calculated by an external code, the Matlab version can either calculate dose conversion factors in advance or perform time-dependent biosphere calculations as part of a probabilistic computational chain.

In addition to the Matlab package, the PC version can use the commercially available risk analysis code @Risk for probabilistic analyses. @Risk can generate a large number of probability distributions, perform probabilistic simulations and run external programs like Matlab. Moreover, the combination Matlab/@Risk provides a transparent environment for safety assessment calculations.

At present, the computational time for a single Comp23 realization with the Fortran77/UNIX version (on the 400 MHz Sun Enterprise 450 that was used in SR 97) and the Matlab/PC version (on an Intel 1,700 MHz Compaq Deskpro workstation) is of the same order of magnitude (a couple of minutes) for runs with the nine nuclides used in probabilistic calculations for SR 97. The far-field and biosphere modules give insignificant realization times in comparison with the near-field model. Due to the high portability of the Matlab code (Matlab is available on a large number of platforms, for example Macintosh OS X and several Unix versions), the Matlab implementation can, with little effort, be run on another platform if the capacity of the PC platform should for any reason be judged to be insufficient.

Figure 14-3 shows a comparison between doses calculated with the Proper modules for radionuclide transport and with the analytical model.

The near-field model

The near-field model Comp23 will be used in SR-Can. This is the same model as was used in SR 97 and it was originally developed from the Nuctran code /14-7, 14-9/. Comp23 is a multiple transport pathway model that calculates transient nuclide transport in the near-field of a repository as occurring through a network of resistances and capacitances connected together in analogy with an electrical circuit network. Analytical solutions are included instead of fine discretization at sensitive zones, for example at the release point from a small hole in the canister and at the entrance to fractures, in order to speed up the calculations. While the Comp23 model used in SR 97 only was able to handle radionuclide transport by diffusion, the present version has been modified so that advective transport can also be simulated. A further development since SR 97 is that all nuclides of a certain element can now share the element's solubilities inside the canister, where solubility limitations are imposed on radionuclide concentrations.

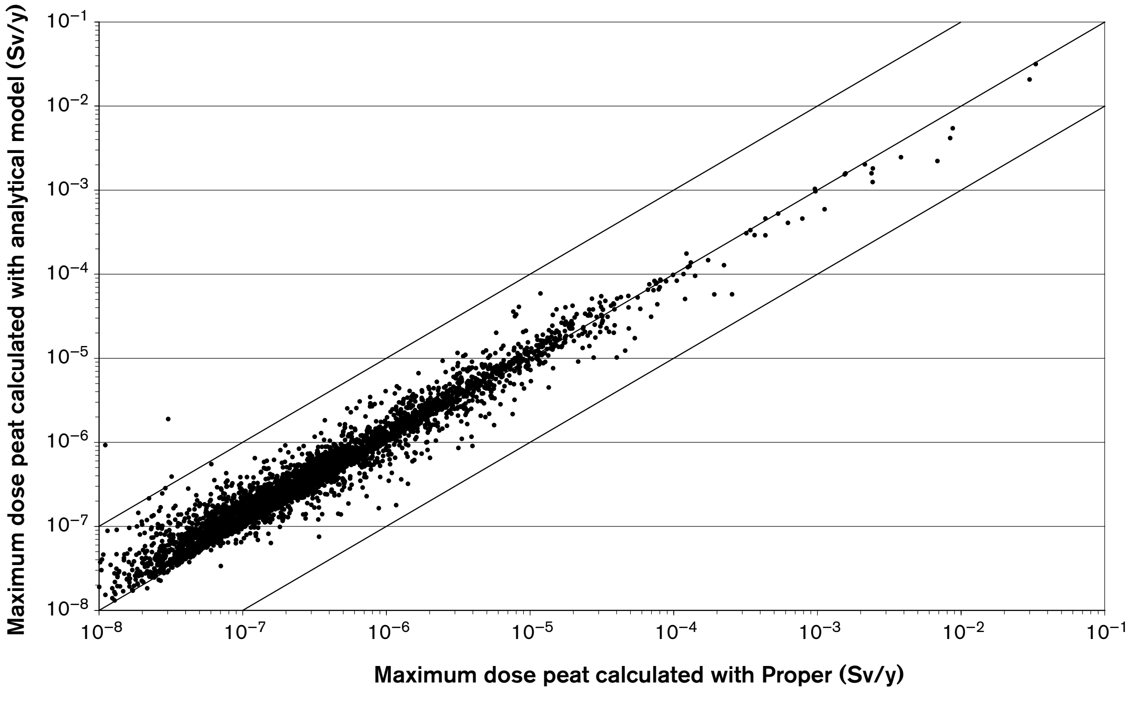


Figure 14-3. *Comparison between doses calculated with the Proper modules and the analytical module. Maximum dose up to a million years after closure of the repository with release to peat bog in 5,000 probabilistic realizations. The deviations within the bounding lines are less than a factor of 10.*

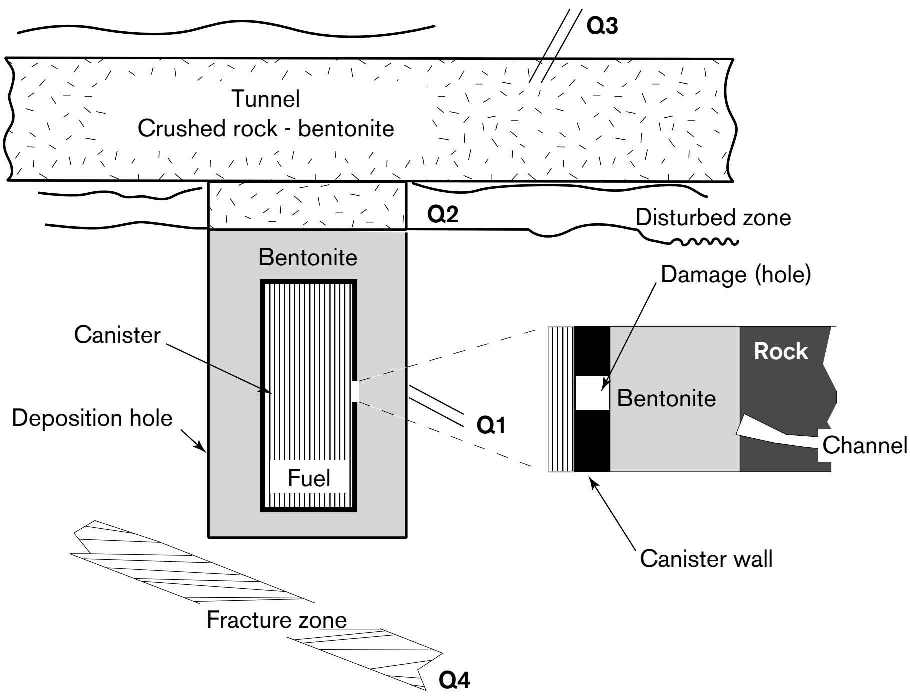


Figure 14-4. *Schematic view of the near-field, with the transport pathways used in SR 97.*

Figure 14-4 shows how the deposition holes and the backfill in the deposition tunnel were modelled in SR 97. In the model, four different flow paths, Q1–Q4, were used for the interface between near-field and far-field.

To represent the barrier system through which radionuclides are transported, Comp23 makes use of an integrated finite difference method and the compartment concept.

The far-field model

The far field model for SR-Can is similar to the one used in SR 97. This model, Farf31, /14-8/ calculates the transport of dissolved radionuclides through fractured rock, the retention caused by interactions between the nuclides and the rock matrix, and radioactive chain decay.

The biosphere model

Radionuclide transport through the biosphere and doses to man were handled in SR 97 by the Proper sub-module Bio42. This module was based on nuclide- and ecosystem-specific dose conversion factors (EDFs), which convert nuclide releases to an ecosystem into doses. In SR 97, the EDFs for the six ecosystems considered (well, lake, river, peat, soil, coast) were calculated in a separate code /14-10/ using generic data for the ecosystem parameters. The different ecosystems were represented by compartment models where each compartment corresponded to a distinct part of an ecosystem. Figure 14-5 shows the example of a peat bog modelled as two compartments, representing nuclides dissolved in water and nuclides sorbed to organic and/or solid material, respectively. The nuclide exchange between the two compartments was modelled using ecosystem- and element-specific distribution coefficients (K_d). In the modelled peat bog, Figure 14-5, both nuclide inflow and outflow take place in the soluble phase and are therefore controlled by the water balance. Depending on the water exchange at the studied site, in- and outflow may take place to other ecosystem models, inflow may take place from release points from the geosphere's streamtubes, or outflow of nuclides may take place from the model domain. However, in SR 97, only single ecosystems were considered with inflow only from release points from streamtubes.

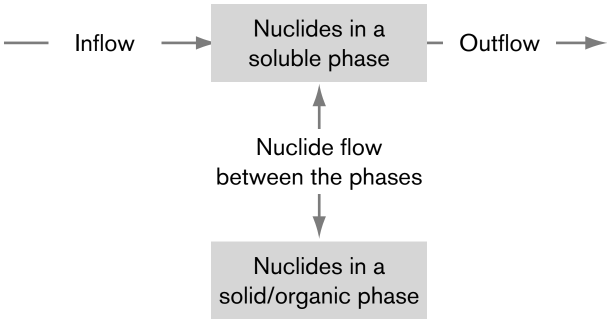


Figure 14-5. *Compartment model of a peat bog.*

In SR-Can the site will be better known and the basis for modelling the ecosystem and interactions between different ecosystems will be improved. Figure 14-6 shows how a downstream nuclide transport can be handled in the biosphere model if the water flow at the site is known. In the sketch, nuclides are assumed to enter a peat bog, which can be modelled as indicated in Figure 14-6, via the groundwater. The radionuclide outflow from this model is shown as inflow to, for instance, a running water model and later to a lake model etc. In contrast to the models used in SR 97, humans may be exposed to nuclides from all modelled ecosystems at the same time, for example to radionuclides from peat combustion, irrigation of agricultural land by stream water and consumption of aquatic foodstuff from a lake.

The biosphere calculations in SR 97 were performed in a separate code and imported to the Proper package as probability distributions. In SR-Can, the biosphere transport calculation will be performed in the Matlab/Simulink version of the safety assessment code. Biosphere simulations can either be performed as part of a probabilistic computational chain or separately with nuclide releases taken from each realization of the near- and far-field modules. EDFs will also be calculated in SR-Can.

As a complement to the compartment-based biosphere models used in SR 97, work is under way to implement so-called process models in the biosphere simulation tool, see section 20.4. These models are based on considerations of energy and nutrition balances and can also be used to generate input data to the compartment models. By using the Matlab/Simulink package for simulation, it is possible to use these models in combination with previously existing compartment models and thereby perform more complex simulations.

Figure 14-6. *Coupling of biosphere modules for radionuclide transport.*

15 Fuel

The spent fuel that will be emplaced (deposited) in the repository comes from nuclear power plants. For an alternative with 40 years of reactor operation, the quantity of BWR fuel is estimated to be 7,200 tonnes and the quantity of PWR fuel 2,300 tonnes /15-1/. 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. The differences between different fuel types are more important when it comes to assessing criticality. The assessments are therefore made with the fuel types that are least favourable with respect to criticality.

15.1 Initial state in fuel/cavity

15.1.1 Variables

For 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, into which water can penetrate if there is a defect in the copper canister. Processes such as fuel dissolution and corrosion of the cast iron insert will then take place in the cavity. 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 15-1.

The initial state, i.e. the value these variables were assumed to have at the time of deposition, was described in the main report of SR 97, section 9.2 /15-2/. The research programme around the initial state for the different variables in the fuel is described in the following.

Table 15-1. Variables in 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 α, β, γ 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.

15.1.2 Geometry

The deep repository will contain fuel of various types and geometries.

Conclusions in RD&D 2001 and its review

SKB announced its participation in the EU project SFS (Spent fuel stability under repository conditions), which was started for the purpose of conducting research on detailed geometry, crack distribution and fission product distribution, and their evolution with time.

No direct viewpoints were offered on this by the authorities.

Newfound knowledge since RD&D 2001

The SFS project is not yet concluded. A final evaluation of the project and a report on the results will not be available until the end of 2004. SKB has had an independent expert conduct a critical review of these issues /15-3/. The conclusions are that there is no reason at present to assume that the geometry of the fuel will undergo decisive changes over long periods of time.

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.

15.1.3 Radiation intensity

The radiation intensity is dependent on the radioactivity, i.e. the inventory of radionuclides and the geometry of the fuel. Both of these are well-known, and the dose rate can be calculated with sufficient accuracy for the needs of the safety assessment.

Conclusions in RD&D 2001 and its review

There was no research programme on this process in RD&D 2001, and no direct viewpoints on this were offered in the review.

Newfound knowledge since RD&D 2001

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.

15.1.4 Temperature

The critical interface in the canister is the transition between the cast iron insert and the copper shell. The copper's emissivity is of crucial importance.

Conclusions in RD&D 2001 and its review

Heat transfer between the canister surfaces, especially the thermal emittance of the copper, needs to be determined so that better calculations of the temperature distribution inside the canister can be performed.

SKI would like to see a more detailed description of the studies of emissivity and temperature evolution in the canister, but is positive to the fact that SKB is planning to use such studies in order to develop design requirements for the canister surfaces.

Newfound knowledge since RD&D 2001

Uppsala University has measured the thermal emittance of a small number of copper specimens taken from those parts of the canister which have undergone all the steps in the fabrication process, including the sealing weld. Despite the fact that the welds exhibited oxidation clearly visible to the eye, the emissivity in the infrared range was low (0.06–0.11). The values are not expected to change during the time it takes to achieve full water saturation in the buffer in the deposition hole. After full water saturation, the thermal emittance is of no importance.

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.

15.1.5 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.

15.1.6 Mechanical stresses

Conclusions in RD&D 2001 and its review

Some activities are planned within the framework of the EU project SFS, in which SKB is also participating, see section 15.1.2. No direct viewpoints were offered in the review.

Newfound knowledge since RD&D 2001

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.

15.1.7 Total radionuclide inventory

Conclusions in RD&D 2001 and its review

SKI has called for a validation of calculation models for certain nuclides (for example ^{36}Cl, ^{79}Se and ^{126}Sn) as well as an account of the importance of other burnups and fuel types, for example Mox fuel. SKI also requests an account of the total inventory of radionuclides as a function of time and space in all parts of the fuel assembly.

Newfound knowledge since RD&D 2001

In SR 97, radionuclide inventories were calculated for burnups of 38 and 55 MWd/kgU for BWR fuel and 42 and 60 MWd/kgU for PWR fuel. The uncertainties in the calculations were discussed in /15-4/. In the calculations for SR 97, however, only inventories from BWR fuel with a burnup of 38 MWd/kgU were used. The differences in nuclide inventory with respect to burnup are often small. Figure 15-1 shows the inventory of radionuclides for different burnups (normalized to BWR 38 and corrected for decay heat). Table 15-2 shows a comparison of the calculated inventories of radionuclides in SR 97 in the Swiss Project Opalinus and the Belgian Safir-2.

It is clear from the data that neither assumed burnup nor calculation tool has any decisive influence on the calculated inventory.

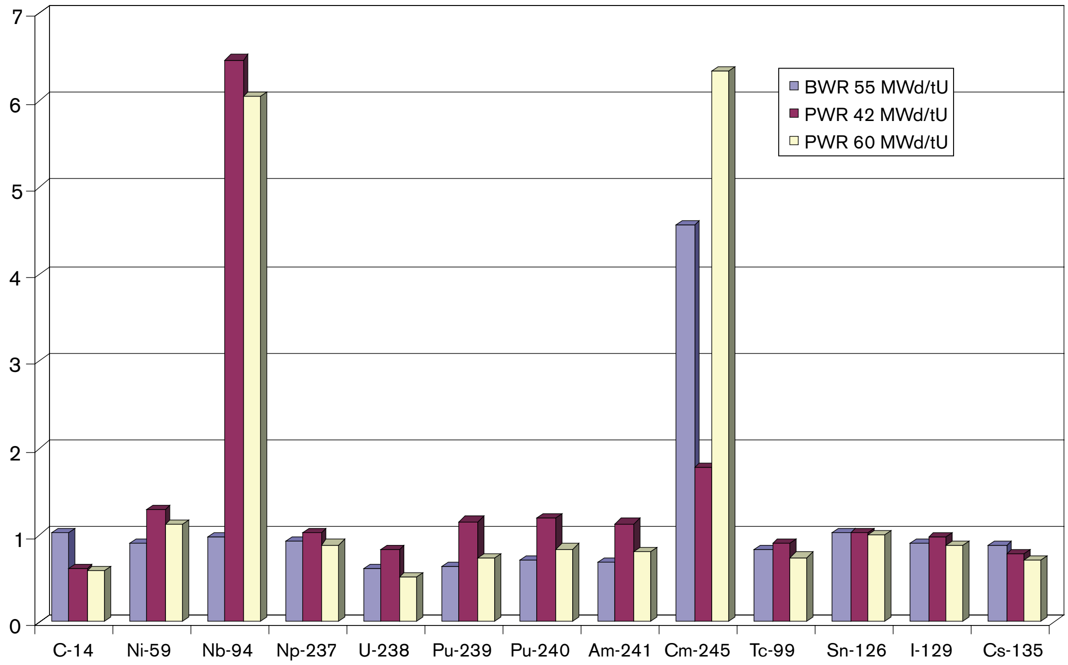


Figure 15-1. *Inventory of radionuclides normalized to BWR 38 and corrected for decay heat 30 years after removal from reactor.*

Table 15-2. Comparison of calculated inventories (SKB's values are interpolated).

Nuclide	Nagra PWR-48	SKB PWR-48	Safir PWR-45
^{14}C	6.40 10^{10}	4.20 10^{10}	1.93 10^{10}
^{36}Cl	1.10 10^{9}	1.16 10^{9}	2.75 10^{9}
^{60}Co	4.70 10^{11}	2.97 10^{12}	
^{59}Ni	8.00 10^{10}	1.52 10^{11}	1.60 10^{11}
^{63}Ni	8.50 10^{12}	1.70 10^{13}	1.75 10^{13}
^{79}Se		3.38 10^{9}	2.04 10^{10}
^{85}Kr	1.70 10^{14}	3.20 10^{13}	
^{90}Sr	1.40 10^{15}	1.36 10^{15}	1.06 10^{15}
^{99}Tc	7.00 10^{11}	6.75 10^{11}	6.29 10^{11}
^{129}I	1.70 10^{9}	1.73 10^{9}	1.61 10^{9}
^{135}Cs	2.50 10^{10}	2.19 10^{10}	2.17 10^{10}
^{137}Cs	2.20 10^{15}	2.27 10^{15}	1.62 10^{15}
^{230}Th	2.20 10^{7}		5.42 10^{6}
^{232}U	1.30 10^{8}		
^{234}U	6.40 10^{10}	4.98 10^{10}	2.17 10^{10}
^{235}U	6.90 10^{8}	4.80 10^{8}	5.64 10^{8}
^{238}U	1.10 10^{10}	1.15 10^{10}	1.17 10^{10}
^{237}Np	2.00 10^{10}	2.05 10^{10}	1.97 10^{10}
^{238}Pu	1.50 10^{14}	1.65 10^{14}	1.21 10^{14}
^{239}Pu	1.40 10^{13}	1.30 10^{13}	1.34 10^{13}
^{240}Pu	2.30 10^{13}	1.74 10^{13}	2.17 10^{13}
^{241}Pu	9.40 10^{14}	1.09 10^{15}	5.86 10^{14}
^{242}Pu	1.10 10^{11}	1.48 10^{11}	1.11 10^{11}
^{241}Am	1.80 10^{14}	2.12 10^{14}	1.95 10^{14}
^{242}Cm	3.30 10^{11}	4.21 10^{11}	
^{244}Cm	4.80 10^{13}	1.00 10^{14}	3.25 10^{13}

Programme

The intention is to supplement the report /15-4/ with information on Mox fuel and possibly some other type of fuel. The alternative would be to recalculate nuclide content, activity and decay heat for "standard BWR and PWR" as well as Mox, but it is uncertain whether this would provide any additional information. It would, however, be an advantage if the calculations were done in the same way, and this would provide new material for comparison.

In order to be able to perform all the different types of calculations that will be needed, it is important to define a model canister with a standard nuclide content so that the canister's decay heat output is 1,700 W.

15.1.8 Gap inventory

Conclusions in RD&D 2001 and its review

Experiments in a hydrogen gas environment with fuel pellets of varying burnup and irradiation history were planned. If possible, such pellets were to be used where the release of fission gas had already been determined.

SKI proposed studies of the occurrence of radionuclides as a function of time and space in the gap and grain boundaries.

Newfound knowledge since RD&D 2001

Tests where a hydrogen-saturated solution is forced through fuel pellets proved to be complicated and require great resources. They are therefore still under planning and development. Various methods for sealing fuel pellets have been tested during the period, and analysis methods for certain readily soluble radionuclides have been described in preparation for a more systematic study.

Programme

The method needs to be further tested. If the results are promising, a systematic study of the gap inventory as a function of burnup and other fuel parameters will be started.

15.1.9 Material composition

Conclusions in RD&D 2001 and its review

SKB decided to conduct a study of the importance of non-radioactive fission products prior to the next safety assessment. No direct viewpoints on this were offered in the review.

Newfound knowledge since RD&D 2001

No new knowledge has been forthcoming.

Programme

The strategy remains as outlined in RD&D 2001.

15.1.10 Water composition

Under deposition conditions where water occurs in vapour form, see section 15.1.11 below.

15.1.11 Gas composition

Conclusions in RD&D 2001 and its review

RD&D 2001 did not include any research programme for this area, and no direct viewpoints were offered in the review.

Newfound knowledge since RD&D 2001

The largest quantity of water in a canister reported in previous research programmes was 50 grams. This may be an optimistic figure, and 600 grams has now been given as a realistic upper limit.

Programme

The consequences of more water entering the canister must be studied. By filling the canister with argon (section 8.1.1), the gas composition inside the canister can be changed from air and water vapour to an inert gas and water vapour, see also section 15.2.9.

15.2 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.

15.2.1 Overview of processes

The radionuclides in the fuel will eventually be transformed into non-radioactive substances by radioactive decay. 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. The temperature in the fuel is changed by heat transport in the form of conduction and radiation, 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 cladding tubes in the fuel.

In an intact canister, radiolysis of residual gases in the cavity will lead to the formation of small quantities of corrosive gases, which could contribute to stress corrosion cracking (SCC) of the cast iron insert.

If the copper canister is not intact, water may enter the canister cavity, radically altering the chemical environment. Radiolysis of the water in the cavity 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 void. This is determined by the chemical conditions in the canister cavity. 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 cavity. 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.

15.2.2 Radioactive decay

Conclusions in RD&D 2001 and its review

SKB decided to carry out a quality review of data on half-lives for all radionuclides of interest in the safety assessment.

No direct viewpoints on this were offered in the review.

Newfound knowledge since RD&D 2001

No new knowledge has been forthcoming.

Programme

As stated in RD&D 2001, the quality review of data on half-lives for all radionuclides of interest in the safety assessment will be carried out by the next safety assessment, i.e. SR-Can.

15.2.3 Radiation attenuation/heat generation

Conclusions in RD&D 2001 and its review

No research programme for this area was included in RD&D 2001, and no direct viewpoints were offered in the review.

Newfound knowledge since RD&D 2001

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.

15.2.4 Induced fission (criticality)

Conclusions in RD&D 2001 and its review

SKB decided to carry out the evaluation of uncertainties in necessary data in order to be able to take into account the lanthanides in the fuel in judging the risks of criticality.

SKI said that they are positive to the fact that SKB is continuing to evaluate the uncertainties in its assessment of criticality. However, SKI agreed with SKB that criticality is not probable, provided that the adequate fuel burnup has been achieved and there is no change in geometry.

Newfound knowledge since RD&D 2001

Completed criticality studies show that it is possible with current knowledge and reasonable estimates of uncertainties to show with the aid of burnup credit that criticality cannot occur in the fuel in the canister /15-5/.

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.

15.2.5 Heat transport

Dealt with in section 15.1.4.

15.2.6 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 16.2.

15.2.7 Thermal expansion/cladding failure

Conclusions in RD&D 2001 and its review

No research programme for this area was included in RD&D 2001, and no direct viewpoints were offered in the review.

Newfound knowledge since RD&D 2001

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.

15.2.8 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. Transport of radionuclides in the near-field is dealt with in section 18.3.

15.2.9 Residual gas radiolysis/acid formation

Conclusions in RD&D 2001 and its review

No research programme for this area was included in RD&D 2001, and no direct viewpoints were offered in the review.

Newfound knowledge since RD&D 2001

The canisters may contain more water (600 grams) than has previously been assumed (50 grams).

Programme

Radiolysis calculations will be carried out to determine whether the canister must be filled with an inert gas in order to prevent radiolytic formation of nitric acid.

15.2.10 Water radiolysis

Conclusions in RD&D 2001 and its review

SKB decided to study iron corrosion in initially oxygen-free water under gamma irradiation. No direct viewpoints were offered in the review.

Newfound knowledge since RD&D 2001

No new knowledge has been forthcoming.

Programme

The investigation of iron corrosion in initially oxygen-free water under gamma radiation is still under way and will be concluded during 2005, see also section 16.2.8.

15.2.11 Metal corrosion

This section concerns corrosion of cladding tubes and metal parts in the fuel.

Conclusions in RD&D 2001 and its review

No research programme for this area was included in RD&D 2001, and no direct viewpoints were offered in the review.

Newfound knowledge since RD&D 2001

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.

15.2.12 Fuel dissolution

Conclusions in RD&D 2001 and its review

Both SKI and Kasam state that the fuel programme has shown positive progress in recent years and has largely been conducted in a manner that is appropriate in relation to the needs of the safety assessment. The results reported by SKB so far provide a necessary basis for the development of a credible and realistic fuel model that allows for a significant barrier function. In SKI's opinion, more experiments and better models that explain the results of the experiments are needed. SKB should study how fuel dissolution is affected by different degrees of exposure (to groundwater), and by canister and buffer damage. SKB should ask itself whether it is possible to take credit for the hydrogen gas from corrosion for very long times in the safety assessment. SKI would like to see a discussion of the influence of other hydrogeochemical parameters (salinity, pH, carbonate concentration etc) and whether they are adequately covered by the experimental programme. SKI welcomes the fact that SKB has taken the initiative to obtain better experimental data for instant release of radionuclides. Kasam judges that the research programme on fuel dissolution, which was of a generally orientational nature to begin with, needs to be focused on the conditions that will exist inside the canister according to the results of analyses.

Newfound knowledge since RD&D 2001

The results described here come from SKB's own research programme and from our participation in two projects within the EU's Fifth Framework Programme (SFS and InCan).

Fuel leaching under different redox conditions

The redox condition is the most important factor for fuel dissolution, and special attention has been devoted to it in recent years. The measurements of the redox potential have given us a better understanding of the expression "anoxic conditions" and the difficulties associated with simulating the repository environment in the laboratory. Oxygen is present in the air around us, but in the anoxic experiments the partial pressure of oxygen must be virtually zero. This is difficult to achieve in practice. Traces of oxygen tend to diffuse in due to the big difference in partial pressure outside and inside the experiment. Despite flushing with inert gas or the use of glove boxes filled with inert gas, the conditions in the experiments tend to be more oxidizing than in the repository.

In order to be able to distinguish the effect of radiolytic oxidation caused by radiation in the experiments with spent fuel, it is necessary to reduce the influence of oxygen contamination. Only then is it possible to observe the influence of different reducing components. The results of experiments involving dissolution of a fuel rod in an argon atmosphere are reported in /15-6/. The use of metal tubes, glass-metal welds and better seals in the measurement system reduced the inward diffusion of contaminating oxygen. It could then be observed how radiolysis alone contributes to an oxidative dissolution of the fuel. After 280 days, two small metal foils of iron and copper were added to simulate the influence of the canister's different materials. The fission products caesium, molybdenum and strontium continued to leach out (Figure 15-2), while the concentrations of uranium, neptunium and technetium fell. This shows that despite the strong radiation, the contact with iron creates reducing conditions.

Two other ways of avoiding contamination with atmospheric oxygen have also been tried: use of an oxygen trap and inert gas under high pressure /15-7/. In the first case, an oxygen trap with saturated iron(II) carbonate solution was placed in the same closed inert-gas-flushed space as the test vessel /15-8/. In the second case, a sturdy and well-sealed pressure vessel was used, where any leakage can easily be checked via changes in the pressure. No leakage may be tolerated, since tests have shown that even if inert gas flows out of the vessel it is possible for oxygen to diffuse in upstream /15-9/.

The term "reducing conditions" should not be used indiscriminately for all experiments with hydrogen-saturated solutions. For even though the hydrogen is potentially highly reducing, it is also kinetically inert at normal temperatures. This, along with the importance of the negative redox potentials measured in hydrogen solutions, is discussed in /15-9/.

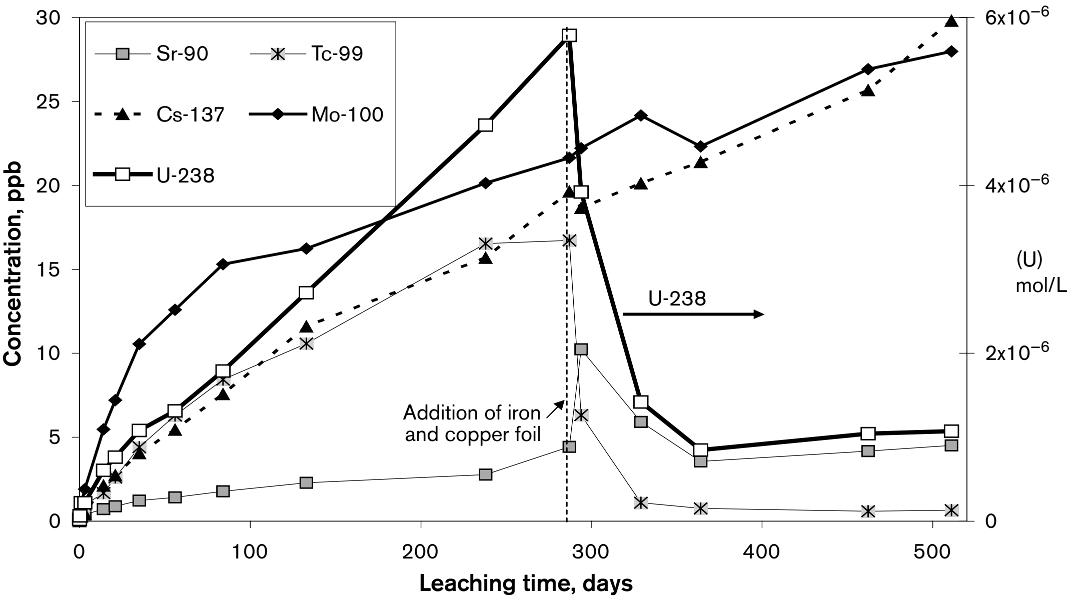


***Figure 15-2**. Measured concentrations of ^{238}U and the fission products ^{137}Cs, ^{90}Sr, ^{99}Tc and ^{100}Mo as a function of leaching time. The concentrations of ^{238}U are shown on the right-hand axis in mol/l. The vertical dashed line shows the time for introduction of iron and copper electrodes (each with a surface area of about 30 mm^2).*

A study has been conducted in cooperation with Posiva of the mechanism for dissolution of pre-oxidized gadolinium-doped uranium dioxide /15-10/. The results show that release of hexavalent uranium in the solution causes an increase in the lattice parameter for uranium dioxide, which suggests that the whole matrix is enriched in tetravalent uranium.

In the EU project In Can Processes (InCan), the dissolution of uranium dioxide was studied with the aid of isotope dilution. This method can be used to measure the dissolution rate even if precipitation occurs /15-11/.

Under oxidizing conditions, unirradiated uranium dioxide from different suppliers was found to have different dissolution rates and give rise to different concentrations of uranium in solution. We believe that this may be a result of differences in the sintering process. The concentrations after extended exposures were between 9 and 13 ppm and showed clear signs of simultaneous dissolution and precipitation in a quasi-steady state. Corrosion experiments under actively reducing conditions showed an initial pulse followed by precipitation and low levels of the uranium concentration after a few days. The concentration of uranium in solution was then less than $4 \cdot 10^{-11}$ mol/l. This is lower than predicted by available data on uranium solubility.

Experiments were also conducted with uranium dioxide that contained 5 and 10 percent uranium-233. These materials have an alpha activity equivalent to that of spent fuel 10,000 and 3,000 years after deposition in a deep repository. It has been assumed that fuel corrosion under reducing conditions can be affected by radiolysis of the water due to alpha radiation. Radiolysis would create local oxidizing conditions at the fuel surface and thereby increase the dissolution rate. No sign of this was seen in the experiments that were conducted within the framework of the InCan project. All samples had uranium concentrations of less than 0.02 ppb, i.e. the same as undoped samples. By adding a solution of enriched uranium-235, it was possible to see that the uranium concentration in an experiment that lasted a month was around 0.005 ppb.

Experiments were also conducted with fuel samples from previous studies. The samples were equilibrated for six months in groundwater with low ionic strength in a 10 bar hydrogen atmosphere to create anaerobic and preferably reducing conditions. The solution was then exchanged for fresh oxygen-free groundwater and a solution enriched in uranium-235 was added. More was added than desirable (the total concentration of uranium after addition was 40 to 125 ppb) and precipitation started immediately. After a week the uranium concentrations were 20 to 50 ppb, and after 18 days they were 6 to 15 ppb. Despite ongoing precipitation, it could be seen from the changes in the isotope ratios that the spent fuel continued to dissolve at a rate of 0.2 to 0.3 ppb per day. This may be due to the effects of beta and gamma radiation.

Influence of hydrogen on dissolution of fuel

Hydrogen is expected to be present in large quantities during long periods of time in a damaged canister with a hole of limited size. This is because hydrogen gas is produced by anoxic iron corrosion at a higher rate than the rate of mass transport by diffusion outside the canister /15-12, 15-13/. The first results from fuel dissolution in stainless autoclaves under a hydrogen pressure of 50 bar showed that hydrogen has a great influence on fuel dissolution /15-14/. The concentrations of actinides and fission products during the entire test period were very low and constant within analytical margins of error, which suggests very low fuel dissolution rates. Even though the concentrations of dissolved hydrogen in the autoclave (approximately 40 mM) were many orders of magnitude higher than the concentrations of redox-sensitive radionuclides and radiolytic oxidants, hydrogen gas is expected to be chemically inert at low temperatures. There are, for example, figures in the literature that indicate that hexavalent uranium /15-9/, heptavalent technetium /15-15/ and pentavalent neptunium /15-16/ are not reduced in the presence of dissolved hydrogen at room temperature.

In order to prevent all contact between the leachant and metal surfaces and thus avoid discussing their influence, a new test was performed in autoclaves with internal quartz surfaces under a hydrogen pressure of five bar /15-17/. The results of analyses of the

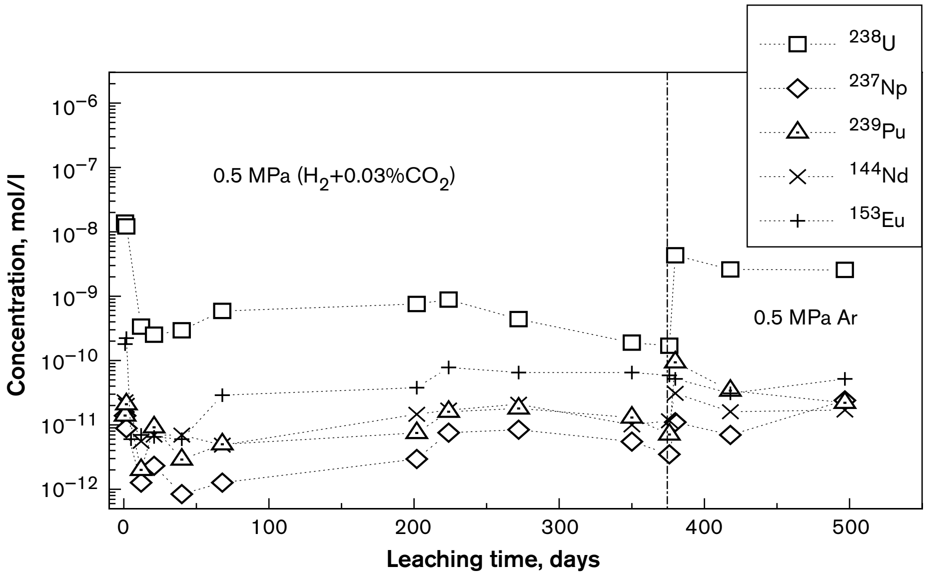


***Figure 15-3**. Measured concentrations of actinides (U, Pu, Np) and lanthanides (Eu, Nd) as a function of the time for leaching of spent fuel powder in a 10 mM NaCl, 2 mM $NaHCO_3$ solution and either 0.5 MPa hydrogen mixed with 0.03 percent carbon dioxide or only 0.5 MPa argon.*

concentrations of actinides and lanthanides in solution samples taken at different points in time (Figure 15-3) show similar values as in the stainless autoclave. Investigation of the behaviour of redox-sensitive nuclides such as uranium, technetium and neptunium during the first days (which were missed before) showed that their already low starting concentrations declined with time. This suggests that they are reduced, which is also found in other studies /15-18, 15-19/. The fact that only low concentrations of radionuclides were measured in autoclave solutions /15-19/ indicates that this reduction takes place at the surface of the fuel.

Another goal of the study was to follow and understand what happens with oxygen that is generated by radiolysis of water in hydrogen-saturated solutions. A gas sample taken from the autoclave after 356 days and analyzed by mass spectrometry showed oxygen concentrations below the detection limit (approx. 50 ppm or $5 \cdot 10^{-8}$ mol/l). The same results were found in another, independent study /15-20/. When these data are compared with the high oxygen concentrations measured in similar tests and during similar time periods /15-21/ but under an argon atmosphere (Figure 15-7), plus the extremely low concentrations of uranium and other experimental observations, it can be concluded that radiolytic oxidants must be consumed by hydrogen under such conditions and that no measurable oxidative dissolution of fuel occurs /15-17/. This is confirmed by an analysis of the released fraction of fission products, such as strontium-90 (Figure 15-4). This was not noticed in stainless autoclaves, and one explanation may be that despite all efforts to avoid contamination with air, the gas analysis showed that there was nitrogen in the autoclave /15-17/. But since corresponding oxygen quantities would have caused a nearly tenfold higher increase of the concentrations of strontium-90 if the oxygen had only been consumed to oxidize the fuel surface, this indicates that dissolved hydrogen consumes not only radiolytic oxidants, but also the oxygen from air contamination.

These and other experimental data suggest that hydrogen must be activated under experimental conditions in order to be able to consume oxidants from radiolysis and oxygen from air contamination, and cause reduction of radionuclides.

There are two possible ways to activate hydrogen under experimental conditions: either by reactions with radicals from radiation-induced radiolysis, or by reaction with fuel surfaces (uranium dioxide surfaces and/or metallic particles in the fuel).

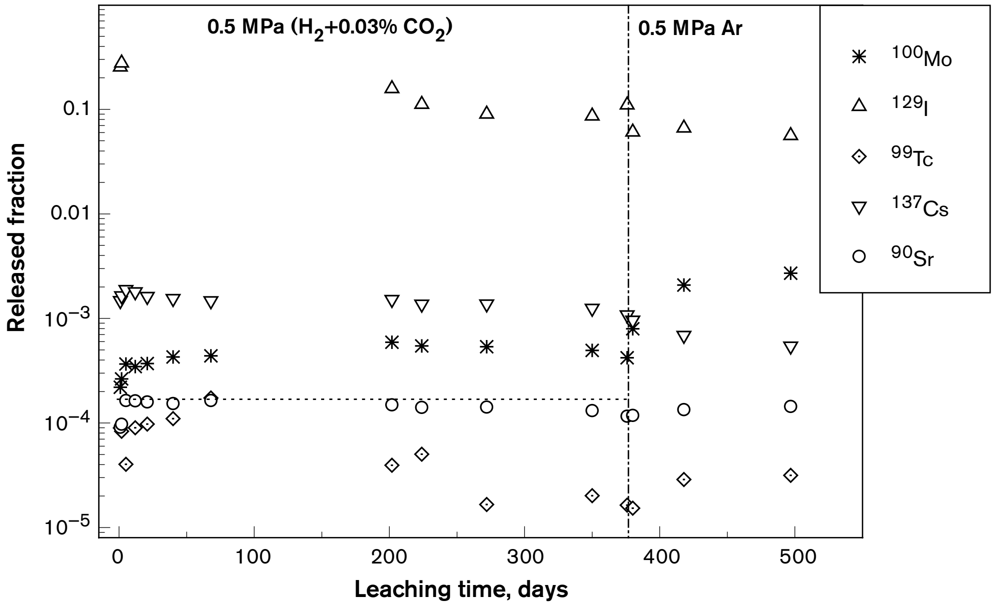


Figure 15-4. *Released fraction of the fission products Sr, Cs, I, Tc and Mo as a function of the time for leaching of spent fuel in powder form in a 10 mM NaCl, 2 mM $NaHCO_3$ solution with either 0.5 MPa hydrogen mixed with 0.03 percent carbon dioxide or only 0.5 MPa argon.*

It is difficult to determine the relative importance of these factors or their combined effects solely on the basis of tests with spent fuel in hydrogen-saturated solutions. Conclusions can only be drawn regarding consumption of the oxidants produced by radiolysis of water by reaction with dissolved hydrogen or with the canister surface. In order to separate and quantify the contributions to the chemical activation of the hydrogen, it is necessary to study separately the effect of clean surfaces of depleted uranium dioxide or metallic particles in hydrogen solutions, and – in separate studies – the effect of different types of radiation in hydrogen solutions. Some new results from such studies in the literature and from the experimental programme are discussed below.

Recently conducted studies of water radiolysis by gamma radiation show that at hydrogen concentrations above a given level, no measurable quantities of oxidants such as hydrogen peroxide occur in the solution /15-22, 15-23/. This is explained by the fact that hydrogen molecules participate in reactions with strongly oxidizing radicals such as OH. The effect of alpha radiation on hydrogen activation in solution is expected to be less, but almost no effect of hydrogen is noted in experimental data from /15-23/.

With the aid of radiolysis models, it is possible to calculate a decrease in oxidant production in hydrogen-saturated solutions caused by mixed radiation (α, β, γ) /15-24, 15-25, 15-26/. Even without taking into account the influence of surfaces, very low fuel dissolution rates are obtained. A modelling study where the presence of iron and the influence of fuel surfaces on uranium reduction are taken into account shows a very low fuel dissolution /15-27/.

The effect of hydrogen which is noted in the experimental studies is difficult to explain solely by reference to a reduction of the concentrations of radiolysis oxidants due to reactions with dissolved hydrogen. In order to explain e.g. reduction of radionuclides during fuel dissolution, oxygen concentrations below the detection limit after long periods of time and a reduction of the uranium dioxide surface after tests with gamma radiolysis /15-28/ or alpha radiolysis /15-29/ in hydrogen solutions, it may also be necessary to take into account the influence of surfaces. The results of a study of the effect of different types of radiation on water sorbed on uranium dioxide surfaces /15-30/ indicate that the surfaces greatly influence the radiolysis of sorbed water. The new knowledge regarding the combined effect of surfaces and radiation may contribute to a better understanding of the processes and a better modelling of experimental data.

The catalytic effect of uranium dioxide on hydrogen reduction is being studied experimentally. Results have recently been obtained from tests with depleted uranium dioxide and hydrogen /15-9/. Dissolved carbonate complexes of hexavalent uranium were used as oxidants. The results showed that the U(VI) concentration in bicarbonate solutions with hydrogen only decreased when uranium dioxide surfaces were introduced. The tests were complicated by sorption of uranyl carbonate on uranium dioxide surfaces. This was investigated in a separate study /15-31/.

There is literature data showing that thorium dioxide surfaces dissociate hydrogen molecules to atoms /15-32/. Another study using the PVT (Pressure-Volume-Temperature) method /15-33/ shows that plutonium dioxide catalyzes the reaction of hydrogen with oxygen to form water at room temperature. The same method was used at Studsvik to investigate uranium dioxide, which, unlike plutonium dioxide or thorium dioxide, is very sensitive to oxidation by oxygen. Owing to the fact that the PVT method requires total pressures of around 0.1 atm, no conclusion could be drawn regarding water formation at such low hydrogen concentrations /15-34/. At the same time, all experimental data suggest a much stronger effect of hydrogen in the presence of radiation than with uranium dioxide alone.

Metallic particles containing the metals of the platinum group plus molybdenum and technetium were extracted selectively from spent fuel with non-oxidizing reagent (phosphoric acid instead of nitric acid) in order to avoid dissolution of the most active metals and changes in composition. Completely bright particles were isolated, in contrast to the black precipitate that collects during fuel dissolution with nitric acid. The dissolution rates of various components from these particles under different redox conditions (pure argon and argon with ten percent hydrogen) have been determined and published /15-35/.

Figure 15-5 shows data from leaching of metallic particles in solution containing approximately 0.08 mM dissolved hydrogen. After the slow saturation of the solution with hydrogen during the first two days, the concentrations of all redox-sensitive radionuclides, including molybdenum, decline rapidly to sub-ppb levels (uranium, strontium and caesium come from a small, poorly soluble fuel fragment). These data clearly show that surfaces of metallic particles in fuel have a very strong effect on hydrogen and contribute to its activation.

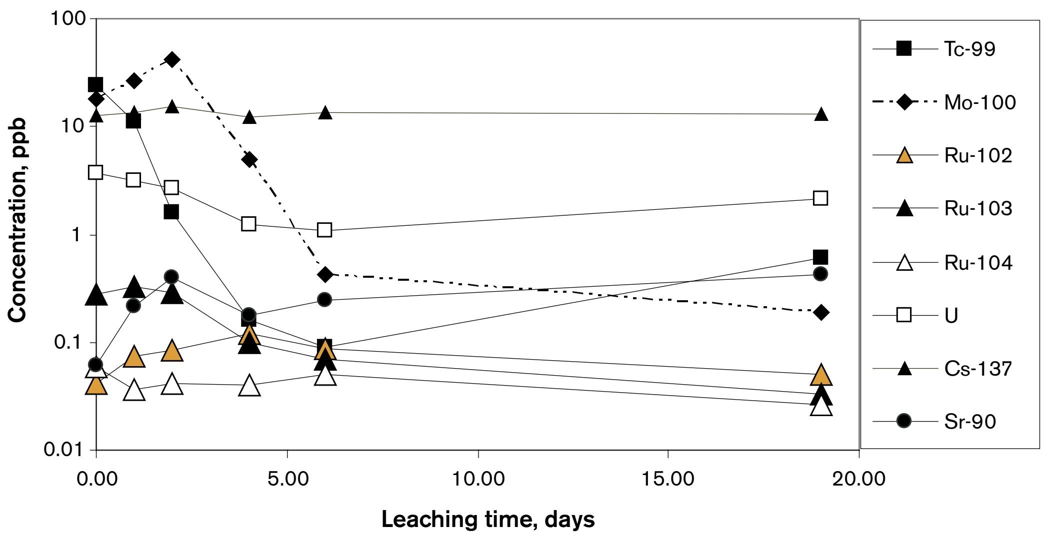


Figure 15-5. *Results of leaching of 4d metal particles in argon atmosphere with ten percent hydrogen /15-35/.*

Influence of hydrogen on dissolution of alpha-doped uranium dioxide

Since radical-rich gamma and beta radiation have a favourable effect on hydrogen activation accompanied by consumption of radiolytic oxidants, the relevance of the results for the scenario with spent fuel in a repository can rightfully be questioned. Since virtually only alpha radiation is expected to persist for a long time, the favourable effect of gamma and beta radiation would diminish progressively. A material that resembles old fuel is alpha-doped uranium dioxide, where different quantities of an alpha-emitting isotope are homogeneously distributed in the uranium dioxide matrix. Alpha-doped uranium oxide has been synthesized in cooperation with ITU in Karlsruhe. As a part of SKB's work in the EU project SFS, leaching of a uranium dioxide pellet doped with ten percent uranium-233 was studied in a titanium autoclave under three different hydrogen pressures. Leaching was started with a 10 mM sodium chloride solution under a hydrogen pressure of 16 bar. Samples of the solution were taken at different times and analyzed by alpha spectrometry. After four months, the estimated uranium concentration in the solution was still less than $3 \cdot 10^{-10}$ M. To dissolve all oxidized uranium from the pellet, a bicarbonate solution was added to the autoclave, but no changes were noted in the uranium concentration. No measurable dissolution of uranium could be observed, not even when the hydrogen pressure was reduced to 1.6 bar during a 178-day period. The hydrogen pressure was further reduced by a factor of ten to 0.16 bar (1.6 bar of argon with a hydrogen concentration of 6.08 percent by volume) during a 141-day period. Preliminary results from alpha radiometric analyses of uranium-233 are shown in Figure 15-6.

The results show that no measurable increase in the very low uranium concentrations in the solution could be observed during the entire test period (more than 15 months). If, in this case, uranyl carbonate species were produced in a layer several tens of microns thick near the surface (range of alpha particles), some of them would diffuse away and contribute to an increase of the uranium concentration in the solution. These results are confirmed by the measured levels of radiolytic oxygen, which lie below the detection limit (10^{-8} M) for the oxygen sensor that was in the autoclave solution during the entire test. The same applies to any radiolytic oxygen or hydrogen peroxide: some of this would diffuse away from the surface and cause an increase in the oxygen levels, which would eventually be recorded by the oxygen electrode, since the test lasts such a long time. There is almost no gamma or beta radiation, and published data /15-23/ with 5 MeV helium ions (alpha radiation) indicate that there is no influence of hydrogen on

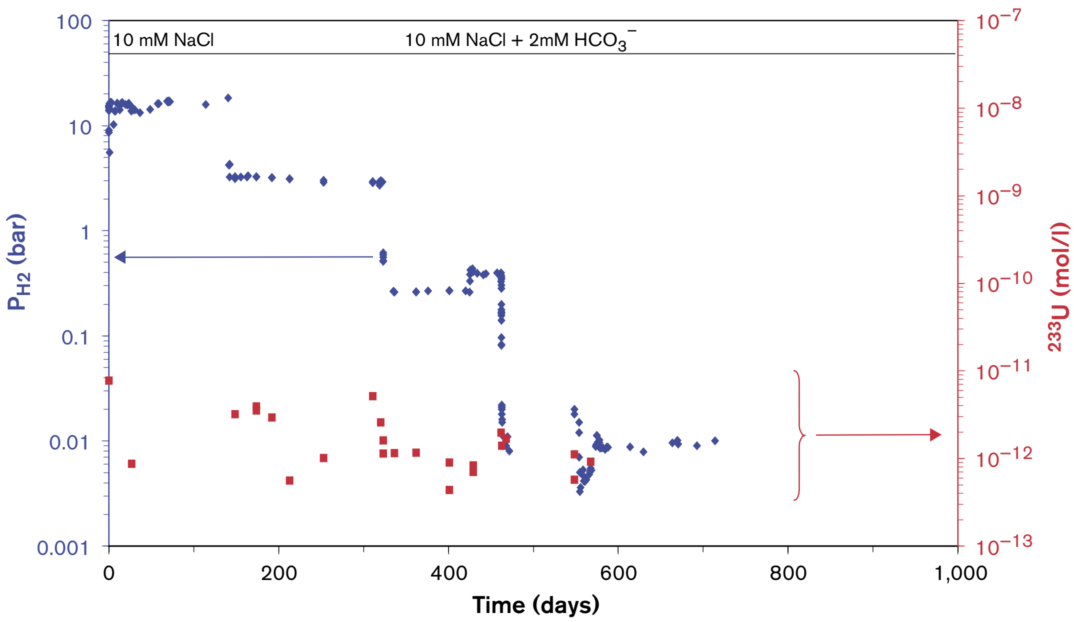


Figure 15-6. *Measured hydrogen pressure and* ^{233}*U concentrations in the solution as a function of time.*

oxidant consumption in the bulk solution. At the end of the test, the uranium dioxide surface will be examined by spectroscopic methods to determine if oxidation has occurred. Published independent experiments with alpha radiolysis in hydrogen-saturated solutions and uranium dioxide surfaces show that no oxidation occurs /15-29/. Titanium surfaces will also be studied with respect to uranium. Even though titanium surfaces are not expected to influence the results, the tests will be repeated in autoclaves with quartz surfaces. Independent results from leaching of similar uranium dioxide pellets in glass vessels with only six percent hydrogen gas in argon do not show any increase in the uranium concentrations with time either /15-20/.

Influence of pH, salinity and temperature

The dissolution rate of spent fuel is dependent on more than just the redox potential, even though this is the most important factor. Other factors that influence the dissolution rate are the composition of the fuel and the groundwater. Experiments with leaching of fuel samples taken from different segments in a fuel rod with burnup varying from 21 to 49 MWd/kgU /15-36/ show a weak and almost linear increase of leaching (cumulative released fraction) up to 40–43 MWd/kgU, followed by a decrease. The influence on the formation of secondary phases in connection with fuel dissolution is investigated separately /15-37/. The water composition in all other studies has been chosen to avoid the formation of secondary phases, since this makes it more difficult to interpret the results /15-38/.

Fuel dissolution at different pHs from 3 to 9.2 and different carbonate concentrations from 0 to 10 mM has been studied by flow-through leaching /15-39/. The tests show that low pHs increase the dissolution rate under oxidizing conditions. In hydrogen-saturated solutions, pH had no influence. The importance of very high pHs typical of concrete leaching has also been investigated /15-40/.

The influence of temperature has been studied in the range 20–70°C with the aid of autoclaves filled with argon or hydrogen, and studies at higher temperature are planned, see under the heading “Programme” below.

SKB has only performed a few of its own measurements of fuel dissolution at high salinities. Studies of the dissolution of alpha-doped uranium dioxide employing the isotope dilution method at low and high salinities and development of analysis methods are planned in cooperation with Posiva within the framework of the EU project NF-Pro.

Radiolysis studies and radiolytic modelling

Mass balance tests have been conducted where the time dependence for formation of hydrogen and oxygen has been studied in a closed system with approximately two grams of fuel fragments and with initially oxygen-free solutions. In order to permit mass balance calculations, a new leaching system has been used permitting simultaneous analysis of both gas phase and solution. Oxygen and hydrogen in the gas phase were measured at different times by means of gas phase electrode detectors. The aqueous phase was analyzed with respect to hydrogen peroxide (luminescence measurements) and dissolved radionuclides (ICP-MS). The way in which the composition of the solution influences radiolytic oxidant production and fuel dissolution has been studied and modelled /15-41/. Carbonate and chloride concentrations in the solution were varied between 0 and 10 mM.

Since analysis of the gas phase during the course of the test always entails a risk of leakage and loss of radiolysis gases, particularly as their concentrations grow higher with time, long-term tests with sealed glass vials have also been carried out. In the test series, the size of the fuel fragment (surface-area-to-volume ratio) and the composition of the solution (chloride and carbonate contents) were varied. The vials were opened and the gas phase and the solution were analyzed after one, two and three years. The measured concentrations of radiolytic oxygen and hydrogen peroxide that did not react with the fuel surface, as well as the concentrations of dissolved uranium, were used to calculate a mass balance of radiolytic oxidants /15-21/.

Oxidation of uranium dioxide with hydrogen peroxide has been studied at KTH. The mechanism of the reaction and the reaction rate have been determined /15-42/. A comparison of the reaction rate with data for other oxidants, including oxidizing radicals determined in a separate study /15-43/, showed that the logarithm of the reaction rate is linearly dependent on the reduction potential. This is of great importance, since it shows that thermodynamic data can be used to estimate kinetic data for oxidation of uranium dioxide with oxidizing radicals, something which is often lacking. Kinetic data from these studies, along with literature data, were used for improved radiolytic modelling of fuel dissolution data from mass balance studies /15-27/. Radiolytic modelling has also been carried out within the EU project SFS. The work was done by Studsvik with the support of SKB /15-44, 15-45/.

Programme

Research activities are planned during the coming period both to obtain data on fuel dissolution under repository-like conditions and to shed light on the mechanisms of the different processes that contribute to fuel dissolution. SKB is participating in the EU project NF-Pro, and some of the studies will be conducted there.

In order to obtain fuel data for the first phases in a scenario with a damaged canister, when the temperature is still high, fuel in the presence of water vapour and hydrogen will be studied. This will be done within the framework of the EU project NF-Pro, in cooperation with ITU.

A new autoclave with soft metal gaskets and other improvements to avoid air contamination has been purchased and will be used to study fuel leaching in different atmospheres of argon and hydrogen. A parameter study of temperature and hydrogen pressure during leaching will be conducted to determine the lowest hydrogen concentration that is required to avoid fuel oxidation.

Test with fuel pellets will be conducted in Studsvik's hot cells in an argon atmosphere and in the presence of siderite (iron(II) carbonate) to study the effect of dissolved divalent iron on fuel leaching. The tests with fuel pellets in an atmosphere or argon with hydrogen and carbon dioxide (ten percent hydrogen and 0.03 percent carbon dioxide) will be concluded and the results reported.

There is some Mox fuel in Clab that must also be disposed of, and studies of this type of fuel are planned. Pending a permit to conduct the experiments in Studsvik, a study of Mox fuel leaching under a hydrogen atmosphere has been started in Germany in cooperation with ITU.

There are many discussions of the behaviour of the so-called rim zone in high-burnup fuel. The alpha activity is much higher there, and there are many small fission gas bubbles (cauliflower structure), which complicates the picture. We are therefore planning a study where the rim zone can be separated from a high-burnup fuel pellet and studied to determine how it is leached under a hydrogen atmosphere. The work will be done in cooperation with ITU.

Leaching of synthetic non-radioactive metallic particles in an argon atmosphere with ten percent hydrogen will be carried out. The results will be compared with what is obtained with radioactive particles under the same conditions. In this way it is hoped that conclusions can be drawn regarding the importance of different contributions to hydrogen activation.

A mechanical study of the hydrogen effect will be conducted within the framework of the EU project NF-Pro. In order to estimate and quantify the contribution of the fuel's surfaces and alpha radiation, these factors must be studied separately. Tests with either depleted uranium dioxide, unused fuel or Simfuel in aqueous solutions with different concentrations of dissolved hydrogen or argon will be conducted to study the effect of surfaces. The production of oxidants will be studied as a function of time in solutions with different concentrations of dissolved plutonium-238, which is a strong alpha emitter, and with different concentrations of dissolved argon or hydrogen. The experiments will be performed at Chalmers University of Technology.

The influence of hydrogen peroxide on uranium dioxide surfaces will be studied in an argon and hydrogen atmosphere. The experiments will be conducted at KTH. The results will be used to estimate the catalytic effect of uranium dioxide surfaces on consumption of radiolytic hydrogen peroxide with dissolved hydrogen.

In cooperation with Posiva, dissolution of alpha-doped uranium dioxide will be studied in solutions with different ionic strengths and redox conditions to determine the matrix dissolution rate by means of the isotope exchange method. This is a part of the EU project NF-Pro.

Reactions with water vapour on the surface of uranium dioxide will be studied by means of experimental microscopy in combination with quantum mechanics and molecular mechanical modelling. The work will be done at the University of Michigan in the USA. Many studies in recent years have shown that molecules of oxygen, hydrogen and water vapour dissociate when they react with the uranium dioxide surface. This is probably a part of the catalytic mechanism.

The planned tests of fuel dissolution under repository conditions in the Chemlab probe in the Äspö HRL are still in a planning phase due to delays of ongoing actinide tests. The experiments require careful radiological monitoring during preparations, execution and associated transport. The exact time required cannot be calculated, but the goal is to be able to start pilot studies in the next few years.

15.2.13 Dissolution of gap inventory

Conclusions in RD&D 2001 and its review

It has always been assumed in the safety assessment that the radionuclide inventory in the gap between fuel and cladding tube and in the grain boundaries is released immediately when it comes into contact with water. In the review of RD&D 2001, SKI emphasized the importance of obtaining better experimental data for this, which is usually described as instant release when fuel dissolution is modelled in the safety assessment.

Newfound knowledge since RD&D 2001

Leaching of metallic particles extracted from spent fuel by selective non-oxidizing dissolution of the fuel matrix in an argon atmosphere gave similar leaching rates for technetium and molybdenum. These were in turn three orders of magnitude higher than the leaching rates for ruthenium, rhodium and palladium. The results from leaching in an argon atmosphere with ten percent hydrogen are dealt with in section 15.2.12.

Programme

Planned leaching tests to determine the fraction of readily soluble radionuclides that are released in the fuel-clad gap are described in section 15.1.8.

15.2.14 Speciation of radionuclides, colloid formation

Conclusions in RD&D 2001 and its review

SKI comments that uncertainty and sensitivity analyses of solubilities based on thermodynamic calculations must be presented and that quality issues relating to database management must be taken into account. Kasam believes that SKB should devote greater attention both theoretically and practically to plutonium chemistry.

Newfound knowledge since RD&D 2001

Solubility calculations show that plutonium can exist in certain groundwaters as trivalent plutonium. A new literature study of the solubility of plutonium dioxide /15-46/ in the presence of divalent iron shows that trivalent plutonium is the dominant soluble species. Studies have been conducted to identify solubility-limiting phases of trivalent plutonium and determine their solubility (Chalmers University of Technology). Experimental methods for preparing and analyzing plutonium in different oxidation states were developed during the period. A study of $Pu(OH)_3(s)$ solubility under a hydrogen pressure of 50 bar /15-47/ showed that the plutonium concentrations in solution after one year were between 10^{-8} M at a pH of 10 and 10^{-5} M at a pH of 3. All attempts to prepare $PuOHCO_3(s)$, which is expected to be formed under repository conditions, resulted in X-ray amorphous phases. The results of measurements of the solubility of solid phases of plutonium carbonate were recently published /15-48/.

In the scenario with a damaged canister, the redox conditions in the near-field are of very great importance. For example, the actinides that are present in the fuel have a much lower solubility in the tetravalent state than in the penta- or hexavalent states. Radiolysis can influence the redox conditions, and the radiation is intensive at the surface of the fuel. This can cause the uranium oxide in the fuel to be oxidized to a higher valence state and go into solution as uranyl ions. The actinides neptunium and plutonium, as well as redox-sensitive fission products such as technetium and selenium, can also be affected in a similar manner and be oxidized to a higher valence state, resulting in increased solubility and mobility. Colloids can also be formed in a damaged canister, especially in conjunction with the reduction of radionuclides released from the fuel to lower and less soluble valence states, or if dissolved divalent iron is oxidized and precipitates. 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. The influence of uranium dioxide surfaces on the concentrations of oxidizing radionuclides has been investigated under anoxic conditions. Other important components in the near-field are cast iron and its corrosion products, as well as dissolved divalent iron.

In the EU project In Can Processes (InCan), two closely-related areas were studied /15-49, 15-50/:

1. Reduction of hexavalent uranium and pentavalent neptunium in the presence of corroding iron (the environment inside a waste canister).
2. Theoretical *ab initio* calculations of the possibility of reducing U(VI) solution with divalent iron.

Reduction of hexavalent uranium and pentavalent neptunium in solutions containing corroding iron showed rapid decreases in the concentrations in solution. Examination of the iron surfaces by Rixs (Resonant inelastic X-ray scattering) showed that tetravalent uranium and tetravalent neptunium had been precipitated on the iron surface. Electrochemical studies of reduction of hexavalent uranium in solution with subsequent determination of the valence state showed that after one day half of the uranium had been reduced to E_h –400 mV due to actively corroding iron in the system, which resulted in elevated concentrations of Fe(II) ions in solution. Tests in 0.1 M sodium chloride solution also showed rapid decreases in the uranium concentration. From the original concentration of 500 ppb, the concentration fell to less than 10 ppb in three days; in the solution, however, 86 percent of the uranium in solution was still hexavalent.

Ab initio calculations showed that Fe(II) ions in solution can reduce hexavalent uranium to pentavalent uranium, which is in turn disproportioned to tetravalent and hexavalent uranium. These results improve our understanding of the electrochemical experiments, which showed reduction of uranium both in solution and on corroding iron.

A study of the interaction between hexavalent uranium and magnetite (synthetic or formed on a corroded iron surface) in the presence of different hydrogen pressures showed a reduction in the concentrations of uranium in the solution /15-51/. Tests with carbon steel coupons, where magnetite had been identified by X-ray diffraction and XPS (X-ray Photoelectron Spectroscopy), show a considerably greater ability to reduce dissolved hexavalent uranium. Examination of the magnetite surfaces by Xanes (X-ray absorption near edge structure) and XPS showed the presence of tetravalent uranium on magnetite surfaces.

A research programme to study cast iron corrosion products and their interaction with oxidized radionuclide species under anoxic conditions has been started in cooperation with Nagra. An accurate experimental method has been developed to achieve completely oxygen-free conditions. A typical study of the interaction between tetravalent selenium and iron started with corrosion of iron in oxygen-free solutions at room temperature. After several months, the corrosion products were examined by various spectroscopic methods (XRD, SEM-EDS, TEM and Raman spectroscopy). After addition of tetravalent selenium, the kinetics of selenium reduction were followed by analyses of the solution at different points in time. Finally, the iron surface was examined after the test by spectroscopic methods, which also included X-ray absorption spectroscopy (XAS) to identify and speciate selenium adhering to the surface. Preliminary results from the XAS characterization have been published /15-52/.

SKB is participating actively in the OECD-NEA project TDB (Thermodynamic Data Bases), where quality issues concerning the use of thermodynamic databases in safety assessment are continuously discussed /15-53 and 15-54/.

Programme

A new calculation of radionuclide solubility is being done within SR-Can. The main purpose is to obtain a better assessment of uncertainties and sensitivities, particularly with respect to variations in the composition of the groundwater and the bentonite's pore water. Activities for improving database quality are planned within the framework of the NEA TDB project. Solubility studies of plutonium dioxide from undersaturation in water-saturated solutions will be compared at Chalmers University of Technology.

Studies of redox kinetics for different oxidized forms of radionuclides (including hexavalent selenium and heptavalent technetium) on fresh and corroded iron surfaces will be carried out in cooperation with Nagra and within the EU project NF-Pro. Geochemical modelling of kinetic data will be carried out, and based on all data conclusions will be drawn regarding radionuclide retention.

15.2.15 Helium production

Alpha particles (helium nuclei) from alpha decay in the fuel form gaseous helium.

Conclusions in RD&D 2001 and its review

In RD&D 2001, it was deemed that the field did not require any further research, development or demonstration, but that developments in the field would be monitored and acted on when appropriate.

Newfound knowledge since RD&D 2001

No new knowledge has been forthcoming.

Programme

SKB makes the same assessment in RD&D 2001, that the field does not require any further research, but that developments should be monitored in case new activities are called for.

16 Canister as barrier

SKB's reference canister consists of an inner container of cast iron and an outer shell of copper. The cast iron insert provides mechanical stability while the copper shell protects against corrosion in the repository environment. The technical development of equipment and methods for fabricating, sealing and testing the canister is described in Chapters 5–7, while design of the encapsulation plant is dealt with in Chapter 8.

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.

16.1 Initial state of canister

By initial state of the copper canister and the cast 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.

16.1.1 Variables

No changes have occurred with regard to the variables for the copper canister and the cast iron insert. It is the same set of variables as that presented in RD&D 2001, see Table 16-1.

Table 16-1. Variables for copper canister and cast 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 α, β, γ 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

16.1.2 Geometry

The variable "canister geometry", which is used in the safety assessment, includes not only the geometric shape of the canister, but also possible initial defects in the seal.

Conclusions in RD&D 2001 and its review

In RD&D-Programme 2001, SKB describes a plan for the development of acceptance criteria and says that experience from trial welding will provide information on the types and frequency of defects that can arise in connection with welding. SKI concurs that this is the right way to go, but wishes to emphasize that acceptance criteria must be established for permissible defects in the copper shell and its welds, as well as the cast inserts. Consequence analyses will show what happens if there are more and/or larger defects than allowed by the acceptance criteria. The effects of minor defects should also be analyzed to assess the sensitivity of the system, as is also pointed out by SSI. When it comes to future safety assessments, SKI says that there must be a strong link between input data to the safety assessment, acceptance criteria and test statistics from nondestructive testing. SKB says that the work will be conducted jointly with representatives from safety assessment, research and technology development, which SKI views very positively.

Newfound knowledge since RD&D 2001

Data and experience since RD&D 2001 are presented in /16-1/.

Programme

SKB's research programme to determine acceptance criteria and in a later stage work towards qualification of equipment for nondestructive testing will continue during the upcoming period. Evaluation of trial weldings is under way at the Canister Laboratory and information is being collected on the types of defects, as well as their frequency, to which electron beam welding (EBW) and friction stir welding (FSW) can give rise, see also Chapter 6.

16.1.3 Radiation intensity

SKB's criterion is that the surface dose rate on the canister may not exceed 1 Gy/h.

Conclusions in RD&D 2001 and its review

No direct viewpoints were offered.

Newfound knowledge since RD&D 2001

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.

16.1.4 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 estimated in an integrated temperature modelling of the repository's near-field, see section 15.1.4.

16.1.5 Mechanical stresses

The residual stresses that may remain in the sealing weld after a very long time are low and not deemed to be of any importance for the lifetime of the canister.

Conclusions in RD&D 2001 and its review

No research programme was presented in RD&D 2001.

Newfound knowledge since RD&D 2001

No new knowledge has been forthcoming.

Programme

As was stated in RD&D 2001, the field is not judged to require any further research, development or demonstration for canisters sealed with an electron beam weld. The size and importance of any residual stresses in sealing welds made by friction stir welding should be investigated during the period.

16.1.6 Material composition

The choice of materials for the insert and the copper shell is based on the design premises.

Conclusions in RD&D 2001 and its review

No research programme was presented in RD&D 2001. The programme for canister design is presented in Chapter 5.

Newfound knowledge since RD&D 2001

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.

16.2 Canister processes

16.2.1 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 cast iron insert. The materials could 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 15.2.8.

The research programme for the different processes in the canister is dealt with in the following sections.

16.2.2 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 2001 and its review

No research programme was presented in RD&D 2001.

Newfound knowledge since RD&D 2001

No new knowledge has been forthcoming.

Programme

As was stated in RD&D 2001, the field is not judged to require any further research, development or demonstration.

16.2.3 Heat transport

No new knowledge has been forthcoming. The process is dealt with as in RD&D 2001, i.e. integrated with the temperature evolution of the fuel, see section 15.1.4.

16.2.4 Deformation of cast iron insert

Deformation of the cast iron insert could theoretically occur in conjunction with large tectonic movements.

Conclusions in RD&D 2001 and its review

SKI says it is urgent that SKB carry out new calculations of the mechanical strength of the canister, where all components are reconsidered, such as:

- Actually obtained material data from fabricated inserts.
- Updated material data for bentonite.
- Loads during glaciation (consistent with scenario selection).
- Defined permissible defects (from the consequence analysis).
- Failure criteria in connection with shear movements.

Newfound knowledge since RD&D 2001

With updated material data for bentonite, earthquake-induced rock shear calculations have been carried out for the canister with insert /16-2/. The rock shear has been modelled and calculated with the finite element code Abaqus. A three-dimensional finite element mesh that models the buffer and the canister has been created and a number of calculations that simulate different rock shears have been performed.

The rock shear is assumed to take place perpendicular to the canister axis either in the centre of the deposition hole or at the quarter point. The shear calculations have been driven to a total shear of 20 centimetres. The buffer has been modelled at four densities between 1,950 and 2,100 kg/m^3 at water saturation and at shear rates between 0.0001 and 1,000 mm/s.

The results show that the influence of especially the density of the buffer and the location of the shear plane are very strong, but also that the shear rate and the magnitude of the shear displacement have a significant influence. At the two lower densities an eccentric shear plane is more dangerous, but at the two higher densities a centric shear is worst. At the conservative combination of a shear rate of 1 m/s, a shear displacement of 20 centimetres and a density of 2,100 kg/m^3, the cast iron insert is strongly affected with a maximum plastic strain of 19 percent, but in the reference case with a buffer density of 2,000 kg/m^3 and a shear displacement of 10 centimetres, the plastic strain is reduced to 1.6 percent.

Programme

A large programme for probabilistic analysis of canister strength was started during 2003. In this programme we are obtaining material data from fabricated canisters. Pressure testing of canister sections is also included in the programme. According to the plans, this programme will be concluded during 2004.

16.2.5 Deformation of copper canister under external pressure

Conclusions in RD&D 2001 and its review

SKI recommends that SKB show how a simplification of the model for deformation of the copper canister affects the results. The simplification entails assuming plastic collapse instead of creep.

Newfound knowledge since RD&D 2001

SKB continued its creep testing of electron beam welds and friction stir welds during the period /16-3/.

Programme

The programme for creep testing will continue during the coming three-year period. Modellings of creep deformation of the copper canister under slow loading are being considered.

16.2.6 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 2001 and its review

Not dealt with in RD&D 2001.

Newfound knowledge since RD&D 2001

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.

16.2.7 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 2001 and its review

SKI considers SKB's continued programme of characterizing corrosion products to be reasonable, but reiterates its recommendation to SKB to continue work on gathering a detailed body of data as a basis for quantifying the corrosion of the cast iron if there is a hole in the copper shell. This work should take into account the local environment in the narrow gap between the cast iron insert and the copper shell with possible effects of, for example, carbonate and sulphide on the composition of the corrosion products and the possibility of aerobic corrosion due to radiolysis of water. Possible effects on the corrosion rate due to the metal coupling between copper and cast iron (galvanic corrosion), as well as transport properties inside and around a damaged canister, should also be included.

Newfound knowledge since RD&D 2001

The consequences of the build-up of corrosion products in the gap between the copper shell and the cast iron insert has been investigated experimentally since SR 97 /16-4, 16-5/. None of the experiments succeeded in showing any pressure build-up as a consequence of the build-up of corrosion products. Attempts have also been made to get an idea of the long-term consequences of the build-up of corrosion products by means of studies of archaeological analogues /16-6/. Here as well, the conclusions were that no signs of heavy deformations could be found on copper-based materials in close contact with anaerobically corroded iron.

Programme

The ongoing experiments will be concluded during the period. The study of analogues will continue during the period, provided that there are good study objects.

16.2.8 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 2001 and its review

See section 16.2.7.

Newfound knowledge since RD&D 2001

The results of the past ten years' research have been summarized in two articles published in the journal Corrosion /16-7, 16-8/. Measurements of corrosion rates based on the amount of hydrogen generated show initially high values of 10–30 microns per year, but after an oxide film has formed the rate diminishes to less than 0.1 microns per year. The corrosion rate proved to be independent of whether the material was immersed in water fully, partially or not at all. Another conclusion drawn from the experiments was that hydrogen pressures of up to 100 bar had no effect on the corrosion rate. No local corrosion was initiated under anaerobic conditions.

A study of corrosion of iron in contact with bentonite is currently being conducted. The initial results show a slightly higher corrosion rate than has been measured in the absence of bentonite /16-9/. It has not yet been clarified whether this increase is due to the interaction between the minerals in the bentonite or whether it is caused by the fact that the bentonite pore water has a different composition than the types of water used in the earlier experiments, where the water composition was found to be of some importance for the corrosion rate.

Programme

Since the water composition in the experiments turned out to be of some importance for the corrosion rate, further experiments with other water types will be carried out during the period. The investigation of corrosion of iron in contact with bentonite will continue during the period.

During the preceding period, an investigation of anaerobic corrosion of iron in a gamma radiation field was started. The investigation is still going on and will be concluded during 2005.

16.2.9 Galvanic corrosion

Metallic contact between cast iron and copper is a precondition for galvanic corrosion.

Conclusions in RD&D 2001 and its review

See section 16.2.7.

Newfound knowledge since RD&D 2001

A project for determining any effects of metallic coupling between copper and cast iron on the corrosion rate was started in 2001. The final report on the project will be published during 2004 /16-10/. The results obtained so far show that even if corrosion rates of up to 100 microns per year could be measured under oxygenated conditions, the rate under oxygen-poor conditions was lower by at least a factor of 100. The experiments were conducted in a glove box 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.

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.

16.2.10 Stress corrosion cracking of cast iron insert

Conclusions in RD&D 2001 and its review

Not dealt with in RD&D 2001. SKB deems the risks of stress corrosion cracking to be small, since only local areas in the insert have tensile stresses.

Newfound knowledge since RD&D 2001

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.

16.2.11 Radiation effects

A study of the risks of radiation embrittlement was carried out prior to RD&D 2001. The study shows that the risks are negligible and that the effect during 100,000 years would not even be measurable /16-11/.

Conclusions in RD&D 2001 and its review

Not dealt with in RD&D 2001.

Newfound knowledge since RD&D 2001

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.

16.2.12 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 2001 and its review

In SKI's view, there are questions that need to be further investigated, primarily the properties of copper oxide films, and in particular the influence of chloride and sulphide ions, and the influence of concrete on copper (saline alkaline water).

Newfound knowledge since RD&D 2001

A literature review of copper corrosion in alkaline waters with different salinities has been published /16-12/. The conclusion in the report was that an increase in pH will passivate the copper surface. The stability of the passive film and its ability to prevent localised corrosion are enhanced by increasing pH. An increase in pH up to 12–13 will therefore have little effect on the integrity of the canister.

Since RD&D 2001, an experimental investigation of intergranular corrosion in electron beam welds and friction stir welds has been started at Swedish Corrosion Institute. Preliminary results indicate that the electron beam welds are not sensitive to intergranular corrosion. This agrees with the results of previous investigations /16-13/. The work will continue during the coming year.

An experimental study of copper corrosion under anoxic conditions in sodium chloride solution (1 molar NaCl) has been conducted since RD&D 2001 in cooperation with Posiva /16-14, 16-15/. The results show that after an initial period of several hours with a high corrosion rate, the corrosion rate declines and is virtually zero after about 30 days.

A project for studying the mechanisms of sulphide action on copper by means of electrochemical and surface analysis methods has been started at the University of Western Ontario. The main goal of this project is to develop a model for predicting the long-term behaviour of copper canisters in a repository environment. The project will continue throughout the coming three-year period.

A programme to investigate the prospects of bacterial corrosion of copper has been under way for several years now. Previous results have shown that sulphate-reducing bacteria will be active in compacted bentonite. No new evidence to contradict this has emerged during the period /16-16/. The work will continue into the coming period.

Field experiments in the Äspö HRL involving multiyear exposure of copper – both to the atmosphere in the underground laboratory and to various groundwaters – have been conducted during the past three-year period. The experiments with exposure to groundwater will continue into the next three-year period. The air-exposed samples have been evaluated and the results show that the corrosion attacks have been less than are normally obtained in a normal urban atmosphere /16-17/.

Programme

In addition to what has been mentioned above regarding already ongoing projects that will continue during the coming period, a project aimed at shedding light on the properties of copper oxide films, and particularly the influence of chloride and sulphide ions, is being started at the Department of Physics at Uppsala University. The project will employ 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.

16.2.13 Stress corrosion cracking of copper canister

Tensile stresses in the copper canister are a necessary prerequisite for SCC. Since the canister is under external pressure it is not likely that SCC could lead to canister penetration.

Conclusions in RD&D 2001 and its review

SKI says that SKB must show that the canister will not be present in an environment that can cause SCC of the copper, or else take into account SCC in the analysis of canister lifetime.

Newfound knowledge since RD&D 2001

No new knowledge has been forthcoming. The pilot tests that were conducted of the possibility of studying SCC by measuring electrochemical noise gave negative results. The technique turned out not to be applicable to measurements of stress corrosion cracking.

Programme

A study of SCC in acetate-containing water will be conducted during the coming three-year period in cooperation with Posiva. In addition to this, a new pilot study is under way, this time of the possibility of studying SCC by measuring acoustic emission from crack growth.

16.2.14 Grain growth in copper

Conclusions in RD&D 2001 and its review

The field was not judged to require any further research, development or demonstration; it would be enough to monitor the field and take action when appropriate.

Newfound knowledge since RD&D 2001

No new knowledge has been forthcoming.

Programme

SKB makes the same judgement as in RD&D 2001, that it is enough to monitor developments in the field.

16.2.15 Radionuclide transport

Radionuclide transport in the near-field is dealt with in section 18.3.

16.2.16 Integrated studies – evolution of damaged canister

If water enters a damaged canister, this leads to hydrogen gas generation, which increases the pressure inside the canister, which in turn reduces the rate at which the water enters. At some point when the pressure difference is small, inward diffusion of water vapour will be greater than the inflow of water. The time until this occurs varies with assumptions concerning the size of the hole and the corrosion rate, but is in most cases thousands of years. The inward diffusion of water vapour means that corrosion will not cease completely. This will lead to a slow accumulation of corrosion products and a pressure build-up inside the copper canister, which could eventually damage the copper shell. To get a picture of the evolution of a damaged canister, different processes must be modelled in an integrated fashion.

Conclusions in RD&D 2001 and its review

In SKI's opinion, SKB's previously reported model for a damaged canister shows that even a defective canister has a significant barrier function. However, the authority is sceptical to too literal an interpretation of the quantitative data obtained from the modelling of a damaged canister and to the direct integration of the data into a consequence analysis.

Newfound knowledge since RD&D 2001

See section 16.2.7.

Programme

Short-term tests aimed at understanding what happens over time spans of hundreds of thousands of years are of limited value, but can nevertheless contribute to a better understanding of the evolution of a damaged canister in the deep repository. During the coming three-year period, SKB will start a number of model experiments where miniature canisters, complete with inserts but with defective copper shells, are deposited in borehole through water-conducting fractures in the Äspö HRL. The experiments are planned to continue for five to ten years and will hopefully contribute to a better understanding of how the corrosion attacks in the gap between copper shell and cast iron insert may develop.

17 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 is dominated 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.

It is also desirable that the buffer should 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 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 horizons of natural clay from Wyoming or South Dakota in the USA. MX-80 specifies a given grade and grain size of dried and ground bentonite. However, 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 17.1.2.

Based on completed Investigations, SKB has concluded that a buffer consisting of MX-80 should have a density of 1,900–2,100 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.

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. The investigations of the long-term properties of bentonite that have been done within and outside of SKB's programme show, however, that compacted bentonite can retain its favourable properties for long periods of time and under varying 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 kind 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 in such a situation.

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 clay 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. To minimize the negative effects of an excessively high temperature and temperature gradient, the maximum canister temperature has been set at 100°C.

Fabrication of buffer blocks is described in Chapter 10.2.2. Fabrication aspects are discussed in the following only insofar as they have a bearing on the research programme presented.

Conclusions in RD&D 2001 and its review

In its review of RD&D 2001, SKI points out that the buffer is essential for the repository, especially as protection for the canister, that SKB's programme for the buffer appears to be comprehensive and gives evidence of a good understanding of relationships between initial properties and long-term processes, and that there is no reason to assume that a buffer with acceptable properties cannot be found.

However, SKI points out that it is difficult on the basis of SKB's account in the RD&D-programme to make independent judgements of individual areas due to couplings and repercussions on other areas.

17.1 Initial state of the buffer

17.1.1 Variables

In SR 97, the buffer was described by a set of variables, see Table 17-1.

The initial state, i.e. the value these variables were assumed to have at the time of deposition, was described in the main report of SR 97, section 6.4 /17-1/. The research programme around the initial state for the different variables in the buffer is described in the following.

Table 17-1. Variables for the buffer and the backfill.

Variable	Definition
Geometry	Geometric dimensions of buffer/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 α, β, γ 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.
Montmorillonite content	Montmorillonite content 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.
Swelling pressure	Swelling pressure as a function of time and space in buffer and backfill.
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.
Impurity levels	Levels of impurities in time and space in buffer and backfill. Impurities also include other minerals than montmorillonite. In backfill, crushed rock is counted as an impurity.

17.1.2 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. In SR 97 and RD&D 2001, the dimensions of the canister were given and the dimensions of the buffer were set at 35 cm on the sides of the canister, 50 cm underneath the canister and 150 cm above the canister. These dimensions still apply to KBS-3V, while there are small differences for KBS-3H.

Conclusions in RD&D 2001 and its review

SKI points out that SKB must make the choice of an optimal buffer (properties and availability) before a permit application is submitted. Kasam takes a positive view of SKB's plans to conduct studies of alternative buffer materials in order to get an alternative reference to bentonite with a high montmorillonite content.

Newfound knowledge since RD&D 2001

A fundamental requirement on the buffer is that it must have swelling and thereby sealing properties. Montmorillonite with sodium as a counterion has a very high swelling potential and is available in sufficient workable quantities to be a realistic buffer alternative. SKB has therefore used such a bentonite grade from American Colloid Co (Wyoming) with the product name MX-80 as a reference material for a long time. A comprehensive programme for studying alternative buffer materials has been initiated and largely carried out. The main purpose is to correlate physical and chemical properties to fundamental mineralogical properties. The project includes:

- 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 large number of commercial bentonites from major producers have been investigated with respect to detailed mineralogy and swelling properties. The investigations have so far been performed on the reference material MX-80 from Wyoming (American Colloid), four samples from India (Ashapura), and one sample from Greece (Silver & Baryte). All materials have a high content of montmorillonite and represent different ratios between monovalent and divalent cations. At present, three samples from Denmark (NCC) and three samples from the Czech Republic (from a university in Prague) are being studied. Four of the samples are examples of materials with a lower montmorillonite content.

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 its sealing properties are equivalent to those of sodium bentonite under buffer conditions. 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.

Programme

Ongoing laboratory investigations will continue for the purpose of correlating desirable physical and chemical properties to fundamental mineralogical properties, for example relationships between swelling pressure on the one hand and the clay mineral's cation exchange capacity, ionic species (sodium or calcium) and charge distribution on the other. The goal is to describe crucial relationships so well that procurement of buffer material can be optimized with respect to safety, availability and cost.

Field tests will be performed with materials shown by the laboratory investigations to be potential buffer materials. The tests are planned to be conducted in accordance with the same experimental principles and on the same scale as the ongoing Lot tests in the Äspö HRL. The purpose is to verify the results from the laboratory investigations under more realistic conditions with respect to temperature, scale and geometric conditions, and to discover any handling problems. The results of investigations conducted to date show that materials from Milos, Greece (S&B Industrial Minerals SA) and Buj, India (Ashapura Minechem Ltd) are suitable for inclusion in the test series.

17.1.3 Pore geometry

Conclusions in RD&D 2001 and its review

In SR 97, it was assumed that the buffer had a dry density of 1,590 ± 30 kg/m^3. This gives a porosity of 41 percent. No questions for further research were identified in SR 97 or its review. In RD&D-Programme 2001, 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.

Newfound knowledge since RD&D 2001

No new knowledge has been forthcoming.

Programme

The very low hydraulic conductivity of the buffer, despite the fact that its porosity is over 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 start a study aimed at quantifying pore structures in potential bentonite materials under different physical and chemical conditions.

17.1.4 Radiation intensity

The initial dose rate on the canister surface was calculated in SR 97 to be 100–500 mGy/h, and on the outside of the buffer about 2 mGy/h. The calculations are based on the same assumptions as the material in section 17.2.2.

17.1.5 Temperature

Buffer and backfill are at ambient temperature at deposition. This varies with repository site and disposal depth and is approximately 10–15°C. 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 17.2.12.

17.1.6 Montmorillonite content

Conclusions in RD&D 2001 and its review

The commercial bentonites that are of interest as buffer materials have a given composition. The montmorillonite content is normally over 80 percent. The delivered product will be quality-tested before being taken to the repository.

Newfound knowledge since RD&D 2001

New methods for determining the mineral distribution in buffer materials have been used and developed. Among other things, the important material parameter cation exchange capacity (CEC) has been determined by means of a simpler and more reliable method /17-2/. Furthermore, a new analysis method (Rietveld technique) for quantification of minerals from X-ray diffractograms has been used. Detailed determinations of the mineralogy of MX-80 material have been performed within the Lot project, for reference material and for exposed material. Other bentonite materials have been studied in the project "Alternative buffer materials", see section 17.1.2. New determinations of the montmorillonite content of MX-80 have been performed for some ten consignments, representing 20 years' production. According to the results, the montmorillonite content is around 85 percent, with a few percent's variation. Previous determinations have found about 75 percent /17-3/, while the manufacturer of MX-80 has stated that the montmorillonite content is over 90 percent. The examined bentonite from Milos has a montmorillonite content of 80 to 85 percent.

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 17.1.2.

17.1.7 Water content

In KBS-3V in SR-Can, the compacted bentonite blocks are assumed to have an initial degree of water saturation of between 70 and 85 percent. It is further assumed that the buffer-rock gaps can be reduced to three centimetres. The buffer-canister and buffer-rock gaps may be filled with water, but in SR-Can it is assumed that they are dry. The water content may be slightly lower in KBS-3H.

Conclusions in RD&D 2001 and its review

Not dealt with.

Newfound knowledge since RD&D 2001

No work has been done on isostatic block pressing since RD&D 2001. Full-sized blocks with a high degree of water saturation have been compacted by uniaxial technique for Lasgit in the Äspö HRL. Rings with 99 percent water saturation and cylindrical blocks with 96 percent water saturation have been made.

Programme

Development of technology for fabrication of blocks with a greater height is under way and will continue. The goal is to optimize the pressing procedure in order to obtain the best quality and the most rational deposition. Since blocks larger than 50–100 cm in height cannot be produced by uniaxial compression, development work is being focused on isostatic pressing. There is no isostatic press in Sweden today that is big enough to press full-scale blocks, but tests of isostatic pressing of blocks with a diameter of about 100 cm are planned.

Large complex blocks with bottom and rings as a unit can entail problems with cracking and disintegration during the wetting/drying process after deposition. Furthermore, in such blocks mean density and swelling pressure are higher in the bottom than around the canister, since the difference in density between rings and cylindrical blocks made for Äspö cannot be achieved in a composite block. These two potential problems will be studied.

17.1.8 Gas contents

The bentonite blocks have a degree of water saturation of 70–85 percent, which means that 70–85 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.

17.1.9 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. 0.1 MPa) and a water pressure of 0–0.1 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.

17.1.10 Swelling pressure

The swelling pressure begins to build up when buffer and backfill come into contact with external water, see sections 17.2.7 and 17.2.8. Initially there is no swelling pressure.

17.1.11 Montmorillonite composition

Conclusions in RD&D 2001 and its review

Further physical and chemical characterization was announced in RD&D 2001.

Newfound knowledge since RD&D 2001

A method for determining the average structural formula of montmorillonite has been developed and has been used for the Wyoming and Milos materials. In the method, the montmorillonite is separated from other material and ion-exchanged to sodium form, after which its metal content is determined (ICP/AES). The cation exchange capacity (section 17.1.6) is determined for the montmorillonite alone and used to calculate the total layer charge. A simple Excel macro has been created to calculate the structure of the montmorillonite based on the basic formula for a unit cell /17-4/.

Programme

A technique for determining the structural formula of the swelling mineral will be developed. An essential point is to determine the valence state of the iron content, since this is decisive for the charge distribution in determination of the structure. Furthermore, any changes due to e.g. exposure to atmospheric oxygen and drying are of interest, since this leads to a change in the total layer charge. Mössbauer analysis will be tried to begin with.

See also 17.1.6.

17.1.12 Pore water composition

Bentonite in nature contains water. After mining, the clay is dried and ground. At delivery the water content is 12 percent maximum, according to the product specification. Prior to compaction to blocks, distilled water is added to achieve a water content of 17 percent, which is equivalent to a degree of saturation of 70–85 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 17.2.15. When the buffer material is delivered, it will therefore be analyzed with respect to constituent minerals and ions in the supernatant of dispersed material (aqueous solution on top of slurried and centrifuged sample), which provides a good idea of the initial composition of the pore water.

17.1.13 Impurity levels

Bentonite is the name of a naturally occurring clay material with variations in composition depending on how it is formed. Bentonite often occurs in different strata with some variation in composition and with intervening strata that may contain other minerals. In commercial products, such as MX-80, materials from different strata are often blended to meet specified quality requirements. Usually, impurities in bentonite 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. The majority of the minerals in the buffer have clear advantages and disadvantages. 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 2001 and its review

SKI considers it important for SKB to formulate acceptance criteria for other minerals and organic impurities in the clay.

Kasam thinks there is reason not only to determine general limits for impurities, but also to investigate how combinations of impurities can affect the long-term stability of the buffer (both positively and negatively).

Newfound knowledge since RD&D 2001

Newly-developed analysis methods (see section 17.1.6) for the mineral distribution in bentonite permit more efficient material inspection at delivery in terms of costs, time and accuracy. The accuracy for individual accessory minerals is approximately one percent, which is a considerable improvement. Different methods have been tried for routine measurement of total carbon content and organic carbon content.

Programme

It is difficult to set limits on impurity levels in the buffer. Most minerals are of little or no importance for performance. SKB considers it more important to show that occurring concentrations of minerals do not seriously diminish repository performance, see section 17.2.18. The work of improving analysis methods and routine inspections of bentonite continues within the Lot project and in the investigations of potential buffer materials.

See also section 17.1.2

17.2 Processes in buffer

17.2.1 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 the 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 originally 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 transport is very slow. Gas transport can occur during the saturation process, when 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, leading to hydrogen formation in the canister.

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. By means of ion exchange and sorption, the buffer's original content of charge-compensating counterions can be replaced by 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 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 is expected to take place in the buffer exclusively by diffusion in the pores of the buffer, and possibly also on the surfaces of the clay particles. 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 broken 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 sections 17.2.12 and 17.2.23, which deal with the evolution of the buffer under unsaturated and saturated conditions, respectively.

17.2.2 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 reaches out into the near-field rock. Our understanding of this process is deemed to be good enough for the needs of the safety assessment.

17.2.3 Heat transport

In a water-saturated buffer, heat is transported by conduction with well-known heat conduction properties. After swelling, at full water saturation, the buffer is in direct contact with both canister and rock and heat transfer takes place by conduction.

The heat transport in the buffer during the saturation process is more complicated, since the buffer's thermal conductivity is dependent on its water content and density.

The heat transfer between the canister and the buffer is also more complicated, since there is a gas-filled gap between these materials during the water saturation phase. The gap will be filled out when the buffer swells, but our understanding of the course of events and thereby the heat conduction properties in the gap is fraught with uncertainties.

In KBS-3H and KBS-3V, there may also be an air-filled gap between buffer and rock. This gap is of importance for heat transport in an early stage of the repository's evolution.

Conclusions in RD&D 2001 and its review

In the calculations of the heat transport in the rock, SKB uses a model with simplified assumptions regarding the geometry of the near-field. In the authorities' view, SKB should shed light on the impact of this simplification when presenting the results. The authorities also think that the couplings between the thermal, mechanical, chemical and hydrological processes, particularly in the buffer, need to be studied further.

Newfound knowledge since RD&D 2001

A report has been published describing how the canister's heat output at deposition, the rock's transport properties, the spacing between canisters and between deposition tunnels, the heat transport conditions in the deposition holes and the rock's undisturbed geothermal temperature together determine the maximum temperature on the canister surface /17-5/. The results are based on combinations of numerical and analytical methods, which means that a large number of combinations of parameter values have been analyzed for KBS-3V and KBS-3H. In the analytical method there are correction factors that have been determined by calibration calculations, making it possible to take into account canister geometry and the heat flow distribution around the canisters.

Altogether, the maximum canister temperature has been calculated for around 1,000 different cases. The results are presented in nomogram form so that the canister spacing required to meet the temperature requirements (a maximum temperature of 100°C on the canister surface) can be read off directly from given assumptions regarding decay heat, heat conduction conditions and safety margins. For some of the cases, independent, numerically calculated results are available for comparison, for example the temperature calculations performed prior to SR 97 for Aberg /17-6/. Independent analytical solutions are also available /17-7/ for use in comparison and verification. All comparisons show good agreement.

The largest uncertainty concerns what temperature margins should be posited. In SR 97 and earlier, it has been assumed that effects of unfilled gaps, in particular between canister and buffer, can give rise to temperature offsets of 10°C. Furthermore, uncertainties in data are judged to warrant an additional margin of 10°C, so that the calculated maximum temperature should be 80°C or less. The size of the estimated temperature offset across the canister-bentonite gap is based on assumptions regarding the emissivity of the copper surface, i.e. its capacity to emit radiative heat.

The measurements currently being performed in the Prototype Repository indicate a temperature offset of at most around 19°C between canister and buffer. This figure applies to the most recently installed deposition hole categorized as dry during boring and before installation. Converted to a standard decay heat output of 1,700 W, and allowing for the fact that this heat output has declined by around ten percent when the temperature peak occurs, this means that the margin for open gaps may need to be 17°C. The buffer-rock gap has been filled with bentonite in the Prototype Repository. In the most recently installed hole, the heat transport across the pellet-filled gap around six months after installation is roughly equal to that through the buffer blocks.

Programme

The results that have been obtained from the site investigations in terms of variations in the thermal properties of the rock need to be evaluated so that inhomogeneities on different scales can be taken into account in a suitable manner in the type of thermal analyses that have now been done /17-5/. The thermal analyses also need to be supplemented with analyses where canister spacing is varied, for example due to the necessity to relocate canister positions to avoid intersecting large fractures.

The problem of temperature offset across gaps and the need for temperature margins needs to be further studied. In the first place, the ongoing tests (Prototype Repository) need to be evaluated, and in the second place the reduction of the gap between canister and bentonite needed to warrant a temperature margin of 10°C or less needs to be determined.

The calculation results currently available indicate that the data uncertainty margin does not need to be 10°C. We need to revise and update the experimental data that underlie the assumed dependency of the bentonite's thermal conductivity on water saturation and porosity /17-8/. The revision is needed in order to reduce the data uncertainty margins for the thermal design of the repository and in order to improve the material models that will be used in further THM modellings of the water saturation phase.

The problem with heat transport in the buffer will be dealt with in the THM calculations that are planned within the framework of the different Äspö projects and thereby within the framework of the activities of Äspö's international EBS task force.

17.2.4 Water transport under unsaturated conditions

When the repository has been sealed, the buffer will absorb water from the surrounding rock. The saturated 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 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 process. With an unlimited supply, 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 2001 and its review

SKI considers that unambiguous experimental data in support of SKB's assumptions concerning the saturation process are still lacking and that SKB should show how an adequate flow of water to the buffer can be ensured (as well as the effects of high salinities). SKI also questions whether SKB can draw any far-reaching conclusions on the natural resaturation of the bentonite from only two short-term tests (five years) in the Äspö HRL.

Newfound knowledge since RD&D 2001

During the past few years, the water transport process has been studied in the laboratory, in the field and in model calculations. Examples of such studies are given in the following.

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 is being studied in a doctoral project, see further section 17.2.12. Water transport in nearly saturated buffer (over 95 percent saturation) has also been studied in the laboratory in conjunction with investigations concerning the wetting of the buffer in the planned field test Lasgit. Furthermore, the wetting phase has been studied in scale tests of KBS-3H, whereby a 1:10 scale model has been built of a tunnel section with two buffer-canister parcels with spacer plugs.

These processes have been studied in the field mainly in conjunction with the wetting of the buffer in a number of full-scale tests in the Äspö HRL (Prototype Repository, Canister Retrieval Test and TBT). The water inflow and the change in the negative pore pressure can be determined by measurement and follow-up of the relative humidity in a large number of points. The temperature gradient is large in TBT, enabling the other major driving force for water, which leads to drying-out in the hot part, to be studied.

An important update of computation capacity has been achieved by the purchase and testing of the finite element code Code Bright developed at UPC in Barcelona. The code is an excellent complement to Abaqus, since it models certain processes in water-unsaturated soil better. For example, it models all three components (particles, water and gas) in unsaturated soil, whereas Abaqus does not model the gas component (except for temperature-driven vapour flow). On the other hand, due to the well-developed models in Code Bright, the material models contain more parameters which are often difficult to determine. A great deal of work remains to be done in determining and validating these models for SKB's buffer materials.

Model calculations of water flow have mainly been done in conjunction with modelling of the field and laboratory tests. The following calculations in particular can be mentioned:

- Modelling of TBT with existing models with both Abaqus and Code Bright and comparisons with measurement data. Evaluation is under way.
- Modelling of the scale test of KBS-3H (1:10) with Abaqus. The final phase of the wetting went slower than predicted.
- Updated calculations of the Canister Retrieval Test. Evaluation is under way.
- Modelling of the saturation and maturity phase for Lasgit with Abaqus. A new and simplified material model developed for nearly saturated soil (over 95 percent) is used in these calculations. The model has been partially verified by comparisons between laboratory tests and modellings of the laboratory tests.
- Modelling of the first 1,000 days of the Febex experiment in Grimsel, Switzerland. The wetting of the buffer and the thermo-hydro-mechanical effects in the rock have been modelled and the results compared with measurements. The most important result from a water transport viewpoint is that the wetting of the buffer agreed well with the measurement results, even for the simplified assumption that the rock acts as a filter with zero water pressure and supplies the bentonite with the water it needs. Another observation is that the measured hydraulic interaction between rock and buffer is not as strong as has been modelled due to the fact that the modelled media have been coupled together. A skin zone is needed to explain the absence of negative water pressures in the rock.

Programme

The wetting process is a part of the THM modelling that will be included in the upcoming research programme. The programme is described in section 17.2.12 "Integrated studies – THM evolution in unsaturated buffer".

17.2.5 Water transport under saturated conditions

Water transport in a saturated buffer is a complex interplay between a number of sub-processes on a microscopic scale. On a macroscopic level, the result is that the permeability of a saturated buffer is very low, and this is also the essential result for the safety assessment. Other uncertainties concern the effect of transformations, which are expected to result in higher hydraulic conductivity. Very high salinities are also of importance for the process, see section 17.2.15.

A special case of water-saturated buffer may arise if the water pressure in the buffer is equal to the total external pressure. The effective pressure between the clay particles is then zero and the buffer loses strength and enters a state of liquefaction. In the case of certain soils (soft sand and soft illitic clay), this can occur as a result of strong vibration or water flows, but great external forces are required in the case of highly compacted bentonite. The phenomenon has been observed in connection with compaction of bentonite blocks with a high water ratio if the compaction pressure has been so high that the bentonite has become fully water-saturated.

Conclusions in RD&D 2001 and its review

SKI does not believe that liquefaction due to earthquake is a problem either, but the issue needs to be monitored. They also emphasize the importance of SKB's continued work on the development of a THM model for water-saturated conditions.

Newfound knowledge since RD&D 2001

Extensive laboratory tests with different salinities and ionic species have been conducted, mainly on bentonite from Wyoming and Milos, for the purpose of determining its hydraulic conductivity.

Some laboratory tests have been performed to show how liquefaction can occur and what the effects are. They have shown that while a rapid increase in the water pressure cannot cause liquefaction of the buffer, a rapid increase in the total pressure can. The effects of liquefaction have not yet been investigated.

Programme

Laboratory tests with different salinities and ionic species will be conducted for other potential buffer materials. A smaller test series will be carried out at elevated temperatures.

Flow tests with measurement of hydraulic conductivity and investigation of the influence of density and pore water composition – in addition to those already done on MX-80 and the Milos bentonite – also need to be done for other buffer candidates, for example Indian bentonites.

The development of the THM models for water-saturated buffer will continue, see section 17.2.23.

The effects of a (highly improbable) liquefaction of the buffer may possibly be studied in a simulated deposition hole with a loaded canister on a scale of about 1:40.

17.2.6 Gas transport/dissolution

In the case when a copper canister is damaged and water can come into contact with an iron insert, hydrogen gas will be formed inside the canister. Dissolved gas is transported slowly through the bentonite buffer, and it is very probable that a gas phase and a gas pressure will be built up in 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 2001 and its review

Kasam considers it positive that SKB is prioritizing gas transport in buffer material.

In SKI's opinion, the Äspö HRL could be used to demonstrate gas transport through the buffer on a full scale.

Regarding gas transport in saturated buffer, it is particularly urgent according to SKI that full-scale tests and tests on other scales be started and evaluated in a shorter period of time than three years if SKB is to keep to its timetable. SKI considers it doubtful whether there will be time to finish the remaining work by the scheduled time for repository licensing and points out that validated models for gas transport in saturated buffer remain to be developed, which requires experiments on different scales and even some long-term tests.

Newfound knowledge since RD&D 2001

The series of tests with gas transport in bentonite that has been under way since the mid-1990s has been concluded and the results reported /17-9/. The questions to be answered were:

- At what gas pressure can hydrogen enter the bentonite?
- How much pore water is displaced by the gas?
- Is the gas dispersed or carried in discrete pathways?
- What controls the direction of the gas flux?
- What is the highest pressure that can be developed in the gas?
- Can the gas have any adverse effects on the buffer?
- How important are the boundary conditions for gas transport?

The most recent experiments have been carried out in a constant volume cell with gas injection in the middle of the specimen, see Figure 17-1. In the walls of the cell there are three rows of filters to capture the gas.

The tests showed that the gas pressure can rise to values that are much higher than the sum of the swelling pressure and the water pressure. This is a departure from the tests performed previously. It is therefore obvious that the boundary conditions are very important for the results of gas tests in bentonite. The highest measured gas pressures were over 22 MPa, for a swelling pressure of about 6 MPa and a water pressure of 1 MPa.

The experimental set-up with three sink filter arrays showed clearly that the gas is not dispersed uniformly in the clay, but chooses to travel in discrete transport pathways. These pathways are not stable, however, but can open and close for no apparent reason.

The tests have also shown that the gas is not capable of displacing water from bentonite; 60 litres of helium with a pressure of at least 8 MPa passed through a specimen with a diameter of 60 mm and a length of 120 mm without any measurable water loss.

Nor is there anything to indicate that gas transport affects the hydraulic or self-healing properties of the bentonite.

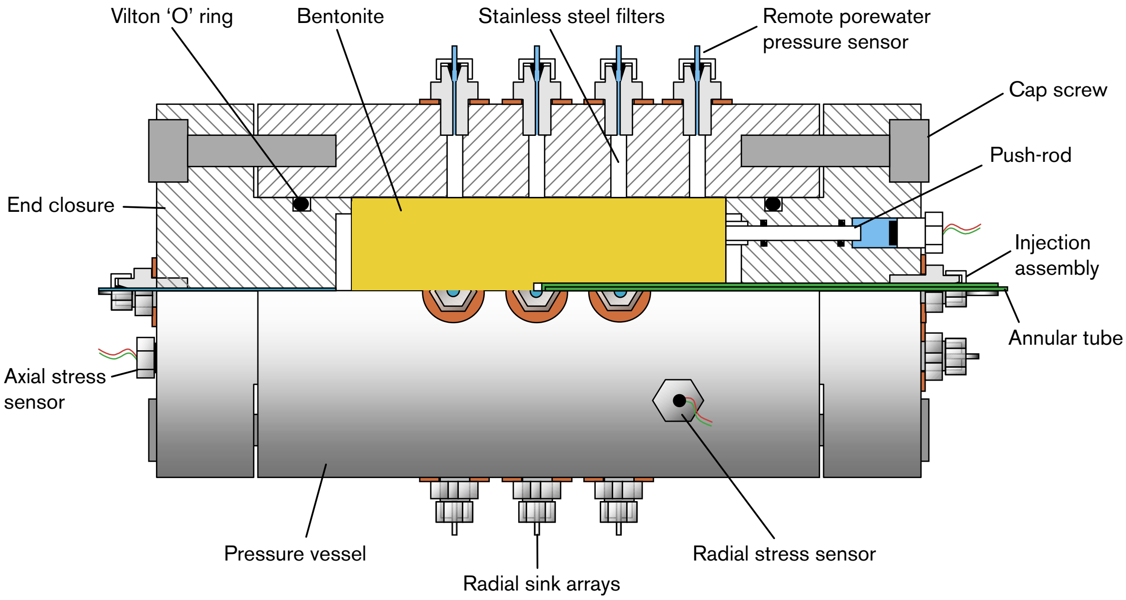


Figure 17-1. *Equipment for gas tests.*

Together with SKB Andra, Enresa, JNC, Nagra and Posiva, SKB has conducted a model development project for modelling of gas migration in bentonite (Gambit). The third phase of the project has been concluded. Unfortunately, the available experimental data does not provide a clear picture of how gas migrates in bentonite. Model development has therefore assumed three different possible mechanisms for gas flow:

1. The bentonite behaves like a conventional porous medium, where gas flow is governed by capillary pressure and relative permeability.
2. The gas flows in microfissures in the bentonite.
3. The gas flows in macroscopic fractures in the bentonite. This differs from mechanism 2 in that the fractures are of the same size as the specimen. In mechanism 2 the fissures are much smaller than the specimen.

The models that have been devised and tested can reproduce experimental data, but there are obvious deficiencies in certain respects. The conclusion is that future model development will require a better understanding of the gas pathways in bentonite and the couplings between stress and strain, gas and water fluid pressures, and gas-filled porosity.

Gasnet was a network within the EU's Fifth Framework Programme. The purpose was to review how gas-related issues were dealt with in safety and performance assessments. Among the issues discussed were:

- Corrosion rates over long time spans.
- Microbial gas formation.
- Release of carbon-14 in gas phase.
- Gas migration in clay.
- Near-field evolution.
- Importance of the excavation disturbed zone (EDZ).
- Human intrusion.
- Importance of gas for water transport.

The treatment of these issues in safety assessments is still associated with considerable uncertainties.

Programme

Our knowledge of gas transport in bentonite is based solely on experiments on a relatively small scale. A clear conclusion from all projects in the area is that gas transport experiments on a larger, preferably full, scale are necessary. SKB has therefore decided to carry out a full-scale experiment in the Äspö HRL (Lasgit). The purpose of the project is to:

- Carry out and interpret a full-scale gas injection test based on the KBS-3 concept.
- Evaluate the questions surrounding scaling-up and their importance for gas transport and buffer function.
- Provide more information about the gas transport process.
- Generate high-quality data for testing and validation of models.
- Demonstrate that gas evolution inside a canister does not have any appreciable negative consequences for the barriers in the repository.

Lasgit consists of three phases:

- An installation phase with design and manufacture of the components for the test, plus deposition of a full-scale canister and surrounding bentonite.
- A water saturation phase where the intention is to saturate the bentonite as fast as possible.

- The gas injection phase will begin when the bentonite is considered to be sufficiently water-saturated. Tests will be performed with constant pressure or constant flow conditions.

Lasgit started in 2003 and is projected to be finished in 2007–2008.

17.2.7 Swelling

Water uptake in the buffer and the backfill after deposition will lead to swelling, which 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. With its higher clay content, the buffer will swell more than the backfill. This leads to a mechanical interaction between buffer and backfill whereby the buffer is expected to swell towards the backfilled tunnel. Buffer movements can also cause the canister to move in the deposition hole. The swelling also causes clay to penetrate into the fractures in the rock. In the long run, chemical changes in the buffer can lead to changes in the swelling properties, see sections 17.2.16 and 17.2.17. 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 17.2.12.

Due to the swelling properties of the bentonite, damage to the buffer – for example due to piping and erosion, gas penetration or rock movements – will swell, shut and self-heal.

Conclusions in RD&D 2001 and its review

The process is not dealt with explicitly.

Newfound knowledge since RD&D 2001

Both theoretical and laboratory experiments have been conducted concerning the influence of pore water composition on swelling and swelling pressure properties. These results are reported in section 17.2.15.

During the work with KBS-3H, a model has been developed for analytical solution of bentonite swelling through the perforated steel container surrounding a canister-buffer parcel. The bentonite swells both through the holes in the container and in between rock and container outside the holes. Calculations and tests show that the swollen bentonite gives rise to a density, a swelling pressure and a hydraulic conductivity that is sufficient to effectively seal against the rock.

Programme

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 17.2.12 and 17.2.15.

Laboratory tests involving measurement of swelling pressure and investigation of the influence of pore water chemistry and density will be performed for other buffer candidates.

Swelling-out of bentonite through the holes in the perforated steel container in KBS-3H will be studied in a test where hole geometry and gap width are simulated on a full scale (Big Bertha).

17.2.8 Mechanical interaction buffer/backfill

In the interface between the buffer and the backfill, the buffer exerts a swelling pressure against the backfill and vice versa. Since the difference in swelling pressure is great, a net pressure arises against the backfill whereby the buffer swells and the backfill is compressed.

The size of the upswelling depends on the original densities of the buffer and the backfill and their associated expansion and compression properties, as well as the friction against the rock. Calculation models, both analytical and numerical, exist for analysis of this interaction.

Conclusions in RD&D 2001 and its review

SKI points out that SKB must make sure that the density of the buffer is not reduced too much when it swells up and displaces the backfill in the overlying tunnel (i.e. provide design premises for the backfill). In SKI's view, studies of the buffer's mechanical and rheological properties are of great importance, especially in view of the buffer-canister-rock interaction and the interaction with the backfill in the deposition tunnel.

Newfound knowledge since RD&D 2001

The upswelling of the buffer against the backfill has been investigated for an alternative backfill material (Friedland clay). Calculations have been carried out using the same methodology as before and with new measurements of the compression properties of Friedland clay. The results show that with the low dry density of 1,400 kg/m^3 that was achieved in the field tests, the swelling is 0.3 m, which requires a cover of 2.7 m buffer above the canister (instead of 1.5 m, which is the current concept) so that the buffer around the canister will not lose in density /17-10/, see also Chapter 18.

Programme

The consequences of this interaction for other types of backfill will be studied in a similar manner as for Friedland clay.

When the Prototype Repository is dismantled, the consequences will be able to be measured and comparisons made with calculations.

17.2.9 Mechanical interaction buffer/canister

Mechanical interaction between buffer and canister is caused by the buffer's clay matrix, which generates both compressive stresses and shear stresses, by the pore water, which generates only compressive stresses, and by gas in the buffer, which also generates only compressive stresses. Changes in these three variables take place during the water saturation process, and can also occur in response to external forces. The weight of the canister acts on the buffer, while the influence of the weight of the buffer on the canister is negligible. Rock movements that arise in the fracture 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.

An important process is the movement of the canister in the buffer after water saturation. The weight of the canister results in a creep movement, caused mainly by shear stresses in the buffer. Extensive laboratory tests have been performed to study these creep movements. An established model for creep in clay has proved to work for the buffer, and calculations with this model show that the movement is only a few millimetres. An uncertainty in the model is the extrapolation to a long period of time.

Conclusions in RD&D 2001 and its review

In SKI's view, studies of the buffer's mechanical and rheological properties are of great importance, especially in view of the buffer-canister-rock interaction and the interaction with the backfill in the deposition tunnel.

Newfound knowledge since RD&D 2001

Existing fractures that intersect deposition holes can be activated and sheared by a earthquake. The effect of such a rock shear has been investigated in a project that includes both laboratory tests and finite element calculations. /17-11, 17-12/.

The buffer material in a deposition hole acts as a cushion between the canister and the rock, which reduces the effect of a rock shear substantially. The lower the density the softer the buffer and the less the effect on the canister. However, at the high densities proposed for the buffer in a deep repository, its stiffness is rather high. Stiffness is also a function of the rate of shear, which means that the canister can be damaged at very high shear rates.

In order to investigate the stiffness and shear strength of the buffer material, a number of laboratory test series have been performed with shearing of water-saturated bentonite samples at different densities and shear rates. Based on these tests, a material model of the buffer that takes into account density and shear rate has been formulated. Tests have been carried out with shear rates of up to 6 m/s.

The rock shear has been modelled and calculated with the finite element code Abaqus. A three-dimensional finite element mesh that models the buffer and the canister has been created and a number of calculations that simulate different rock shears have been performed, see section 16.2.4. Figure 17-2 shows examples of calculation results.

Programme

There may be reason to further verify the modelled effect of a rock shear. The need for additional tests and possibilities for conducting such tests are being considered.

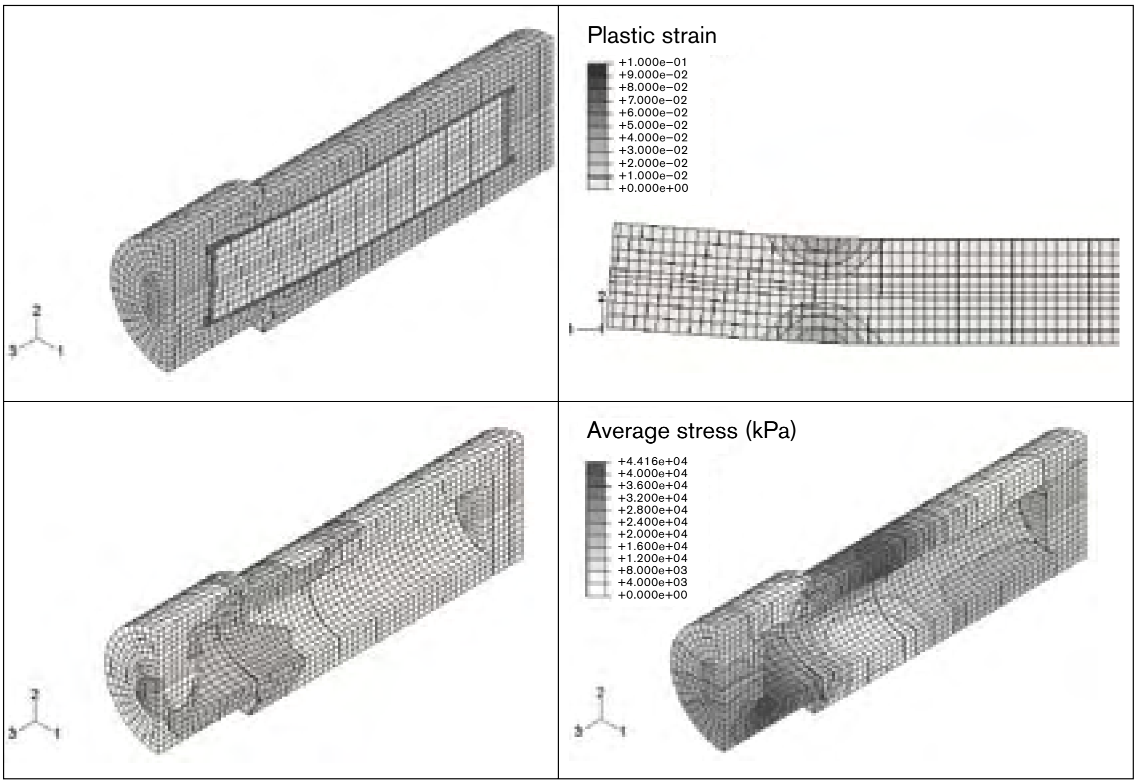


Figure 17-2. *Examples of results from a calculation with 20 cm eccentric rock shear (density at water saturation 2,000 kg/m³ and shear rate 1 m/s). Deformed structure (upper left), plastic strain in the cast iron insert (upper right), plastic strain in the buffer (lower left) and average stress (kPa) in the buffer (lower right).*

17.2.10 Mechanical interaction buffer/near-field rock

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 19.2.5 Movements in intact rock.

In KBS-3H the outer container will corrode. The transformation from iron to magnetite entails a volume increase and an increased pressure against rock and canister.

Conclusions in RD&D 2001 and its review

Not dealt with.

Newfound knowledge since RD&D 2001

Effect of rock shear is dealt with in section 17.2.9.

Theoretical studies and model tests of the extrusion of the bentonite through the holes in the container in KBS-3H have led to a theoretical model that can be used to optimize the hole pattern and understand how the bentonite penetrates in behind the perforation. The hydraulic conductivity of the bentonite between the perforation and the rock wall has been measured in the model test (scale 1:10) to be about 10^{-12} m/s, which is slightly higher than expected based on the results of other measurements and of theoretical calculations, but still fully acceptable. The model test is described further in section 17.2.12.

Scoping calculations for KBS-3H concerning the influence of extreme cases where the steel container either doubles its volume or disappears completely due to corrosion show that the buffer can be designed so that both extremes result in a density and a swelling pressure that lie within the required values.

Programme

The large-scale laboratory test Big Bertha will simulate, for KBS-3H on a full scale, the swelling-out of the bentonite through the perforated container and the interaction between the bentonite and the simulated rock wall. Swelling pressure against the rock wall will be measured in numerous points and, together with sampling after dismantling, provide additional information on how buffer, container and rock wall interact.

17.2.11 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, and 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. In the interface against the backfill, the process can lead to upward expansion of the buffer. The process is well understood for water-saturated bentonite. For non-water-saturated bentonite the thermo-mechanical 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 17.2.12.

17.2.12 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 2001 and its review

Kasam thinks it is gratifying that SKB is conducting research on wetting and temperature differences in the buffer with subsequent heat transport as a function of time and water quality.

SSI comments that SKB should give an account of how initial defects and the short-term evolution of the buffer in the resaturation phase can influence the long-term performance of the repository and to what extent the experiments at the Äspö HRL might be expected to yield answers to these questions.

SKI finds that an urgent issue in this context is the resaturation phase for both the buffer and the backfill, for which the experiments at the Äspö HRL play an important role. SKB needs to clarify the expectations on the experiments and the evaluation criteria that will be used.

SKI considers it doubtful whether there will be time to finish the remaining work by the scheduled time for repository licensing and points out that validated models for combined heat and water transport in unsaturated buffer remain to be developed.

Newfound knowledge since RD&D 2001

Model studies

An integrated model for simulation of unsaturated coupled THM processes has previously been developed and applied to the finite element code Abaqus. This model has proved less sufficient for certain applications. Formation, condensation and transport of water vapour cannot be modelled in a physically correct manner, nor can the pressure effects of generated or trapped gas. Both water vapour and other gases are of importance for heat transport and water saturation.

For simple and idealized conditions, for example if the possibility that water vapour may leave the buffer to condense in the backfill is not taken into consideration, it was possible to simulate the effects of temperature-driven vapour transport fairly well with the calculation models previously used without explicitly modelling the vapour phase. Effects of other gases could not, however, be taken into account.

Inventory, evaluation and use of alternative calculation models has therefore been done. The codes that have been tested are Compass, which was developed at the University of Wales in Cardiff, and Code Bright, which was developed at UPC, Universidad Politécnica de Cataluñya, in Barcelona. In these codes, the effect of negative pore pressure on the stress state (and thereby the hydromechanical processes) can furthermore be handled according to modern models for unsaturated soil materials.

As a result of the evaluation, Code Bright has been chosen and adapted to SKB's buffer material. Code Bright has been developed specially for analysis of THM processes in porous, unsaturated materials. A study of the water saturation process in KBS-3V has been carried out and the results reported /17-13/. The results showed that the area between canister and rock wall becomes saturated with water in two to four years, provided there is a supply of water at atmospheric pressure in the buffer-rock transition. To be able to fully take into account all aspects of the water saturation process, however, it is necessary to consider not only those aspects that have to do with T-H couplings, gas movement and vapour diffusion, but also the hydromechanical aspects.

The new model has been applied to the TBT test at the Äspö HRL. The TBT test is being conducted by Andra with SKB as the organizing and executive partner and concerns THM processes at high temperatures (over 130°C). The new model produces physically realistic results, including considerable vaporization and drying-out at the hot canister edge, vapour diffusion in the direction of the thermal gradient and condensation in colder parts of the buffer. The measurement results that are gradually emerging confirm the relevance of the model /17-14, 17-15/. The effect of the dry air that is present from the start in the pore system and in joints and gaps is not quite clear, since it has not been possible to rule out the possibility that some of the dry air might have leaked out from the experiment.

Investigations of the hydromechanical properties of the bentonite, above all the influence of swelling pressure evolution, mechanical constraint and external pressure on the pore pressure potential at incomplete water saturation, are under way. The results will be used to determine values for material parameters in Code Bright. With a better model for how the porosity distribution changes during swelling and compression, and for how the redistribution affects e.g. the pore pressure potential, it will be possible to model processes around gaps, for example at the transition between rock and buffer, in a physically realistic manner.

A number of model studies have also been done with Abaqus, see section 17.2.4.

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, Canister Retrieval Test and TBT test are the foremost examples. These tests cover both wet and dry conditions and will be conducted for various lengths of time. This means that the measurement results from installed sensors, as well as measurements on samples taken from future 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.

Laboratory experiments

Fundamental understanding of and relationships between the negative pore water pressure, the swelling pressure during wetting and the degree of water saturation are being investigated in an ongoing doctoral project whose results will be reported this year. In this project, laboratory technique for measurement of the swelling pressure at different relative humidities has been developed. The methods have been used to determine the influence of pressure (swelling pressure and total pressure) on the negative pore water pressure. These studies consist of e.g. enclosing a sample of unsaturated bentonite in an oedometer and controlling the relative humidity in the sample either by circulating air with a given relative humidity through filters that are in contact with the sample, or by surrounding the sample with an atmosphere with a given relative humidity. By changing the relative humidity gradually and continuously measuring the relative humidity in the middle of the sample, measuring the sample's swelling pressure and determining the sample's water ratio, an understanding has been gained of the evolution of the swelling pressure and its influence on the negative pore water pressure, as well as important relationships for the material models.

The wetting process with associated swelling and homogenization has been studied in the laboratory for the KBS-3H concept. A 1:10 scale model of a horizontal deposition hole has been built in the laboratory. A deposition tunnel with two parcels containing canister, bentonite block and perforated steel container as well as spacer plugs was modelled in the experiment. The rock was simulated by a steel tube partially lined with filters for wetting of the bentonite and for the application of hydraulic gradients between the filters so that the resulting flow can be studied. Figure 17-3 shows a cutaway diagram of the experimental set-up.

The model was instrumented with total pressure sensors, pore pressure sensors and RH (relative humidity) sensors, which were attached to the outer steel tube and to one of the canisters. The canisters were not heated.

The experiment was terminated one year after start to permit evaluation of wetting, homogenization and interaction between buffer and perforated container. The results show that wetting and pressure build-up had proceeded largely as expected but more slowly towards the end. To study the hydraulic function of spacer blocks and the rest of the buffer, a hydraulic gradient was applied between the filters in different increments. The hydraulic conductivity of the bentonite behind the perforation has been evaluated at about 10^{-12} m/s, which is slightly higher than expected from the swelling pressures and the water ratio measured in the model test and from

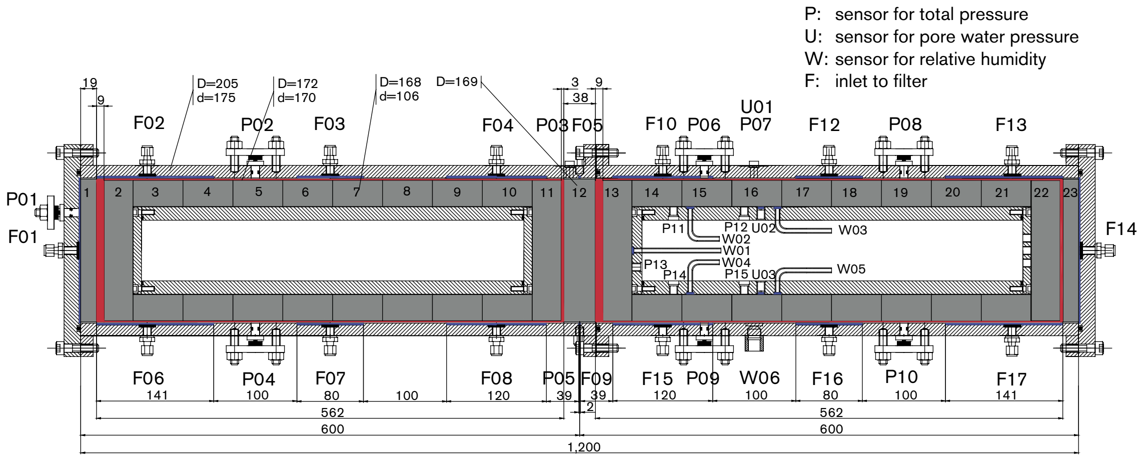


Figure 17-3. *Cutaway diagram of experimental set-up for the KBS-3H model on a scale of 1:10. P measurement of swelling pressure, U measurement of pore water pressure, W measurement of relative humidity, F inlet to filter. The dimensions are in millimetres.*

the theoretical calculations, but still fully acceptable. Other results of the model test were that the perforated outer container burst (as expected) and that a clear effect of the steel could be seen on the bentonite. The scale test, which lasted one year, also showed that full swelling pressures developed behind the container but that the pressure variation was greater than in earlier measurements without a container, see also 17.2.10.

A large-scale Czech experiment (Mock-up Experiment) has been started with support from SKB. The experiment simulates a deposition hole of the KBS-3V type with buffer and canister designed for Czech conditions and with the following constituents:

- A rock which is simulated by a steel cylinder with a wall thickness of 8 mm, an inside diameter of 800 mm and a height of 2,300 mm which is lined with a filter for wetting.
- A canister with an outside diameter of 320 mm and a height of 1,300 mm that contains two heaters.
- A surrounding buffer that is 160 mm thick between the canister and the steel cylinder. The buffer is composed of 70 mm high sectoral blocks consisting of a mixture of RMN bentonite (Czech), ten percent silica sand and five percent graphite.
- A 50 mm wide gap between the bentonite blocks and the filters on the steel cylinder. The gap is filled with manually compacted buffer of the same composition as the blocks.

Temperature, pressure, relative humidity and strain are measured. The experiment started in May 2002.

Programme

Model studies

The programme of experimentally investigating the buffer's thermo-hydro-mechanical properties will continue, with an emphasis on obtaining values of material parameters for use in Abaqus and Code Bright. Several of these parameters are difficult to determine and require calibration and verification tests in the laboratory. For Code Bright in particular, some numerical and theoretical testing work is needed to be able to use the code's hydro-mechanical models in an optimal manner. The doctoral project currently under way to investigate how the pore pressure potential is affected by mechanical constraint will serve as an important point of departure for further studies. In particular, parameters having to do with how void ratio changes affect the pore pressure potential must be determined. Temperature gradient tests under controlled gas pressure conditions also need to be performed.

Results of tests being done abroad, for example by CEA, under the auspices of Andra and by Enresa can be evaluated and utilized to broaden the body of experimental data. CEA's test is being done on MX-80 bentonite which is exposed to large temperature gradients and relates to one of the most important processes, namely redistribution of the initial water content by heat-driven vapour transport.

In the TBT test, the work of applied simulation is continuing. As data are generated and trends become clear in the test, a phase of evaluation modelling will be initiated. The purpose is to evaluate the relevance of the models used in the blind predictions that were made at the start of the test. The evaluation modelling is being done in cooperation with modelling groups organized by Andra and Enresa.

As the material models are developed, they are applied in the Code Bright and Abaqus modellings of the Prototype Repository, the Canister Retrieval Test, the Backfill and Plug test and Lasgit. The modelling work is being conducted within the various projects, but will also be included in a joint project where modelling groups from different organizations participate (EBS Task Force).

The modelling work is also being conducted in the form of simulation of ongoing field tests (see below) and follow-up and analysis of the measurement results. Modelling of the Buffer-Container experiment at the URL in Canada and modelling of the continuation of the Febex experiment at Grimsel, Switzerland, will also be done.

Field studies

The field studies are being conducted by follow-up of the ongoing Prototype Repository project, Canister Retrieval Test and TBT test (Temperature Buffer Test) at Äspö. Dismantling of the outer section in the Prototype Repository is planned to take place in 2008, and dismantling of the Canister Retrieval Test with test of retrieval technology in certain parts is planned to take place in 2007.

Laboratory experiments

In parallel with the model studies and follow-up and modelling of the field tests, laboratory experiments on water-unsaturated bentonite will continue for the purpose of gaining a better understanding of the unsaturated processes and gathering data to determine parameter values in existing models. The following types of tests are planned:

- Oedometer tests on unsaturated samples with controlled negative pore pressure in the bentonite (different constant relative humidities). These tests will be done to determine some parameters in the mechanical model Code Bright.
- Tests with constant volume and measurement of negative pore pressure and swelling pressure at changed water content. Supplementary tests for further verification and parameter determinations in the model that is under development (of the relationship between negative pore pressure, degree of water saturation, void ratio and swelling pressure).
- Tests with temperature gradients applied across bentonite samples under controlled forms. The purpose of these tests is to improve the models for water redistribution in a temperature gradient.
- Tests of vapour transport and water transport through unsaturated samples. The wetting rate is measured by applying elevated relative humidity (RH) to one side of a bentonite sample and measuring the inflow of water, and alternatively by applying free water on one side of a bentonite sample. The samples are kept at constant volume during the tests. The purpose of the tests is to obtain better data as a basis for the vapour and water transport models.

- Tests of the wetting process close to full water saturation. The time to water saturation appears to be longer than expected in some cases, due to the fact that the processes in the final phase of water saturation have not been carefully studied.

To verify the course of swelling, extrusion and homogenization during the interaction of the buffer with the perforated container in KBS-3H, a nearly full-scale test will be performed in the laboratory. A portion of a deposition hole with rock, perforated tube and bentonite will be simulated. To reduce the dimensions but nevertheless maintain the full scale of the tested components, only the bentonite portion will be tested, i.e. no canister will be included. this means that a steel cylinder with an inside diameter of 0.8 m and a length of about 1.0 m will be used to enclose and wet the bentonite, i.e. to simulate the rock. To facilitate dismantling, the tube will be axially split. The deposition container (thickness and holes) and all gaps will be made full scale. In order to monitor the wetting process, total pressure and relative humidity (RH) will be measured at 6–10 points in the bentonite. Sensors will be placed on the outer tube and in the centre of the bentonite. The volume of incoming water will also be measured. The test is planned to start in 2004 and be terminated in 2006.

Continued follow-up and evaluation will be done of the large-scale Czech laboratory experiment, the Mock-up Experiment. SKB is supporting both the test and its evaluation.

17.2.13 Advection

Solutes can be transported with pore water by pressure-induced flow – advection. 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 17.2.14. Water flow in the buffer under unsaturated and saturated conditions is dealt with in sections 17.2.4 and 17.2.5.

17.2.14 Diffusion

Solutes can be transported in stagnant pore water by diffusion, whereby 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 section 17.2.23 as regards the chemical evolution of the buffer and in section 17.2.25 as regards radionuclide transport.

17.2.15 Osmosis

The physical properties of the buffer, including swelling pressure and hydraulic conductivity, are intimately linked to the buffer's ability to absorb and bind water. The binding force of bentonite is mainly dependent on the proportion of montmorillonite and on variations 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 with the aid of thermodynamics, e.g. in the form of osmotic pressure.

Conclusions in RD&D 2001 and its review

In SKI's opinion, SKB has good insight into the processes of swelling and osmosis in the bentonite clay.

Newfound knowledge since RD&D 2001

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 quantity of layers. The prerequisite for equilibrium in such a system is that the product of the 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 product between the mineral layers will therefore be dominated by the montmorillonite's counterions. An increase in the groundwater's ion concentration therefore leads to a much smaller increase in the ion concentration between the mineral layers. 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.

Extensive laboratory experiments have been conducted in cooperation with Posiva, Finland. The results show that pressure calculation with the aid of Donnan equilibrium accurately describes the conditions for a wide range of sodium concentrations and bentonite densities /17-16/.

Bentonite with a naturally high content of sodium chloride due to exposure to sea water has been investigated in cooperation with Enresa in the Barra project /17-17/. The main purpose of tests and analyses was to study the stability of the bentonite in connection with long-term exposure to high salinities. Sodium chloride concentrations of more than two moles per litre were measured in most analyzed samples. Swelling tests were performed with pure water after desalination and with sodium chloride concentrations of up to three moles per litre. The results showed pressure conditions that closely resembled those measured for MX-80 over a wide range of densities.

Programme

Laboratory investigations of osmotic effects for other ionic species than sodium (mainly calcium) have been commenced and will be finished during the coming period. The experimental programme includes various bentonite materials as well as bentonite density and ion concentration as variables. Swelling pressure and hydraulic conductivity are determined for each individual ion equilibrium. A small number of tests will be conducted at elevated temperatures. Development of the theory for Donnan equilibrium and the effects of swelling pressure and ion concentrations in the buffer will continue.

The results of the laboratory tests are also expected to provide information on the pore structure in the bentonite, which will be supplemented by special analyses of the test material, for example by means of X-rays.

17.2.16 Ion exchange/sorption

Conclusions in RD&D 2001 and its review

SKB concluded that the physical properties of the buffer are greatly affected by the ion content of the pore water. Under the chemical conditions that are expected to prevail in a deep repository, it is above all the total salinity and exchange from sodium ions to calcium ions that can influence these properties to an appreciable extent.

SKI maintains that SKB should evaluate what saline groundwaters mean for the repository.

Newfound knowledge since RD&D 2001

The effect of total ion exchange has been investigated for bentonite from Milos (Ibeco Deponit CA-N) and from Wyoming (MX-80). The materials were investigated in their natural form, which is primarily calcium for the Milos material and sodium for the Wyoming material. Both materials were subsequently purified of accessory minerals and ion-exchanged to both calcium and sodium form. The mineral structure of the montmorillonite was calculated, and swelling pressure and hydraulic conductivity were determined for different densities. The results show that the two bentonites have more or less identical properties after ion exchange, and that the difference in properties at buffer density is minimal, regardless of ionic species. The swelling potential of the materials that were ion-exchanged to calcium form was, however, appreciably lower, which leads to poorer buffer properties at low densities.

Geometric modelling of ion exchange in an MX-80 material as a consequence of exposure to groundwater from Äspö has been done in the Lot project /17-18/.

Programme

Effects due to ion exchange will be studied during the coming period by means of laboratory tests with other potential buffer materials, and with materials of lower quality. Geometric modelling will continue with the ultimate goal of being able to describe the effect of the water saturation phase and of temperature gradients. Laboratory tests will probably have to be performed to determine equilibrium constants for compacted bentonite at elevated temperatures.

17.2.17 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, see section 17.2.15, and by changes in the mineral structure of the montmorillonite. 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. The ideal structural formula of montmorillonite can be written:

$(Al_{(4-x)} Mg_{x}) (Si_{(8-y)} Al_y) O_{20}(OH)_4 k^z_{(x+y)/z} n(H_2O)$

The sum of x and y can vary by definition between 0.4 and 1.2 units (charge per $O_{20}(OH_4)$ unit), 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).

Minerals occur in nature with a similar structure but great differences in layer charge. If the charge (x+y) is close to zero (for example pyrophyllite), the interaction with water is insignificant, which results in radically different properties compared with montmorillonite. An increase of the layer charge, and thereby more balanced cations, leads to greater interaction with water. If the layer charge increases enough, the ions may be bound more tightly to the mineral, resulting in less interaction with water. The end mineral in such a series has a layer charge of 2 per $O_{20}(OH_4)$ unit (mica). The typical properties of the montmorillonite are thus a consequence of a medium-high layer charge.

The binding of charge-balanced ions is due 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, for example, bound to some extent in an illite clay, but not sodium or calcium ions. Binding of multivalent ions, usually iron or magnesium, can also take place via a bridge of hydroxide, which gives a chlorite mineral.

Thus, 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,
- 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).

Conclusions in RD&D 2001 and its review

Kasam considers that it would be valuable if SKB, in connection with its studies of other compositions, also investigated how a limited illitization and cementation affects parameters of importance for the buffer.

In SKI's opinion, the mineral transformations should be studied in the laboratory, and cementation during the unsaturated phase is an important process.

Newfound knowledge since RD&D 2001

Extensive laboratory experiments have been conducted to study the stability of the buffer at very high pHs in the groundwater. The investigation was a part of the EU project Ecoclay, whose purpose was to shed light on the effects of cement use in a final repository. The results show that the montmorillonite is greatly affected by cement pore water from fresh Portland cement, i.e. at pHs between 13 and 14. A heavy release of silicon was measured, causing an increase in the layer charge and a loss of density in the bulk material. At lower pHs, the results showed a significant difference between highly compacted bentonite and bentonite dispersed in solution. A preliminary interpretation is that a favourable ion equilibrium is established between highly compacted bentonite and the pH solution, see section 17.2.15.

Programme

The results of the Ecoclay project are in the process of being evaluated and published. The results are judged to be very valuable. Further modelling and verification tests will probably be carried out.

Laboratory tests with natural materials of lower quality than commercial bentonites are planned. The investigations involve mineralogical description and determination of physical properties of e.g. natural materials with different degrees of transformation, for example potassium bentonite from Röstånga, Skåne.

SKB plans to study changes in the buffer properties as a result of reactions with iron in bentonite with regard to two aspects:

- Valence change in the octahedral layer in the mineral structure will be studied by means of diffusion tests with reducing and oxidizing solutions.
- Binding of iron as a charge-compensating counterion and/or as a central ion for a hydroxide bridge between the mineral layers; this may lead to an increased corrosion rate of surrounding iron.

Figure 17-4. Natural redox front in the bentonite mine at Angeria on the Greek island of Milos.

17.2.18 Dissolution/precipitation of impurities

Besides montmorillonite, the buffer material also consists of accessory minerals, which are counted here among the material's impurities. In the repository environment, these impurities can be dissolved and sometimes re-precipitated depending on the prevailing conditions. The properties of the buffer can thereby be changed.

Most of the conceivable processes are well known in themselves and can be modelled for less complex systems. However, conditions in the buffer with respect to transport and reaction kinetics are not fully understood for all processes. Transport of substances can take place in different forms and cannot be thoroughly described today. In particular there are remaining modelling problems during the water saturation phase, when water is transported in both vapour and liquid form. Modelling of the system must therefore be coupled to the THM processes that proceed in parallel with transport and reaction kinetics.

Conclusions in RD&D 2001 and its review

Kasam underlines the need for further studies on the release, transport and precipitation of dissolved silicon and other substances in the buffer.

Newfound knowledge since RD&D 2001

In the Lot tests at Äspö, buffer material is exposed to large temperature gradients (a maximum of 130 to 80°C over a distance of 10 cm). Material from the three completed one-year tests has been analyzed in a large number of points with respect to e.g. distribution of elements and rheological properties. The results show that a minimal redistribution of silicon and magnesium has taken place. The changes were so small that they cannot be related to specific minerals. The bentonite was generally more plastic after the test, which shows that no cementation had taken place in most of the buffer. On the other hand, a clear precipitation of gypsum in particular was observed on the simulated copper canister and in the innermost one to two millimetres of the bentonite. Geochemical modelling of redistribution of minerals in a MX-80 material as a consequence of exposure to Äspö groundwater was done in the Lot project /17-18/.

Programme

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 latter is conceivable, since e.g. gypsum and calcite exhibit declining solubility at increasing temperature.

At present, four long-term tests are being conducted within the Lot project. According to the original plan, a high-temperature test will be terminated in the spring of 2005, entailing an exposure time of five years. A five-year test with KBS-3 temperature is planned to be terminated in 2006. According to the current plan, the remaining two tests will be conducted for a much longer time.

Continued geochemical modelling is planned within the Lot project, partly with respect to redistribution of minerals and partly with respect to transformation of montmorillonite.

17.2.19 Colloid release/erosion

The estimates in SR 97 suggest that there is little risk of erosion, whether chemical or mechanical, of large quantities of bentonite. However, the process should be further studied. One remaining question concerns the importance of very low ionic strengths in the groundwater.

Conclusions in RD&D 2001 and its review

SKI notes that erosion of the buffer material is not mentioned in the RD&D-Programme, but is of the opinion that SKB has taken the necessary initiatives to move forward in the colloid issue (for example by means of the Colloid Project in the Äspö HRL).

Newfound knowledge since RD&D 2001

Tests conducted in conjunction with KBS-3H studies have shown that piping from water-conducting fractures accompanied by erosion could be a problem before the buffer has become water-saturated. These phenomena are particularly serious for KBS-3H, since they can affect all canister parcels that have been installed downstream of the water-conducting fracture. But this could also conceivably affect certain deposition holes in KBS-3V. The following description pertains primarily to KBS-3H, however.

If the inflowing water causes piping and erosion in the buffer, the buffer may be unable to seal properly before closure, which means the flow of water must be stopped in some other way. The base scenario is that 0.1 litre of water per minute runs into a section with a deposition parcel in a KBS-3H tunnel and that the build-up of water pressure in the rock is about 100 kPa/hour if the inflow is stopped. No matter how this inflow occurs, it is likely that the bentonite inside the perforated container will be unable to stop the inflow before all gaps are first filled out from the bottom at the same rate as the distance block swells and prevents further outward transport. After at least ten days the gaps have been filled and the distance block has swollen (mainly as gel) out against the rock. The last part expected to swell is at the roof. When this part has also become impervious, the water cannot escape and the pressure in the fracture then builds up. If the pressure builds up too quickly, the bentonite will not have time to swell fast enough without piping occurring in the gel and erosion can start if the flow is heavy.

These phenomena have been studied both in basic laboratory tests and in model tests on different scales. The former were done either with constant flow rate or constant water pressure in drilled holes with a diameter of 2–4 millimetres through 5–10 centimetre long bentonite pellets. The results showed that only very low water flow rates or very low water pressures could be stopped by the bentonite. Since these tests can be regarded as conservative extremes, model tests were performed, first on a scale of 1:10 and then on full scale. The result of the model tests on a scale of 1:10, where the gap at the top of the simulated distance block was four millimetres, was that a pressure increase rate of about 200 kPa/h was the upper limit below which piping did not occur, but also that the water fill-up rate was an important parameter. When the test was scaled up to full scale, however, the upper limit was only 5 kPa/h, since the gap there was four centimetres. At the same time, the leakage rate during fill-up was very great. In other words, the requirements cannot be met without an engineering solution, and a collar was applied to the "rock" in the most recent test. The collar was attached to the "rock" and its annular disc was made so big that it closed off the gap between the "rock" and the spacer block and extended another five centimetres into the spacer block. This arrangement could cope with 50 kPa/h up to a pressure of 2 MPa without piping occurring and without any leakage occurring before fill-up was finished.

The conclusion is thus that a gap on the order of several centimetres between the roof and the distance block cannot handle the base scenario without an engineering solution, but also that it should be fully possible to either devise solutions that meet the requirements or to make spacer blocks with smaller gaps against the rock (for example, wedge-shaped three-piece blocks).

Independent tests have been conducted within the Colloid Project, as well as field tests at Äspö. The results clearly show that spontaneous dispersal of montmorillonite from a bentonite buffer does not occur if the calcium concentration in the groundwater exceeds 1 mM. The results complement and confirm previous investigations both qualitatively and quantitatively /17-19/.

The problem of spontaneous release of montmorillonite is thereby probably reduced to the concentration of divalent ions in the groundwater.

Programme

The tests with piping and erosion for KBS-3H will continue both on a small scale and on full scale to gain a better understanding of these processes. If it proves difficult to guarantee that piping will not occur, a series of erosion tests must be done for the purpose of being able to estimate the quantity of eroding bentonite in different situations.

Quantitative modelling of a possible removal of montmorillonite colloids from the buffer is planned.

17.2.20 Radiation-induced montmorillonite transformation

Montmorillonite in the buffer can be broken down by gamma radiation. The result is a decrease in the montmorillonite concentration. Experiments have shown that the accumulated radiation dose to which the bentonite will be exposed in a deep repository does not cause any measurable changes in the montmorillonite concentration.

17.2.21 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 which 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 17.1.4.

17.2.22 Microbial processes

Conclusions in RD&D 2001 and its review

SKB concluded that microbial processes can under certain conditions result in the formation of gas and sulphide. Gas formation can give rise to disrupting mechanical effects on the buffer, and sulphide can corrode the copper canister. Sulphide formation must take place in the buffer, near the canister, and be of considerable scope for corrosion to be possible, mainly due to the fact that the solubility of sulphide, and thereby its diffusive transport capacity, is very low. It is also known that bacteria can bind and transport metals in ionic form. In order for the above-described processes to take place, however, the bacteria must be active and have access to water, nutrients and space.

Newfound knowledge since RD&D 2001

Nothing new has been learned since the previous study in conjunction with the Lot project at Äspö /17-20/, see also section 16.2.12.

Programme

Termination of ongoing five-year test with microbes in bentonite within the Lot project during 2005.

17.2.23 Integrated studies – evolution under saturated conditions

Integrated model studies for the buffer under saturated conditions are being conducted for the integrated chemical evolution.

Conclusions in RD&D 2001 and its review

In SKI's opinion, SKB should update the THMC couplings – especially the chemical aspects – with the results of the most recent temperature calculations.

Newfound knowledge since RD&D 2001

The THM studies of integrated processes that have been carried out on unsaturated buffer since RD&D 2001 are as follows:

- Influence of rapid pressure pulses on the buffer, see section 17.2.5.
- Effect of earthquake-induced rock shear through deposition holes, see section 17.2.9.

No further development has been done of the THM material model for saturated conditions.

Programme

The mechanical part of the THM model for water-saturated bentonite is complex and has certain remaining questions as regards both parameter values and model. It actually consists of two models: One that handles the relationships between stresses and deformations, and a creep model that handles the time dependence. The models are used to model:

- The interaction between buffer and backfill.
- Homogenization of the buffer.
- The canister's movement in the buffer with time.

The work with these questions and follow-up of model development will continue.

Tests for studying the influence of pressure pulses will continue, see also sections 17.2.5 and 17.2.9.

17.2.24 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.

17.2.25 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). One possible explanation for this phenomenon is the theory of surface diffusion. The process is handled in the safety assessment by assigning higher diffusivity values to caesium, strontium and radium.

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 2001 and its review

SKI questions whether it is correct to describe the surface diffusion process by postulating higher diffusivity values for caesium, strontium and radium, see also section 17.2.26.

Newfound knowledge since RD&D 2001

A number of laboratory tests have been carried out to investigate in detail various processes that influence ion diffusion in bentonite clay. Anion diffusion in bentonite clay compacted to different dry densities has been investigated /17-21/. The results indicate that anion diffusion in bentonite clay consists of two processes, a fast one and a slow one. The explanation that has been proposed is that the rapid diffusion process is diffusion between the bentonite layers, while the slow one is diffusion between the bentonite particles, where the anions to some degree sorb to edge positions on the montmorillonite and/or to other minerals in the bentonite.

Diffusion in bentonite clay has been investigated in two in situ experiments in the Äspö HRL: Chemlab and Lot. Chemlab is a down-the-hole laboratory probe in which diffusion tests have been conducted with cations (Cs^+, Sr^{2+} and Co^{2+}) and anions (I^- and TcO_4^-) in bentonite and with natural groundwater. The water was taken from a fracture in the same borehole in which the test was performed /17-22/. The redox-sensitive pertechnate ion (TcO_4^-) diffused unreduced, despite the fact that it should have been reduced thermodynamically and precipitated as $TcO_2{\cdot}nH_2O$ /17-23/. The technetium activity was much higher at certain places, however. The activity peaks are attributed to iron-bearing minerals where Tc(VII) has been reduced to Tc(IV) and precipitated. The cations Sr^{2+}, Cs^+ and Co^{2+}, as well as the anion I^-, behaved in the same way as in a laboratory test.

In the Lot tests /17-24/, cylindrical bentonite blocks were placed around a copper tube in a four-metre deep vertical borehole. The hole was then sealed and the bentonite blocks were left in the hole for one year, five years or a much longer time than five years. When the bentonite is water-saturated, the copper tube is heated to simulate the energy that is liberated by radioactive decay in the spent nuclear fuel. Bentonite that has been doped with radioactive caesium and cobalt was placed in one of the lowermost blocks. When the test was concluded, the activity-containing bentonite block was taken to a radiological laboratory, where the activity distribution in the block was determined. The activity distribution was as expected from laboratory studies for both the cations.

The results of the laboratory, Chemlab and Lot tests provide a clear picture of the diffusion behaviour of the studied ions. The data obtained, i.e. diffusivities and distribution coefficients, agree well in the three different studies.

Programme

SKB intends to evaluate an alternative description of the diffusion process in bentonite based on ion equilibrium. The overlapping electrical double layers entail that there are charge-compensating counterions in the entire space between the mineral layers. Since only the counterions can diffuse freely, the ion balance with surrounding groundwater will be controlled by the counterion concentration, section 17.2.15. This leads to lower concentration of groundwater ions in the bentonite than in the surrounding groundwater. The cations from the groundwater can, however, replace the original charge-compensating cations by means of ion exchange. The anions, on the other hand, cannot replace the negatively charged mineral layers, so that the concentration of introduced anions is lower than the concentration of introduced cations (anion exclusion). The higher concentration of introduced cations leads to a higher concentration gradient and thereby more rapid diffusive transport (surface diffusion). The advantage of this description of diffusion in bentonite, if it turns out to be correct, is that it permits a theoretical quantification and a better conceptual understanding.

Transport resistance for radionuclides in the interface between bentonite and water-conducting fracture /17-25, 17-26/ will be investigated experimentally. The plans include both laboratory and in situ experiments. The latter will be performed in the Chemlab probe.

17.2.26 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.

Conclusions in RD&D 2001 and its review

Kasam believes that it should be possible to develop a more sophisticated sorption model (ion exchange, adsorption and surface precipitation of radionuclides as a function of concentration and pH).

SKI questions the way SKB dismisses the sorption process as it does in RD&D 2001.

Newfound knowledge since RD&D 2001

The results of in situ tests with the Chemlab probe have been described in section 17.2.25.

As a basis for SR-Can, SKB has published an updated report describing diffusion and sorption of radionuclides in bentonite /17-27/. The report contains the data that will be used in the assessment and a detailed description of uncertainties in data. Most diffusivities have been chosen on the basis of diffusion tests with HTO, which are insensitive to the extreme parameters. Thermodynamic sorption models have been used for the radionuclides where the data are good enough.

Programme

SKB does not consider sorption in bentonite to be a prioritized research area. However, existing data will be updated prior to each new safety report.

17.2.27 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 15.2.14 and the evolution of the chemical environment in the buffer in section 17.2.23. In SR-Can, the same types of speciation calculations are carried out for e.g. the buffer environment as in SR 97.

17.2.28 Radionuclide transport – colloid transport through bentonite

The buffer is supposed to prevent colloids with radionuclides from escaping from a damaged canister.

Conclusions in RD&D 2001 and its review

In SKI's opinion, SKB should investigate the importance for the safety assessment of the fact that organic colloids can diffuse through the buffer, as well as whether the same phenomenon applies to inorganic colloids.

Newfound knowledge since RD&D 2001

Diffusion of organic colloids in bentonite has been studied in a doctoral thesis /17-28/. The purpose of the thesis was to obtain knowledge of the sorption and diffusion of organic colloids in compacted bentonite, and to investigate whether bentonite is an effective barrier to colloids. The transport properties of radionuclides in bentonite may be altered in the presence of colloids due to the fact that speciation and sorption processes are altered. It was found that humic acids, unlike bentonite colloids, are stable in granitic groundwaters. Despite the fact that humic acids give rise to charged and relatively large aggregates, they diffuse easily through compacted bentonite (diffusivity D_e about 10^{-11} m/s). The experiments show that humic acid diffuses in the entire pore volume, i.e. both intralamellarly and in the spaces between particles. The transport of Eu(III) and Co(II) in bentonite increases significantly in the presence of humic colloids, while the transport of Sr(II) is unaffected.

Programme

It is important that colloids that are formed inside the canister be filtered in the bentonite. According to /17-28/, it is clear that organic colloids are not filtered by the bentonite in the same way as inorganic colloids. Understanding of the properties of colloids in bentonite will require further research.

18 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.

SKI points out in its review of RD&D 2001 that the backfill is a prerequisite for ensuring that the buffer performs as intended and that the near-field rock is not short circuited as a barrier against groundwater flow. SKI therefore urges SKB to rapidly determine the requirements and criteria that the backfill material must meet so that, prior to licensing, data and methods can be developed that show how these requirements are met (for example with respect to material choice, application technology and inspection methods).

18.1 Initial state of the backfill

18.1.1 Variables

More or less the same set of variables is used to describe the backfill as for the buffer, see Table 17-1.

18.1.2 Geometry

The dimensions of the backfill are given by the dimensions of the tunnels.

18.1.3 Pore geometry

The initial pore geometry (porosity) of the backfill follows trivially from its material specifications.

18.1.4 Radiation intensity

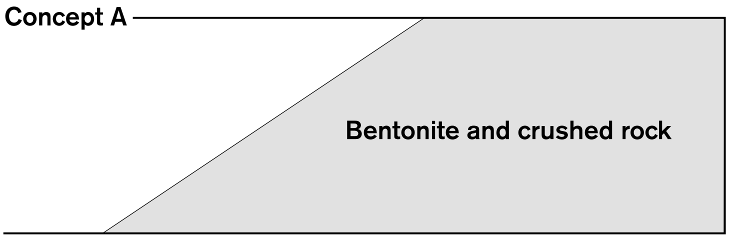
The initial radiation intensity in the backfill is negligible.

18.1.5 Temperature

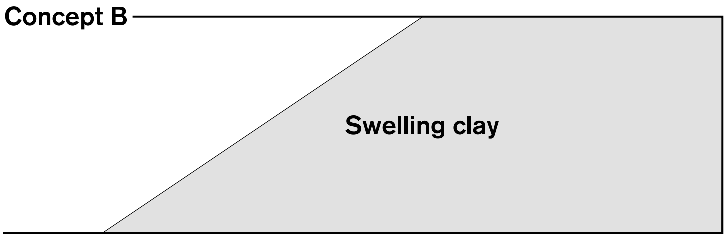
A determination of the initial temperature in the backfill is trivial. It will be close to the initial temperature of the rock.

18.1.6 Smectite content

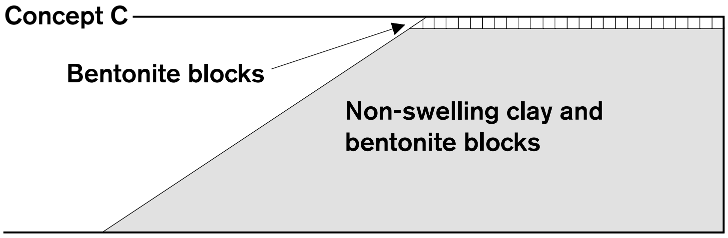
SKB, together with Posiva, is currently studying a number of different concepts for tunnel backfilling /18-1/. The concepts currently being considered for assessment in SR-Can are either a 30/70 mixture of buffer material and crushed rock that is compacted in situ, or block-pressed Friedland clay, see Figure 18-1.



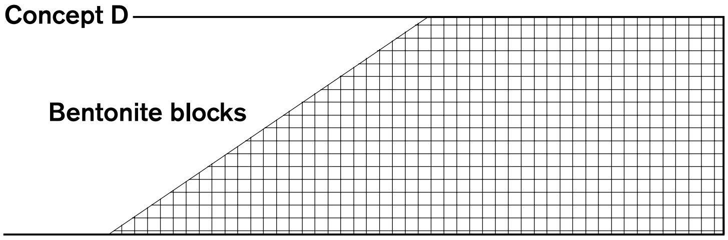
The original reference concept: bentonite (same as for buffer) mixed with crushed rock.



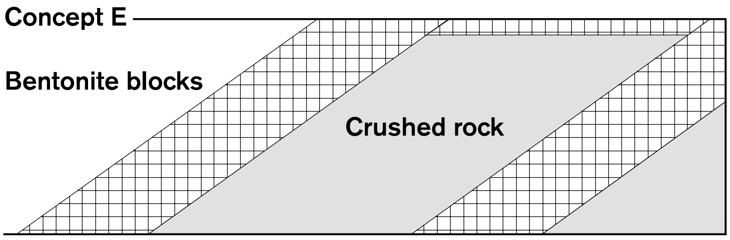
Swelling clay that is compacted in-situ in the tunnel. Friedland clay is currently used as a reference, but many different clays could be possible.



Non-swelling clay with bentonite blocks in the roof.



Swelling clay that is compacted to blocks and placed in the tunnel. Friedland clay is currently used as a reference, but many different clays could be possible.



Blocks of bentonite of buffer quality alternating with layers of crushed rock in a compartment system.

Figure 18-1. *Different concepts for backfill currently being investigated.*

Conclusions in RD&D 2001 and its review

SKI points out that an essential issue that must be resolved before an application can be submitted for a permit to build the final repository is the ultimate choice of a suitable backfill material, particularly the clay component.

Kasam points out that materials with different properties may be needed in different chambers.

Newfound knowledge since RD&D 2001

See section 18.2.2.

Programme

See section 18.2.2.

18.1.7 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.

18.1.8 Gas contents

The initial gas content in the backfill follows trivially from its specifications.

18.1.9 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 atm (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.

18.1.10 Swelling pressure

The swelling pressure begins to build up when buffer and backfill come into contact with external water. Initially there is no swelling pressure.

18.1.11 Smectite composition

At present there are several alternative backfill concepts and backfill materials, see section 18.1.6. In some of the concepts the clay portion consists of the same material as the buffer, see section 17.1.2, and in other concepts of a completely different material, for example Friedland clay.

Conclusions in RD&D 2001 and its review

See section 18.1.6.

Newfound knowledge since RD&D 2001

See section 18.2.2.

Programme

See section 18.2.2.

18.1.12 Pore water composition

The water in the backfill is a blend of water from the crushed rock (if concept A is chosen), the bentonite's original water and water added during mixing. Its composition is mainly dependent on which water is added.

18.1.13 Impurity levels

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.

A related question is the importance of foreign engineering materials and materials forgotten in the tunnels, see section 18.2.16 (general), 17.2.17 (iron and cement) and 19.2.19 (cement).

Programme

See sections 18.2.16, 17.2.17 and 19.2.19.

18.2 Processes in the backfill

18.2.1 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.

18.2.2 Integrated studies – composition and function

The properties of the backfill are determined not only by its composition, but by the salinity of the groundwater as well. Salinity is of great importance for these properties, due to the fact that both swelling pressure and hydraulic conductivity are determined by the properties of the bentonite in the spaces between the crushed rock (concept A and possibly concept D). Since the bentonite density is low, the properties are very sensitive to salinity in certain concepts. As a result, the original composition of 15 percent bentonite and 85 percent crushed rock may be suitable for a site with a non-saline groundwater, while a site with a more saline water may require a higher proportion of bentonite. The exact composition of the backfill will be chosen when the necessary data are available from the site in question.

The function of the backfill in general was identified as a priority research area in RD&D 2001. The requirements on the function of the backfill (swelling pressure, conductivity) are strongly related to its content of smectite or other swelling minerals.

Conclusions in RD&D 2001 and its review

SKI comments that SKB should make sure how useful the results from the Backfill and Plug Test in the Äspö HRL are for choosing backfill materials and for investigating the interaction between backfill and buffer in the deposition holes.

SSI points out that SKB should give an account of the importance of the backfill for the long-term protective capability of the repository and what research, development and demonstration is needed to accumulate sufficient knowledge for the needs of the safety assessment.

Kasam is of the opinion that if the different requirements on the backfill are found to be incompatible, the function of limiting the swelling of the buffer should be prioritized.

Newfound knowledge since RD&D 2001

Studies of backfill are taking place mainly within the framework of three projects that are being conducted in the Äspö HRL: The Backfill and Plug Test, Backfilling and Closure of Tunnels and Rock Caverns, and the Prototype Repository. Separate studies have also been made of the alternative backfill material Friedton.

The Backfill and Plug Test is a full-scale test of concepts A and C, see Figure 18-1. Installation of the test was finished at the end of 1999 /18-2/.

In the Backfill and Plug Test, a 28-metre long tunnel section was backfilled and instrumented. Half of the length of the tunnel was backfilled with a mixture of 30 percent bentonite and 70 percent crushed rock (30/70 mixture). The other half was backfilled with crushed rock (0/100 mixture) and with bentonite blocks placed nearest the roof. The backfill was applied and compacted layer by layer with vibrating plates developed and built for this purpose. The technique with compaction of inclined layers was used in the entire tunnel section from floor to roof with an inclination angle of about 35 degrees. The backfill was divided up by permeable mats about every two metres for the purpose of artificially wetting the backfill and permitting a hydraulic gradient to be applied between the mats for flow testing. The backfill and surrounding rock were instrumented with about 200 sensors for measurement of water pressure, total pressure and water content. A concrete tunnel plug with a half-metre thick bentonite O-ring was installed at the end of the test section.

An evaluation of the installation showed that the equipment and the technique for backfilling and compaction worked well in terms of both function and obtained density, but needed improvement in terms of the reliability, durability and safety of the compaction equipment. Although the dry density of the 30/70 backfill close to the roof and walls was lower than 1,650 kg/m^3 near the rock walls and the roof, it is estimated that the mean dry density was between 1,650 and 1,700 kg/m^3. The measured mean dry density of the 0/100 backfill was 2,170 kg/m^3.

Water saturation of the backfill was started after installation and was predicted to be completed in the spring of 2003, i.e. after about 3.5 years. In order to speed up the wetting of the 30/70 mixture, salt was added to the water that fed the wetting mats so that a mean salinity of 1.2 percent would be reached after full water saturation. In addition, a water pressure of 500 kPa was applied to the wetting mats.

The results of the measurements of the water saturation process agreed well with the model calculations obtained when the model of the unsaturated hydraulic conductivity that had been calibrated in laboratory experiments was used. However, the hydraulic conductivity used in the model differs from the one measured in the laboratory on water-saturated samples with constant gradient in oedometers. This is mainly attributed to the inhomogeneity of the backfill /18-3/, but may also be due to the difference in experimental technique.

The backfill in the Prototype Repository is very similar to the 30/70 mixture used in the Backfill and Plug Test. The difference between the materials is that ground sodium-converted calcium bentonite from Milos has been used instead of the natural sodium bentonite MX-80 /18-4/. The mean density of the backfill as measured by a density meter was 1,750 kg/m^3, while the mean density estimated by dividing the hauled-in quantity of backfill by the available volume was only 1,630 kg/m^3. This is presumably due to compaction problems in portions with many instruments and cables and to lower density near walls and roof.

The wetting of the backfill from the rock is measured by emplaced psychrometers and provides valuable information on the hydraulic interaction between the rock and the backfill.

The goal of the project "Backfill and Closure of Tunnels and Rock Caverns" is to develop materials and technique for backfilling and closure of a deep repository for spent nuclear fuel of the KBS-3 type. The goal of phase 1, which has consisted solely of technical studies and was concluded in early 2004, was to describe the potential of the proposed backfilling concepts for meeting the requirements formulated by SKB and Posiva, select the most promising concepts for further studies and describe methods for verifying the performance of the backfilling concepts. The proposed backfilling concepts differ with regard to backfill materials and installation method (compaction of the material in situ in the tunnel, emplacement of blocks, or a combination of the two methods) and are described in brief in section 18.1.6.

The assessment of the concepts has been based on performance requirements formulated to ensure a safe environment for canister and buffer during the deep repository's operating period. These requirements, along with assumed conditions in the deep repository (salinity of groundwater etc), comprise the basis for the design premises used to compare and discriminate the concepts. The design premises pertain to requirements on the backfill's compressibility, hydraulic conductivity, swelling pressure, long-term stability, negative effects on the barriers in the final repository, and technical feasibility. The risks involved and the need for further studies for the individual concepts have also been dealt with in phase one.

The principal recommendations can be summarized as follows: Concepts A and B (see Figure 18-1), which are based on compaction in situ in the tunnel, will be further studied in the next phase of the project to determine if high enough densities can be achieved for the materials in question. Concept D has good potential for meeting the requirements, but it is a new backfilling concept and some uncertainties regarding material choice, manufacture and emplacement of blocks therefore need to be investigated in the next phase. The heterogeneous concept E differs in terms of design and performance from the other concepts. This concept will not be further investigated for the time being, but some of the work that will be done for the other concepts can be applied to assess concept E as well, if it should prove to be of interest. Concept C, where most of the backfill material consists of non-swelling clay, will not be further studied since it has been judged unlikely that it will be able to meet the stipulated requirements.

An alternative backfill material that has been thoroughly studied is the natural montmorillonite clay Friedton. Studies have been conducted in the form of laboratory tests /18-5/ and compaction tests in the field /18-6/.

The results show that the material's hydraulic conductivity is sufficiently low at the density measured in the field tests and for the salinity foreseen in the groundwater. However, the achieved field density gives a compressibility that is too high to prevent excessive upswelling of the buffer in the deposition holes. The field tests also showed that it is difficult to apply the material so that a gap at the roof is avoided. However, the preparation of the material and the compaction technique should be able to be improved so that adequate density can be achieved in the field.

Programme

Studies of backfilling concepts will continue within the three described projects.

Now that the backfill is water-saturated, the Backfill and Plug Test has entered a new phase with flow and compression tests. The water pressure in the backfill, which is 500 kPa today as a result of pressurizing in the filter mats, will gradually be reduced and the flow between the mats measured. The mats near the roof and near the floor have been separated from the mat in the central part of each section, enabling the hydraulic conductivity of the backfill to be measured in these different parts. After concluded flow tests, compressibility will be measured by means of the four pressure cylinders attached to the floor and the ceiling.

In parallel with the field tests, the tests will be modelled in an attempt to understand the flow paths in the backfill and the connection with the properties of the rock. Furthermore, supplementary laboratory tests will be conducted to gain a better understanding of the influence of test technique and inhomogeneities in the backfill.

Monitoring of wetting and swelling pressure will continue in the Prototype Repository. Valuable information can be obtained about the hydraulic interaction between rock and backfill by modelling of the processes and comparisons with the measurement results. Supplementary laboratory investigations will also be conducted. Dismantling of the outer section is planned to take place in 2008.

The project "Backfill and Closure of Tunnels and Rock Caverns" is continuing with the next phase, whereby the selected alternatives and materials will be studied more closely. Laboratory tests will be performed on alternative materials such as Milos calcium bentonite and Ashapura bentonite (Indian) in order to determine hydraulic and mechanical properties as well as compaction properties. Technology for in situ compaction in the tunnel, block pressing (concept D) and block emplacement will be studied. The hydraulic interaction of the backfill with the rock, as well as possible problems with piping and erosion, will also be studied. Phase two will continue until 2005, after which pilot tests with prototype equipment will be carried out to verify and improve the emplacement and compaction techniques with some selected materials and concepts. A large-scale field test aimed at verifying the function of the backfill is planned in phase four.

18.2.3 Radiation attenuation/heat generation

The process can be neglected in the backfill.

18.2.4 Heat transport

Conclusions in RD&D 2001 and its review

The unchanged conclusion is that the temperature of the backfill is determined by the surrounding rock, which has a higher thermal conductivity. The backfill's inherent heat transport capacity is only a factor insofar as the average effective heat transport resistance of the near field will be slightly greater if the heat transport capacity is low. However, the tunnel's volume fraction of the near field is so small that changes in the backfill's contribution to the heat transport resistance have insignificant effects on the temperature, both in the backfill itself and in the buffer.

Newfound knowledge since RD&D 2001

The temperature evolution in the backfill in the Prototype Repository will be measured and monitored in many points. These measurement results, together with the temperature evolution in the upper part of the buffer in the deposition holes, can be used to verify that heat transport in the backfill is being accurately modelled.

Programme

The measurements and evaluations of the temperature evolution in the Prototype Repository continue. The thermal conductivity can be calculated theoretically. These calculations should also be done for the new backfilling concepts and verified by some laboratory measurements.

18.2.5 Water transport under unsaturated conditions

It is possible that the backfill will be the primary source of water to the buffer in certain deposition holes.

Conclusions in RD&D 2001 and its review

Not dealt with.

Newfound knowledge since RD&D 2001

Water uptake in the backfill is being measured in the Äspö HRL in the Backfill and Plug Test (water saturation achieved) and the Prototype Repository. Modelling and laboratory experiments have yielded good information on the parameters that drive this water flow, see section 18.2.2.

Programme

The resaturation phase in the backfill will be modelled within the framework of SR-Can. The results of this work will provide boundary conditions for the calculations of the buffer's resaturation.

Studies of unsaturated water transport will take place within the framework of the projects that deal with backfilling according to section 18.2.2.

18.2.6 Water transport under saturated conditions

The permeability of the backfill after water saturation is determined by the content of montmorillonite and other clay minerals, the composition of the pore water and the density. In contrast to the buffer, the backfill of crushed rock mixed with bentonite cannot be made highly homogeneous, 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 entire cross-section and length of the backfill.

Conclusions in RD&D 2001 and its review

The conclusion is unchanged that there are a number of uncertainties for bentonite-mixed backfill. The properties are measured directly after mixing. The risk and effect of possible homogenization of the bentonite density in the aggregate pores are not known. The measured hydraulic conductivities presume that there are no channels or gaps. The effects of very high salinities also require further study.

Newfound knowledge since RD&D 2001

The properties of saturated backfill are being investigated for bentonite-aggregate mixtures mainly in the Backfill and Plug Test, and for other backfill concepts mainly in the project "Backfill and Closure of Tunnels and Rock Caverns", see section 18.2.2.

For backfilling with a mixture of bentonite and crushed rock, homogeneity is an important factor for the hydraulic conductivity achieved. The experimental conditions and thereby the stress state in the backfill in the tunnel are also important. A comparison between measured and theoretically calculated hydraulic conductivity, the latter assuming that the bentonite is evenly distributed in the pore space between the particles of crushed rock, shows that the measured permeability is generally higher. The lower the bentonite content and the higher the salinity of the added water, the greater the difference /18-3/. Homogenization with time would thus reduce the permeability.

Programme

Investigations of saturated hydraulic conductivity of mixtures will continue and are mainly taking place within the Backfill and Plug Test, while the investigations for other concepts are primarily being done within the project "Backfill and Closure of Tunnels and Rock Caverns", see section 18.2.2.

18.2.7 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.

18.2.8 Swelling and compression

It is important that the backfill can swell to prevent the formation of conductive transport pathways in the boundary zone between backfill and rock, see sections 17.2.4 and 18.2.17.

Compression properties are important. They may not be such that the swelling of the buffer against the backfill in the deposition holes is too great. Compression properties are mainly a function of the density of the backfill. Determining the compression and swelling properties and the density that can be achieved in compaction of the backfill is an important part of the studies of different backfilling concepts and materials, see section 18.2.2.

18.2.9 Mechanical interaction buffer/near-field rock

The permeability of the backfill is determined by its material composition. The mechanical properties of both the backfill and the near-field rock determine the backfill's stabilizing capacity. An understanding of the interplay between rock and backfill is of great importance in both design and site-specific safety assessment in conjunction with the site investigations.

The following factors are of importance for the interaction between backfill and near-field rock:

- Swelling pressure and weight of the backfill.
- Indirect effects of the buffer's upswelling.
- Creep movements in the rock around the tunnel.

Conclusions in RD&D 2001 and its review

The conclusion is unchanged that the swelling pressure against the roof is dependent on what density can be achieved in compaction of the clay phase. The difficulties of compaction against the roof make it difficult to guarantee a given swelling pressure. The swelling pressure is caused by the bentonite in the space between the particles of crushed rock and is dependent not only on the mean density of the bentonite but also on its homogeneity. An inhomogeneous mixture can give rise to a high swelling pressure to start with in certain spots. It is not known whether the swelling pressure subsequently decreases due to homogenization because the bentonite swells out from pores with high bentonite density.

Newfound knowledge since RD&D 2001

General aspects of the problem of spalling and the stability of the walls of the deposition holes are discussed in /18-7/, and particularly the importance of a light support pressure from the buffer to prevent initiation and propagation of failure that can lead to spalling. Background material is the theory of brittle failure developed at AECL's Underground Rock Laboratory (URL) in Canada. The general conclusion, that a small support pressure is enough to improve stability, also applies to other types of failure, for example breakout of rock wedges in the tunnel periphery.

Experience from the URL Mine-by Test Tunnel in Canada confirms the importance of light support. Removal of floor muck led to rock breakout /18-8/.

For slow creep movements that take place over a long period of time and lead to stress relaxation in large rock volumes, swelling pressures on the order of several hundred kPa are of no importance /18-9/. To limit such a slow creep-induced convergence, the tunnel backfill must have a compression modulus that is several orders of magnitude greater than is theoretically possible.

Programme

Even if the tunnel backfill cannot limit the creep-induced tunnel convergence, the backfill is affected. A programme for computational bounding of tunnels and other cavities in the host rock has been initiated with literature studies and will be followed up by application calculations.

18.2.10 Thermal expansion

The importance of this process will be illustrated with simple scoping calculations in SR-Can.

The thermal expansion of the structure and the particle phase in the backfill is small and has only a marginal effect. On the other hand, the thermal expansion of the water is great and rapid heating in a water-saturated backfill where the expanding water does not have time to drain off can give rise to large pressures against a rigid host medium. In a deep repository, heating is so slow in relation to hydraulic conductivity that the expanding water has time to drain.

18.2.11 Advection

Conclusions in RD&D 2001 and its review

The backfill has a hydraulic conductivity and a diffusivity that lie in a range where both diffusion and advection can be important transport mechanisms.

Newfound knowledge since RD&D 2001

Water flow in backfill is being studied on a full scale in the Backfill and Plug Test in the Äspö HRL, see sections 18.2.2 and 18.2.6.

Programme

Water flow in backfill will be studied in the laboratory and on a full scale in the Backfill and Plug Test, see sections 18.2.2 and 18.2.6.

The importance of advection in the backfill for radionuclide transport will be examined in SR-Can.

18.2.12 Diffusion

If the backfill material has low hydraulic conductivity, diffusion will be the dominant transport mechanism for dissolved species.

18.2.13 Osmosis

Due to limitations in existing compaction technique, combined with the quantity of bentonite mixed into the backfill material, the density of the montmorillonite phase is considerably lower than in the buffer. In the basic state, the montmorillonite has therefore swelled to a volume equivalent to the maximum swelling at a given salinity. If the salinity exceeds this critical limit, the pore structure changes, leading to a sharp increase in hydraulic conductivity, lost contact with the rock, and an increased risk of piping at high water flows. With the compaction results that can be achieved today, there is a risk of considerable deterioration in the function of the backfill even at relatively low groundwater salinities (several percent TDS).

Conclusions in RD&D 2001 and its review

SKI points out the importance of the influence of saline groundwater on the hydraulic properties of the backfill. Future changes in the salinity of the groundwater must also be taken into account, see also Kasam's viewpoints in section 18.2.21.

Newfound knowledge since RD&D 2001

In principle, the backfill works in the same way as the buffer, see section 17.2.15. Saline groundwater will, however, have a greater relative influence on the physical properties of the backfill, since the density of the montmorillonite fraction is lower in the backfill. Current compaction technology for backfill materials in a deposition tunnel does not provide sufficiently high montmorillonite density to meet the safety margins under sea water conditions.

Programme

See section 17.2.15. For backfill materials, the development work will be focused on emplacement technique to increase the montmorillonite density, see section 18.1.6, and testing of different clay materials.

18.2.14 Ion exchange/sorption

Ion exchange from sodium to calcium leads to similar effects as high salinity in the groundwater (see section 17.2.16) in a backfill material with a low content of swelling clay, i.e. the pore geometry in the backfill material is altered and the backfill risks losing its swelling and sealing properties.

Conclusions in RD&D 2001 and its review

SKI maintains that SKB should evaluate what saline groundwaters mean for the repository.

Newfound knowledge since RD&D 2001

See section 17.2.16.

Programme

See section 17.2.16.

18.2.15 Montmorillonite transformation

What is said about montmorillonite transformation in the buffer is largely applicable to the backfill as well, see section 17.2.17. The boundary conditions exhibit certain differences, however. The temperature in the backfill is lower and less iron is available, which would lead to slower transformation. On the other hand, the density may be lower and the quantity of cement may be higher, which could lead to more rapid transformation.

Conclusions in RD&D 2001 and its review

In Kasam's opinion, SKB should set a limit on how much potassium the crushed rock may contain.

Newfound knowledge since RD&D 2001

See section 17.2.17.

Programme

See section 17.2.17.

18.2.16 Dissolution/precipitation of impurities

Natural impurities in the backfill material do not have any bearing on its long-term performance. On the other hand, engineering materials and forgotten materials can have an effect on the repository, especially those that remain in large quantities. There are two compilations of the materials that might be left behind in the repository /18-10, 18-11/.

Conclusions in RD&D 2001 and its review

The properties of low-pH cement and its effects on a final repository were discussed at an international meeting organized by SKB. The meeting concluded that there was a need for further development of low-pH materials for use in the final disposal of nuclear waste. Materials whose leachate has a pH lower than 11 are judged to have negligible effects on the buffer and the backfill.

Programme

Grouts with relatively low pHs are being developed and tested in a project together with Posiva, see Chapter 10.

The importance of engineering and forgotten materials will be analyzed within the framework of SR-Can.

18.2.17 Colloid release/erosion

The risk of erosion in the backfill is greatest if water flows in a gap or channel at the roof between the backfill and the rock, where the density of the backfill will be lowest. This can happen if there is a gap to begin with due to insufficient compaction or piping during the compaction phase due to high water pressure and heavy water inflow. When fully wetted, the backfill strives to expand and consolidate the boundary zone.

Conclusions in RD&D 2001 and its review

At the low density that will probably exist in the backfill at the tunnel roof, there is a risk that the expansion capacity of the backfill according to the repository's specification will not be sufficient to maintain contact with the roof and upper walls in the tunnels, whereby the risk of erosion and considerable heterogeneity in the backfill remains. This can be avoided by backfilling with blocks with a higher bentonite content near the tunnel roof.

Newfound knowledge since RD&D 2001

The phenomenon of piping/erosion in the backfill may occur in the two Äspö projects Backfill and Plug Test and Prototype Repository. When these tests are terminated and excavated, it will presumably be possible to see whether the phenomenon has occurred and what its consequences are. Furthermore, an artificial water pressure gradient is being applied during the flow tests in the Backfill and Plug Test. The results will show whether piping has occurred.

Programme

Piping and erosion for different backfill materials will also be studied within the project "Backfill and Closure of Tunnels and Rock Caverns".

18.2.18 Radiation-induced montmorillonite transformation

The process is judged to be negligible in the buffer and therefore also in the backfill.

18.2.19 Radiolysis of pore water

The process is judged to be negligible in the buffer and therefore also in the backfill.

18.2.20 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 break down organic material, methane, iron(II) and sulphur.

Conclusions in RD&D 2001 and its review

The conclusion is unchanged that bacterial activity in the backfill can be advantageous, since it will make a significant contribution to oxygen reduction there.

Newfound knowledge since RD&D 2001

No new knowledge has been forthcoming.

Programme

See section 17.2.22.

18.2.21 Radionuclide transport – advection

The backfill has a hydraulic conductivity and a diffusivity that lie in a range where both diffusion and advection can be important transport mechanisms.

Conclusions in RD&D 2001 and its review

In Kasam's view, SKB should conduct performance assessments of the buffer-backfill-geosphere system in order to clarify advantages and disadvantages of different types of backfill (natural clays, mixtures of crushed rock and clay, and only crushed rock with a size distribution that best withstands the expansion of the buffer). The performance assessment should also include long-term evolution in environments with various salinities.

Newfound knowledge since RD&D 2001

No new knowledge has been forthcoming.

Programme

A thorough study of radionuclide transport in the backfill under different conditions and assumptions will be conducted within SR-Can.

18.2.22 Radionuclide transport – diffusion

Diffusion of radionuclides in the backfill is of subordinate importance for repository safety.

18.2.23 Radionuclide transport – sorption

Sorption of radionuclides in the backfill is of very limited importance for repository performance. It was assumed in SR 97 that the distribution coefficients were proportional to the content of bentonite and crushed rock.

Conclusions in RD&D 2001 and its review

SKI says there is no justification for SKB's conclusion that determination of the K_d values does not require additional work.

Newfound knowledge since RD&D 2001

No new knowledge has been forthcoming.

Programme

No further research is considered necessary.

18.2.24 Radionuclide transport – speciation of radionuclides

The speciation of radionuclides is of importance for sorption and diffusion in the backfill. 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 15.2.14. In SR-Can, the same types of speciation calculations are carried out for e.g. the buffer environment as in SR 97.

18.3 Integrated modelling – radionuclide transport in the near field

The probabilistic risk calculations in SR 97 (and previous safety assessments) were carried out with the software package Proper. Proper is a package of calculation codes which, besides routines for generating probabilistic input data and routines for handling communication between different parts of the code, consists of a number of submodules for calculating radionuclide transport in different parts of the repository. The version of Proper that has been used is written in Fortran 77 and has been run on a Unix platform. In SR 97, radionuclide transport in the near-field was calculated with the Proper module Comp23. The conceptual model that has been implemented in Comp23 includes such processes as fuel dissolution, precipitation and dissolution of solubility-limited radionuclides, diffusion through a specified breach in the copper shell, diffusion and sorption in the buffer and the backfill, transport out to the surrounding geosphere, and chain decay.

Radionuclide transport in the interior of the canister was simplified in the modelling in SR 97 in the following manner: After a certain "delay time" has passed since a breach occurred in the canister's copper shell, the entire void in the canister, approximately 1 m^3, is assumed to be filled with water. The length of the delay time is determined on the basis of the size of the breach in the copper shell and the subsequent water flux and corrosion. After the delay time, all water in the canister was assumed to be available for the fuel dissolution process, i.e. to be in direct contact with all fuel without being impaired by Zircaloy cladding or other structures. The water was assumed to be constantly stirred so that there are no concentration differences between different parts of the canister interior. The fuel dissolution process then determines the rate of release of matrix-bound radionuclides. Segregated nuclides and radionuclides in the structural parts of the fuel are assumed to be accessible for dissolution in water immediately after the end of the delay time. Sorption of radionuclides to the internal parts of the canister is neglected.

Conclusions in RD&D 2001 and its review

SKI questions whether it is possible to obtain an improved understanding of the transport phenomena by using a simple analytical model.

According to SKI, it is not clear whether SKB has improved the description of the transport and reaction processes included in Comp23.

Newfound knowledge since RD&D 2001

As a complement to and for evaluation of the near-field code used in SR 97, Comp23, an alternative code, Compulink, has been developed. This alternative code is based on the same conceptual model as Comp23 and includes the same processes; the two codes should therefore yield comparable results. Like the whole Proper package, Comp23 is written in Fortran 77, while the alternative code is written as an application that is run in a Matlab and Simulink environment. (Information on Matlab and Simulink is available on the Web at http://www.mathworks.com/). Matlab is a well-established commercial program that is used to solve various types of numerical problems. Matlab also contains a script language that makes it possible to write programs and/or applications where Matlab's own commands are used. This makes it possible to change parameters, start simulations and save results, which in turn makes it possible to carry out probabilistic simulations based on random number distributions generated either directly in Matlab or by a free-standing program. Simulink is a program package that supplements Matlab and contains routines for carrying out simulations in a graphic environment, offering the possibility of easily combining different computation modules and thereby easily simulating complex models. We believe that Simulink's graphic environment, in combination with Matlab's built-in mathematical functions, make a model implementation in Compulink even more easily accessible and comprehensible for developers and reviewers than the existing Fortran 77 implementation in the Proper package. The lower learning threshold also allows access to a larger group of developers, making the development work less sensitive to changes in the development team. At present the Compulink application has been developed on a Windows PC, but since applications developed in Matlab and Simulink can be run on several platforms (Windows, Unix/Linux or Macintosh OS X), the porting work connected with platform changes is minimized. Near-field releases calculated with Compulink show good agreement with Comp23.

Figure 18-2 shows releases from the near-field to the geosphere for a test case where an initial canister defect occurs after 6,500 years and a larger defect after 25,000 years. The agreement between the releases from the two codes is good for all nuclides. The computation time for the Compulink simulation on an office computer (1,700 MHz Pentium 4 and Windows XP operating system) is around one minute per realization, which makes the code suitable for probabilistic simulations too.

Programme

The development of the Simulink-Matlab implementation of Compulink will continue during the coming period; among other things, the user interface must be improved so that selection of input data is simplified. Some of this work will be pursued in cooperation with the development of a new Matlab-Simulink-based code for biosphere simulations. The software development of Comp23 will, on the other hand, not continue at the same rate as before during the coming three-year period. The reason for this is not that development resources are being shifted from Comp23 to Compulink, but that the development need is not as great as before. There are however areas where refinements and implementations of models are possible. An example is models for fuel dissolution, where development of new models is taking place.

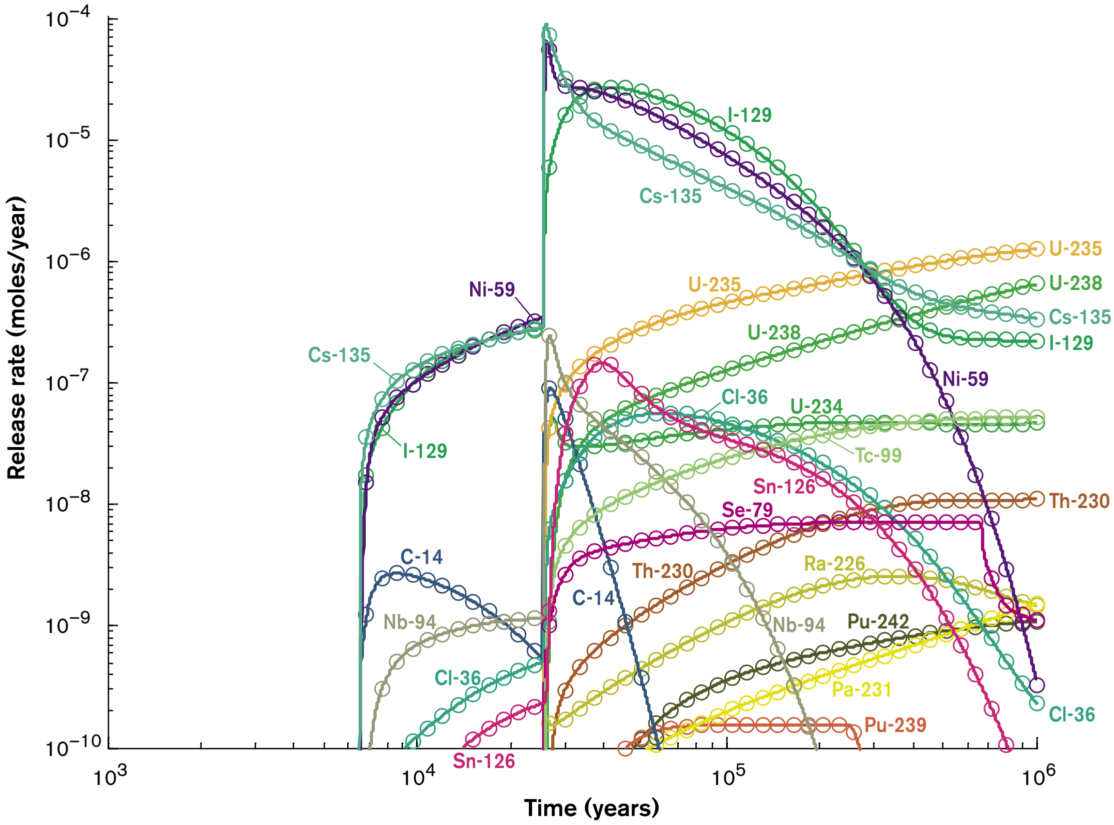


Figure 18-2. *Release from the near-field for a realistic test case from Comp23 (circles) and Compulink (lines).*

19 Geosphere

19.1 Initial state of the geosphere

The deep repository will be built in crystalline rock of granitic composition. The starting point for the safety assessment is the situation that prevails when the repository has just been built and closed. For the geosphere, this situation is a disturbance of the state that prevailed before the repository was built.

Above all, drainage of the repository affects groundwater flow and pressure. The chemistry of the groundwater can also be affected by the flow of groundwater, if water of a different composition flows towards the repository. The chemical conditions are also influenced by the fact that the repository is kept open and various materials are introduced. The magnitude of this influence depends on several factors, for example how the repository is built and how long it is drained.

The results of the site investigation comprise the most important basis for determining the post-closure state of the geosphere (the initial state). The programme for this has been presented in special reports.

19.2 Processes in the geosphere

19.2.1 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 fracture systems on the repository site plus the changes to which construction of the repository has given rise.

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 to which the heating of the repository leads, 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.

If radionuclides are released, they can be transported with the flowing groundwater by advection. Diffusion can also be important if the water is immobile or moves very slowly.
An important aspect of this is matrix diffusion, i.e. 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 crucial particularly for the 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 for the different processes in the geosphere is discussed in the following sections.

19.2.2 Heat transport

Conclusions in RD&D 2001 and its review

In RD&D 2001, the viewpoint is expressed that heat is transported in the geosphere by conduction in the intact rock, and that existing models and calculation methods are sufficiently verified to enable the design criterion to be met.

In the opinion of the authorities, the maximum temperature nearest the canister is underestimated in large-scale models with widespread heat loads, and the influence of simplified calculation assumptions should be examined more closely. The THMC modellings that are done in the future should be updated with the latest temperature calculations.

Newfound knowledge since RD&D 2001

The problem of the temperature evolution in the rock has been thoroughly addressed since RD&D 2001, above all with a view to the maximum temperature nearest the canisters /19-1/. The studies reveal relationships between the maximum temperature of the canister, 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 geometry of the individual canister is taken into account so that the temperature evolution in the near-field, above all at the hottest part at canister mid-height, is correctly calculated. Figure 19-1 shows an example. In the calculations, which are performed with different combinations of analytical and numerical methods, the heat transport problem is dealt with on all scales. The study also shows how sensitive the calculated maximum temperature on the canister surface is to errors in input data, such as errors in the thermal conductivity and heat capacity of the rock. The impacts of the simplified assumptions that are generally made, for example the approximation to disregard the temperature dependence of the thermal conductivity and the influence of the different heat transport properties of the tunnel backfill, are analyzed and quantified.

Different laboratory-based methods for prediction of the thermal conductivity of the rock nearest a borehole have been compared with a large-scale method for direct measurement in boreholes, the thermal response test /19-2/. The thermal response test overestimates the thermal conductivity by about 25 percent compared with the results obtained using laboratory methods to determine the properties of the individual mapped rock types and calculate the effective thermal conductivity based on the mapped rock type distribution. The interpretation is that the full-scale method needs to be developed to compensate for the effects of water movements in the borehole during measurement.

A systematic evaluation has been carried out of several methods for determination of thermal conductivity and heat capacity in the laboratory /19-3/. The methods yield on average differences on the order of a percent or so for a number of measured samples, while the variation between individual samples can be considerably greater.

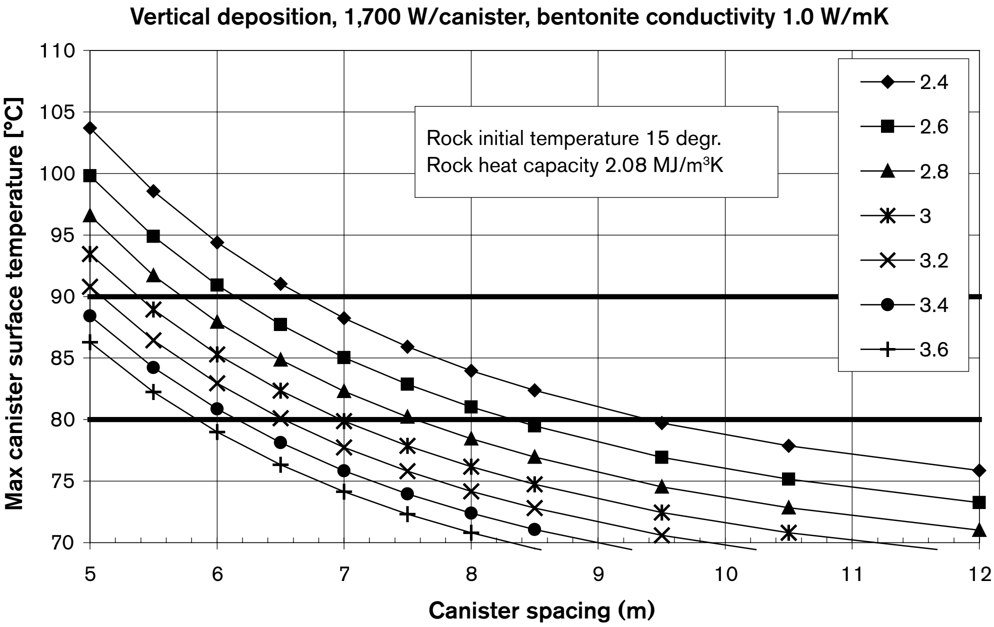


Figure 19-1. *Maximum temperature on canister surface for different assumptions regarding the thermal conductivity of the rock. The horizontal lines are threshold values that correspond to different margins to the design criterion temperature of 100°C.*

A strategy has been formulated for how a thermal site descriptive model should be developed during the site investigation phase /19-4/. The basis for the thermal model is the geological and hydrogeological site descriptive models and direct measurements of thermal and geophysical properties.

The scale dependence of the effects of rock type distribution has been analyzed as a step in the development of a thermal model for the Äspö HRL /19-5/. Furthermore, thermal conductivities, measured or calculated from mineralogical composition, have been analyzed statistically. In addition, a relationship between density and thermal conductivity has been determined for the rock types in the Äspö HRL. Based on this, geophysical density loggings have been utilized in an attempt to analyze the distribution and scale dependence of the thermal properties of the rock mass at Äspö.

Programme

The analyses that have now been done to determine the spacing between the canisters will be expanded and coordinated with the analyses that are being done for the canister/buffer system (e.g. to arrive at an appropriate way to handle air gaps). Furthermore, the calculations will be broadened to include the effects of relocating canister hole positions with unchanged, or only marginally increased, average canister spacing. The effects of variations in the thermal properties of the rock, on different scales, on the determination of canister spacing will be investigated numerically and analytically.

The work of developing, calibrating and verifying methods for determination of thermal properties will continue, as will the work of translating the results into thermal models on different scales.

The temperature measurements in the rock being done in the Prototype Repository and the Canister Retrieval Test at the Äspö HRL will be evaluated to determine heat transport properties by back-calculation.

A thermal model will be constructed for the Prototype Repository in the Äspö HRL using the proposed techniques for measurement and estimation of the thermal properties and distribution of the different rock type components. By means of back-calculation from the results from the Prototype Repository, it will be possible to test and evaluate the accuracy and reliability of the thermal model.

The results of this work will be used to refine the strategy for the thermal site descriptive model.

The Prototype Repository and the Canister Retrieval Test in the Äspö HRL will be modelled with THMC codes. The purpose of these calculations is to test and verify models that describe simultaneous transport of heat, water, vapour, gas and dissolved salts in the incompletely saturated buffer. The heat transport conditions in the geosphere, i.e. in the near-field rock, are not crucial for these calculations, but need to be included and reconciled with data from thermal geosphere models.

19.2.3 Groundwater flow

Conclusions in RD&D 2001 and its review

It was observed in RD&D-Programme 2001 that model development using the codes Connectflow and DarcyTools would continue, and that model studies of recharge and discharge areas had high priority.

Kasam observed in its review of the programme that modelling of groundwater flow in a regional perspective and modelling of the magnitude of groundwater formation at different depths were important to determine.

SKI observed in its assessment that studies of recharge and discharge areas are important, but that the development of a general hydrogeological process understanding of these matters is also important. Further, SKI pointed out that the use of a stochastic continuum hypothesis for modelling on a site scale has not been adequately justified.

Newfound knowledge since RD&D 2001

Fundamental knowledge concerning groundwater flow is good. Current efforts are focused more on development of calculation tools (numerical models). Certain theoretical studies have, however, been conducted to acquire more knowledge concerning specific issues such as near-surface groundwater flow and large-scale groundwater flow in order to better understand the problems surrounding recharge and discharge areas.

The two modelling tools Connectflow /19-6 to 19-8/ and DarcyTools /19-9 to 19-11/ have been further developed over the past three-year period. Today, Connectflow can handle nested models (models where different scales are nested). It is, for example, possible to have a continuum description of the repository with deposition tunnels and deposition holes nested in a local-scale discrete network model, which is in turn nested in a regional-scale continuum model. Transient density-driven flow can also be handled (density-driven flow only in the continuum model). Furthermore, functionality for incorporating discrete zones has been developed, known as implicit fracture zone functionality. Different interfaces against the modelling tool RVS have been developed, as well as new tools for post-processing of results (for example routines for Tecplot).

The development of the code Connectflow, where modelling of groundwater flow through individual deposition holes and tunnels in a closed repository is possible, enables detailed information to be produced for further calculations of radionuclide transport. This is further described in section 19.2.12. Connectflow has also been developed to make it possible to describe groundwater flow around an open repository, i.e. for tunnels at atmospheric pressure /19-12/. The important issues to highlight in this type of analysis are upconing of salt water to repository depth, inflow of water to the tunnel system in an open repository, and time for

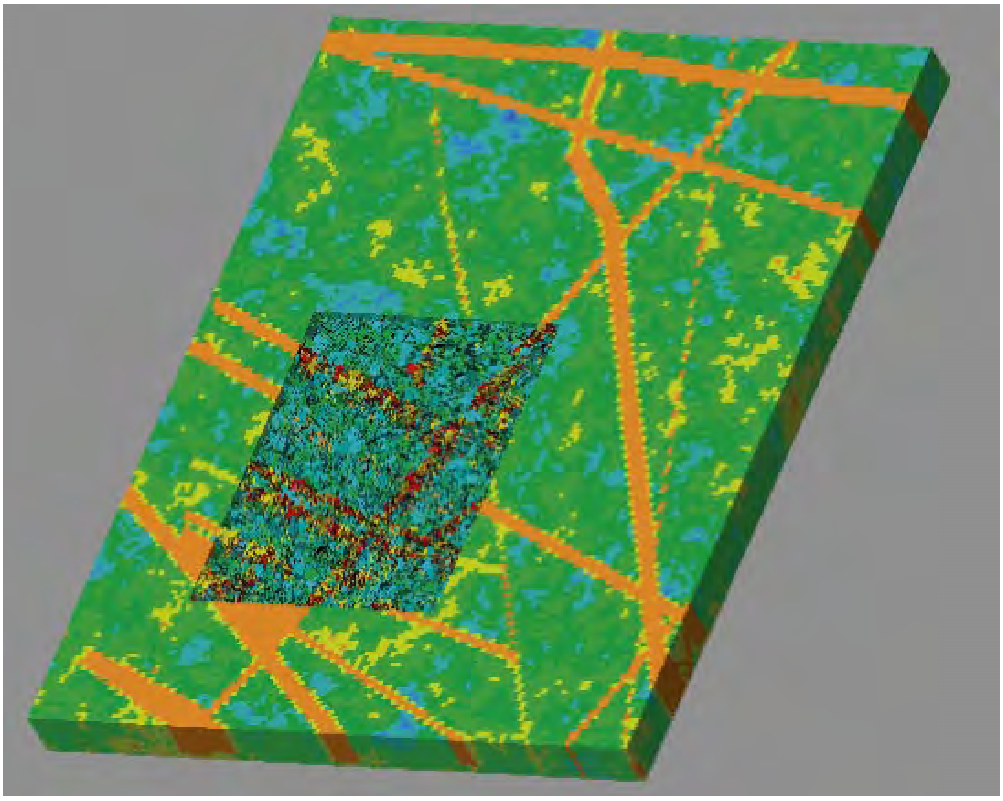


Figure 19-2. *Connectflow representation of a discrete fracture network model in a continuum model.*

resaturation of the repository after closure. Other issues of interest in an open repository may be e.g. the influence on near-surface conditions, such as water levels in wells.

The code DarcyTools has also undergone considerable development over the past three years. DarcyTools is basically a continuum model, but makes use of a special technique for generating continuum fields. A discrete fracture network is created, which is then transformed into a continuum field by a volume-based weighting of permeability properties for individual structures. For transport of salt and tracers, a multi-rate matrix diffusion model has been incorporated in DarcyTools. This technique makes it e.g. possible to describe the historic evolution of salinity in the Baltic Sea in a credible manner, i.e. with realistic parameters for e.g. rock porosity. DarcyTools has also been equipped with a new numerical equation solver that makes it possible to simulate models with up to several million fractures and elements.

Connectflow and DarcyTools have both been used in the ongoing site modelling projects for Forsmark and Oskarshamn /19-13, 19-14/. These studies have entailed that the models have been tested against each other, and that some functionality such as interfaces has been developed. Connectflow has also been used to redo the glaciation simulation that was produced within SR 97 /19-15/.

New process knowledge regarding groundwater flow has been obtained in the super-regional simulation studies conducted for Northern Uppland /19-16/ and Eastern Småland /19-17/. These studies show that local flow patterns (flow cells), caused by the ratio between local and regional gradients, dominate the groundwater flow down to typical repository depths. Since the local topography strongly determines the local gradients, it is of the utmost importance to have a good database and numerical resolution of the topography. Furthermore, these studies show that the presence of saline groundwater at depth may serve as a floor for the groundwater flow and thereby further reinforce the effects of the local flow cells.

In a continuation of the super-regional modelling of Northern Uppland, a more detailed study has been done of groundwater flow near the ground surface, the so-called geosphere-biosphere interface /19-18/. In this study, the Quaternary deposits have been modelled at high resolution, at the same time as seasonal variations in groundwater infiltration have been included. The results show that even though groundwater discharge areas exist over large parts of the model's upper surface, discharge of water particles from repository depth takes place in well-defined low points. Such low points are typically lakes, below the sea, and other low points in the terrain. This picture of discharge from repository depth is only marginally affected by not explicitly including the Quaternary deposits. Further, it is shown that even though seasonal variations in groundwater infiltration are of great importance for water flow in the Quaternary deposits, the effect on flow patterns for particles released at repository depth is negligible. Finally, it is also shown that the flow paths in the Quaternary deposits are relatively short in length (about ten times longer than the thickness of the Quaternary deposits). The longest flow paths are often beneath lake bottoms; the denser the bottom sediment, the longer these paths tend to be. This study indicates that the modelling strategy that is normally used to describe the deep groundwater is adequate for describing discharge patterns for radionuclides from repository depth with sufficient accuracy. Coupled biosphere-geosphere models are thus not needed for this purpose.

Programme

During the coming three-year period, the two calculation tools for groundwater flow will be used and tested within the site modelling projects and the safety assessment. Furthermore, targeted activities are planned to shed light on individual issues. Such an issue is understanding how the composition, in particular the salinity, of the groundwater has evolved and will evolve in the future. All new hydrogeological and geochemical data that have become available since the last official model version for Äspö are being compiled in a project connected to the Äspö HRL, Äspö Models 2005 /19-19/. These data will be used together with DarcyTools to try to provide a coherent picture of how the water chemistry (salt distribution) has evolved and will evolve in a 10,000-year perspective. A hypothesis is that diffusion of salt into the rock matrix is an important process to bear in mind for understanding the historic salt evolution. The results of this study are expected to be directly applicable to the site modelling projects.

Additional resources will also be devoted to an improved understanding and development of modelling tools for near-surface hydrology. Two parallel tracks will be followed in this phase: a simplified version and a coupled hypothesis. In the simplified version, it is assumed that the models for the deep groundwater provide sufficient information and accuracy for predicting the release points of radionuclides in the biosphere, see above discussion. In this case, all that is needed is a model for the surface water hydrology that provides relevant information regarding what dilution can be expected to occur with surface water. However, these processes must be correctly conceptualized and implemented in the models. This simplified approach should be compared with a coupled strategy where both the deep and near-surface groundwater flow, as well as the surface water hydrology, is described in the same model. An open question is how detailed the biosphere description in these models should be, i.e. can the biosphere processes be described in a separate model, or should they also be incorporated in the coupled hydrological model for groundwater and surface water? These types of studies are expected to be conducted as an integral part of the site modelling work.

Some model development is expected to take place in the coming years, for example development of boundary condition options for simulation of an open repository so that the effect of a groundwater lowering in the near-surface soil layers can be studied. In general, the modelling tools should be tested more rigorously for applications with an open repository, since studies of this type have not been conducted previously to any appreciable extent.

The development of Connectflow is being pursued effectively via multilateral cooperation in the iConnect Club. Our hope is that this activity will continue during the coming three-year period. A doctoral project will be initiated where more fundamental issues relating to processes such as density-driven flow and two-phase flow in discrete fracture networks can be investigated.

DarcyTools is being developed internally by SKB. During the coming period, version 2.1, which has primarily been developed for the needs of the site analysis, will be further developed to a version that can meet the specific needs of the safety assessment.

Another modelling tool that will continue to be developed is the channel network model Chan3D /19-20/. Even if it isn't used for production purposes in site modelling and safety assessment, this model serves an important purpose for shedding light on some specific issues. One such issue is radionuclide transport in transient flow fields. This issue can be handled by Chan3D, since flow and transport are simulated coupled in the same model /19-21/. The effects of transient flow fields, for example due to shoreline displacement, will be further studied. This is described in greater detail in section 19.2.12.

19.2.4 Gas flow/dissolution

Conclusions in RD&D 2001 and its review

No questions for further research were identified in RD&D 2001 or its review.

Newfound knowledge since RD&D 2001

Knowledge concerning the processes of gas flow and transport in the gas phase has been compiled for the EU project Retrock /19-22/, and it is observed there that there is no great need for further research for the intended application. Certain open questions are noted, however, namely that it is not clear whether the gas quantities generated in a deep repository for spent nuclear fuel are great enough to constitute a possible problem. If so, i.e. if a free gas phase can be formed, this question should be further investigated. Specifically, better and above all experimentally verified models for bubble flow are needed, as well as methods for devising representative K-S-P (permeability-saturation-pressure) relationships.

Programme

Another question that should be investigated is whether gas flow (or rather two-phase flow with water and gas phases) should be incorporated in the analysis of the resaturation process in a previously open repository. The imagined sequence is an air-filled repository at atmospheric pressure that is packed with backfilling material, after which pumping ceases so that the repository slowly refills with water. In other words, we are dealing with a system that goes from a complete gas phase to a complete water phase. It is an open question whether this situation can be approximated with water flow alone, i.e. the gas phase in the repository is neglected when the water pressure rises and the repository is resaturated. A probable limitation in a two-phase description is, however, that the parameterization of the model may be associated with great uncertainties.

19.2.5 Movements in intact rock

Conclusions in RD&D 2001 and its review

RD&D 2001 described the plans for site descriptive rock mechanical models. The need for research initiatives regarding movements in intact rock was to be identified and analyzed within the framework of this work.

The authorities have not made any comments on this process.

Newfound knowledge since RD&D 2001

The fundamental issues relating to characterization of the rock's mechanical properties as well as relevant scales for this and description and/or modelling of the stress state were addressed within the framework of the development of a strategy for a site descriptive model /19-23/.

A thorough overview has been done of stress measurement methods and methods for evaluation of stress measurements in the light of the work with stress description in the site models /19-24 to 19-28/.

The strategy for developing site descriptive models was first tested on data from Äspö /19-29/, and was then applied to Laxemar /19-30/ and in the so-called version 0 reports for the site investigations /19-31, 19-32/. The strategy is also applied in the continued site modelling.

The importance of the stress paths for e.g. loading and movements in the intact rock has been described systematically in an overview study and compared with criteria for different modes of failure that can occur around underground openings in the repository /19-33/. The study particularly shows that light support, for example from the tunnel backfill, can be of importance in preventing the occurrence and growth of brittle failure.

Detailed characterization and modelling of stresses and deformations has been carried out in the ongoing Apse experiment in the Äspö HRL /19-34/. The results are being compared with measurement data.

During blasting of the Apse tunnel, detailed convergence measurements were performed in nearly fracture-free rock. A set of back calculations of the convergence movements has been carried out /19-35/. If it is assumed in the numerical model that the elasticity properties of the rock are close to those that have been measured for intact rock, the back calculations confirm the predicted stresses: $\sigma_1 = 30$ MPa, $\sigma_2 = \sigma_3 = 10$ MPa, where σ_1 is horizontal and perpendicular to the tunnel. Figure 19-3 shows that the agreement is good and thereby also verifies that the response to the rock excavation is primarily elastic, which is expected in view of the low fracture density in the measurement section.

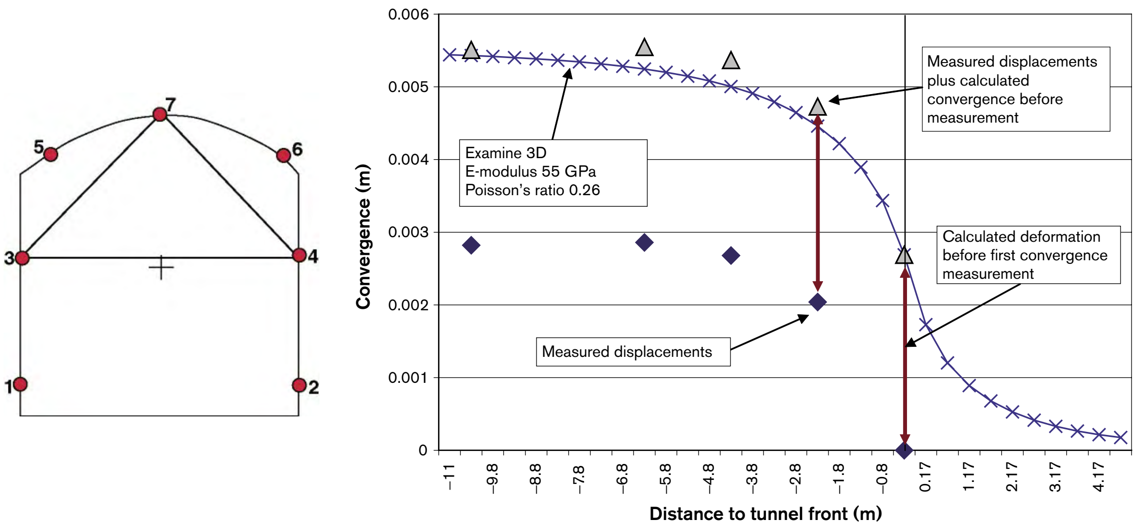


Figure 19-3. *Convergence measurement of the Apse tunnel. The pins were installed at a distance of between 0.3 and 0.5 metre from the tunnel front. The principle of convergence measurement and the positioning of the pins in the measurement section are shown at the left. The decrease in the distance between studs 3 and 4 as the distance to the tunnel front increases (Measured displacements) is shown at the right. The calculated deformations, "Examine3D", apply to a case where stress field and elastic properties have been determined by back calculation to provide the best possible total agreement with the measurement values, corrected to include calculated convergence movement before the first measurement.*

Programme

The Apse experiment is being conducted during 2004. A complete evaluation will be made in 2005.

The strategy for site-descriptive rock mechanical modelling is being applied and developed within the framework of the site investigations (Deep Repository Project).

In-depth analysis will be carried out in connection with the evaluation of the Apse experiment regarding calibration of the strategy for site-descriptive rock mechanical modelling, mainly based on comparison between predicted properties and experimental results.

19.2.6 Thermal movement

Conclusions in RD&D 2001 and its review

General plans for construction of descriptive rock mechanical models were described in RD&D 2001. The risk of canister damage due to thermomechanical loading was addressed in RD&D 2001 under the process "reactivation" and can in practice be set equal to zero, provided that it can be assumed that no canister holes will be intersected by fractures with a minimum length of 700 metres in the dip direction /19-36/.

The authorities note the absence of a reference in RD&D-Programme 2001 supporting the claim that thermomechanical loading does not cause canister damage. SKI believes this remains to be shown.

Newfound knowledge since RD&D 2001

Within the Decovalex project, the rock's thermohydromechanical response to tunnel excavation and heating has been analyzed with a number of different tools, including the commercially available code Abaqus. The evaluation and reporting of the SKB work, i.e. simulation of the Febex experiment, is under way.

Programme

The Apse experiment is continuing with updated analyses of the thermally generated movements and stress changes.

Within the framework of the design process (stage D2 in SKB's planning), thermomechanical numerical analyses will be carried out using site data. General thermomechanical 3DEC analyses may be done first as reference cases, where the rock is assumed to have continuum properties equivalent to those obtained from the first versions of the site models. Other input data, i.e. thermal loads, canister spacing etc, will be determined on the basis of the latest thermal dimensioning analyses.

19.2.7 Reactivation – movements along existing fractures

Conclusions in RD&D 2001 and its review

In RD&D 2001 it was noted that the risks of induced fracture movements had been overestimated in SR 97 due to the exaggerated safety margins that had been applied in the numerical analyses. Furthermore, RD&D 2001 described plans to broaden the body of numerical data for assessment of potential seismically induced fracture movements by defining and executing a programme of dynamic calculations.

The authorities are of the opinion that SKB's judgement that the risk in the tectonics scenario has been overestimated is probably correct (since the judgement is based on friction-free fractures) and that it is positive that earthquake effects on underground structures are now being documented.

The authorities are of the opinion that it is urgent that SKB report all evidence available to support the contention that new fracturing will not affect a tectonic lens, such as the one in Forsmark, in the event of a future glaciation, and that the possibility that future fault movements will take place along new lines is taken into account.

The authorities are of the opinion that SKB's planned research activities within the area of fracturing and reactivation appear to provide answers to most of the questions.

Newfound knowledge since RD&D 2001

The role of the fracture system for deformations in the near-field in connection with tunnel excavation and boring of deposition holes has been dealt with in a 3DEC study /19-37/. The fracture system, with fractures on the order of five to 15 metres, was based on a statistical DFN model of the TBM tunnel in the Äspö HRL. 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. Even if the fractures in the system are low-strength, the fracture movements will be small except in the immediate vicinity of tunnels and deposition holes. The stress redistribution that accompanied the movements in the fracture system was small and did not cause any part of the modelled intact rock to come close to the rupture limit. 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. It can be noted that the general conclusion that the deformation pattern was primarily elastic agrees well with the back calculations that were done in conjunction with the convergence measurements in the Apse experiment /19-35/.

Deformations in conjunction with the excavation of the Zedex tunnel and the TBM tunnel in the Äspö HRL were calculated with the codes 3DEC and Flac3D /19-38/. The study was carried out by NGI in cooperation with SKB. The calculated results were compared with the results of measurements with extensometers during the construction phase. A main conclusion was that the role of the fracture system may be smaller than previously assumed. Qualitatively, this agrees with the results of the SKB study /19-37/ and with the results of the Apse experiment /19-35/.

The general problem of translating a statistical representation of the geometry and mechanical properties of fractures to an equivalent continuum representation is dealt with in the programme for development of descriptive rock mechanical models /19-23, 19-39, 19-40/.

Seismically induced shear movements in fractures have been analyzed dynamically with the codes Wave and Flac3D /19-41/. Equivalent problems were analyzed in SR 97 using a static (non-dynamic) calculation method and statistically generated earth-quakes which induced movements in statistically generated site-specific fracture populations containing fractures of different lengths and orientations. The dynamic calculations have so far included earthquakes of magnitude 6.0 with fault movements that may be representative of postglacial conditions. The distance between the seismically active zone and the fracture with a radius of 200 metres which is affected by the earthquake in the models has been varied between 200 metres and two kilometres. At the least distance, 200 metres, the shear movement in the fracture was 0.065 metre, i.e. less than the movement that corresponds to canister failure according to the present criterion. The results now available suggest that the static contribution to the induced fracture movement dominates, at least at the short distances that will be important for the deep repository. This might mean that for the deep repository it ought to be enough to carry out purely static analyses (as in SR 97), which would greatly simplify the continued work, especially for large earth-quakes, for which dynamic models may entail calculational limitations. Furthermore, for large earth-quakes, where the active zone may extend down to depths where the properties of the rock differ considerably from those in the upper part of the crust, uncertainties exist as to the best way to represent the movement in numerical models. The attempts made so far indicate that the effect of large earth-quakes does not necessarily have to be greater than the effect of earth-quakes of magnitude 6.0 for fractures at small distances from the active zone. If the active zone is of great horizontal extent, perhaps hundreds of kilometres, the seismic moment will be great and large quantities of strain energy will be released. 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 has been published /19-42/. The purpose is to obtain empirical evidence for understanding the concept of respect distance. The study shows that the effects, in the form of documented permanent deformations, are limited to the area nearest the earth-quake, even in cases where road or rail tunnels intersect the active zone.

Possible thermohydromechanical effects of future glaciations on the repository have been analyzed in the Decovalex project. The effects at repository level are probably small, in terms of both impact on general mechanical stability and hydraulic fracturing /19-43/.

Programme

The validity of the general relationships that exist between the length of a fracture and the movement that takes place along the fracture (at a given load and set of fracture parameters) will be evaluated by means of 3DEC analyses. The general relationships are formulated for idealized conditions, above all for elastic host rock, and are therefore conservative so that the calculated movements are generally overestimated. The work is described in the planning report for SR-Can /19-44/.

The movement of two or more small fractures that interact via a bridge of partially intact rock can be underestimated if the interaction between the fractures is not taken into account. This will be investigated with the same basic method as in the 3DEC study mentioned above (general relationship between size and movement).

The programme of dynamic analyses of seismically induced movements of fractures that intersect canister hole positions will continue, above all with Flac3D models. The possibility of simulating large earth-quakes as well will be investigated. The overall objective is to arrive at a well-defined and systematic body of data which can be used together with e.g. the results of other types of earthquake studies /19-42/ to determine respect distance.

A programme will be carried out for analysis of the mechanisms (stress evolution of loaded elastic crust resting on viscous mantle) behind the occurrence of postglacial fault movements. The analyses will be performed with two- and three-dimensional Abaqus models.

The possibility that the repository, in interaction with fractures and fracture zones, may act as a plane of weakness will be investigated numerically with the aid of 3DEC models.

19.2.8 Fracturing

Conclusions in RD&D 2001 and its review

It was stated in RD&D 2001 that compared with reactivation, fracturing is of little importance for possible changes in canister hole geometry after closure.

The authorities point out that SKB should devote resources to the development of useful calculation models for fracturing – both new fracturing and propagation of existing fractures. On the other hand, they also say that the planned activity seems to provide answers to most questions.

Newfound knowledge since RD&D 2001

General aspects of the problem of spalling and stability of the deposition hole walls have been elaborated on in an overview study /19-33/. In particular, the importance of a small support pressure from the buffer to prevent initiation and propagation of failure that can lead to spalling is discussed. Background material is the theory of brittle failure developed at AECL's Underground Rock Laboratory (URL) in Canada.

A compilation of geological, mechanical and thermomechanical parameter values for the rock mass around the Apse experiment has been published as a basis for prediction of the occurrence of spalling under thermomechanical loading of the Apse pillar /19-45/.

A preliminary BEM analysis of the Apse experiment has been done with the code Examine3D in a feasibility study /19-34/. The elastic Examine3D model cannot be used to simulate failure, but comprises a basis for assessing which areas can enter a failure state and can therefore be a platform for the development of models where failure and fracture propagation are modelled explicitly with, for example, Fracod or Particle Flow Code.

Preliminary 3D results have been obtained from thermomechanical Flac3D simulations of the Apse experiment /19-46/. The results are based on an elastic material model, but give, like the Examine3D study, indications of the stresses and how they may compare with levels that are relevant for brittle failure.

The results of thermomechanical JobFem simulations, with sensitivity analyses, have also been obtained for a horizontal two-dimensional section through the centre of the pillar's height /19-47/.

A BEM code, Fracod, for calculation of fracturing has been further developed and applied to the Apse pillar /19-48/.

Programme

The problem of coalescence of individual fractures (on a 100-metre scale) will be addressed in calculation projects for reactivation. Furthermore, different methods for representing the effects of fracture propagation on large single fractures will also be tested. One of the objectives is to investigate to what extent fracture movements at large loads can be limited because strain energy is consumed by fracture propagation. A preliminary model already exists for this /19-49/, but an improved and more systematic analysis is needed.

The Apse experiment will be completed and evaluated. The technique for modelling of brittle failure and fracture propagation will be developed, in part by further applications with Fracod and in part by means of new calculation tools and methods. Different types of models will be docked to a coherent analysis. Areas that may enter a failure state, for example areas adjacent to the deposition hole wall in the Apse experiment, are represented by PFC (Particle Flow Code) models, while rock outside such areas is represented by continuum models. In addition, there has been recent progress in the application of the PFC code to stress-induced failure by simulation of the entire failure curve for both tensile and compressive stresses /19-105/.

19.2.9 Time-dependent deformations

Conclusions in RD&D 2001 and its review

It was stated in RD&D 2001 that the handling of creep movements in rock had so far been based on conservative estimates, or boundings, of possible effects on the geometry of the cavities.

The authorities have not made any comments on this process.

Newfound knowledge since RD&D 2001

Preliminary calculations have been made with 3DEC to investigate to what extent the tunnel backfill can limit the convergence of a deposition tunnel /19-50/. The general conclusion is that the tunnel backfill cannot contribute towards 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, although it may be sufficient to limit the scope of block breakout and the initiation and development of progressive failures in the rock nearest the tunnel walls.

A literature study of creep in rock masses, and especially along fractures of different types (filled, unfilled), has been conducted and the results reported in preliminary form. One of the conclusions of the study is that the stress-strength ratio must exceed a certain threshold value in order for any creep to take place.

Programme

A literature study will be conducted aimed at bounding the stress changes to which the host rock may be exposed over time as a consequence of slow tectonic movements.

The modelling technique which was used in the preliminary modelling in the Rock-Backfill project is being systematized with the aid of data and conclusions from the literature study and applied generally to the host rock, above all to the various cavities. The objective is to be able to bound the possible convergence of tunnels and deposition holes that could occur as a result of the inherent time-dependent material properties of the rock mass.

19.2.10 Erosion

Erosion of the crystalline bedrock is judged to be limited under current climatic conditions in the areas being studied by SKB. Weathering of exposed rock is estimated to be on the order of a millimetre or so per thousand years /19-51/. A colder climate with permafrost can be expected to lead to increased weathering and erosion of exposed rock. The most extensive erosion is assumed to occur in conjunction with glaciations. The erosion in conjunction with glaciation is strongly linked to the basal conditions of the ice sheet. An ice sheet that is frozen to its bed preserves the bed, while an warm-based ice sheet that slides over its bed is expected to redistribute the loose soil layers and erode the bedrock. Erosion is further dealt with in Chapter 21.

Conclusions in RD&D 2001 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 deep repository. In the review of SR 97, the authorities deemed the process as potentially unfavourable. In RD&D 2001, SKB wrote that they intended to study the process more closely.

Newfound knowledge since RD&D 2001

An estimation of the scope of glacial erosion /19-52/ has been done based on the assumption that the sediments formed during the Quaternary Period as a result of erosion by continental ice sheets still remain within the formerly glaciated area. Based on this assumption, glacial erosion has been estimated with the aid of soil depth mapping.

Programme

Erosion is strongly linked to prevailing climatic conditions, and in particular the presence of continental ice sheets. The process is therefore being studied within the framework of the climate programme, see Chapter 21.

19.2.11 Advection/mixing – groundwater chemistry

This section deals with 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 influences the groundwater chemistry. The next section deals with advection and dispersion in connection with radionuclide transport.

Conclusions in RD&D 2001 and its review

Mixing calculations, utilizing for example the code M3, that were originally carried out with data from the Äspö area have been supplemented by calculations including data from other investigated sites in Sweden and Finland. It turns out that the mixing pattern is similar, but the proportions of the different "typical waters" vary from site to site. However, there are clear similarities in the probable hydrological and chemical evolution undergone by the sites. Modern meteoric and glacial water can always be identified. Often, though not always, deep saline water is present, and in coastal locations modern and old seawater is always present.

Results from the modelling exercise within the international Task 5 Äspö Task Force on Modelling of Groundwater Flow and Transport of Solutes showed that it is possible to numerically handle the advection/mixing process on a large scale and thereby utilize both hydrological and chemical data.

SKI points out that SKB should also report the calculated salinity evolution for scenarios that involve extensive climate changes over long periods of time.

Newfound knowledge since RD&D 2001

New models for groundwater flow have been developed, see also section 19.2.3 concerning groundwater flow.

Programme

The computer code M3, which is used for statistical processing by multivariate analysis, has been developed with support from SKB. M3 is planned to undergo a number of updates and verifications within the next six years.

One of the models developed for groundwater flow (Darcy Tools) will be evaluated in a recently started project. The purpose is to model the conditions around Äspö by including both chemical parameters and hydrological data, see 19.2.3.

Within the site investigations, site-specific mixing calculations will be important for understanding the evolution of the water on the site. Calculations of salinity evolution in connection with extensive climate changes over long periods of time will be carried out within the framework of the next few safety assessments. An attempt will be made to link hydrochemistry with hydrogeological data and calculations in coming site modellings and safety assessments.

19.2.12 Advection/mixing – radionuclide transport

Conclusions in RD&D 2001 and its review

No questions for further research were identified in RD&D-Programme 2001 or its review. RD&D-Programme 2001 dealt with flow-related transport parameters under the two headings "Groundwater transport" and "Radionuclide transport – molecular diffusion and matrix diffusion".

Newfound knowledge since RD&D 2001

Advection is a process that is generally well-understood /19-53/. Accordingly, no new knowledge has emerged during the present period which contradicts previous knowledge. However, some additional support has emerged for existing knowledge. An example is simulation of advective transport in individual fracture planes /19-54/. Even though the study mainly deals with diffusion processes, certain conclusions can nonetheless be drawn regarding how the advective and dispersive processes influence transport. Specifically, it is shown that the effect of transverse dispersion is small with regard to the transport resistance (F factor).

Simulations of discrete fracture networks have been done to understand the dependence of the transport resistance (F factor) on various properties of the network /19-55/. The results show that the assumption of complete mixing, or streamline routing, at fracture intersections does not significantly affect the results. This is important, since it is difficult to prove which assumption is most correct. Furthermore, it is shown that the results are sensitive to whether the fracture intensity, expressed by the so-called P32 value, dramatically decreases. Finally, it is shown that retention is typically underestimated in the type of channel models /19-56, 19-57/ that are often used for transport calculation in conjunction with FracMan simulations. In the study in question, transport has been simulated directly in the two-dimensional fracture planes rather than being simplified to one-dimensional channels. The results in /19-55/ have also been used in a parallel study /19-58/. This study shows that the distribution of $(bv)^{-1}$, where b is the half-aperture and v is the velocity of the water, follows a power-law distribution. The transport resistance (F factor) is in turn dependent on the distribution of $(bv)^{-1}$. The results indicate that transport that is characterized by this type of power-law distribution cannot be described by a classic advection-dispersion equation, but that more sophisticated methods are needed if analytical approaches are to be used. The results from /19-55/ have also been used in /19-59/, where it has been investigated whether the transport resistance can be estimated from quantities measured in the field. Under certain circumstances the transport resistance can be expressed as a linear function of the advective travel time and an effective retention aperture. This aperture can be estimated from transmissivity data or fracture density and porosity data. However, the results indicate that these simplified estimates tend to overestimate retention, which is why explicit calculation of the transport resistance in a numerical discrete model is preferable.

Numerical simulations have also been carried out with the code Chan3D for transport in transient flow fields /19-21/. In this study, transport (advection and matrix diffusion) were simulated in a flow field that changes with time. The results indicate that transient flow can be important to incorporate in the analysis of radionuclide transport when shoreline displacement occurs. This type of study requires a coupled modelling strategy, i.e. that both flow and transport are simulated in the same model. SKB's primary modelling strategy is to model flow and transport separately. To justify such an approach, the limitations must be investigated in detail. This can be done with the type of modelling tool presented in /19-21/.

Programme

No programme will be initiated to specifically understand advection as a process. However, the studies of advection and matrix diffusion during transient flow will continue. The objective here is to understand specifically how transient flow effects that occur due to shoreline displacement affect radionuclide transport, and how simplified analyses based on separate flow and transport modelling can be bounded. The purpose is thus to be able to use, in the safety assessment for example, a coupled model in order to get a feeling for the limitations implied by a simplified analysis.

A project aimed at studying how the transport resistance (F factor) can be up-scaled from detailed to block and site scales has been commenced and will continue. Preliminary results have been presented in /19-60/. The results show how sampling of the transport resistance on a small scale can be used to calculate the transport resistance on a larger scale by means of a so-called Markov-directed Random Walk technique. This technique, which is independent of whether the distribution of $(bv)^{-1}$ is power-law or not, will be further developed and tested numerically for different discrete fracture networks. The purpose of this type of upscaling is to be able to extrapolate in modelling contexts from smaller scales, where a discrete fracture network model exists, to larger scales that are typically described with continuum models where the transport resistance cannot be explicitly calculated.

19.2.13 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 the hydrochemical conditions. Molecular diffusion and matrix diffusion and their importance for nuclide transport are dealt with in the next section 19.2.14.

Conclusions in RD&D 2001 and its review

Site investigations in Finland have shown that the hydrogeochemical conditions in Olkiluoto and in Äspö are 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. It is possible that the clear boundary between the dynamic and the deeper water has been caused by diffusive transport that has occurred over a period of around a million years. 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.

Newfound knowledge since RD&D 2001

The hypothesis has been forwarded that the deep brine was created by salt exclusion during cold climatic periods /19-61/. The authors based their hypothesis on analyses of iodine-29 to estimate the retention time for the deep brine at a sampling site in Canada at between 200,000 and 1.6 million years. Regardless of the origin of the brine, it tends to stay in place due to its high density.

Programme

This field is not judged to require any extensive research, development or demonstration today. Groundwater analyses and modelling studies aimed at determining what is required for the deep brine to be permanent are planned, both in preparation for the next safety assessment and within the site investigations. We will also investigate whether it is possible to utilize data from Greenland, where there is a thick ice sheet, to check the models for groundwater flow and salt distribution under such conditions, see also section 19.2.24.

19.2.14 Diffusion – radionuclide transport

Conclusions in RD&D 2001 and its review

The project for measurement of diffusivity in the field was presented in RD&D 2001, but results were not available at that time. It was further stated that a consensus should be reached between the concerned safety assessment parties in matters relating to retention, in particular matrix diffusion.

SKI observes in its evaluation of RD&D 2001 that SKB should investigate how quantities that influence matrix diffusion, for example the flow-wetted surface, can be measured in the field, see section 19.2.12. Further, SKI wants SKB to conduct process-oriented studies of matrix diffusion in fracture-filling materials and intact rock.

Newfound knowledge since RD&D 2001

By "diffusion" is meant here both diffusion in the flowing water and diffusion from flowing to stagnant water. The stagnant water tends to be present in the matrix (matrix diffusion) or in low-conductive parts of the fracture plane.

Diffusion in flowing water is uninteresting in the longitudinal direction, i.e. the flow direction of the water. In the transverse direction, this diffusion process is of interest for determining relevant length scales over which mixing takes place on different time scales. For example, mixing takes place over shorter lengths on experimental time scales than on the time scales of interest for the safety assessment. These length scales are of interest when radionuclide transport is to be conceptualized for modelling. The question of whether mixing takes place in fracture intersections is also dependent on diffusion in the aqueous phase. These issues are being examined in the ongoing EU project Retrock /19-62/.

When it comes to diffusion into stagnant water, matrix diffusion is the most relevant process. This also includes diffusion into the fracture-filling material (gouge) and altered rim zones which are typically present in natural fractures. Field tests carried out at Äspö, True-1 /19-63/ and True Block Scale /19-64 to 19-67/, show that it is presumably mainly diffusion in gouge and an altered rim zone that are observed on time scales that are typical for field tests. The studies also confirm that this diffusion is heterogeneous in nature, mainly due to a spatial variation of the porosity in the materials in which diffusion takes place. A porosity profile perpendicular to the fracture plane has been observed: The altered rim zone nearest the fracture has a relatively high porosity, while the intact rock further in has lower porosity /19-68/. Modelling tools have been developed for describing this type of heterogeneity /19-66, 19-69/.

Since transport experiments in the field with tracers typically measure matrix diffusion into materials other than the intact matrix, it is also of interest to be able to measure diffusion in the field in the intact matrix. An experiment called the Long Term Diffusion Experiment (LTDE) is planned for this purpose /19-70/. Geological characterization of the planned site for the experiment has been done, and hydrogeological tests will be conducted. The experimental equipment and the concept for the experiment will be reviewed during 2004.

Electrical methods (electrical conductivity) can be used in situ as an alternative to estimate the formation factor (which controls the rock's influence on diffusion). An ongoing doctoral project has summarized the state of knowledge, identified open questions and presented preliminary results /19-71, 19-72/. The parameters needed in order to estimate the formation factor are rock resistivity, pore water resistivity and the estimated contribution made by surface conduction. The effect of surface conduction decreases as the salinity of the water increases.

Programme

According to current plans, the real measurements in the Long Term Diffusion Experiment will start during the current period, after characterization has been completed and the experimental concept has been evaluated.

The doctoral project, which is concerned with electrical methods for estimating the formation factor in situ, will be finished during the current period. The method is being tested on drill cores from the site investigation programme. Furthermore, methods are being studied for estimating the conductivity of the pore water (normally it is assumed that the pore water and the water in the fractures have the same conductivity). Finally, methods are being investigated for correcting measurements at low salinity, when the effect of surface conduction can be great.

Diffusion measurements in the laboratory on site-specific material are also being performed within the site investigation programme. These investigations are described in greater detail in /19-73/.

19.2.15 Reactions with the rock – groundwater and rock matrix

Conclusions in RD&D 2001 and its review

In the long term, the chemistry of the groundwater is determined by reactions with the primary minerals in the rock, which weather and release dissolved substances into the groundwater.

The composition of the groundwater in fractures, a relatively well-studied area, is often affected by both mixing and reactions. The composition of the matrix water, on the other hand, is expected to depend mainly on reactions between rock minerals and groundwater. An experiment aimed at studying the composition and age of the matrix water and determining the effect of diffusion processes on this composition was started at the Äspö HRL. One interpretation of the results is that so-called matrix water comprises a very small fraction of the water that has been collected in the borehole. Most comes from fractures and microfractures that are connected to larger structures. There is therefore no reason to suspect that a very saline water caused by the matrix would enter the deposition holes at any point.

Newfound knowledge since RD&D 2001

In the Matrix Fluid Chemistry Experiment in the Äspö HRL /19-74/, analyses have been made of in situ matrix fluid, i.e. water present in the pores in the rock that is accessible for interaction with water circulating in the fractures. The results of the experiment show that contact between matrix fluid and groundwater in the fractures takes place through flow 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 and saline waters that are old, dating back to at least the last glaciation, i.e. more than about 10,000 years old. This relatively rapid turnover rate for the matrix fluid at Äspö is supported by observations of the fact that the rock generally has high permeability. The matrix fluid therefore contains only a small component that originates from long-term reactions between rock and water.

Experience from the Matrix Fluid Chemistry Experiment at Äspö has been applied to the site investigations. Diffusion experiments on a laboratory scale have been conducted on samples from different depths in Simpevarp. The experiments indicate different compositions with salinities that increase with depth.

Programme

The Matrix Fluid Chemistry Experiment at Äspö may be supplemented by additional measurements. Aside from these investigations, the field is not judged to require any further research, development or demonstration today. New developments are being monitored and will be acted on when appropriate.

19.2.16 Reactions with the rock – dissolution/precipitation of fracture-filling minerals

Conclusions in RD&D 2001 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 and 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 thus 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 Äspö/Klipperås (occurrence of redox-sensitive minerals etc) and other places /19-75/.

Evaluations of both water chemistry /19-76/ and fracture mineralogy /19-77/ show that there are clear indications that components of a glacial meltwater have reached great depths (deeper than 500 metres). But there is no evidence 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 prevailed at depths below 100 metres for a long time /19-77, 19-78/. It is therefore misleading to associate the presence of glacial meltwater with oxidizing conditions.

In the Rex Project (Redox Experiment in Detailed Scale), studies were made of how oxygen remaining after closure of a repository can react with minerals and groundwater in the rock around the tunnel, the deposition holes or along the water-bearing fractures /19-79/. The results from the in situ experiment were confirmed by a replica experiment in the laboratory. Both investigations showed that oxygen had been completely consumed after a few days. The agreement was strikingly good, considering the differences in experimental conditions. The main conclusions from the project were:

- Oxygen consumption in the geosphere was found to be substantial and speedy.
- Microbial activity contributed substantially to the oxygen consumption.
- Methane and hydrogen gas that diffuse up through the earth's crust are expected to make a considerable contribution to reduction capacity.

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. As far as the capacity of microbes is concerned, quite a bit of fundamental research remains to be done, see microbial processes, section 19.2.18.

SKI pointed out in its review of RD&D 2001 that a scenario with changed redox conditions at repository depth can be considered to have a very low probability, but that it cannot be reasonably ruled out.

Newfound knowledge since RD&D 2001

Experiments have been conducted with weathering of the fracture-filling mineral chlorite /19-80/. Chlorite is a common mineral in fractures and also occurs in alteration minerals in the surrounding rock matrix. Chlorite usually contains significant quantities of iron(II) and can therefore give some of the buffer capacity against intrusion of oxygen-containing groundwaters.

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 /19-77/. 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. Equip has been succeeded by the EU project Padamot, which will last until 2006.

Uranium series analyses from clay- and hematite-rich fracture fillings from Äspö have been evaluated together with analyses of uranium-234 and uranium-238. 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 /19-81/.

The prevailing paleohydrogeological picture of the Äspö/Laxemar area is that four different zones have been distinguished: (1) an upper zone where the redox conditions have varied and where both calcite dissolutions and precipitation have taken place, then (2) a zone (down to about 500 metres) with active calcite precipitation under various groundwater regimes (both marine and meteoric), as a result of which zoned calcites are commonly occurring and old hydrothermal calcites have been preserved as well. A supply of organic matter creates the necessary conditions for activity of sulphate-reducing and iron/manganese-reducing bacteria. (3) Down to about 1,000 metres, potential freshwater carbonates have been found in the fractures. There are no clear indications of marine carbonates, however. Organic matter reaches down to these depths, but becomes progressively less abundant with increasing depth. (4) Below about 1,000 metres conditions are relatively stagnant, and low-temperature calcites are rare /19-82/.

Programme

Further experiments with weathering of iron-containing fracture-filling minerals are planned within the coming six-year period. Studies of fracture-filling minerals as indicators of former groundwater chemistry will continue within the EU project Padamot. A project aimed at studying Fe(III) oxides on Äspö has been started. The properties of these oxides may be useful for determining previous redox conditions.

New calculations are planned in preparation for the next safety report to find out how deep a glacial water can penetrate and how deep oxygenated glacial water can reach before the oxygen has been consumed. The problem of direct and indirect datings of fracture-filling minerals has not yet been solved. New developments are being monitored and will be acted on when appropriate.

19.2.17 Reactions with the rock – sorption of radionuclides

Conclusions in RD&D 2001 and its review

It is stated in RD&D 2001 that experiments with the Chemlab probe will continue, but that no other major work is planned.

SKI pointed out in the review of RD&D 98 that both a relevant database of K_d values and a good process understanding of sorption are important. This standpoint is repeated in the review of RD&D 2001. SKI also says that surface complexation models should be developed to support the K_d concept, and that sorption kinetics should be investigated. Furthermore, the authority would like to see sorption studies of site-specific material.

Newfound knowledge since RD&D 2001

Several projects are aimed at investigating sorption, including the Äspö projects RNR (Radionuclide Retention) and True (Tracer Retention Understanding Experiments).

In the project RNR Actinide, migration of actinides has been studied in a drill core with a longitudinal fracture. The core was installed in the borehole laboratory Chemlab-2, which was then placed in a borehole at a depth of 450 metres in the Äspö HRL. The fracture was equilibrated with groundwater before a solution of actinides (maximum solubility concentrations of tetravalent plutonium-244, trivalent americium-243 and pentavalent neptunium-237) was injected into the fracture from a compartment in Chemlab-2. After the actinide injection, groundwater was pumped through the fracture for a long period. In the experiments, between 20 and 40 percent of the injected neptunium accompanied the groundwater in the form of uncomplexed neptunyl ion (NpO_2^+) (same breakthrough as HTO). The longer the residence time in the fracture, the lower the concentrations of pentavalent neptunium were observed in the eluate. No plutonium was found in the eluate, while americium was found in concentrations on the order of 10^{-11} mol/l /19-83/. Similar experiments have also been conducted in above-ground laboratories. Within the framework of RNR Actinide, batch sorption tests have also been performed in above-ground laboratories with the same actinides as in the field tests and fracture-filling material/crushed granite. These tests showed a clear time dependence for sorption of the actinides in question.

Some knowledge of sorption has also emerged from the True experiments. These results are described below in section 19.2.26.

Knowledge of sorption and sorption mechanisms is being compiled in the ongoing EU project Retrock /19-62/. The final report for Retrock will be completed during 2004.

Programme

Within the framework of actinide migration in a drill core with a longitudinal fracture, a test will be conducted with uranium and technetium using the same experimental set-up as for actinide migration (see above).

It has emerged from various joint international projects, such as Geotrap within the OECD/NEA and Retrock within the EU, that a more process-oriented description of the retention processes that are often lumped together under the heading of sorption may be needed for the purposes of safety assessment as well. The processes that are principally of interest besides pure sorption are precipitation, co-precipitation and surface precipitation. The processes that are normally included in sorption are mainly ion exchange and surface complexation processes.

Process-based models can provide better process understanding and be used to bound simplified models based on distribution coefficients at equilibrium (K_d values). SKB plans to evaluate the need for process-oriented sorption modelling specifically for safety assessment during the current three-year period. If a need to develop this type of modelling capacity emerges, work will be initiated. An obvious advantage of models of this type is that they can be used to study how retention is affected by changes in groundwater chemistry, such as pH changes. A new task has also been proposed for the Äspö Task Force on Modelling of Groundwater Flow and Transport of Solutes that would involve reinterpreting the True-1 experiments with a more process-oriented modelling strategy for retention. SKB is also continuing to support more fundamental studies of surface complexation.

During the current period, a licenciate project will be conducted to develop methods for determining K_d values on intact pieces of rock with the aid of electrical methods. A problem with traditional measurements of K_d values is that they are done either on crushed rock material or via diffusion tests on intact pieces of rock, which is more relevant but takes a very long time. The idea of the planned project is to investigate whether an electrical potential can be used to speed up the penetration of sorbing nuclides in intact pieces of rock. In preliminary tests with non-sorbing substances, the penetration rate increased by around a factor of 1,000 /19-84, 19-85/.

In the site investigation programme, sorption measurements on site-specific materials are also being carried out in the laboratory. These investigations are described in greater detail in /19-73/.

19.2.18 Microbial processes

Conclusions in RD&D 2001 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 /19-86/.

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 have shown /19-87/. When oxygen is not present as an oxidant, different microbes can instead make use of other compounds, such as the sulphur in sulphate ions (SO_4^{2-}) with formation of sulphide (S^{2-}), and the iron in various minerals (Fe^{3+}), which then dissolves in the groundwater (in the form of Fe^{2+}). Manganese (Mn^{4+}) in brownstone can also be used by microbes, and then dissolves in the groundwater (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. Together, the lives of these microbes in the groundwater have an important influence on the geochemical environment in the water-filled fractures in the rock /19-88/.

Newfound knowledge since RD&D 2001

Bacteriogenic iron oxides (Bios) are formed by bacteria when anaerobic iron-bearing groundwater reaches environments with oxygen. Large quantities of iron oxides mixed with microbes and their excretory/secretory products have proved to be very effective filters for trace metals /19-89/. The tests have been conducted at the 300-metre level in the Äspö HRL. Retardation of trace metals in Bios considerably exceeds retardation in inorganic iron oxides. Bios are formed where groundwater seeps up to the earth's surface. Any migrating radionuclides will be effectively captured by Bios, leading to locally increasing concentrations but regionally lower concentrations compared with a situation without Bios.

Laboratory investigations of capacity to mobilize metals have been carried out on strains of bacteria isolated from great groundwater depth. The results show that the studied organisms excrete/secrete complexing agents which can, for example, mobilize uranium out of Ranstad shale /19-90/. Further investigations have shown that these complexing agents are also able to mobilize radionuclides from solid phases of silicon and titanium oxide. The tests have been conducted in an aerobic environment. Investigations are currently being conducted under anaerobic conditions.

Fungi, mainly yeasts, have been found in groundwater from repository depth in small but significant quantities /19-91/.

Microbial oxygen consumption in a fracture has been modelled /19-92/. The calculations also included inorganic processes, for example pyrite oxidation, and 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.

Programme

A laboratory at a depth of 420 metres in the Äspö HRL permits continued work on microbes and their importance in the deep repository in a project called Microbe. 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. It is possible to work anaerobically in the laboratory in a box. Three systems with circulating groundwater from fractures inside the rock permit studies of microbial processes under repository conditions (in situ 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. Artificial ditches have been installed at a depth of 300 metres for investigations of Bios (bacteriogenic iron oxides). A series of different experiments is planned at these two sites.

Bios have proved to have very high affinity for trace metals. Anaerobic biofilms (thin layers of microbes on surfaces) consist of substances similar to those in Bios. Experiments are being conducted where immobilization of different radionuclides, including cobalt-60 and promethium-147, is being studied. Continued experiments include studies of biofilms on different minerals.

Complexing agents have been identified from bacteria that grow with oxygen. These ligands are formed so that the microorganisms can obtain vital trace elements, many of which have very low solubility under oxic conditions, such as iron. The availability of trace metals increases under anoxic conditions, which should mean little or no need for complexing agents. Experiments will be conducted on microbes that grow anoxically in the Microbe laboratory at the 420-metre level in the Äspö HRL. We intend to study whether complexing agents are produced under repository-like anoxic conditions.

In the Rex experiments /19-87/ it was found that microbial oxygen reduction is an important process. In a new project we are investigating the occurrence and activity of methane-oxidizing microbes in the Äspö HRL and on the investigation sites. Methods for measurement of microbial oxygen reduction are being developed.

The knowledge base on microbial processes in host rock is growing continuously. There is now so much information that meaningful modelling work is possible. Several different important microbial processes will be modelled. Microbial oxygen reduction with methane and organic matter is being calculated. Calculations of sulphate reduction near deposition holes are being performed. The contribution made by microbial processes to the rock's long-term barrier performance is also in focus.

19.2.19 Decomposition of inorganic engineering material

Conclusions in RD&D 2001 and its review

The process is of importance for the geosphere in an initial phase and close to the repository, when the conditions are affected by the construction of the repository.

Newfound knowledge since RD&D 2001

An in situ experiment is being conducted in Grimsel, Switzerland, for the purpose of studying how concrete pore water reacts with rock minerals. The results obtained so far are presented in Chapter 25.

Programme

A project has been started in cooperation with Posiva to develop and test grouting materials that yield leachate with a pH lower than 11.

The other principal inorganic engineering material is steel. This field is judged today not to require any further research, development or demonstration.

19.2.20 Colloid formation – colloids in groundwater

Conclusions in RD&D 2001 and its review

Colloids are tiny particles that do not sediment. This means that they can accompany the groundwater and even act as carriers of radionuclides. SKB has been conducting studies and measurements on 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, and that the mean concentration is 20–45 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 of plutonium show that colloid fractions in the groundwater could be detected 1.3 kilometres from the detonation site. This is an indication of rapid colloid transport.

Newfound knowledge since RD&D 2001

The Colloid Project was initiated in the autumn of 2000 and will be concluded in 2004. The purpose of the project is to clarify the stability of colloids, their potential to transport nuclides, and the potential of the bentonite to generate 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, among other things.

The background concentration of colloids in different water types and fracture zones was measured with a high-resolution laser. The results show that the natural colloid concentration declines with increasing salinity and depth. The colloid concentration on Äspö is less than 300 ppb, and at repository depth the concentration is less than 50 ppb.

A total of six bentonite reactors were installed in the Äspö HRL and in Olkiluoto, Finland. It was found that colloid production from the bentonite under natural conditions is small and that it was not affected by the flow rate.

Programme

There are plans to study transport of colloids between two nearby boreholes at the Äspö HRL. The boreholes penetrate the same fracture zone, known as True feature A, which has a relatively homogeneous geology. The experiment will be supplemented by laboratory experiments and experiments with colloid transport of radionuclides in a drill core in the Chemlab apparatus in the Äspö tunnel.

19.2.21 Colloid formation – radionuclide transport with colloids

Conclusions in RD&D 2001 and its review

It is stated in RD&D 2001 that some model development, mainly of an analytical nature, will take place to be able to quantify the importance of colloidal transport.

In its review of RD&D 2001, SKI concludes that SKB should acquire a better understanding of the processes that control transport and mobility of colloids, and if necessary incorporate these processes into the safety assessment.

Newfound knowledge since RD&D 2001

Generic modelling of nuclide transport with colloids has been carried out during the current three-year period. It is shown in /19-93/ that colloids can have a significant impact on plutonium transport under certain combinations of parameters and conditions that are otherwise comparable to the situation on Äspö. Specifically, it is shown that the filtration rate of colloids is an important parameter. However, the values of this parameter are in principle unknown. This study shows that relevant processes can be incorporated in models of radionuclide transport, but that the uncertainty in parameter selection is great. This uncertainty is largely due to inadequate process knowledge.

Scoping calculations have been performed in preparation for a possible field-scale tracer test with colloids /19-94/. The test, if it takes place, would be included in the Colloid Project and be conducted on the site down in the Äspö HRL where True-1 is situated. The calculations show what parameter combinations would then be appropriate for detecting colloid-facilitated transport /19-94/. The work also shows how colloid transport can be incorporated into models for radionuclide transport.

A numerical variant of SKB's code for radionuclide transport in the geosphere, Farf31, has been developed to handle colloid-facilitated radionuclide transport /19-95/. The same conceptualization of colloid transport has been used as in SKI's study /19-96/. This concept implies that nuclide transport takes place on a separate colloid phase, and that the uptake of nuclides on the colloids is described by a sorption-desorption model. The numerical Farf model can reproduce the results in SKI's study and also handle chain decay.

Programme

If tracer tests with colloids are conducted in the Colloid Project, see section 19.2.20, then modelling of the experiments will also be carried out. This modelling will be based on the experience and code development described in /19-94/.

The newly developed numerical version of Farf31 will be utilized to study the impact of colloids on radionuclide transport in greater detail for different scenarios and parameter variations. Based on these studies, a strategy will be formulated for how colloids are to be handled in the safety assessment.

19.2.22 Gas formation/dissolution

Conclusions in RD&D 2001 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, ethene, acetylene, propane and propene also occur. The total quantity of dissolved gas per litre of analyzed Swedish groundwater varies from about 30 millilitres to about 100 millilitres, down to a kilometre beneath the surface. These quantities are well below the solubility limits for the encountered gases at the pressure prevailing at the depth in question. Larger quantities of gas of differing composition have been encountered in Finnish groundwaters, up to 0.3–0.4 dm^3 gas per litre of groundwater /19-97/. No issues for further research were identified in RD&D 2001.

Newfound knowledge since RD&D 2001

The database of dissolved gases in groundwater is being added to continuously /19-86/, both with data from groundwater around the Äspö HRL and with data from groundwater at the site investigations.

Programme

Systems for gas analysis and research on gases have been installed under ground at the Äspö HRL and at a laboratory at Göteborg University. 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 microorganisms on gas content and composition. The results of these investigations are reported in section 19.2.18.

19.2.23 Methane ice formation

Conclusions in RD&D 2001 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.

Newfound knowledge since RD&D 2001

Together with researchers from Finland and Canada, SKB has studied a gold mine in the permafrost area in Canada (the Lupin Mine). No methane ice was found.

Programme

Studies around the mine in Canada will continue.

19.2.24 Salt exclusion

Conclusions in RD&D 2001 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.

Newfound knowledge since RD&D 2001

Investigations in the Lupin Mine in the permafrost area in Canada have not been able to demonstrate the effect of salt exclusion.

Programme

The investigations in the Lupin Mine will continue. 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 greater depths. It is therefore not likely that accumulations of saline groundwater will be found beneath layers of permafrost. See also section 19.2.23 above.

19.2.25 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 groundwater chemistry programme aims at describing the chemistry of the groundwater in the deep repository volume and its environs from a safety assessment perspective and producing the body of chemical data required for design of the deep repository. In general, the geochemistry programme contributes towards 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 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 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 with each other, their different evolutionary pathways can be identified regardless of where in the volume they occur. A typical water is defined for each class. Typical waters comprise the basis for continued calculations of reactions and mixing ratios. Measurement data for e.g. the ten most important components can be included in these calculations /19-76/. 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 19.2.11. The reasonableness of the results is checked by alternative modellings, for example geochemical simulations with the code Phreeqc.

Knowledge of the microbial processes has increased in recent years /19-88/. They have been found to have a great influence on the hydrogeochemical evolution and thereby on the hydrogeochemical interpretation.

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 project Equip /19-77/ 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 on Äspö indicate a division into three zones, where the zone below a depth of 800 metres appears to be relatively isolated.

Conclusions in RD&D 2001 and its review

Taken together, the results of specific hydrochemical modellings based on data from Äspö and Olkiluoto have yielded a picture of what changes in groundwater composition can be expected in the future /19-98/. 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 change will influence today's situation in a way 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.

Newfound knowledge since RD&D 2001

New data gathered within the site investigation programme do not contradict the mixing pattern that has emerged from data from other investigated sites in Sweden and Finland. But the number of chemical analyses available is still too small to allow any definite conclusions to be drawn.

Programme

There are no plans for method development in the field. The methodology is being applied in the site investigation programme.

19.2.26 Integrated modelling – radionuclide transport

Conclusions in RD&D 2001 and its review

It was observed in RD&D 2001 regarding model studies that the one-dimensional description of transport and the dispersion formulation should be evaluated with the aid of more complex models. It was further observed that Farf31 should be compared with models with a higher process complexity for retention. The reference was specifically to models with heterogeneity in diffusion and sorption properties in the matrix. Finally, it was observed that Farf31 should be updated with respect to how input data are formulated so that information regarding the transport resistance can be used directly in the model.

In RD&D 2001, it was observed with regard to field studies that further evaluation of True Block Scale results should be done.

In its evaluation of RD&D 2001, SKI supported the development of transport models for radionuclides that can take heterogeneity (variable penetration depth) in matrix properties into account. Further, SKI wanted to see a report that summarized conceptual assumptions, mathematical formulations and scientific support for Farf31. SKI also observes that if the results from True indicate that retention can only be described in the context of transport in a three-dimensional network of fractures, SKB should describe the simplification errors that can result from an application in the one-dimensional Farf31 model.

Newfound knowledge since RD&D 2001

Model studies

In the international Äspö Task Force on Modelling of Groundwater Flow and Transport of Solutes, Task 4 has been completed and Task 6 is in progress. Task 4 dealt with numerical modelling of the True-1 experiments; Task 6 deals with upscaling of transport to time and space scales that are relevant to the needs of the safety assessment.

The modelling in Task 4 has been evaluated, and it turned out that most of the modelling groups utilized similar conceptualization of the retention processes /19-99/. All groups included matrix diffusion and equilibrium sorption as the dominant mechanisms in the modelling of the experiment. However, the predictions exhibit a progressively increasing spread for the more strongly sorbing tracers (for example cesium). Remaining uncertainties in modelling and evaluation of results are judged to be mainly due to incomplete knowledge of the flow field in the experiment.

In Task 6, modelling results have been presented for the two initial phases. In these phases, transport has been modelled in a single fracture (length scale 10 metres) for experimental time scales and for time scales of relevance to a safety assessment. The purpose of these two exercises has been to evaluate how different conceptualizations and models behave when the time scale increases. Final results have not yet been presented. In Task 6C, a fracture network model with associated retention parameterization has been constructed on a 200-metre scale for use in the later parts of Task 6 /19-100/. The method presented in this report has also served as a basis for formulating a strategy for the modelling of transport properties within the site investigation /19-101/.

An evaluation of how retention mechanisms in connection with radionuclide transport should be incorporated in modelling in safety assessment has also been done within the EU project Retrock. Specifically, a number of open questions and recommendations have been compiled. The final report is expected to be finished in 2004, but it can already be concluded that most of the questions and recommendations presented are covered by activities in the geosphere part of this RD&D-programme.

A validity document for SKB's code for radionuclide transport in the geosphere, Farf31, has been published /19-102/. The document discusses numerical verification of the code and then concludes regarding validation that the code is suitable for its stated purposes. These purposes are, within safety assessment, to calculate radionuclide transport in fractured rock and to obtain correct results for the type of problems for which the code is intended. A numerical finite-volume representation of Farf31 has also been developed /19-95/. Comparative calculations between the standard Farf31 and the numerical Farf31 confirm that the codes give the same results. This also entails a verification of Farf31. The numerical Farf31 can also be used to study more complex conditions that those that are possible in the standard Farf31. For example, the effects of a heterogeneous matrix or other initial and boundary conditions can be studied. The standard Farf31 has also been reformulated so that the transport resistance (F factor) from discrete models can be used directly as input data.

The effects of describing one-dimensional advective/dispersive transport in fractures as in Farf31 have been investigated /19-54/. In this study, a Farf31-like solution is compared with a complete two-dimensional solution in simulated fracture planes. The study shows that the effect of the one-dimensional approximation is relatively small with respect to e.g. the resulting transport resistance.

A project has been conducted to obtain simple measures of the retention capacity of the geosphere which also includes natural variability and/or uncertainties. This methodology applied to Äspö is presented in /19-104/. The study is based on groundwater flow modelling performed in FracMan/PAWorks /19-57/. Such simple measures of the geosphere's retention capacity can be used to compare alternative repository volumes within a site or alternative sites where knowledge (uncertainty) varies between the volumes or the sites.

Field studies

The experiments within the Äspö projects True Block Scale, True Block Scale Continuation and True-1 Continuation have been under way for the past three years. These experiments show clearly that retention of tracers can be observed in the results of tracer tests conducted in the field. Specifically, diffusion into stagnant (immobile) zones has also been demonstrated. Although the exact distribution of the different types of immobile volumes has not been established explicitly, a conceptual model has been presented which contains and quantifies the presumed immobile components /19-67/.

The porosity variation in the altered zone in the fracture wall and further into the intact rock has been studied under laboratory conditions by means of the PMMA method /19-68, 19-105/. A porosity gradient from the fracture surface with decreasing porosity into the matrix has been observed, although it has not been possible to quantify the phenomenon in statistical terms. Similar measurements have also been done on pieces of breccia (centimetre-scale) and pieces of breccia fragments (millimetre-scale); also here a gradient can be noted in the larger pieces. Quantitative porosity determinations of fine-grained fault gouge with elevated clay content have not been done, but it is hoped that this type of result will emerge in True-1 Continuation, where a characterization of fracture zones is included as an important component. Both qualitative information for geometric conceptualization and quantitative data in terms of porosity variation are expected to emerge.

Sorption properties have been determined (calculated) for intact rock material by utilizing known mineralogy, CEC (Cation Exchange Capacity) values, selectivity coefficients and existing hydrogeochemistry. The usefulness of the method is currently being verified by laboratory experiments where corresponding sorption properties (K_d values) are being measured on altered material and fine-grained fault gouge.

Tools for numerical modelling have been developed and used to show how groundwater flow and retention processes affect tracer transport in tracer tests performed in the field over length scales of up to about 100 metres /19-66, 19-67/. These results clearly show that different modelling tools, from simple one-dimensional codes with an emphasis on the description of retention to more complex three-dimensional codes with an emphasis on the geological and hydrogeological description, have been utilized to describe the experiments. The conceptual development that has taken place has also been incorporated in the planned strategy for transport modelling within the site investigation programme /19-101/.

Results from True Block Scale have also been utilized to develop the geological structure and retention model used in Task 6 within the Äspö Task Force, see under the heading "Model studies" above.

Programme

Model studies

Within the international Äspö Task Force, Task 6 is continuing with modelling exercises in a block-scale (200 metres) fracture network. Both experimental time scales and time scales relevant to the needs of the safety assessment will be analyzed. The main purpose of Task 6 is to study how models that have been conditioned on the basis of data from field investigations (on a limited scale) predict transport when extrapolated in both time and space. Not only does the exercise provide indications of how different model concepts work when extrapolated, it also provides answers to what kinds of investigation data are useful and decisive in modelling.

Methodology for radionuclide transport is being developed in the ongoing safety assessment project SR-Can, within integrated modelling for safety assessment. See the planning report for a description of this development work /19-44/. With regard to transport in the geosphere, mention can be made here of methodology for analyzing flow and transport through backfilled tunnels, as well as transport calculations where detailed information from discrete fracture network models concerning fractures and flows on a canister scale is transferred to the codes for nuclide transport in the near- and far-field.

Field studies

Both True Block Scale Continuation and True-1 Continuation will continue during parts of the coming period. Together, these projects comprise a platform where data collected from the laboratory and the field are utilized to evaluate conceptual and numerical models for radionuclide transport.

The current phase of the Äspö project True Block Scale Continuation (BS2B) includes predictions and evaluations of tracer tests in an intermediate structure over distances of up to 30 metres where prediction on the basis of geological information is emphasized. Another goal is to analyze how background fractures in the fracture network are activated in connection with tracer tests. In the numerical modelling, microscale fracture heterogeneity is included in the analysis, along with variability in retention properties perpendicular to the fracture plane (i.e. variability in the direction for matrix diffusion).

Additional laboratory investigations of sorption will be conducted in the Äspö project True-1 Continuation. Specifically, the purpose is to analyze sorption properties in fine-grained fault gouge and material in the altered rim zone nearest the fracture. A better understanding of the sorption properties of these materials is important for predicting tracer tests in the field.

20 Biosphere

SKB's biosphere programme for the coming six years was described in RD&D-Programme 2001. After nearly half the time it can be noted that the programme has largely proceeded according to plan and that the research has had the desired results. More than 40 reports, ten articles in international scientific journals, two doctoral theses and two licentiate theses have been published during the period. The ambition stated in RD&D 2001, including increased publication in international journals, has been realized.

A unique site investigation programme for the biosphere was started and a new organization for site investigation was created during the period. The research programme has participated with resources, experts and development of methods to make this possible. A breakthrough was also made during the period in the development of new, modern tools for biosphere modelling within the safety assessment. SKB is thereby equipped to conduct safety assessments with effective tools and relevant data.

The coming period will be characterized by extensive efforts when it comes to analysis of site-specific data, as well as several major safety assessments. The long-term biosphere research is well designed to contribute methodology and data for these tasks, but is also prepared to conduct targeted research to solve any new problems that may emerge.

Interest on the part of Swedish and international research groups working with radioecology and environmental problems will probably increase during the upcoming period as new findings and methods are published by SKB. This will stimulate discussion while leading to further publication and dissemination of the results in international forums.

20.1 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 possible release from the deep repository in the form of radiation dose to humans and other organisms are seen 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 authorities' requirements on safety and limit values expressed in doses and risk are met, and to compare 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. These conditions are climate-dependent.

In the site investigations and subsequent siting of the deep repository for spent nuclear fuel, consideration must be given to how the activities directly affect the surface ecosystems. The biosphere will also be included in any monitoring of the repository area, and during the monitoring period the surface ecosystems are expected to change naturally. Good knowledge of the original state of the ecosystems and continuous follow-up of natural changes are required to be able to distinguish natural changes from the effects of a repository. All of this demands early and thorough investigations of the biosphere on a candidate site.

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 to assess the environmental consequences of constructing and operating a repository.

20.2 Review of RD&D 2001

Following are the most important comments from various reviewers on the biosphere programme in RD&D 2001. General comments on RD&D 2001 are responded to below, while specific viewpoints are commented on in the following programme descriptions. The authorities presented their review and decision regarding the renewed safety assessment of SFR, called Safe, in the spring of 2004. Their viewpoints will be worked into the research programme for the upcoming six-year period, if possible.

In the review of the biosphere programme in RD&D 2001, all the regulatory authorities (SKI, SSI and Kasam) judged the programme to be both methodical and ambitious. They further commented that SKB's ambition to publish in international journals was positive. Both SSI and SKI wanted to see more concrete plans for how the transition between biosphere and geosphere will be handled by SKB, especially with respect to the site investigations. Kasam offered similar viewpoints when it comes to the link between recipients and geohydrology. Newfound experience as well as the coming programme are described in sections 20.4 and 20.5 and Chapter 19.

SSI and Kasam are positive to the systems ecology approach and proposed typical ecosystems, but would like to see descriptions of how different systems are linked together and a plan for development and coordination in conjunction with the site investigations. This is described in the planning report for SR-Can /20-1/ and in the strategy report for the site descriptive modelling of the biosphere /20-2/. These documents make it clear that model development is being pursued in parallel with the site investigations, since model development is dependent on understanding and data gained from the sites.

SSI is positive to the description of the biosphere processes, but desires more extensive documentation and that the RD&D report be written in process form for the biosphere as well. The intention of this RD&D report has been to fulfil this desire. Since there are many processes in the biosphere and they are included in many scientific disciplines (geology, chemistry, hydrology, meteorology, oceanography, ecology, etc), it has been difficult to find available experts who have the qualifications and the time to carry out an interdisciplinary synthesis. It is also doubtful whether the review of the biosphere programme is facilitated by the fact that it is in process form, since the process descriptions cut across the disciplines. However, the ambition is still to write a process report for SR-Can and the next RD&D report.

SSI appreciates the fact that SKB participated in Fasset, but would like to see a discussion of how the results will be used in the safety assessment and the site investigations. When RD&D-Programme 2001 was written, no results were available from Fasset so it was not easy to describe how they were going to be used. As far as site investigations are concerned, data already collected will far exceed the needs indicated by Fasset. SKB's continued programme for the environment is described in section 20.10.

SKI notes with satisfaction that work with inventories and monitoring programmes within the site investigations has been started. SSI wants future monitoring programmes to be investigated. This has been done in SKB's Programme for monitoring, see Chapter 12. In this context, Kasam wants indicators to be established for impact on the biosphere. Since the limit for the permissible quantity of radionuclides falls far short of the background radiation level, it is not likely that any change of the biosphere will be measurable.

SSI and Kasam want particular attention to be given to accumulation and release of radionuclides in seabeds and sediments, since the sites are near the coast. Obtained results and the planned work are described in greater detail in sections 20.5 and 20.7. SKI calls for continued work with alternative safety indicators and Kasam would similarly like the risks to be compared with other risks. This work is closely linked to the EIA work, while other safety indicators are more related to the geosphere research programme. According to SSI's regulations /20-3/, the dose to today's biosphere shall be a comparison measure, and this is a good indicator of how the repository's barriers perform during all periods.

20.3 Understanding and conceptual models

The authorities' 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 /20-3/. The site investigations make the biosphere concrete, which entails that simplifications in how the biosphere is conceptualized must be valid for 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 a numerical result is obtained for the safety assessment, see section 20.4. 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 deep repository.

In order to get a credible description of the evolution of the biosphere, the conceptual models that are used must be in harmony with scientific opinion within the fields of not only radioecology, but also ecology, ecotoxicology and environmental protection.

Conclusions in RD&D 2001 and its review

See section 20.2.

Newfound knowledge since RD&D 2001

SKB has begun the work of compiling process descriptions in a similar manner as for other repository parts /20-4/. It is a large task due to the multitude of processes in the biosphere. Interaction matrices have been a useful tool for identifying important processes and for defining the parameters and variables that need to be determined in the site investigations /20-5/, see further section 20.11.

SKB has continued to adapt the systems ecology approach to describe the cycling of radionuclides in the biosphere. Long-term work with doctoral candidates is being pursued at the Department of Systems Ecology at Stockholm University, the Department of Limnology at Uppsala University and at the University of Kalmar. The results of this work are presented below within the relevant programme area.

Several general studies have been published which compile current radioecological knowledge. A review of bioaccumulation factors in aquatic environments and a statistical analysis of relationships between various environmental factors have been done /20-6/. A knowledge compilation has been made of biosphere parameters for the radionuclides in the most recent safety assessments /20-7/ and comprises the basis for a radionuclide catalogue. Knowledge regarding radioecology and environmental effects is being compiled in the international programmes Bioprota, Embras, the IUR's waste task group and the EU projects Fasset and Erica, see section 20.9.

Several international symposiums have been followed up: Ecorad 2001, IUR-Setac in Antwerp and IUR-Andra in Nancy have provided valuable information and good contacts for this work.

Programme

The long-term support for competence development continues as described above. Documentation for the biosphere matrix will be supplemented during the upcoming period. Submatrices will be created for the subprogrammes described below. The process compilation work will continue, particularly in international cooperation. Moreover, newfound knowledge in the subprogrammes presented below (e.g. model development, transport processes, forest ecosystems, mireland, sediments) will be intercepted.

20.4 Model development

SKB's modellings of radionuclide transport in the biosphere in the safety assessment have been carried out with the tools Biopath and Prism. These have been developed by Studsvik with support from SKB since the 1970s. The tools have been utilized for the KBS studies, SFR, SKB 91, SR 97 and Safe and have been gradually refined by work by e.g. SKB /20-8 to 20-11/. 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 models were based on releases around nuclear power plants and were later adapted to a hypothetical deep repository, but it was still assumed that the release takes place directly in the recipient as an annual unit release. The model concept has largely been taken over in most models that handle radionuclide transport in the biosphere in other countries, for example /20-12, 20-13/. The concept is based to a large extent on the use of generic factors, for example 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 without a mechanistic explanation /20-14, 20-15/. The models describe the pathways that affect man and human food, while other parts of the biosphere are seldom dealt with.

These simplifications may be warranted for safety assessments where doses to man are overestimated, but they are insufficient for a proper understanding and an explanation of the simplifications. A thorough validation of the data is moreover difficult when alternative models and conceptualizations are lacking /20-16/.

It is stated in RD&D 2001 that alternative models are needed to validate the assumptions that are made. Other models are also needed to be able to make use of site-specific information about 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 future consequences of the deep repository. To estimate the consequences for surrounding fauna and flora in accordance with the regulations in /20-13/, models are needed that are based on the flow of radionuclides 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 is an appropriate way to solve some of these problems. The transfer between compartments is then based on natural processes such as photosynthesis, degradation, food ingestion, metabolism, nutrient needs, etc. These processes are coupled and the flows are driven for the most part by the mass balance between the fixation and degradation of organic material, which is sustained by other flows of organic and inorganic materials (e.g. oxygen, carbon dioxide, water, 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 conditions are measurable in the field and are not nuclide-specific, e.g. geometry of the catchment areas, insolation, water balance, and composition of the ecosystem.

Conclusions in RD&D 2001 and its review

See section 20.2.

Newfound knowledge since RD&D 2001

In SR 97, the biosphere was divided into squares sized 250 x 250 metres that were associated with the typical ecosystems lake, running water, sea (archipelago and coast), mire (bog), agricultural land and well. Biopath models that described the different typical ecosystems were developed /20-9, 20-18/. The advantage of this approach is that the causes of the variation in estimated dose can be separated. Uncertainty analyses and sensitivity analyses showed that the biological processes need to be described better and that the physical parameters need to be measured better /20-9, 20-11/. The site-specific information was limited in SR 97, however, since few biosphere investigations have been conducted on the old study sites.

In the Safe project, the safety assessment for SFR, a time-dependent evolution was introduced for different types of ecosystems /20-10/ and site-specific biosphere data. Investigations were conducted to obtain a better body of data /20-19/.

New models for the coastal area were developed for Safe based on the principles of systems ecology /20-20, 20-21/. They describe the flow of carbon-14 through the food web and the concentration of carbon-14 is calculated in different compartments without using concentration factors. The transfer of radionuclides is based solely on mechanisms such as food ingestion, photosynthesis and degradation. This model was tested for other radionuclides, such as cesium. The results are promising and are described in internationally published articles /20-22 to 20-24/ and are included in Linda Kumblad's doctoral thesis /20-17/.

Similar development of systems ecology models is under way for lakes and is being tested for Eckarfjärden, which is included in the Forsmark area. The models are based on previous studies /20-25 to 20-27/.

A general systems ecology modelling tool, Ecopath, was evaluated in 2004 as an independent general modelling tool for radionuclide transport in the food web /20-28/.

A review of modelling tools has been initiated to evaluate the potential of the Biopath and Prism tools vis-à-vis other modern modelling tools, both general graphic modelling software (e.g. Simulink/Matlab, Stella/Ithink, Powersim, Modelmaker, Madonna) and specific codes for safety assessments (Amber, Goldsim, Ecolego and Ecopath). After a cursory review, Simulink/Matlab were selected as having the greatest potential and flexibility for future biosphere analyses. The probabilistic simulations are handled in the code @Risk coupled to Matlab. The biggest advantages are high computing power and an open, well-used and transparent code, which means there are many users and therefore a good base for updating and maintenance of the tool. Another advantage is that systems ecology models can easily be implemented in Simulink/Matlab /20-29/. The disadvantage is that a tool library must be built up to provide a rational working environment for safety assessment. A basic tool library, Biomat and Tensit, was developed during 2003 and 2004 to enable compartment models and radionuclide chains to be handled and improve data management. Development of Biomat was done in cooperation with Posiva. The tool has been tested with the biosphere models from SR 97 and in international comparisons (PSACoin) against Biopath/Prism and Amber /20-30/, see Figure 20-1. The tool is promising, and it will be used for the biosphere calculations in SR-Can. The tool will be tested for other parts of the computational chain as well, see further section 18.3 and Chapter 14.

Programme

The systems ecology models will be further developed for lake and land. The Tensit toolbox in Simulink/Matlab will be further developed to provide a good environment for safety assessments and ready-to-use models for wells, dose to man, irrigation and templates for the lake, sea and land ecosystems. Methods for how site-specific data is to be used will in particular be studied. This presumes an integration with Gis databases and other numerical tools such as Femlab. The goal for SR-Can is to have a fully functional simulation environment with Tensit.

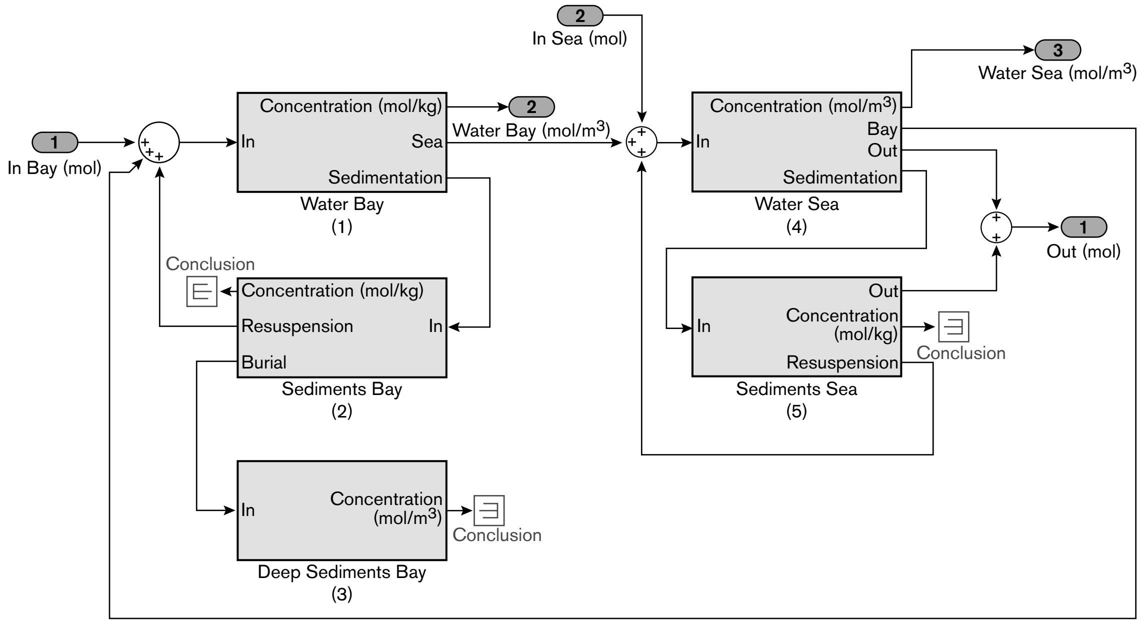


Figure 20-1. *Coast model from SR 97 constructed in Tensit. The graphic environment for constructing the model is similar to a conceptual formalization of the most important processes and state variables /20-30/.*

20.5 Transport processes

The transport processes determine which ecosystems and organisms will be exposed to radionuclides and how great the dilution will be. Much of this is handled with current models, under the provision that the radionuclides are dissolved in water.

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.

Conclusions in RD&D 2001 and its review

It was described in RD&D 2001 that the water exchange models for coastal waters were improved in the Safe project /20-31, 20-32/, and that there is a model that covers the entire Baltic Sea and provides boundary conditions for the local coastal models /20-31/.

In RD&D 2001 it is pointed out that the surface hydrology is important for understanding what transport pathways and dispersal and dilution processes affect contaminated water after it has left the rock. Several comments from the regulatory authorities have wished for deeper studies. In its review, for example, SSI said that in preparation for the safety assessments accompanying the permit applications, SKB should develop its analysis of radionuclide transport in the transition between geosphere and biosphere. Kasam wished to see a deeper understanding of the hydrological relationships between a deep repository and different ecosystems.

See also section 20.2.

Newfound knowledge since RD&D 2001

The water exchange model's sensitivity to different climatic changes (temperature and ice formation), salinity changes and a change in land uplift was evaluated for Öregrundsgrepen /20-32/. The model has also been used by the Swedish Environmental Protection Agency and the Finnish Meteorological Institute to study water exchange in coastal waters. It is fundamental for water exchange calculations in the Stockholm archipelago. Results and applications have been published in scientific journals /20-33, 20-34/. In the site investigations and the analysis work, the model will be applied after calibration with site-specific measurements and improved depth data from the sea bays at the sites.

Certain interactions in the boundary layer between rock and surface water were studied in the Safe project /20-35/. It has, for example, been found that water flowing out of the rock is to a great extent diluted by the groundwater in the Quaternary deposits by a factor of about 100. The study showed that it is possible that the water may follow conductive layers in Quaternary deposits and discharge near the shoreline. A follow-up of this study was done with a better resolution of the near-surface strata /20-36/. It confirms previous results that discharge takes place at low points in the terrain, preferably lakes, sea and wetlands. Depending on the hydraulic conductivity, the water will discharge through the bottom layers or against the shoreline, see further sections 19.2.11 and 19.2.12. The site investigations will provide more information on how hydraulic conductivity varies in the lake and sea beds at the site. Radionuclide transport can also be affected by diffusion through bottom layers /20-37/.

Surface hydrology calculations were performed at KTH for two lakes in northern Uppland /20-38, 20-39/. Different studies have been conducted with simple Gis tools to calculate the surface runoff in a catchment, for example PCRaster /20-40/. The site investigation programme has identified several important hydrological studies and measurements that should be conducted to facilitate the biosphere modelling /20-5/. These data will also be used to develop the models. The studies are being coordinated with the programmes for hydromodelling and hydrogeochemistry, see section 19.2.11.

Preliminary results from model studies to identify discharge areas from existing map material with the aid of Gis show that approximately 80 percent of the areas (wetlands, lakes, sea) can be identified with the aid of morphometric data (topography, elevation differences, slope, convex or concave surfaces). This means that it may be possible to predict which ecosystems discharge takes place to without knowing exactly where they are located in the future. The systems ecology models that are being developed describe the flow of particles (as organic matter) in a coastal area /20-20 to 20-22, 20-41, 20-42/. The net transport of sedimenting materials can be calculated from the studies of sediments /20-43 to 20-46/. Flow rates and the quantity of particulate matter are obtained from the hydrological measurements and chemistry samplings in surface water in the site investigations.

Programme

The projects described above will continue and can be summarized in the following main topics:

- In-depth surface hydrology with evaluation of surface hydrology models or simplified Gis tools, for example Shetran topographical indices.
- In-depth model studies of nuclide transport at discharge points from the rock. Particular attention is being given to how nuclides move near lake and sea basins.
- Continued model and literature studies of particle transport as described above, supplemented with field data from the site investigations.
- A model and literature study of human transport activities under various conditions as a delimitation of how large a population can be affected by a contaminated area, which facilitates a judgement of the representativeness of the most heavily exposed group, in accordance with SSI's regulations.

The above work will be pursued in cooperation with the programmes for geochemistry and hydrology and is dependent on the results of the surface hydrology measurements on the sites.

20.6 Terrestrial ecosystems

The terrestrial ecosystems – for example forest, agricultural land and mire – are characterized by the fact that they normally have a groundwater table that always or usually lies just below the ground surface. The dominant transport processes from the groundwater up to these systems are root uptake, capillary force and the groundwater's level fluctuations. Root uptake and accumulation in biomass are, however, the most important processes for radionuclide transport to people 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 have properties similar to those of land types where the groundwater table is always below ground level. General soil processes will therefore be dealt with in this section, and then forest and wetlands as special cases.

Forest is the dominant ecosystem for the hypothetical sitings /20-47/ and can be a possible recipient, see Figure 20-2. However, the results of studies of discharge of deep groundwater from repository depth show that few streamlines end up in the forest, see section 20.5. Most exit under streams and on the shorelines of lakes and seas, as well as in wetlands. The forest has been the focus of several projects that have studied the fallout from Chernobyl, among other things, see further /20-48/. Most studies have mainly been concerned with the short-term consequences of radionuclide transport. Few calculations have been done of the migration and accumulation of radionuclides from a deep repository in forest. An attempt was made in the Forest Working Group of Biomass /20-49/. 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 forest question is closely linked to near-surface hydrology and

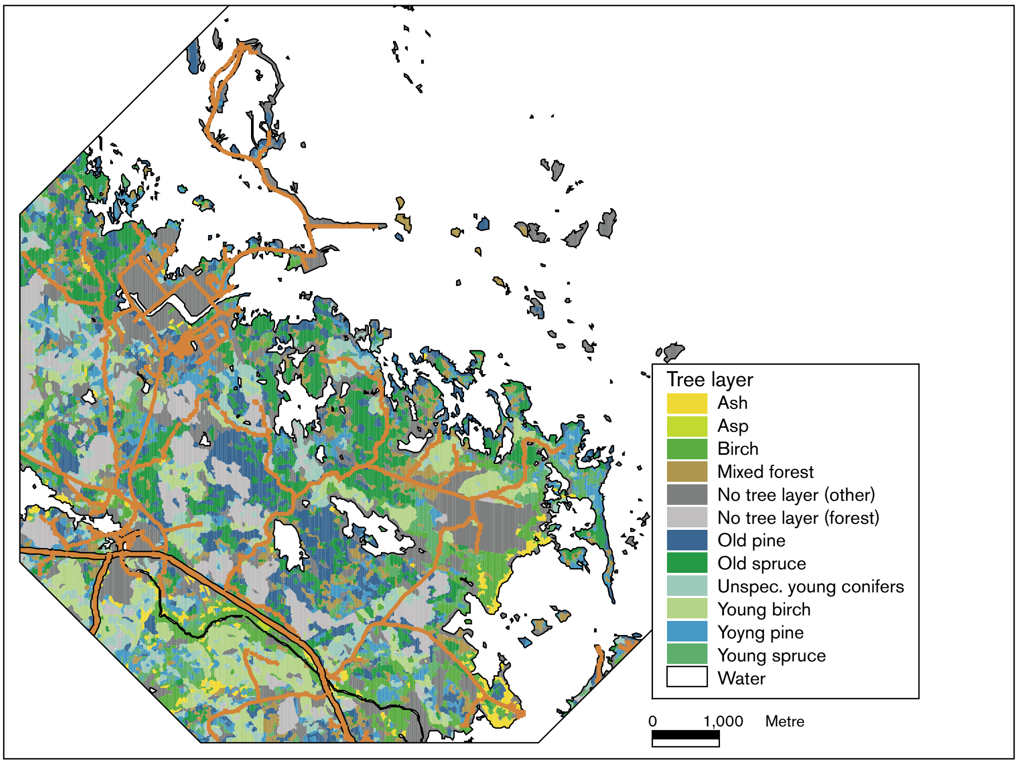


Figure 20-2. The forest in the Forsmark area after satellite image interpretation /20-47/.

the evolution of wetlands. It is above all forests in depressions, for example swamp forests, that will be of interest with respect to the effects of a deep repository, and not highland forests such as flat-rock pine forests.

Mires and wetlands are important recipients for the hypothetical sitings. In SR 97, mires were 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. At the same time, the assumptions that were made in SR 97 were simplified and probably overestimates. 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 further noted in SR 97 and Safe 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 /20-50/ and in the Simpevarp area. 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.

Conclusions in RD&D 2001 and its review

See section 20.2.

Newfound knowledge since RD&D 2001

The primary production is the accumulation of organic matter due to photosynthesis. In order to grow, plants must be able to obtain nutrients from the transpiration stream or actively, for example by secreting complexing agents etc to dissolve nutrients from mineral particles, clay particles, etc. Radionuclides, which have properties similar to those of nutrients, will then be taken up by the plant. The rate of nutrient uptake is proportional to the growth rate, which means that radionuclide uptake, as an analogue of nutrient uptake, must also be proportional to the growth rate. The mass flow of radionuclides in plants can thus be modelled with the aid of two variables: growth rate and transpiration. These two variables are scalable to climate change and vegetation type and are an alternative approach to the root uptake factors that are used in radioecology. Similar ideas have recently been applied to e.g. radium and radon uptake in plants within other disciplines /20-51/.

A development of models is also necessary in order to be able to apply this alternative approach. A powerful model that can handle transpiration, growth and nutrient uptake for vegetation has been developed by SLU and KTH (the so-called CoupModel, /20-52/). The CoupModel, or its predecessor Soil, has been used successfully by several research teams to study various phenomena within forestry, agriculture, hydrology and climate, see bibliography in /20-52/. The advantage of the CoupModel is that it is largely based on processes – such as heat balance, mass flow, transpiration, primary production – and that it has a large database for parameters collected by SLU over a long period of time from various parts of Sweden. The model has been modified at SKB's request to include transport of other substances, such as radionuclides. The CoupModel is currently undergoing testing. If the results are good, the model will be used for all types of land, i.e. forest, agricultural land and wetland.

A compilation is currently being made at the Department of Botany at Stockholm University of how different substances get into plants via root transport /20-124/. The intention is to classify substances into those that can be expected to passively accompany the water flows, those that are actively prevented from entering the plants, and those that are actively taken up and accumulated. Experimental work has also been done in greenhouses with sallow shoots at the Department of Botany. Uptake of a dozen stable analogue elements has been correlated to the willow's transpiration and primary production. Transpiration is the water flow that passes through the plant; substances can passively accompany this stream of water into the plant, but due to evaporation the substances accumulate in the plant. The plant is able to discriminate certain substances, such as uranium, which means that they do not accompany the water stream but are accumulated outside the root.

In parallel with the work with the CoupModel, a compilation has been made of existing radioecological models for forest. It will result in a forest model that uses existing methodology with uptake factors to calculate doses in forest ecosystems.

A field study of how different substances are accumulated in fungal mycelia has been initiated by SLU in the Forsmark area. Together with element analyses of soil profile type and vegetation from the site investigations, this study will provide a valuable quantification of root uptake factors for different substances.

An important source of greater understanding of terrestrial ecosystems is the site investigations, and the unique studies that have produced e.g. vegetation maps /20-47, 20-53, 20-54/ and the soil map /20-55/ are a good starting point. The work which SKB's analysis group will do to describe the site /20-2/ is essential to both describe the dominant processes and obtain data for the models. A further development of the satellite image interpretation of the vegetation has been used to compile and test different indices for determining the vegetation's production /20-56/.

There has been a regular exchange of information on forest ecosystems with Posiva via meetings and workshops. Posiva has an extensive research programme regarding certain processes in the forest /20-57/.

The ontogeny (succession) of a marine area to a lake and then a mire was described in connection with the Safe project /20-45, 20-58 to 20-60/. This was followed up by subsequent studies where lake infilling is simulated /20-43/ and lake ontogeny is described /20-44/.

An extensive literature review has been performed where the occurrence, ecology, hydrology and transport properties of wetlands are compiled /20-61/. It is the basis for a process description for wetlands.

Additional information is now being compiled for the more than 400 boreholes in northern Uppland. The compilation is being done by the limnology departments at Uppsala and Umeå universities. Wetlands have been mapped in the Quaternary geology investigations on the sites, and wetlands without groundwater connection have been discovered. Furthermore, the vegetation map /20-47/ provides valuable information.

A review of the consequences of crop irrigation has been done and dose models using irrigation have been updated /20-62/.

Programme

The work of defining and describing the dominant processes in terrestrial ecosystems will continue. The CoupModel will continue to be evaluated and a coherent transport model for terrestrial ecosystems will be developed. The succession and dynamics in the terrestrial systems – for example grazing, harvesting and decomposition – will also be modelled during the period.

The site investigations will be an important source of understanding of the processes in the ecosystem, in addition to providing important data for the models. It is above all the quantification of different processes that will provide important information and support for models and assumptions. The results of the hydrological measurements and the chemical measurements of soil and biota composition will be important.

The following activities have been commenced or are planned during the upcoming period:

- Studies of 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.

- Further refinement of today's wetland models.
- Studies of the hydrology of mires and wetlands.

Data will primarily be generated by the site investigations.

20.7 Aquatic ecosystems

Knowledge concerning the dominant transport processes in the aquatic ecosystems – i.e. running water, lake and sea – are relatively good /20-63/. 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 in order to parameterize the models. Model development and transport processes are described in previous paragraphs, and data from the site investigation is described in section 20.11.

In many potential discharge areas, the radionuclides will pass a sediment layer. In this way, the sediments in the sea, rivers and lakes will at least potentially exercise a strong influence on the transport of radionuclides to biota. The permeability and adsorption of 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 radionuclide discharge and result in lower doses. In the long term, however, radionuclides can accumulate, 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.

Conclusions in RD&D 2001 and its review

See section 20.2.

Newfound knowledge since RD&D 2001

A project at the Department of Limnology at Uppsala University has studied Eckarfjärden in Forsmark for the past few years /20-26, 20-27, 20-64 to 20-66/. Many interesting results show how the internationally and nationally unusual oligotrophic hardwater lakes work. An initial systems ecology model of Eckarfjärden has been constructed, and results with a bearing on radionuclide transport will be evaluated. The work has provided guidance on how other lakes in the area should be investigated in the site investigations /20-67 to 20-69/, see below. The measurements of above all water chemistry in the site investigation programme /20-25/ have provided not only data for the models, but also valuable information on process rates and seasonal dynamics. The mapping and characterization of lakes in the site investigation programme /20-70/ has furthermore provided a perspective on how commonly occurring these lakes are. The limnology department has published its work in international journals /20-65, 20-71/ during the period and also disseminated the information to e.g. the Swedish Environmental Protection Agency /20-72/ and other forums /20-73/.

The systems ecology models have been further refined in a doctoral project at the Department of Systems Ecology at Stockholm University, see section 20.4 /20-17/. Field studies concerning the importance of bioturbation (stirring caused by animals) in Baltic Sea sediments and how it affects radionuclide cycling have also been conducted /20-42/.

A database of investigations and results from marine inventories of flora and fauna on shallow bottoms over the past 30 years has been compiled /20-74/ in order to be able to compare site-specific data to national data. The work will be supplemented by a compilation of data from the Kalmarsund area. The site investigations in Oskarshamn have examined fauna and flora on the bottoms around the Simpevarp Peninsula /20-75/.

In connection with the Safe project, the sedimentation environment in northern Uppland was modelled from approximately 10,000 years ago to 5,000 years in the future /20-76/. The controlling parameters were the openness of the sea, which determines the force of wave erosion, and the land uplift process, which determines depth and the creation of protective islands and archipelagos. The study showed good agreement with the Quaternary geology map of the area. Most recent Quaternary geology investigations have further confirmed the model predictions by dating of erosive phases /20-46/. Lake infilling has also been simulated /20-43/. The study also shows that the minerogenic sedimentation in a lake can for the most part be explained by biological production. It is above all the silicon skeletons of diatoms and stoneworts that contribute to this. The site investigations have yielded large quantities of sediment data, both from the approximately 140 boreholes in the Forsmark area /20-77/ and from the Quaternary geology investigations /20-78/.

The results of an older study of sediment cores on Äspö have been reported /20-79/, along with the results of an interesting study at Kallrigafjärden in Forsmark, carried out in conjunction with a methodology course at Stockholm University /20-80/. In the latter study, the seabed and surrounding lands were mapped by means of different methods and a map was drawn of what Kallrigafjärden will look like when it has become dry land.

A study of the distribution of various substances in sediment profiles from lakes has been started to permit calculations of the mobility of stable analogues of radionuclides in sediments /20-44/.

The site investigations in the two areas have involved extensive investigations in the aquatic environments, which besides descriptive data will also yield important information on processes and process rates.

Programme

The projects described above will continue.

The site investigations are expected to furnish necessary data on the distribution of sediments and accumulation rates. The work will also be done in cooperation with the hydrological, geochemical and geological programmes and coordinated with research on mireland and transport processes. Some important areas where studies will be conducted are:

- Modelling of migration processes beneath and through sediments (under way).
- Modelling of reworking and accumulation of sediments, supplemented with field data.
- Modelling of nuclide transport through sediments, or through the shore zone.
- Development of a systems ecology model for the lakes on the sites.
- Development of a general model for radionuclide transport in sea bays.
- Development of a model that describes sorption processes in small streams.

20.8 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 biotope is dominant in an area. Water flux, groundwater formation 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.

Shoreline displacement in Scandinavia after the last ice age is described in /20-81/ and a forecast is given for the next 5,000 years. Shoreline displacement during several glaciations was studied for SR 97 /20-82/. Shoreline displacement can be influenced by global warming, which is expected to cause rising sea levels. The sea level may rise approximately 0.4 metre over the next 100 years /20-83/. This means that shoreline displacement will cease for a period of time, which has also been measured /20-84/. In the longer term, a future glaciation will once again bind water in glaciers, resulting in a lowering of the sea level by around 100 metres /20-82, 20-85, 20-86/. At the same time, the earth's crust will be depressed under the ice load by up to 800 metres in the central parts of the glaciated area and about 200–500 metres on the sites being investigated by SKB /20-87/. This influences discharge areas on the coast, and the environment around the deep repository. It also influences the salinity of the Baltic Sea and the composition of the biosphere.

Conclusions in RD&D 2001 and its review

See section 20.2.

Newfound knowledge since RD&D 2001

The model that describes the salinity of the Baltic Sea /20-88/ has been further refined to predict future salinities in the Baltic Sea depending on different climatic evolutions and shoreline displacements /20-89/. The work has also resulted in international publications /20-90/.

The climate also influences groundwater recharge and water turnover in lakes and watercourses, which can be important factors for flows at repository level, but also for which biosphere can be expected. The greatest uncertainties concern the variations in precipitation and runoff. A project was therefore initiated that studies and dates the occurrence of horizons in peat bogs that have a deviant degree of humification which is considered to be due to dry periods /20-91 to 20-93/.

Further information on land uplift in Uppland has been obtained from compilations of field studies /20-46, 20-94/, see sections 20.7 and 20.8.

Long-term climatic variations are also dealt with in Chapter 21.

Programme

Above all, climate change in Scandinavia during an interglacial stage will be studied. Fundamental questions are how precipitation and runoff change. In addition, more information is required on processes and formation rates in connection with permafrost and how this affects the surface ecosystems. Parts of this knowledge are being produced in several national and international projects, for example regarding short-term climate changes in Sweclim and long-term ones in Bioclim. SKB is also planning projects for the next 1,000 years and an interglacial stage, see section 21.3.

The climate questions are closely linked to the geosphere and geochemistry programmes as well as scenario development. The site investigations will also produce data, especially when it comes to the land uplift process, but also when it comes to the local climate. The main issues that will be studied in upcoming research programmes are:

- Climate change in Scandinavia during interglacials in the form of a compilation of information from completed studies.
- Knowledge compilation regarding permafrost and the importance of the tundra for radionuclide transport in the biosphere.
- Follow the global warming discussion.

20.9 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 and 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 2001 and its review

See section 20.2.

Newfound knowledge since RD&D 2001

The international Biomass project under the IAEA was concluded in the autumn of 2000 and produced several reports. SKB participated actively in the work under Theme 1 (Radioactive Waste Disposal) and Theme 3 (Forest and Fruits Working Group) /20-49, 20-95, 20-96/. Even though the main purpose of Biomass was to work with radioecological issues in connection with radioactive waste, it only produced limited new knowledge for SKB. The results from the Forest Working Group were the scientifically most fruitful ones.

SKB participated in a three-year EU project within the Fifth Framework Programme, Fasset, which was concluded in November 2003. The purpose of Fasset was to compile knowledge concerning radiological effects of ionizing radiation on the environment, i.e. flora and fauna, and propose a framework for how such matters can be handled by industry and regulatory authorities. 14 organizations participated in the work with representatives from radiation protection authorities and national radiation protection research bodies from several countries. SSI was the coordinator of the project. SKB participated, along with the Department of Systems Ecology at Stockholm University, in the working groups that are studying migration models in various ecosystems, biological effects, and the framework itself. The results of Fasset have been reported by the EU. Notable results include a dose model for various geometries of organisms, a literature database (Fred) of effects on organisms, and new ideas concerning how the exposure of animals can be scaled according to the size of the animals. A very important consequence of Fasset is that other international organizations have been stimulated to take an interest in environmental effects, for example the IAEA, the ICRP and the IUR. This has also affected progress in national programmes, for example the Environment Agency /20-97 to 20-99/, and been discussed at international conferences, for example Ecorad 2001, the IAEA Stockholm conference 2003, IUR in Monaco and SPEIR 3 in Darwin. Unfortunately, there has been limited discussion of effects at higher organizational levels than individuals, i.e. populations and ecosystems, which are the levels that are usually intended to be protected. Furthermore, there has been no discussion of problems with regard to possible releases far in the future, which are important questions to which SKB needs answers in order to be able to implement the knowledge. SKB is also participating in Erica, the successor of Fasset in the EU's 6th Framework Programme.

Together with KSU, SKB lent its support to a project aimed at shedding light on a proposal for a changed view of the ICRP's recommendations /20-100/ with examples from Swedish questions /20-101, 20-102/.

The working group Bioprota was started in the autumn of 2002. A technical secretariat is funded by the participating organizations: Andra, BNFL, Ciemat, Enresa, Nirex, Numo, Posiva and SKB. Other organizations that are contributing to the work are e.g. Ecomatters and Studsvik Alexandria Sciences, and ones that have shown an interest in the work are e.g. Nagra, Ondraf, the NRC and Ontario Power Generation. The purpose of Bioprota is to examine important issues for a waste repository under different themes. SKB is a member of the steering committee and is participating actively in compiling a radionuclide database, developing irrigation models and developing protocols for site investigations.

SKB is also participating in the International Union of Radioecology's (IUR) Task Group on Radioecology and Waste.

SKB's cooperation with Posiva has been expanded as regards the biosphere and surface ecosystems. This work is particularly concerned with the development of new modelling tools (see section 20.4), but also with soil ecosystems (see section 20.6).

In addition to the above, SKB has presented material on the biosphere work at several symposiums, for example Ecorad 2001, SPEIR, NKS, IAEA, IUR /20-103 to 20-105/. Information on SKB's biosphere work is disseminated regularly via lectures for ecotoxicologists and ecologists, and by participation in various ecological, hydrological and Quaternary geology seminars and symposiums.

Programme

In addition to following and actively participating in the discussions in the various organizations, the goal is to publish the results obtained in international journals.

The following main activities are planned:

- Active work within the EU project Erica.
- Active participation in Bioprota and the IUR's Task Group on Radioecology and Waste.
- Deepen the collaboration with Posiva.
- Follow the work within the EU, NKS, ICRP and IRPA.
- Follow and present the work at important meetings on radiation biology, environmental protection and systems ecology.
- Follow the work at SKI and SSI and keep track of legislation.
- Present the work in the biosphere field to interested researchers and students.

20.10 Safety assessment

The purpose of the programme for research on the biosphere which is described in previous paragraphs is to provide a scientific basis for conducting safety assessments. One of the most important tasks is to achieve 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 as parameters for the models and to supplement site data, see section 20.11.

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.

Conclusions in RD&D 2001 and its review

See section 20.2.

Newfound knowledge since RD&D 2001

The most recent safety assessment of SFR, Safe, is the most complete safety assessment when it comes to the biosphere and is expected to be a good basis for future assessments. The regulatory authorities' review /20-106/ and decision were presented to SKB in the spring of 2004, and various review reports have previously been published /20-107 to 20-112/. The review and the underlying material are currently being studied to enable general conclusions to be drawn regarding how the biosphere should be handled in future safety assessments in order to satisfy the authorities' demands and wishes.

The planning of future safety assessments (SR-Can and SR-Site) has yielded new insights on how future safety assessments should be conducted /20-1/. The development work that is needed to be able to conduct the assessment is presented in section 20.4.

The work of addressing radiological effects on the environment was begun in the EU project Fasset, see section 20.9, and at the Department of Systems Ecology at Stockholm University and was aimed at compiling experience from ecotoxicology and protection of the environment from toxic substances.

Programme

Several safety assessments will be conducted and planned during the coming period. Most of the work will therefore be aimed at conducting these assessments and supplementing or improving present-day knowledge or methods, see for example /20-1/ and /20-2/. The intention is to be able to handle time-dependent and coupled ecosystems, see Figure 20-3.

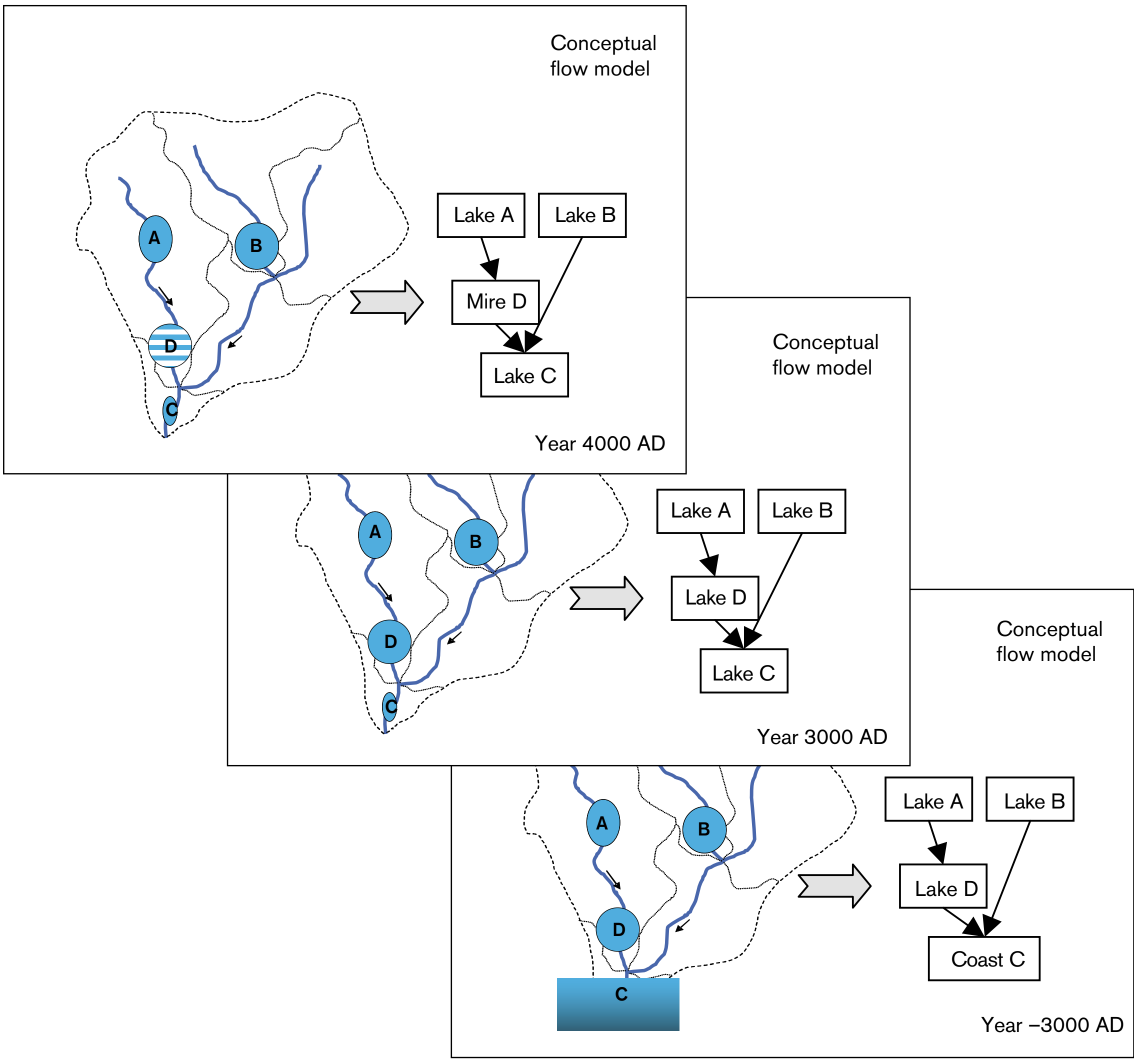


Figure 20-3. *Schematic illustration of how the ecosystems are coupled together with how the surface water runs through them at different points in time during an interglacial period.*

One of the central questions is how the risk measure is to be applied in accordance with SSI's regulations and how the tools and models are to be adapted accordingly. SKB is awaiting SSI's general recommendations when it comes to this question. The tools also need to be developed to be able to handle, effectively and flexibly, the new processes that have been identified and the site-specific data that will be produced, see section 20.11. Planned workshops will be important forums for coordinating the assessment of site data with the assessment of the repository's long-term safety.

Methods and knowledge concerning the consequences of radionuclides for the environment will be developed in close connection with the results that have been produced by Fasset and will be produced by Erica. The systems ecology models being developed by SKB are well-suited for calculating the concentration in different types of biota.

20.11 Supportive research for site investigation programme

Conceptual and quantitative uncertainties in the biosphere are largely caused by a lack of, and poor quality of, site data. To support the development of dose models and 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. When it comes to the biosphere, in contrast to other disciplines, SKB has relatively little experience historically of gathering data from field investigations. That is why 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 should take place within SKB's site investigation organization. The site investigation programme is one of the most extensive data collection efforts for simultaneous measurement of parameters ever undertaken in Sweden on a limited site. Variables and parameters judged to be important to collect in a site investigation were given in a report /20-5/. 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 site investigation programme is described in /20-2, 20-5/, and the first summarizing results can be found in version 1.1, which is the first site investigation for each site. The site descriptions are based on a series of background reports which describe the various parts of the ecosystems, for example vegetation /20-47/, fauna, topography, climate, land use and deposits.

Conclusions in RD&D 2001 and its review

See section 20.2.

Newfound knowledge since RD&D 2001

The biggest effort of recent years has been to convey the safety assessment's data needs to the site investigation organization, and furnish experts in different fields to plan and execute investigations in the surface ecosystems /20-55, 20-69, 20-70, 20-78/. A heavy emphasis has been placed on planning and optimizing the site investigations and the analysis work so that the results are of good enough quality to be used for safety assessment, understanding of processes and modelling /20-2/. A technical group, EKG, has been started with monthly meetings to expedite the exchange of information between site investigations, the analysis group, safety assessment and research.

Important new insights that have led to a better understanding of processes and the distribution of features in the ecosystems have been described in a number of reports. The aquatic ecosystems have been investigated and described in /20-70, 20-75, 20-113/.

These reports describe dominant functional groups, and their extent and biomass in sea and lakes. Furthermore, the geometric demarcations, for example catchments and their morphometric parameters, have been described /20-70/. Abiotic features in the biosphere such as hydrology, meteorology and Quaternary deposits have been described in /20-25, 20-114 to 20-116/ and terrestrial ecosystems in /20-47, 20-53, 20-54, 20-55, 20-117 to 20-123/.

Programme

During the coming period, research activities will mainly be needed to support analysis of collected data and to perform in situ measurements of process rates. Close cooperation between research, safety assessment and the site investigations is necessary, and information exchange in the form of workshops and meetings will be developed. Workshops are planned to compile and process information from the sites and build models that describe the flow of materials and radionuclides. At present, workshops have been planned for the terrestrial ecosystems, the interface between geosphere and biosphere, lakes, sea, mire and man.

21 Climate

On the time scale for which the performance and safety of a final repository for spent nuclear fuel are studied, i.e. hundreds of thousands of years and even longer, the Scandinavian climate has undergone repeated ice ages. Over the past 800,000 years or so, a cyclic pattern has dominated climate variation. A cycle consists of roughly 100,000 years long periods with a progressively colder climate, known as *glacials*, ended by a rapid transition to shorter periods with a warm climate similar to today's, known as *interglacials*. During the glacial periods, which consist of warmer and colder phases, ice sheets have successively – by repeated advances and decays – grown to reaching a maximum extent towards the end of the period, see Figure 21-1.

With a view towards the processes that are of importance for the performance and safety of a deep repository, three characteristic *climate-driven process domains* can be identified during a glacial period and the intervening interglacial periods. Climate-driven process domains, in the following called *climate domains,* are defined as climate-determined environments in which a number of characteristic conditions prevail. The three climate domains are:

- Glacial domain.
- Permafrost domain.
- Temperate/boreal domain.

The climate domains comprise a general description of the characteristic conditions, with an emphasis on those processes that are of importance for the performance and safety of the deep repository. Extremes, which can be made site-specific, can be identified within each climate domain. Changes in the climate can be seen as variations of the extent of the climate domains in time and space. The different climate domains succeed each other in a cyclical pattern, see Figure 21-2. On any given site, the succession may not include all the climate domains shown in the figure. On a high-lying site in southeastern Sweden, for example, a period with permafrost may be followed directly by a temperate/boreal domain without an intervening period with a glacial domain. Depending on the geographic location, the periods with different climate domains will also differ in length.

It is reasonable to assume that the climatic progression we have seen over the past 800,000 years, with glacials succeeded by interglacials, will be repeated in the future. In recent decades, man's impact on the climate has been a much-debated scientific and social issue. The debate has focused on human greenhouse gas emissions, which are believed to cause global warming. Model simulations /21-1, 21-2/ show that as a result of human emissions of

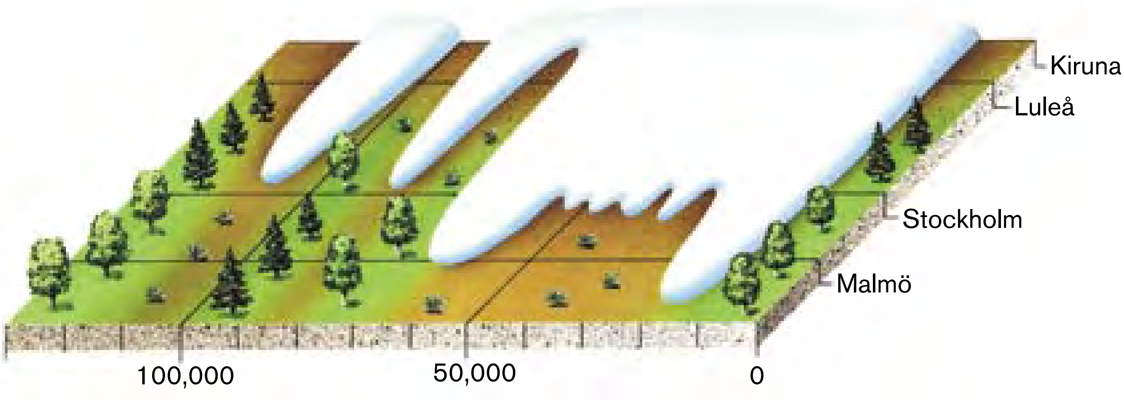


Figure 21-1. *Schematic drawing of the advance of the ice sheet during the most recent glacial period – the Weichselian.*

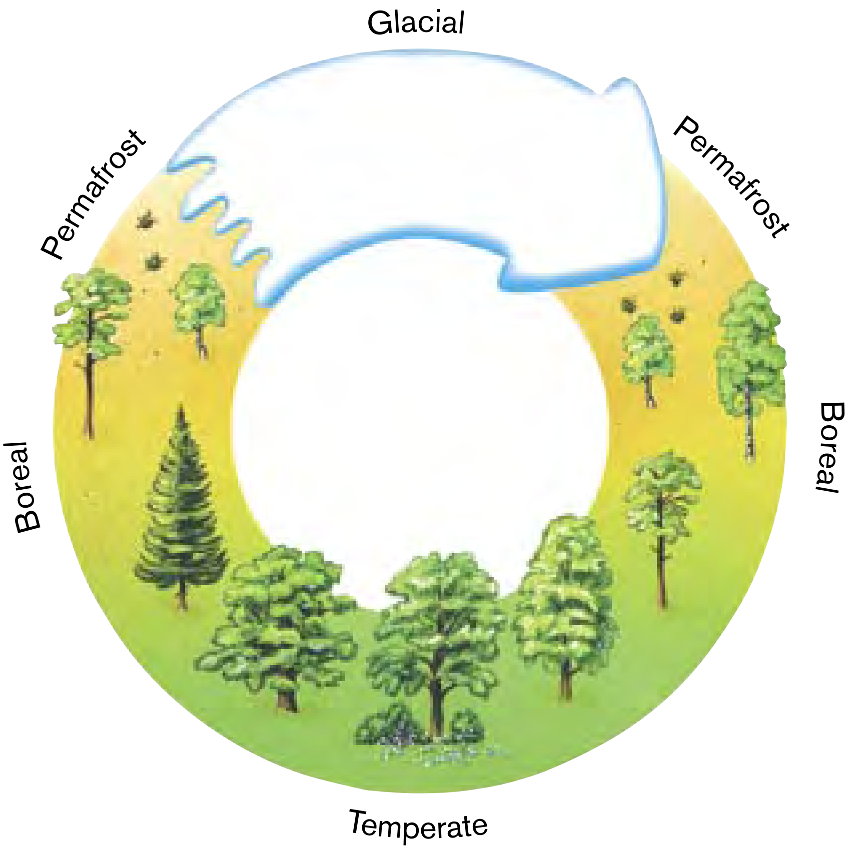


Figure 21-2. *Climate-related changes can be viewed as a cycle with successive transitions between periods of different length when different climate domains prevail.*

greenhouse gases, the current period of warm interglacial climate may turn out to be very long. This is another conceivable future scenario.

Current knowledge of the earth's climate system is not sufficient to predict the climate over the long spans of time involved here. There are great uncertainties associated with each climate scenario, both ice age and greenhouse scenarios. Based on current knowledge, it is however possible to describe with resonable confidence the limits within which the Scandinavian climate has varied, and will vary, both in a long-term perspective and with regard to man's influence on the climate. If it can be shown that the repository will remain safe during the different possible climate domains, the actual climatic evolution is of less importance. SKB is therefore focusing its research efforts within the climate field on identifying and understanding the conditions and processes within each climate domain that are of importance for the repository and its safety.

In the studies of the climate domains, it is important to include conceivable transitions between different climate domains and to investigate the importance of the duration of the different domains. An important process in the latter contexts is shoreline displacement. It is caused above all by the build-up and melting of ice sheets, which are processes that belong to the glacial domain but is of great importance also for the conditions during both the permafrost domain and the temperate/boreal domain.

The extent of the continental ice sheet is crucial for the prevailing climate domain. Simulations of the Scandinavian ice sheet using numerical ice sheet modelling therefore comprise a key project in SKB's climate programme. A well-underpinned description of the most recent glacial period – the Weichselian – is necessary to interpret and understand current conditions and to study many of the climate-related processes that are of importance for the performance and safety of a deep repository.

Conclusions in RD&D 2001 and its review

In SKI's opinion, activities within the climate area should be given high priority. RD&D 2001 lacks a clear plan for how SKB intends to conduct research in the climate area. Both SKI and SSI emphasize the importance of shoreline displacement, in view of the fact that two near-coast areas are being studied as possible sites for a deep repository. This imposes stringent requirements on the account of climate impact and the role of the biosphere in the safety assessment.

The authorities also deem it important to examine the importance of the greenhouse effect for climate change more closely. This includes its possible importance both in a long-term perspective, i.e. thousands to tens of thousands of years and even further in the future, and for the next 1,000 years. SSI further notes that special attention should be given to the possible climate variations during the next 1,000 years. SKI believes that SKB should, in addition to participating in international projects, deal with Scandinavian conditions in its own projects.

SKB has no objections to the authorities' comments.

Newfound knowledge since RD&D 2001

A project aimed primarily at investigating the basal conditions and hydrology of the Scandinavian ice sheet was initiated in 2002. The project includes compilation of glacio-geological information, numerical ice sheet modelling and process studies of the hydrology of ice sheets. The project and knowledge gained so far are described in greater detail in section 21.1.

Empirical studies of the shoreline displacement since the retreat of the most recent ice sheet have been concluded /21-3/. The study embraces a large number of shoreline curves from all over Scandinavia and the Baltic countries as well as Swedish lake-tilting data. The lake-tilting data have enabled the *isostatic* (downwarping or upwarping of the earth's crust) and *eustatic* (changes in sea level) components to be distinguished. The data have been fitted to mathematical expressions that provide a coherent description of the process of land uplift and shoreline displacement all over Scandinavia and northeastern Europe. The expressions have been entered into a Gis application with the ability to produce detailed descriptions of specific areas and/or time periods. Archaeological findings show good agreement with the calculated shorelines. The study is further mentioned in sections 21.1 and 21.3.

SKB has not conducted any studies of its own during the period on the earth's climate system and climate change. Particularly worthy of mention among the projects that have been followed is the EU project Bioclim /21-1, 21-2, 21-4/. Other projects which SKB has deemed important to follow are Sweclim /21-5/ and the work being done under the auspices of the IPCC /21-6/.

The long-term consequences of carbon dioxide emissions have been studied within Bioclim /21-1, 21-2, 21-4/. The assumptions and models used indicate that atmospheric carbon dioxide concentrations will remain high for a long time, approximately 200,000 years. This will presumably perturb the cycle of glaciations characteristic of the Quaternary Period, and a very long period – up around 200,000 years – with temperate/boreal conditions can be expected in Sweden.

Programme

As already mentioned, studies of the Scandinavian ice sheet employing numerical ice sheet modelling comprise a key project in SKB's programme. To begin with the simulations are being focused on the Weichselian Glaciation. A well-underpinned description of the Weichselian period, where the model has been calibrated and validated against a large body of relevant geological information, provides important input data for studies of shoreline displacement, postglacial quakes, erosion and subglacial hydrological systems. The description also provides input data for studies of permafrost, both periglacial and subglacial. The project is also described in section 21.1.

Shoreline displacement has an isostatic and a eustatic component. The process must be studied globally, which can be done with GIA (Global Isostatic Adjustment) models /21-7, 21-8/. A project in which GIA modelling is a central part and whose purpose is to understand and quantify shoreline displacement, given different ice sheet scenarios and earth models, is planned to start in 2004. The descriptions of ice extent and thickness during the Weichselian that have been formulated within the project "Basal conditions and hydrology of continental ice sheets" are important as input data for the modelling. The review of shoreline displacement since the Late Weichselian /21-3/ will also be used in the project.

A compilation of northern European climate archives, which cover periods longer than 10,000 years, has been initiated and is planned to be completed in 2004. Data will be compared with the climate input data used in modelling of the extent of the ice sheet during the Weichselian. In combination with ice extent and shoreline data, they will also serve as a basis for planned permafrost studies, see further section 21.2.

The evolution of the climate in Scandinavia during an interglacial period and the past 2,000 years will be studied in special projects. They are described in greater detail in section 21.3.

Climate and climate-related questions are also dealt with in section 20.8.

21.1 Glacial domain

An overview of the processes studied within the glacial domain is shown in Figure 21-3. The figure shows the margin of a warm-based ice sheet. The basal conditions and hydrology of the ice are of great importance for the thermal, hydrological, mechanical and chemical conditions both on the surface and in the bedrock and the repository.

Questions of special interest are:

- Possible depth of subglacial permafrost.
- Water pressures and water flows.
- Possible infiltration of glacial meltwater and up-coming of deep saline groundwaters.
- Changes in rock stresses and tendency towards rock movements.
- Couplings between hydrological and mechanical processes.

Conclusions in RD&D 2001 and its review

Besides the general conclusions presented above, SKI points out that SKB should clarify what importance the meltwater production at the base of a continental ice sheet has for hydrology and groundwater composition. SKB concurs with this and also intends to clarify the importance of these basal conditions and meltwater production for thermal and mechanical conditions.

Newfound knowledge since RD&D 2001

Extensive geological information intended to be used as calibration and validation data in ice sheet modelling has been compiled as a subproject within the aforementioned project "Basal conditions and hydrology of continental ice sheets". Examples of such data are ice margin positions during the Weichselian, occurrence of weathered bedrock, block fields, Veiki moraines, till-covered eskers and soil depth or bare rock /21-9/. The compilation also includes a qualitative evaluation of the information, as well as alternative interpretations in the literature. The purpose of the compilation is to identify and evaluate ice margin positions in order to use the results to calibrate the ice sheet model, as well as to identify areas where periods of glaciation have been dominated by either cold-based or warm-based ice conditions, information that will be used for validation of output data from the model.

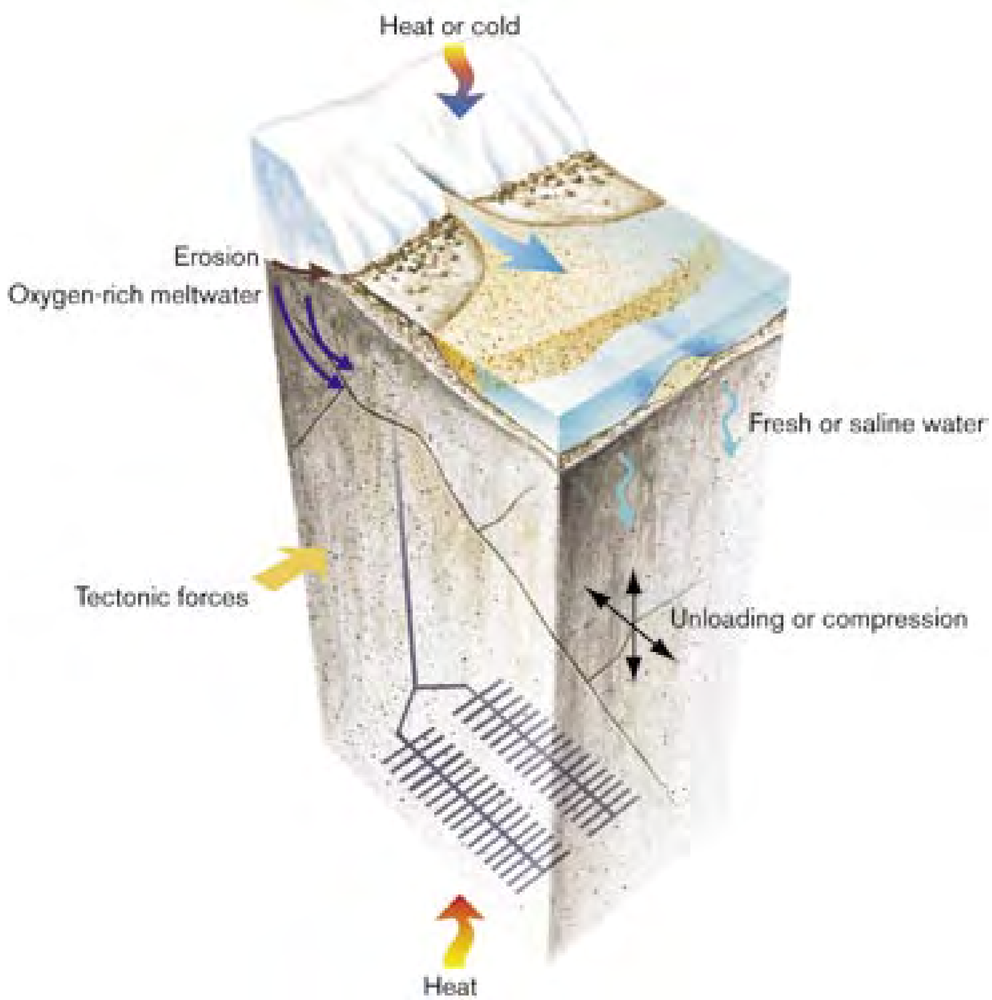


Figure 21-3. *As an ice sheet advances and retreats, changes occur in temperature, hydrological conditions, rock stresses and groundwater composition.*

The geothermal heat flow and its variations have previously been judged to have an important influence on the basal conditions of continental ice sheets, above all on basal ice temperatures and meltwater production /21-10 to 21-12/. The temperature and quantity of water at the base of the ice in turn influences the dynamics of the whole ice sheet. A dataset that describes the spatial variation of the geothermal flow over Scandinavia has been compiled with the purpose to, for the first time in ice sheet modelling, examine the effects of spatially varying geothermal heat flow on basal conditions, as well as to determine a correct average value /21-13, 21-14/. The dataset has been used for simulations of the Weichselian period with an ice sheet model developed at the University of Maine in cooperation with Stockholm University /21-15 to 21-17/. The initial results show that the use of realistic geothermal data is important in numerical modelling of the ice sheet's basal conditions and the meltwater production in the interface between the ice and its substrate /21-14/.

The thermohydromechanical effects of a continental ice sheet over a repository site have been studied with the aid of different numerical models in the international Decovalex/Benchpar project /21-18/. Data from the Whiteshell area in Canada have been used in the project, but the results can in principle be considered to be representative for Swedish conditions as well. An important conclusion of the modellings is that hydraulic and mechanical processes of importance for the performance of the deep repository are coupled and that transient effects are significant.

The hydromechanical modellings that were carried out /21-19/ gave the following results regarding conditions at depth in the rock mass beneath the ice sheet:

- When a warm-based continental ice sheet with considerable meltwater production expanded over the studied area, the water pressure increased rapidly during the first 1,000 years, in particular within conductive fracture zones.
- A high horizontal hydraulic gradient was obtained during the same period, due in part to the compression of the pore system caused by the ice load.
- When the ice sheet completely covered the area, a large downward gradient arose.
- When the ice then retreated, the gradient reversed and became upward.
- Where the hydraulic conductivity of the rock mass was very low, residual high water pressures could remain at depth for a long time.
- Since the ice load's contribution to the stress was compensated to a great extent by high water pressures, the change in effective stress was relatively moderate.

Shoreline displacement is above all a result of glaciations, both directly due to the isostatic downwarping of the crust by the weight of the ice, and indirectly due to the fact that eustasy is affected by the fact that sea water is bound up in or released from continental ice sheets. The empirical model of shoreline displacement referred to above /21-3/ provides a well-underpinned picture of the sequence of events following the retreat of the most recent continental ice sheet. It provides support for interpreting present-day conditions and can also be used to predict what will happen in the immediate future.

Programme

The programme is divided into three subprogrammes:

- Scandinavian ice sheets.
- Stress states in the earth's crust.
- Shoreline displacement.

Scandinavian ice sheets

The project "Basal conditions and hydrology of continental ice sheets" was started in 2002 and is planned to be concluded in 2006/2007. An ice sheet's basal conditions and meltwater production, and the water pressures and flows it generates, are of central importance for the thermal, hydrological, mechanical and chemical conditions in the repository. The purpose of the project is to provide a both spatially and temporally high-resolution picture of the basal conditions and the hydrological system beneath continental ice sheets. The project includes both processes that control the subglacial hydrology of ice sheets and the glaciological processes that control the spatial and temporal variation of this hydrology. The subglacial hydrology system is supplied by water from the following two sources:

- Melting of basal ice, due to for example deformation heat and geothermal heat.
- Meltwater from the ice surface, generated by the prevailing climate.

Basal melting occurs in warm-based areas which can be very large and exist over long spans of time. The variations in this melting, caused by the general dynamics of the ice, are relatively slow. Extensive basal meltwater production can occur beneath ice streams, common during the Weichselian Glaciation. Surface melting generates much more water than the basal meltwater system, but in a smaller, frontal area. The variations in water production from surface melting are rapid. These variations may be great on both a daily and a seasonal basis, and generate great variability in both pressure and flow. The two systems may overlap in the frontal portions of the ice sheets. One of the project's goals is to establish a model that includes both basal and surface meltwater production.

Another goal of the project "Basal conditions and hydrology of continental ice sheets" is to describe the ice sheet's subglacial hydrology and the hydrological features of subglacial channels and their importance for pressures and flows, as well as to study how they are formed. Numerical modelling is combined with field studies in the project. The field studies include measurements on Storglaciären /21-20, 21-21/. The possibilities of utilizing the Greenland Ice Sheet as an analogue are also being explored. Scandinavian glacial land forms also reveal a great deal about subglacial conditions, in particular during deglaciation. A compilation of paleo-geohydrological data was started in 2003 and is planned to be completed during 2004. These data, combined with the results of ice sheet modelling, should result in a better understanding of subglacial hydrology. An example is co-interpretation of esker orientations and modelled basal meltwater flows, ice thickness and ice movement.

The ice sheet varies greatly in size during a glaciation. This means that the extent of areas with warm-based conditions, and thereby an active subglacial hydrology, will also vary to a high degree. Up to now, very little has been done to examine these temporal and spatial variations during the most recent ice age. Another goal of the project is therefore to devise a well-calibrated model simulation of the Weichselian ice sheet, based on our geological knowledge of the most recent ice age. With the aid of better input data, calibration data and validation data compared with previous studies, useful information will be obtained on the basal thermal and hydrological conditions of the ice sheet.

The well-calibrated Weichselian scenario can then form the basis for modelling previous ice sheets, preliminarily their basal conditions, as well as for studying the consequences of extreme climatic conditions. Such experiments provide bounds for the possible span in conditions that could conceivably occur.

Simulations on a large scale using the ice sheet model (e.g. northern Europe) can provide input data for simulations on a smaller scale. This means that local conditions, including both input data (for example topography, geothermal flow) and output data (for example temperature, basal meltwater) for the ice sheet model, can be evaluated site-specifically. Data obtained from the site investigations can thereby simultaneously support the ice sheet project and be interpreted against the background of the project's results.

The results of the ice sheet modelling will be stored – together with geological input, calibration and validation data – in a Gis database. The main analysis work is also done here. Data can be freely extracted from the Gis database to be used in other projects.

Stress states in the earth's crust

A project aimed at understanding the mechanisms that lie behind postglacial earthquakes was commenced in 2003 and is planned to continue for three years. The project will apply finite element modelling. In an initial phase, basic studies will be conducted with simple earth and ice models to obtain a good understanding of the physical relationships and the most important parameters. Since postglacial faults in the Arctic area of Scandinavia are well-known and investigated, a simulation of the evolution in this area will then be performed. The simulation will make use of the above-mentioned ice sheet model and also include pore pressure variations, so the ice sheet's basal conditions are important here as well. Sensitivity analysis and validation against available stress and land uplift data will be carried out. As a final step, modelling will be done for the two candidate sites based on then-available information to indicate whether, and if so where, postglacial quakes may occur.

Shoreline displacement

In order to be able to describe changes in the shoreline over a glacial cycle and for different scenarios, a research project is planned where GIA (Global Isostatic Adjustment) modelling plays a central role. The goal of the project is to identify the factors and processes that influence the Scandinavian coastline in a 100 to 100,000 year perspective and to develop an isostatic model that includes these factors and processes. Such a model can then be used to describe historical and possible future shorelines. The project will use the calibrated ice sheet model described above. The GIA modelling can also provide feedback to the ice sheet modelling, since the change in the shoreline is evidence of what ice load the earth's crust may have been subjected to.

21.2 Permafrost domain

Permafrost is divided with respect to its thickness into sporadic, discontinuous and continuous. The presence of permafrost, or rather of frozen ground, affects the hydrological conditions. Groundwater recharge is assumed to decrease and the groundwater flow is limited to unfrozen ground. Salt exclusion affects the groundwater composition.

Conclusions in RD&D 2001 and its review

SKB observes that current knowledge concerning the occurrence of permafrost in Scandinavia far in the future is limited. Moreover, the hydrological conditions and groundwater composition caused by permafrost should be studied more closely. SKI considers it positive that SKB is planning co-ordinated efforts to investigate permafrost.

Newfound knowledge since RD&D 2001

A literature review of permafrost, with a focus on hydrology and conditions in the bedrock, has been carried out /21-22/. The study concludes that even though some information is available on permafrost at greater depth from e.g. the arctic mining industry, most references deal with near-surface processes. An important observation is that permafrost in general does not occur beneath large lakes and rivers. Furthermore, exclusion of salt and hydrates occurs in today's permafrost areas. It can also be observed that mechanical effects of freezing are limited to the surface or near the surface.

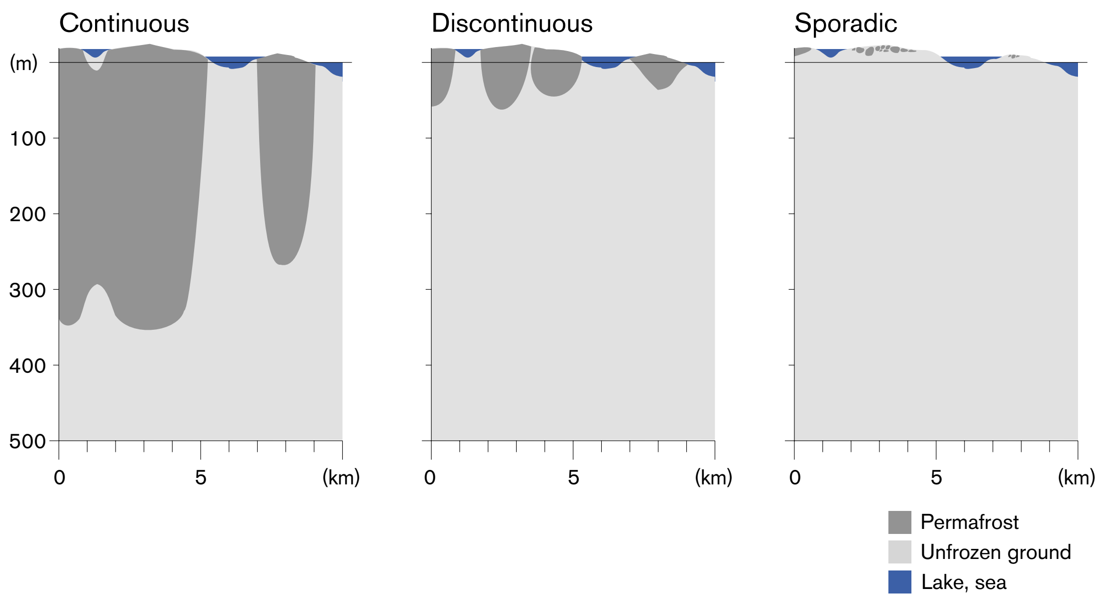


Figure 21-4. *Illustration of sporadic, discontinuous and continuous permafrost.*

A field study of permafrost and its importance for hydrology and groundwater composition is being conducted in cooperation with Posiva, Nirex and OPG at a gold mine in Canada, the Lupin Mine. Besides field investigations, the study includes laboratory experiments /21-23/. The results can above all be used to show how permafrost can affect the groundwater composition.

Programme

Possible depth and extent of permafrost is planned to be studied with the aid of a numerical model developed at Helsinki University /21-24/. The purpose of the study is to survey to what extent permafrost and frozen ground can be expected to occur on the two sites being investigated by SKB. The study consists of two parts. In the first part, the factors that can affect the evolution of permafrost will be identified. Examples of such factors are: topography, soil layers (materials, depth), watercourses (depth, extent, flow and salinity), groundwater composition (salinity), groundwater flow, heat flow (surface, geothermal) and temperature climate including annual variations. In the second part, permafrost on the two candidate sites will be studied in the light of obtained results. Important site-specific parameters will be included in these studies. They will also analyze how the heat from the deposited fuel can influence the evolution of Permafrost.

The occurrence of periglacial permafrost will be analyzed to begin with, but subglacial permafrost will also be studied. Information from the aforementioned ice sheet project will comprise important input data for the latter analyses. Results of simulations of permafrost will be used in geohydrological and geochemical analyses.

21.3 Temperate/boreal domain

A temperate/boreal climate domain prevails in all of Sweden today, with the exception of parts of the Caledonide mountains. Today's variations in the north-south direction, from northernmost Sweden down to Central Europe, are judged to cover the full amplitude of the variation that could possibly occur in the country and this climate domain, even in a long-term perspective.

The process judged to have the greatest importance for conditions in the deep repository in this climate domain is shoreline displacement. The consequences of shoreline displacement are described schematically in Figure 21-5. The position of the shoreline affects the hydrological boundary conditions for the deep repository. The figure illustrates what happens in connection with *regression*, i.e. when a water-covered area becomes dry land. The course of events is reversed in the case of *transgression*, i.e. when water covers the land.

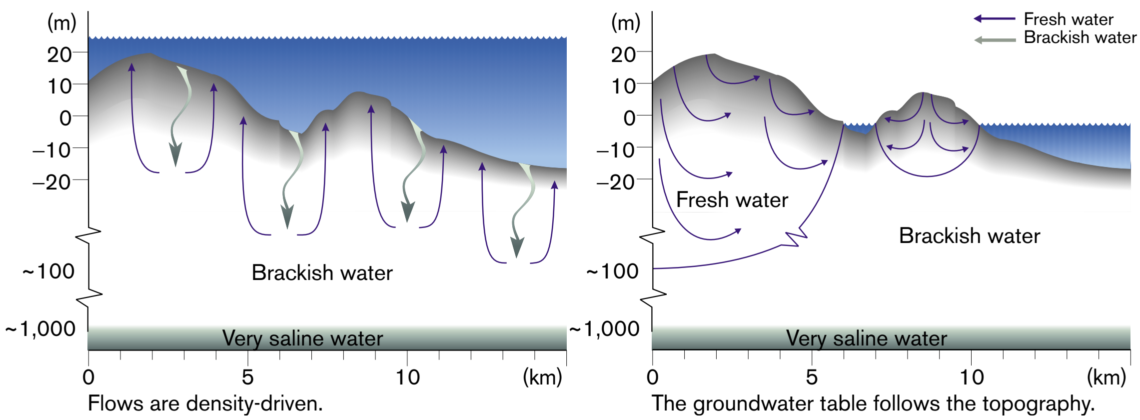


Figure 21-5. Schematic illustration showing variations of hydrology and salinity in connection with regression on a hypothetical site on the present-day coast of the Baltic Sea.

The salinity of the sea, inland sea or lake corresponding to today's Baltic Sea in various stages of a glaciation is affected by connections with the oceans. These connections are in turn dependent on the thickness and extent of the continental ice sheet and the position of the shoreline. Studies within the biosphere programme show that freshwater influx is at least as important for the salinity, see section 20.8. Possible variations in salinity have been described for various possible combinations of freshwater influx and shoreline.

The state of knowledge concerning conditions and processes in the temperate/boreal climate domain and their importance for repository safety and conditions in the biosphere is good.

Conclusions in RD&D 2001 and its review

Both SKI and SSI are of the opinion that in coastal regions, the future position of the shoreline and its impact on groundwater conditions and the biosphere is an important issue.

Newfound knowledge since RD&D 2001

As already mentioned, empirical studies of land uplift since the most recent deglaciation have been concluded /21-3/. More detailed studies have been conducted of land uplift in Uppland, see section 20.8. This means that our current knowledge of historical conditions and our ability to predict the isostatic progression over the next 1,000 years are very good. Together with the aforementioned results, the descriptions of sea level changes arrived at by the IPCC /21-6/ provide information on shoreline displacement for the next 1,000 years that is judged to be sufficient for the needs of the safety assessment.

Human impact on the climate is the process that has been studied more than any other in order to predict the future evolution of the climate. SKB has not conducted any studies of its own within the area. Published results, particularly within the projects Sweclim /21-5/ and Bioclim /21-1, 21-2, 21-4/ and through the IPCC, are judged to be sufficient for SKB's purposes.

Programme

A compilation and synthesis of climate variations, mainly in the Holocene but also in earlier periods since the most recent deglaciation, has long been planned. The study is intended to shed light on climate variations during interglacials as well as possible climatic conditions southeast of an ice sheet that partially covers the country. The study will also provide data as a basis for setting limits within which temperature and precipitation vary during the temperate/boreal domain.

A project has been started for the purpose of describing and understanding the causes of the climate variations we can see in Scandinavia during the past 2,000 years, and evaluating how information from climate archives can be used together with climate models to describe the climate. This project is expected to provide data as a basis for describing climate changes over the next 1,000 years, even taking into account possible human impact on the climate.

The above-mentioned GIA project will provide information on the shoreline in various stages of a glacial cycle. The results can also be used to simulate what would happen with the shoreline in a greenhouse scenario where the cycle of ice ages is disrupted and today's continental ice sheets melt.

The current state of knowledge concerning conditions in the temperate/boreal domain is good. Model simulations within Bioclim /21-2/ show that a very long period with a warm climate similar to today's could be a consequence of human impact on the climate. In view of this, the consequences of a very long period with temperate/boreal conditions is planned to be studied more closely, see also section 20.8.

22 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 the environmental impact and effects of the planned facilities and activities. The EIS must also contain descriptions of projected consequences for the environment, the landscape, human health and society. In order to be able to present a broad and complete account of societal aspects together with the permit application, SKB intends to conduct and fund social science research.

In the eight feasibility studies carried out by SKB between 1993 and 2000, considerable interest was devoted to societal aspects /22-1 to 22-11/. The feasibility study reports contain descriptions and analyses of population development, 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 socioeconomic development of the municipality and the region, both with and without the establishment of a deep repository.

Conclusions in RD&D 2001 and its review

The social sciences and SKB's research in the field since the early 1990s were not discussed in RD&D 2001. The reviewing bodies offered viewpoints on how societal issues should be studied, primarily decision processes, EIA (environmental impact assessment) and psychosocial issues. A number of municipalities, universities and interest organizations wanted the RD&D programme's technical and scientific focus to be broadened to include a social science aspect with research on e.g. attitudes, decision making in complex societal issues, and long-term social development. This has also been SKB's intention, and the planning was actually begun even before RD&D 2001 but was never included in the report, since the programme was in a very early stage of surveying and planning.

Newfound knowledge since RD&D 2001

During 2003, in preparation for the 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. The two social science research seminars that have been held with scientists and concerned municipalities during 2002 and 2003 have also been an important part of SKB's preparatory work.

The purpose of the social science research supported by SKB should be 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 decisions and the EIS.
- Contribute 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.

With these goals in mind, four general areas of research emerge as being relevant for the waste issue and the municipalities:

- Socioeconomic impact.
- Decision processes.

- Public opinion and attitudes – psychosocial effects.
- Global changes.

A general description of the four chosen research areas is provided below.

Socioeconomic impact

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 or activity. 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 might 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 socioeconomic effects such as travel to and from the community, in- and out-migration to or from the community, and the community's reputation and attractiveness.

Decision processes

The siting of the deep repository is a controversial issue in part because it involves a nuclear activity and a time perspective that is impossible to comprehend. The issue has repercussions for community planning, national energy policy and international research. 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 important contributions to the consultation procedure, studies, planning and decision-making. SKB, the concerned municipalities and other stakeholders, such as 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.

Public opinion and attitudes – psychosocial effects

Opinions and attitudes are highly 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 the deep repository is furthermore a drawn-out process, involving different actors in different phases. The purpose of research in this area is to study how opinions and attitudes are formed and change during the various phases of the project. This knowledge can make essential contributions to an understanding of the different actors' decision-making and to the conduct of 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 also influence public opinion and attitudes. It is therefore also important to shed light on the "symbolism" surrounding the deep repository and its activities.

Global changes

The establishment of the deep 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 the research is to gain greater knowledge about the deep repository, relevant global factors and global changes. This knowledge can make a very valuable contribution to planning, studies, consultations and decision-making leading up to a permit application. 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 will the Swedish state, which bears responsibility for the deep repository, look like in the future? National legislation, regulation and financing, as well as the country's economic situation, are factors of importance. Another important and concrete change in the global situation is Sweden's participation in European political and economic cooperation. What kind of relationship will Sweden have with the EU in 30 years? What will the EU look like? What impact will deeper European integration in the future have in general on nuclear waste management, and to what extent will this affect Sweden's own nuclear waste management programme?

Programme

The principal emphasis of the research in the areas which SKB has now identified and intends to support is on applied research. The results should preferably be able to be put to practical use, but there may also be an interface with basic research. Furthermore, SKB's research areas, site-specific studies and investigations should have clear links with each other and support each other.

An external evaluation and screening group has been appointed to make sure that the projects have the necessary scientific quality and relevance, and that the assignments go to suitably qualified researchers and research teams. The screening group consists of researchers in the social and behavioural sciences.

Relevant parts of the results obtained in the research programme will be included in the supporting documentation for permit applications and EISs for the encapsulation plant and the deep repository. The programme will primarily be carried out during a three-year period, followed by evaluation and a decision regarding possible extension.

Decision-makers and other stakeholders will be kept informed of the results from the ongoing research. A part of the research task is therefore to communicate interim results to different target groups during the course of the research. This includes active participation in seminars and meetings and publication of research results both in scientific journals and in a more accessible and popular form. The main target groups for the popular presentations are the consultation parties.

An interest inquiry, based on the work plan drawn up in the autumn of 2003, was sent out to a number of universities and institutes of technology in the spring of 2004. Eight research projects to be included in SKB's social science research programme were selected in an initial application round and granted funds. Most are two-year programmes to allow time for supplementary work after the research results start coming in. The principal focus of the projects are presented below under the main theme covered.

Socioeconomic impact

- Local development and regional mobilization around technical and large-scale projects.

The project, which is being carried out by the Department of Economic History at Umeå University, will investigate the relationships between large-scale technical investments and the long-term socioeconomic and political development of the local community during different periods. The purpose is to learn how the socioeconomic structure of an individual community is affected by the establishment of a new, large and technically advanced facility. This knowledge will contribute to SKB's, the municipalities' and other stakeholders' judgements of how the establishment of the deep repository will affect the community's economy in the short and long term. The project will last two years, starting in the autumn of 2004.

In the study, Oskarshamn and Forsmark will be investigated at the time of the decision to establish a nuclear power plant (innovation project with new technology), ten years before and ten years after. Comparisons will be made with reference communities where there was no such establishment during the period in question. Comparisons will also be made with reference communities where projects involving conventional technology have been sited, for example railway, hydropower (implementation projects with mature technology). Population, commuting, income, property values and industrial structure are examples of important indicators in the project.

- Long-term socioeconomic effects of large investments in small and medium-sized communities.

The long-term local effects of investments on population and employment will be analyzed in this project, which is being carried out by the Department of Social and Economic Geography at Umeå University. This will be done by modelling the socioeconomic system in a dynamic simulation model where the long-term effect of the investment is determined by comparing scenarios with and without the investment. The model will be an instrument for consequence analysis to answer important questions concerning the importance of investments for e.g. population development and labour dynamics in the community where the investment is made. The project will last two years, starting in the autumn of 2004.

A specially adapted microsimulation model will be used in the project where individuals are followed and studied rather than groups of individuals (aggregates). Information on the individual's unique situation is crucial for being able to depict the dynamics of the socioeconomic system with precision. Some examples of questions that will be addressed in the study are how commuting streams change, how the size and demographic and socioeconomic composition of the population can be affected, how the number of jobs in different segments of the labour market is affected, and so on.

Decision processes

- Public, experts and deliberation.

The research project will be conducted at the Man-Technology-Environment Research Centre at Örebro University. The study will start in January 2005 and last one and a half years.

Many different factors must be weighed together in deciding whether to establish a deep repository, some of which may conflict with each other. Stringent safety and health standards must be met, at the same time as broad participation in the decision process must be guaranteed. The reason is that better judgements can be arrived at by making sure that other perspectives than purely scientific ones are represented in the process, and that the credibility of risk assessments and the legitimacy of decisions are perceived to be greater.

The purpose of the project is to learn more about how the different perspectives and judgements of members of the public and experts are combined in consultation and decision processes associated with the establishment of a deep repository. The study addresses the question of how it is possible in a planning process to take into consideration both the public's and experts' perception of the risks associated with a deep repository.

The consultations and decision processes created during the feasibility study period are analyzed in the project. However, the main focus is on the ongoing site investigations in Oskarshamn and Östhammar, where interviews are being conducted and participant observations are being analyzed along with written material.

- Resource or waste? International decision processes relating to spent nuclear fuel.

The project, which is being carried out by the History of Science and Technology Department at KTH, is aimed at clarifying and analyzing decision processes relating to nuclear waste in an international and historical perspective. How have decisions been negotiated, and what groups have participated in the process? In what way does the Swedish decision process differ from the decision processes in, for example, Finland, France and Germany? By studying several countries from these two perspectives, the study will contribute to insights regarding which factors influence these decisions, what role has been played by the political structure and the public's attitude towards nuclear waste, and how public attitudes towards spent fuel have changed with time. The project will last for two years, starting in the autumn of 2005.

It will be carried out by means of interviews with key persons in the selected countries. KTH's networks and contacts with historians of technology in other countries will be used in different ways. Articles and other publications will also be studied.

Public opinion and attitudes – psychosocial aspects

- Identity and security in time and space – cultural perspective on the existential dimensions of the nuclear waste issue.

The research project will be conducted by the Human Ecology Division at Lund University. It will start in the autumn of 2004 and last for one year.

Time and space are objectively measurable dimensions but are at the same time experienced in highly varied and subjective ways by different persons in different contexts. The nuclear waste issue involves time spans and spatial distances that lie beyond the experiential frames of reference of individual human beings. This is one of the reasons why the discussion concerning final disposal of spent nuclear fuel is difficult to conduct in purely technical terms. It inevitably touches upon existential questions regarding the duration of the world and the survival of humanity.

In this project, tacit symbolic and experiential aspects of the debate concerning facilities for management and disposal of nuclear waste will be studied in time and space. The project will help improve people's understanding of the terms for the siting of complex infrastructure projects. The intention is to facilitate communication between experts, stakeholders and the concerned local population through better knowledge of the cultural dimensions underlying the different parties' perspectives and standpoints. The project will attempt to identify specific communicative problems that deserve special attention in future deliberations. In-depth and follow-up interviews will be conducted with various parties.

- Nuclear waste – from energy resource to disposal problem.

The purpose of the project, which will be carried out by Theme Technology and Social Change at Linköping University, is to study how opinion formation by the media in the nuclear waste issue has changed on the national plane between the 1950s and today. The idea is to examine how the waste problem has been interpreted and understood at different times by the various parties who have taken an interest in the issue. The long-term historical shifts in value patterns on the national level concerning proposed solutions to a common management problem have never been studied before. Finding a solution to the nuclear waste issue is a project that spans several generations, and it is therefore important to gain a better understanding of changes in values over the long term.

Previously existing material is being used in the study, comprising approximately 9,000 articles, debate books, pamphlets, surveys and research reports. The project will take two years, starting in the autumn of 2004.

- Attitudes towards a deep repository for spent nuclear fuel.

The project is being carried out by the Centre for Risk Research at the Stockholm School of Economics. The project will last for two years, starting in the autumn of 2004.

International research on risk attitudes is dominated completely by pessimistic results concerning the possibilities of siting a repository for spent nuclear fuel in consensus between industry, politicians and the local population. American research has often been accepted without any closer critical examination, and there is a need for research from a special Swedish perspective. The factors which have contributed towards the constructive development of the siting process in Sweden and Finland are therefore of great interest to investigate. Among these factors are trust and morals, which have often been neglected in previous research.

The factors that influence risk perception and risk attitudes regarding final disposal of spent nuclear fuel will be studied in the project. The purpose is to contribute towards a better understanding of risk and policy attitudes, which is in turn a prerequisite for better and more effective risk communication. The study is a continuation of the internationally acclaimed investigation which was conducted in 2001 and which for the first time observed a positive or accepting attitude towards the siting of a deep repository. Some of the material that will be used in the project will be collected by questionnaire surveys on two occasions (September 2004 and March 2006) in Östhammar and Oskarshamn, plus a suitable reference municipality.

Global changes

- National nuclear fuel policy in a European union.

The purpose of this study, which will be carried out by the Department of Law at the School of Economics and Commercial Law at Göteborg University, is to clarify and analyze the legal situation at both the Swedish national and European community level when it comes to responsibility for and authority over nuclear waste management. The project will last for two years, starting in the spring of 2005.

Based on the interest of Sweden, and certain other member states, in maintaining a national nuclear fuel policy, it is of vital importance to analyze relevant parts of community law in this area. The purpose of such an analysis is to try to make a forecast of the interpretation of the rules and to define more precisely the legal potential for a national nuclear fuel policy. Such knowledge is necessary in order for rational political decisions to be made at the national level. The research task also includes a forward-looking, analytical perspective: What are the likely future trends in European community law, and how could they impact the formulation of a national nuclear fuel policy?

23 Alternative methods

In practice, we in Sweden have already prioritized geological disposal as a method for disposing of our spent nuclear fuel. We are pursuing a main line with a system based on deep geological disposal according to the KBS-3 method. Various alternatives to this main line have been described and analyzed in depth /23-1/. The results of this analysis provide strong support for the choice of the main line (deep disposal according to the KBS-3 method). At the same time, however, SKB has decided to continue to follow and support the development of alternatives to the main line. The two alternatives currently attracting the most interest are Partitioning and Transmutation (P&T) and Very Deep Holes (VDH).

23.1 Partitioning and transmutation (P&T)

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 expressed for transmutation is to reduce the quantity of long-lived radionuclides by a factor of 100. If this goal was attained, 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 deep repository, however.

Transmutation or 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. For transuranics it is primarily nuclear fission that provides effective conversion. 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.

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 2001 and its review

In RD&D 2001, SKB concluded that accelerator-driven systems is currently the alternative line of development for partitioning and transmutation that is attracting the greatest interest, both in Sweden and in other countries. The development of such systems is very costly and highly dependent on international collaboration. SKB further observed that several fundamental technical questions must be further clarified by research before major projects regarding accelerator-driven systems can be defined. Considering the development situation, the required resources and the current energy policy in Sweden, SKB does not deem it reasonable to undertake major development projects on its own.

The reviewing bodies had no specific comments on this policy. However, some bodies (including KTH and Uppsala University) were of the opinion that Swedish efforts in this area are inadequate. This was commented on by SKI /23-2/, who stated that the evaluation of SKB's research within partitioning and transmutation is complicated by several factors, of which the following points were mentioned:

- It is a question of extremely cost-intensive research and development where the Swedish funding will always be marginal.

- The driving forces behind the development of a partitioning and transmutation system will be beyond the control of SKB and Sweden within the foreseeable future.
- There is no political support for the application of partitioning and transmutation in Sweden.
- Considerable uncertainties still exist regarding whether functioning systems that meet reasonable requirements on efficiency will become available, and if so when.

SKI's conclusion is that the current level of effort is adequate to actively follow and contribute to the international development work in a meaningful way, but that at the same time it is a minimum level that should not be reduced. If Swedish nuclear power had been in an expansive phase, they say, a greater effort would have been justified.

According to SKI, SKB's partitioning and transmutation programme has a suitable direction which covers everything from basic research to technological development. System- and safety-related research as well as work on project coordination are particularly valuable since they provide good insight into major international programmes at a reasonable cost.

Furthermore, SKI emphasizes that partitioning and transmutation is one of the few research areas in nuclear technology that can still attract young and committed researchers. The work that is being done in partitioning and transmutation in Sweden should therefore be seen as a part of the effort to preserve national competence in nuclear technology, particularly reactor physics and nuclear chemistry. This is the reason why SKI also funds research in partitioning and transmutation in the amount of about SEK 0.5 million per year.

Kasam has no objection to the picture presented by SKB of newfound knowledge in the transmutation field /23-3/. In Kasam's opinion, there are good reasons for the current direction of the Swedish nuclear waste programme, namely further development work focusing on direct disposal in accordance with the KBS-3 method.

But at the same time, Kasam says it is important that SKB should actively monitor developments in the area of partitioning and transmutation, and proposes that the Government should request that SKB, in RD&D-Programme 2004, should present more detailed information for assessing suitable levels of funding for this monitoring.

Kasam shares SKB's opinion that it is not reasonable for the company to initiate major development projects in the field of partitioning and transmutation at present, but in Kasam's opinion SKB should remain open to the possibility of increased efforts within the framework of EU-funded research in the transmutation field, which is currently being discussed and could lead to the need for increased Swedish efforts.

Newfound knowledge since RD&D 2001

At the request of SKB, a reference group of Swedish researchers published a report on the status of research on partitioning and transmutation in early 2004 /23-4/. The information for the following account of the current state of knowledge on P&T is taken from this report. The report summarizes developments since 1998, when a similar report was produced for SKB /23-5/.

In the past few years, a number of system studies on P&T have been published. These studies provide a good overview of the extensive work required for implementing P&T, the relative large and complex system of facilities that are needed, and the problems that must be solved before such a system can be realized.

The first of these system studies was done by an expert group within the OECD/NEA and was published in 1999 /23-6/. Important conclusions from this study were:

- Basic R&D for partitioning and transmutation requires long lead times and large investments in dedicated fast neutron devices, extensions of reprocessing plants and construction of remote-controlled facilities for fuel fabrication.

- Partitioning of long-lived radiotoxic elements from spent nuclear fuel can be done in additions to existing reprocessing plants. But a great deal of work is required to develop the new processes from laboratory to industrial scale.
- Transmutation with fast neutrons is more effective than in existing light-water reactors. Transmutation of transuranics can best be achieved in fast reactors or in accelerator-driven systems with a fast neutron spectrum.
- Partitioning and transmutation will not eliminate the need for a deep geological repository for certain long-lived radioactive wastes from spent fuel.

In the USA, some interest was aroused in transmutation with accelerator-driven systems in the early 1990s. The centre of this interest was Los Alamos National Laboratory, which introduced the concept of ATW (Accelerator-driven Transmutation of nuclear Waste). This eventually led to a study of ATW by the US Department of Energy at the request of the Congress. The study, published in the autumn of 1999 /23-7/, proposed a research programme for ATW that could be the start of a large-scale investment in such a system. Certain portions of this work have since been started, in particular those portions involving international cooperation. The programme as a whole has, however, not been accepted as a basis for American research on advanced nuclear fuel cycles or a future nuclear waste strategy. It was probably not intended as a complete programme either, but rather as more of an in-depth evaluation of one of many possible scenarios for the development of partitioning and transmutation.

In 2003, the USA announced the so-called Advanced Fuel Cycle Initiative (ACFI), which was aimed at a broad study of the fuel cycle for future nuclear power reactors – also known as Generation IV reactors /23-8/. This initiative is planned to consist of three phases: Phase I Basic Technology Evaluation; Phase II Proof of Principle (5–6 years); Phase III Proof of Performance (15–20 years). The programme is broadly conceived and includes a review of all current systems, reactor types and partitioning methods.

After an initiative by the research ministers in France, Italy and Spain, a European technical working group – TWG – was formed in 1999. This working group proposed a roadmap for development of an accelerator-driven system (ADS) in Europe. The report from TWG was published in the spring of 2001 /23-9/. The ambition from the group was that the roadmap should form the basis for continued EU-funded research on ADS. The roadmap proposes construction of a small experimental plant with an ADS of about 100 MW thermal power. The plant is envisaged to start operation in 2015. The cost for the first twelve years of research and development plus design and building is estimated at 980 million euro. In addition, another 180 million euro is proposed for R&D on nuclear fuels suitable for ADS. This first phase would then be followed by a second where a prototype for a full scale ADS is developed and built. After successful operation of this prototype for several years, industrial plants could begin to be built in around 2040. This study is in fairly good agreement with the US DOE study in terms of the projected schedule. In their details, however, the two studies have considerable differences. The American study has a much more specific choice of systems for both partitioning (pyrochemical process) and transmutation (ATW cooled by liquid lead-bismuth eutectic mixture) than the European one. The latter is defined as transmutation with ADS, but keeps several parts of the ADS open for later choice of design: accelerator, coolant, etc.

The work within the OECD/NEA continued within another expert group, which published a comparative study of fast reactors and ADS for transmutation in the spring of 2002 /23-10/. The group went through a number of strategies for partitioning and transmutation of transuranics based on light-water reactors, fast reactors and accelerator-driven systems. Among the general conclusions in the report are the following:

- While P&T will not replace the need for a deep repository for high-level waste, the study has confirmed that different transmutation strategies could significantly reduce (by a hundred-fold or more) the radiotoxicity of the waste that must be emplaced in such a repository. This improves the environmental friendliness of the nuclear energy option and could contribute to a sustainable nuclear energy system.

- Very effective methods for transmutation in fast reactor spectra and for multiple recycling of the nuclear fuel with very low losses would be required to achieve this objective.
- Multiple recycle technologies that manage Pu and other transuranics either together or separately could achieve equivalent reduction factors for the radiotoxicity of wastes to be disposed.
- Pyrochemical reprocessing techniques (partitioning) are essential for fuel cycles containing fuels with a very high content of americium and/or curium that are burned in ADS or fast reactors.
- In strategies where plutonium and other transuranics are managed together, the choice between ADS and fast reactors must be based on economic, safety and other considerations.
- In strategies where plutonium and other transuranics are managed separately, plutonium can largely be burned in conventional (light-water) reactors, minimizing the need for ADS and/or fast reactors.
- Further R&D on fuels, recycle, reactor and accelerator technologies would be needed to deploy P&T. The introduction of transmutation systems would probably occur incrementally and at a pace geared to national situations and policies.
- Fully closed fuel cycles can be achieved with a relatively limited increase in electricity cost of about 10 to 20 percent compared with the LWR once-through fuel cycle.
- The deployment of these P&T schemes requires a long lead time to develop the necessary technology and make it cost-effective.

Some of the more important technical conclusions from this study are:

- To achieve the goal of reducing the amount of long-lived radionuclides in the waste by a hundredfold or more, the losses in each partitioning cycle must be less than 0.1 percent.
- Transmutation of plutonium alone will reduce long-term radiotoxicity by only a factor of five compared with spent fuel.
- Transmutation can be achieved either by fast reactors or by different combinations of light-water reactors, fast reactors and accelerator-driven systems.
- Due to physical limitations, a long time is needed to carry out a complete transmutation. This means that the indicated goals can only be achieved if the technology is used for at least 100 years.
- The use of pyrochemical methods for partitioning involves new potential chemical and radiological risks that must be mastered.
- All transmutation strategies for light-water reactors produce considerable quantities of depleted and irradiated uranium that must be disposed of.
- Transmutation of long-lived fission products involves many technical and practical difficulties. At present, technetium-99 and possibly iodine-129 appear to be the foremost or perhaps the only candidates.
- Experimental research on transuranium fuel is a highly prioritised area. A bottleneck for such research is the availability of facilities with a high fast neutron flux.
- The basic research and development on fast reactors as well as accelerator-driven systems would be simplified if better agreement was obtained on the advantages and disadvantages of different coolants for such systems.

Current research on partitioning

The so-called Purex process, which is used in existing reprocessing plants, uses phosphorus-based organic compounds as extractants. A drawback with these is that they produce considerable amounts of intermediate-level waste, which is contaminated with long-lived radionuclides.

Extractants consisting solely of carbon, hydrogen, oxygen and nitrogen are therefore being sought. These extractants can be burned completely, whereby the radionuclides are trapped in filters. The volume of radioactive waste can thereby be reduced considerably compared with current technology. The current research is largely focused on this type of extractant.

The research on aqueous partitioning processes has made some progress in the past few years, and there is good hope of being able to develop a process that recovers over 99.9 percent of both the uranium and all transuranics from spent fuel. The main problems are the cost and the irradiation stability of the organic molecules.

However, once a process has been defined that works well on a small scale, extrapolation to an industrial scale is no great problem. The technical components needed for such a process are tried and tested in other applications.

The limited stability of organic molecules under the influence of the strong ionizing radiation from the high-level waste was a factor contributing to the early search for non-aqueous partitioning processes. The research soon came to be focused on pyrochemical processes. Such a process was built at the EBR-II breeder reactor in the USA in the 1950s. This reactor had metallic fuel and was cooled by liquid sodium. The reprocessing of the fuel was done by controlled oxidative slagging after the fuel had been melted. The purified fuel was then recast to new fuel rods which were returned to the reactor. Another, more promising method was fluoride volatilization, which was tested in the MSRE project with fuel in the form of molten salts. This method was further developed for light-water reactor fuel, but encountered great difficulties in the early 1970s. The difficulties included keeping process losses down, control of criticality, handling of small amounts of water vapour and oxygen, and corrosion.

Due to the technical problems, development of pyrochemical methods declined greatly during the 1970s and 1980s. Interest in these methods was, however, renewed when interest in P&T increased in the early 1990s. This research increased above all in Japan, but later also in the USA, Russia and Europe. The pyrochemical methods are considered to be of interest in particular for reprocessing or partitioning of fuel with a high level of radiation, for example fuel with mainly americium, curium and plutonium with a large fraction of heavy isotopes.

The development of pyrochemical partitioning processes also requires technical development of equipment suitable for industrial application. Material and corrosion problems must be solved as well as technical and radiological safety issues. The road to industrial application is probably longer for the pyrochemical processes than for the aqueous processes.

Current research on transmutation

The radionuclides that are primarily of interest for transmutation are the transuranics. These elements are most suitably transmuted by neutron-induced fission. Many of these nuclides are, however, only fissionable with fast neutrons. Two types of facilities are being considered to achieve a sufficiently strong flux of fast neutrons: fast reactors with self-sustaining chain reactions and accelerator-driven subcritical systems (ADS). A number of fast reactors were constructed in several countries during the period 1950–1985. Most of them had liquid sodium as a coolant. The biggest was the French Superphénix, an electricity-generating plant with 1,200 MWe of power. Only a few of these fast breeder reactors are still in operation, however.

Interest in accelerator-driven systems increased in the 1990s, and currently there is considerable interest in research on such systems. In Sweden nearly all transmutation research is focused on ADS. An ADS consists of the following main components:

- A proton accelerator that can provide a strong current (from a few up to several tens of milliamperes) of protons with up to about 1 GeV of energy per proton.
- A spallation source where the proton current hits heavy atomic nuclei (lead, bismuth, tungsten, tantalum etc) and creates via spallation a neutron flux of several tens of neutrons per impinging proton.

- A subcritical nuclear reactor with fuel that contains the long-lived radionuclides to be transmuted. Since transmutation is caused by nuclear fission, additional neutrons are released. For each neutron from the spallation source, about 20 new neutrons are released, which cause further nuclear fissions. The reactor is designed so that a self-sustaining chain reaction cannot occur.
- Equipment to remove the heat that is generated and make appropriate use of the energy (for example for electricity generation).
- Equipment to control and monitor the entire system.

Proton accelerators can be of two different basic types: a linear accelerator (linac) or a cyclotron (with a circular particle track). Cyclotrons have certain technical limitations with regard to proton energy, beam current and flexibility. As a result, interest has focused increasingly on linacs. A linac for the required proton energy is very long – several hundred metres – and requires advanced technology and advanced radiation protection.

So far accelerators have mainly been built for pure research purposes where the requirements on availability have been modest. However, a plant for transmutation contains large systems with high temperatures and built-in inertia to changes in the states of the systems. This, along with requirements on efficiency and reasonable economy, imposes high demands on the availability of accelerators for ADS.

The spallation source is a central component in an ADS situated between the accelerator and the subcritical reactor. It is exposed to a demanding environment with high radiation, high temperature and highly varying pressure and requires very effective cooling. Some heavy materials can in theory be used for the source (lead, bismuth, tungsten, tantalum etc), but considering the cooling requirements and other factors the foremost candidate at present is a eutectic mixture of liquid lead and bismuth. An important question is the design of the window between the source and the vacuum tube that conducts the proton beam from the accelerator to the lead-bismuth target. The alternatives are a "hot" window consisting of a radiation-resistant special metal close to the target or a windowless version, by which is meant a "cold" window located some distance from spallation source. The latter design requires a sufficiently good vacuum to be maintained in the access tube between the window and the spallation target so that the protons will not lose energy on the way. A "hot" window, on the other hand, makes very high demands on radiation resistance and strength so that window replacements can be limited to no more than one per year. Currently, two major spallation sources with liquid lead-bismuth are being built or are planned in Europe: Megapie at PSI in Switzerland, where a hot window design has been chosen, and Myrrha at Mol in Belgium, where a windowless version will be tested.

Different designs are being considered for the subcritical reactor. Fuel as well as coolant are still open for choice. Water is not a feasible coolant for a fast flux reactor. Possible options are gas (particularly helium) or liquid metal. Gas cooling requires high pressure and is therefore often rejected due to the risk of loss of cooling. Considerable experience exists with liquid sodium from previous fast reactor programmes. The problems encountered are clearly discouraging, at least for the present time, and interest is increasingly focusing on a eutectic mixture of liquid lead and bismuth. This mixture has a relatively low melting point and a high boiling point and is also the prime candidate for the material in the spallation source. The latter naturally simplifies the design of the systems. Experience from reactors cooled with liquid lead-bismuth exists only in Russia, where seven submarine reactors have been built and operated with this coolant.

The research on fuel for ADS is being pursued along several parallel lines. Nitrides and alloys with inert metals, such as zirconium, are attracting considerable interest. The requirements on the fuel include good thermal conductivity for high power density, good irradiation resistance and an ability to achieve high burn-up – tens of percent compared with a few percent in today's light-water reactor fuel. Fuel rods with plutonium nitride will be irradiated in the R2 reactor in Studsvik during the next few years within the framework of an EU-funded project.

As mentioned above, fast reactors can be used for transmutation. During the 1990s, fuel research was focused on combustion of plutonium in sodium-cooled fast reactors. Special types of fuel were studied in France. In recent years, interest has also been directed towards gas-cooled fast reactors. The fast reactor can also be used for transmutation of other transuranics. However, this requires a special design in order to prevent serious deterioration of the dynamic and safety-related properties of the reactor. If the fast reactor is designed as a breeder reactor, very high level of energy recovery can be achieved from the mined uranium as well as an effective transmutation of all transuranics. Studies by the OECD/NEA indicate that a breeder reactor can extract up to 100 times more energy per tonne of natural uranium compared with a light-water reactor with direct disposal (once-through fuel cycle) /23-10/.

The Russians are also interested in civilian applications of fast reactors cooled with liquid lead-bismuth. Furthermore, some work is being done on ADS with funding mainly through the so-called ISTC (International Science and Technology Centre) programme.

As already mentioned, systems with a high flux of fast neutrons are of greatest interest when a virtually complete transmutation of all long-lived transuranics is desired. If one is content with transmutation of plutonium alone, however, other systems may also be used. French studies show that with specially designed fuel assemblies, the amount of plutonium generated by a light-water reactor park can be limited and stabilised. Studies by General Atomics in the USA and others have shown that a fuel can be developed for gas-cooled high-temperature reactors that permits a burn-up of up to 700 MWd/kg and combustion of more than 90 percent of the actinide content, including plutonium-239.

Research in the EU

Current research was dealt with to some extent in the previous section. As noted above, relatively large research programmes are under way in several countries. The biggest national programmes are in France, Japan and the USA. In the EU there is also considerable collaboration between the member states within projects partially funded by the European Commission. The scope of the EU programme for research on partitioning and transmutation has grown over the past decade, see Table 23-1.

The EU's Fifth Framework Programme is coordinated in so-called clusters associated with the EU's Adopt network, whose purpose is to ensure coordination and consistency between the various EU project and the national programmes. Adopt is also trying to identify gaps in the programmes and is supposed to provide input for future research projects. With regard to transmutation, the projects are strongly focused on accelerator-driven systems. The biggest project is a preliminary design study of an accelerator-driven system: PDS-XADS. It is being led by Framatome in France and has no fewer than 25 participating partners. Fuel studies concerning plutonium and americium nitrides (Confirm), oxides (Future) and thorium fuels are included in the cluster Fuetra. A number of technological special studies have been gathered within Testra. They concern irradiation effects on materials, particularly windows, for spallation sources (Spire), technology for systems cooled with lead-bismuth (Tecla) and participation in the Megapie project at PSI involving testing of a spallation source with lead-bismuth. Basic data are being gathered within the projects included in Bastra. The Muse project involves reactor physics measurements on subcritical systems with a fast neutron spectrum and is being carried

Table 23-1. Scope of the EU's programme for research on partitioning and transmutation.

Programme	Period when projects are approved and started	EU grants in millions of euro for research and development on partitioning and transmutation
FWP 3	1991–1994	4.8
FWP 4	1994–1998	5.8
FWP 5	1999–2002	28.6
FWP 6 tentative	2003–2006	30–35

out in Cadarache, France. Hindas and N-TOF concern measurements of reaction cross-sections for neutrons with high energies etc. Pyrochemical partitioning processes were studied within Pyrorep. The project Partnew examined different organic compounds with a view towards possible use for partitioning of heavy transuranics. Calixpart studied organic compounds of another type for partitioning of e.g. actinides, cesium and technetium. Within the Sixth Framework Programme, all partitioning studies are coordinated within a so-called integrated project Europart, which started at the beginning of 2004. In a similar manner, a coordination of the transmutation projects within Eurotrans is planned. But this is not expected to start until early 2005 at the earliest.

Research in Sweden

The Department of Nuclear Chemistry at Chalmers University of Technology (CTH) has been conducting SKB-funded research on partitioning since 1991. The research on transmutation at the Royal Institute of Technology (KTH) in Stockholm is principally concentrated on accelerator-driven systems (ADS). The research at the Department of Nuclear and Reactor Physics has been supported by SKB since 1993. Projects for measurement of cross-sections for neutrons in the high-energy range 20 to 100 MeV are being carried out at The Svedberg Laboratory (TSL) and the Department of Neutron Research at the University of Uppsala. The projects are being funded in part by contributions from SKB, the nuclear power plants and SKI.

The Swedish research groups are participating in several EU projects. The Department of Nuclear and Reactor Physics at KTH is the coordinator of the project Confirm, where plutonium nitride fuel (PuN fuel) will be irradiated at the R2 reactor in Studsvik. Additional EU projects where Swedish research groups are participating are PDS-XADS (KTH), Future (KTH), Spire (KTH), Tecla (KTH, Nuclear Safety is coordinator), Muse (KTH), Hindas (UU) and Partnew and the new Europart (CTH, Nuclear Chemistry is participating in both). In the Tecla project, a special circuit has been built in a laboratory at KTH for studying thermohydraulic conditions during lead-bismuth cooling. This project is being funded in the EU's Fourth Framework Programme. A continuation is planned within the Sixth Framework Programme, as a part of Eurotrans, where, incidentally, both KTH and Uppsala University plan to participate.

The Swedish research programme is being funded primarily by SKB and is partially coordinated with the EU projects in which the Swedish groups are participating. SKB has provided some support to all of these projects except Tecla. The results of the Swedish research are reported in various scientific publications. Furthermore, annual reports are compiled by the three groups at CTH, KTH and Uppsala University. The last three years' reports /23-11 to 23-20/ contain summaries of the most important results as well as abstracts, reprints and/or references to the scientific papers. During the period 2001–2003, two doctorates, five licentiate degrees and five undergraduate degree projects have been based on work within the Swedish programme for Partitioning and Transmutation.

In recent years, the nuclear chemistry group at CTH has increasingly tied their P&T research to the partially EU-funded projects described briefly above. The following are among the more important projects in recent years. The formation of nitrate complexes with promethium, europium, americium and curium has been investigated. The results of these studies will soon be ready for publication. Nitrate complex formation has also been investigated experimentally for other lanthanides.

The basic chemical properties of bromodecanoic acid have been determined. It is important to know how this extraction reagent works when it is used in combination with various nitrogen-based synergy reagents. The results will hopefully be able to provide information on the extraction mechanism.

The basic chemical properties of several nitrogen-based synergy reagents have further been studied. The results have been published for two of the reagents. Several other compounds, synthesized by the University of Reading, have also been tested, but the results are not yet ready for publication.

A mixer-settler battery has been put into operation and modified for process studies of ligands developed in the Partnew project. First process parameters were determined for an analogue system, after which the results were used to design a partitioning process for the desired substances. However, due to the cost of the specially formulated reagent, this process could not be test-run. Hopefully it will be able to be tried in the Europart project by use of a new micro-separation technique.

Predictions of the distribution of metal between organic phase and aqueous phase can be done with models using the theory of solubility parameters. It has been shown that distribution coefficients for solvent mixtures can be simulated with good accuracy. The improved theory has been published.

The emphasis in research on transmutation at the Department of Nuclear and Reactor Physics at KTH is on safety aspects of accelerator-driven systems. A computer code based on the Monte Carlo method for simulating burn-up in a subcritical reactor connected to an accelerator-driven source has been developed at the department. The program uses extensive data libraries with continuous energy-dependent reaction cross-sections, decay schemes, isomeric states, exchanges of fission products from various nuclides, etc. The program can simulate neutron transport, material density and burn-up in three dimensions.

In recent years, the research at KTH has been tied to projects within the EU's framework programmes, in which the department actively participates. The following examples can be mentioned:

- Studies of core design in subcritical reactors for ADS optimized for high transmutation rates and good safety features. Both lead-bismuth-cooled and gas-cooled systems have been analyzed as a part of the EU project PDS-XADS.
- Analyses of ADS dynamics and assessment of major reactivity feedbacks.
- Emergency heat removal from ADS.
- Participation in subcritical experiments in Cadarache (EU project Muse – fast neutrons) and in Minsk (ISTC project Yalina – thermal neutrons).
- Participation in design of subcritical experiment in Dubna (ISTC project SAD – fast neutrons).
- Sensitivity analyses for nuclear data in association with PDS-XADS.

The department is also participating in studies of the potential of transmutation in high-temperature gas-cooled reactors (HTGR).

Within the EU's Sixth Framework Programme, the KTH group is coordinator for the project RedImpact, whose purpose is to determine what waste streams arise in conjunction with partitioning and transmutation and how they affect waste management compared with currently applied methods for disposal of spent nuclear fuel. SKB also has a small part of this project.

Transmutation requires advanced fuel types. Different alternative fuel materials are being studied in the EU programme. The KTH group is coordinator of the project Confirm, which is investigating nitride fuels with plutonium and americium, in part by irradiation of PuN rods in the R2 reactor in Studsvik.

Activities within the Department of Neutron Research (INF) at Uppsala University are focused on experimental studies of nuclear reaction probabilities for different application areas, such as transmutation of nuclear waste, biomedical effects and electronics reliability. The experimental activities are primarily being conducted at The Svedberg Laboratory (TSL) in Uppsala, where the group has previously developed two unique instruments: Medley and Scandal. Together with SKI and the power utilities, SKB is funding the project Natt, Neutron data for Accelerator-driven Transmutation Technology.

Important results since 2001 include:

- Two unique experimental facilities have been completed, and the first results have been published.
- Analysis and documentation have been completed of previously performed measurements of elastic neutron scattering from carbon and lead at 96 MeV. The precision in the results surpasses all previous data by at least an order of magnitude. These measurements represent the highest energy in neutron scattering where the ground state has been resolved from the excited state. The results show that all previous theory models have underestimated the probability of elastic neutron scattering at this energy by 0–30 percent.
- A new method for measuring absolute probabilities of neutron-induced nuclear reactions solely by means of experimental techniques has been developed. Previously, only two such methods have been known.
- TSL has decided to build a new, radically improved neutron beam facility. The first experiments with this facility were carried out in January 2004.
- A new experimental instrument for measurement of inelastic neutron scattering has been built, tested and found to meet the specifications. This work has been performed in collaboration with two French research groups from Caen and Nantes. The instrument will be used for a series of experiments during the coming years.
- Previous work by the group on nuclear data for assessment of electronics reliability has lead to a new industry standard in the USA.
- Clear evidence of three-body forces has been found in neutron scattering from deuterium. In the long term, this may be of very great importance for advanced theories of complex atomic nuclei.
- The activities have expanded substantially now than INF is conducting contract education for KSU since 2003.

Future development of P&T

Research and development efforts on P&T have increased somewhat during the period 1998–2003. Internationally, research on P&T has taken a prominent position in the R&D being conducted with regard to future nuclear power and nuclear fuel cycle systems.

Even though P&T research has been on the agenda for many years, there are still a number of questions that need to be cleared up before R&D in the field can be given a clearly focused direction. Previously mentioned studies in the USA and Europe have tried to define the programme that is needed to get into such a position. The studies proposed research programmes covering about six years at costs of a couple of hundred million euro.

Building a small experimental ADS facility is a necessary step in developing and demonstrating the concept. This experimental facility should then be followed by a near-full-scale demonstration facility. Such a facility cannot be ready before the mid-2030s.

However, due to a number of factors the speed, intensity and funding for the work are much lower than proposed.

There is no consensus on the strategic goals of partitioning and transmutation. Many see the goal as a way to gain broad acceptance for nuclear energy as a whole. Others see it as a way to break the impasse that has prevented progress towards a final repository in many countries. Still others attach great importance to the risks of proliferation created due to growing stocks of plutonium from light-water reactor fuel, from other reactor fuels and from dismantling of nuclear weapons.

There is no consensus on the need to develop accelerator-driven systems or on the role played by these systems in partitioning and transmutation. Some recommend that ADS should be used to transmute all transuranics from uranium fuel in present-day light-water reactors. Others see ADS as a complement that is particularly suitable for transmuting neptunium, americium and curium, while most of the plutonium should be burned in light-water reactors. In the long term, these systems may be replaced by fast reactors.

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. The universities in many countries, including Sweden, also show strong interest. The research is attracting considerable interest among students in nuclear science. Numerous important research programmes are being pursued at universities and research laboratories in many countries.

The nuclear energy industry, however, 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 deep 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, launching and operating an efficient system for partitioning and transmutation.

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 deep geological disposal obsolete. The complex processes will inevitably generate some waste containing small amounts of long-lived radionuclides. A deep repository is required for this waste. Successful development of P&T may, however, reduce the requirements on the engineered barriers in the deep repository, as well as the volumes needed for waste deposition.

For Sweden it is important to follow international development efforts and to maintain a reasonable level of competence in the country at least as long as a substantial part of our electricity is produced by nuclear power. Competence developed through P&T research is also valuable and useful in the work of maintaining and developing safety and fuel supplies for the existing light-water reactors. And it is also of importance for assessing the further development of the 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 a system for P&T in order to efficiently reduce the quantity of long-lived radionuclides that must be disposed of in a geological deep 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 from 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 specifically for transmutation of americium, curium and neptunium.

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 and when, this can be utilized to simplify, improve or develop a system for final disposal of nuclear fuel 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. An overall assessment will also be made in connection with the evaluation after the first stage of deposition of encapsulated nuclear fuel in the deep repository.

SKB concludes that accelerator-driven systems is currently the alternative line of development for partitioning and transmutation that is attracting the greatest interest, both in Sweden and in many other countries. In view of the development situation, requisite resources and current energy policy in Sweden, SKB does not deem it reasonable to undertake major development projects on its own.

A question that was touched upon in the review of RD&D-Programme 2001 is what is a reasonable scope of the Swedish research activities for P&T. Some universities and institutes of technology thought that the scope of SKB's activities was too small, SKI found them to be of a reasonable scope in the given situation, while Kasam called for an inquiry to determine a reasonable scope. The scope of the necessary efforts is of course dependent on the goal and the level of ambition, but also on the time perspective. As is evident from the studies described in brief above, the time perspective is very long. It will take several decades or so before the technology could be ready for industrial application. Furthermore, the programme of research and development that is required for success is of particularly large scope and can only be carried out in broad international collaboration. The Swedish contribution can only be marginal in this context. However, it is important to develop and maintain competence so that international development efforts can be followed and assessed. When SKB became involved in the research on P&T, the judgement was made that it is important to develop competence both in partitioning and in transmutation. In view of the desire not to siphon off too many resources from the prioritized area for research and development – deep geological disposal – it was judged appropriate to support research and development at universities and other institutions of higher learning, mainly as doctoral theses, and to concentrate this support on a couple of institutions. Supporting research on partitioning and transmutation also contributes to the development of specialist competence which is of interest and benefit in a broader perspective for the entire area of nuclear waste and nuclear energy. As mentioned above, this was also pointed out by SKI in its review of RD&D-Programme 2001.

The result of these arguments was that SKB undertook to fund research concerning partitioning at the Department of Nuclear Chemistry at Chalmers University of Technology (CTH) and concerning transmutation at Department of Nuclear and Reactor Physics at KTH. In order to reach an effective level, it was regarded as a minimum to have a couple of doctoral candidates at each location, plus some faculty supervision and good opportunities for international contacts. Later SKB also went in as a partial sponsor, together with the nuclear utilities and SKI and others, of research on nuclear data at Uppsala University. Access to fundamental competence in the field of nuclear data is necessary for all nuclear activities in the country.

SKB's annual budget for P&T research has been around SEK 5 million in recent years; it is SEK 5.2 million for 2004. The work largely funded by SKB has also enabled the three groups to establish broad international cooperation both inside and outside the EU. This has in turn meant that additional projects and funding have been obtained within the framework of the EU programmes. In recent years, this funding has totalled around SEK 3 million annually. SKB agrees with SKI's judgement that the funds allocated by SKB to research on partitioning and transmutation should not decrease below the current level. On the other hand it is difficult at present to find strong reasons to increase the funding. The judgement of in what direction and at what pace the field will develop is still unclear and highly uncertain. A relatively large study of a European experimental facility with ADS is planned within the EU's Sixth Framework Programme. Furthermore, the big French programme during 2006 will probably undergo a thorough evaluation according to the special law from 1991. These events may lead to a clearer picture regarding the future of P&T. It does not seem reasonable to increase the Swedish efforts in P&T at this time.

SKB intends to continue to conduct domestic research at universities and institutes of technology on roughly the same scale as now. The purpose of the research will primarily be to participate towards clarification of fundamental technical questions surrounding P&T. The focus should particularly be on questions of safety, materials, process design, and composition of the waste streams. In this way, domestic competence will be created and SKB will have a basis for judging the prospects for and features of systems for P&T. The work will also be pursued in close contact with international development efforts in the field.

SKB may also want to participate – in an appropriate way, at an appropriate time and on an appropriate scale – in international (particularly EU) projects that may be launched.

23.2 Disposal in Very Deep Holes

In the disposal alternative known as Very Deep Holes, canisters of spent nuclear fuel are deposited at a depth of between two and four kilometres. The rock constitutes the most important barrier for isolating the waste. At a depth of two to four kilometres, groundwater conditions are assumed to be very stable. Any groundwater movements that do occur are expected to occur at great depth without any contact with the ground surface. This would mean that no radionuclides could be transported up to the surface, but this remains to be shown.

Conclusions in RD&D 2001 and its review

SKB has previously studied what scope and content would be needed in an R&D-programme to make it possible to evaluate the Very Deep Holes concept on equivalent grounds as KBS-3 /23-21/. The study 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. Development of drilling technology involves great uncertainties and could delay the programme further and also increase the costs. SKB's judgement is that there is no evidence that safety would increase or costs decrease if the spent fuel were instead disposed of in Very Deep Holes. There is therefore no reason to carry out the programme. The resources should instead be concentrated on realizing a repository based on the KBS-3 method in the near future.

SKI says in its review that the need for and scope of a safety assessment of the VDH concept should be discussed within the framework of the consultation between SKB and the authorities that the Government decided on in 1996 and 2001.

SSI says that an account that includes a safety assessment of VDH could comply with the requirement for an account of alternatives that is mentioned in the Environmental Code.

Kasam shares SKB's opinion that adequate reasons do not exist for implementing the outlined RD&D programme for Very Deep Holes. They believe that strong reasons exist for the current direction of the Swedish nuclear waste programme, i.e. continued development work aimed at direct disposal according to the KBS-3 method.

Kasam says that disposal in Very Deep Holes is not a realistic method such as is required in the environmental impact assessment according to the Environmental Code. The alternatives to the KBS-3 method which are supposed to be described according to the Environmental Code should be sought in the category "built repositories within the uppermost kilometre".

Newfound knowledge since RD&D 2001

A literature review was recently conducted to supplement previously gathered geoscientific information about conditions at depth in the earth's crust /23-22, 23-23/. The focus was the same as before, i.e. to provide information as a basis for judging the possibility of depositing radioactive waste in four-kilometre deep vertical boreholes. The update consisted of geoscientific information published in the open literature since 1997, and the emphasis was on crystalline rock of relevance to SKB's disposal concept.

The literature shows that scientific investigations in existing deep boreholes in the world have continued. Examples are the KTB Field Laboratory in Germany and the Kola SG-3 Deep Geolaboratory in Russia. New deep boreholes are also being drilled, for example the geothermal borehole in Skåne down to a depth of about four kilometres, of which about two kilometres are being drilled in underlying crystalline bedrock.

It is generally expected that fracture frequency, hydraulic conductivity and porosity will decrease with depth in crystalline rock due to increasing rock stresses. At a depth of four kilometres it can be expected that groundwater circulation will virtually cease, that hydraulic conditions can be regarded as static, and that diffusion will be the dominant mechanism for mass transport. Another contributory reason for this would be the increasing salinity gradients that are normally observed with increasing depth. Solutions of such high salinity that they can be designated as brines are often encountered. The higher density of this saline water should inhibit vertical circulation for purely physical reasons. Petrologists have maintained that free fluids are probably absent at even greater depths. Long-term geochemical reactions can be expected to have consumed the free fluids. It is important to note – after the completed literature review – that this simplistic view of how conditions ought to be at great depth has not been borne out by the studies that have been carried out on the Kola Peninsula in Russia and in Germany /23-23/.

The literature review summarizes the most recent results and draws a series of general conclusions regarding what this means for disposal in Very Deep Holes. As far as thermal properties are concerned, it is clearly difficult to estimate temperature and thermal conductivity at great depths, particularly if the bedrock is of heterogeneous composition. Hydraulically speaking, much of the information suggests virtually stagnant conditions in the groundwater at great depths, and the high salinities would contribute to this. At the same time, however, there are observations that indicate that relatively rapid transport of solutions may be possible even in environments with brine concentration /23-24/. Claims that flow and transport occur over great distances down at a depth of several kilometres may therefore be difficult to prove wrong. This is of special interest for SKB, since the rock would be an important barrier in a concept with disposal in Very Deep Holes.

The presence of bacteria at great depths is also discussed in the report /23-23/. It is assumed that the temperature at a depth of four kilometres will not exceed 115°C and that bacterial life will therefore be fully possible. In other words, a sterile environment cannot be guaranteed.

Programme

SKB will continue to follow development work in the field of VDH. Four years ago the German company Deutag was commissioned by SKB to conduct a review of the technical prospects for VDH /23-25/. This review may possibly be redone during the coming three-year period, but this needs to be discussed, since the value of additional studies is limited.

Part IV
Low- and intermediate-level waste

24 Decommissioning

The facilities covered by SKB's RD&D-programmes are the Swedish nuclear power plants and SKB's own facilities. When it comes to radioactive waste management, the programmes also include the waste from Studsvik, the Fuel Factory in Västerås, Ranstad, and, last but not least, the Ågesta reactor. The costs for management and disposal of radioactive waste from these suppliers are not covered by the funds allocated to the Nuclear Waste Fund, but are funded and paid separately. SKB's work for decommissioning of the Swedish nuclear power plants in Oskarshamn, Barsebäck, Ringhals and Forsmark is discussed in the following.

24.1 Planning

The timetable for decommissioning of the nuclear power plants has not been finalized. The power companies estimate that the operating time of the reactors could end up being 60 years or more. SKB's planning and cost estimates in Plan 2004 are based on the assumption that the power plants are operated for about 40 years and are then decommissioned as soon as possible. The final planning for construction, operation and decommissioning of SKB's facilities is based on the planning at the NPPs. Other facilities are decommissioned so that they fit in chronologically with these plans. They are financed outside of the Financing Act, and not by the Nuclear Waste Fund.

The cost of decommissioning a nuclear power plant is updated annually based on the knowledge and experience gained from our own studies and from following international development efforts. A detailed estimate of the decommissioning costs is presented in SKB's annual Plan report /24-1/.

Current situation

Owners of nuclear installations are obliged to ensure that the installations are decontaminated and dismantled to a sufficient extent when they have been taken out of service. There are no specific regulations governing this in Sweden today; judgements are made by the regulatory authorities (SSI and SKI) from case to case. There have not yet been any large-scale decommissioning projects in Sweden. As of the closure of Barsebäck unit 1 in 1999, however, planning for a future decommissioning has assumed more concrete forms.

The division of responsibility between SKB and its owner companies is such that SKB carries out general decommissioning studies and ensures that the necessary technology and competence exists and that the costs are estimated correctly. The nuclear power utilities take responsibility for the planning, licensing and execution of decommissioning of their own facilities. Management of the waste is coordinated with SKB. SKB keeps track of international developments in the decommissioning field by participating in the decommissioning studies undertaken by international organizations, but also by direct contact with various decommissioning projects that may be of value for planning in Sweden.

The experience we have of decommissioning in Sweden today is limited to small research plants that have been decommissioned. The biggest one is the R1 research reactor on Drottning Kristinas väg near KTH in Stockholm. Decontamination and dismantling of the ACL (Active Central Laboratory) in Studsvik is under way, and SKB is learning from this experience.

Decommissioning logistics

The Swedish NPPs were commissioned during a relatively short span of time. The oldest is from 1972 and the youngest from 1985. Assuming that the service lives of the NPPs are equally long, they will be taken out of service over a 13-year period. An exception is Barsebäck 1, which was shut down in 1999, long before the end of its technical lifetime.

When should a deactivated nuclear power unit be decommissioned? International experience shows a multitude of variants, ranging from immediate and complete dismantling and demolition to variations of safe enclosure/safestore for an indefinite length of time. The reasons for these variants are many, and the method chosen must be tailored to prevailing conditions. In Sweden, dismantling is assumed to take place relatively soon after shutdown and removal of the spent fuel. This is also the trend that can be discerned internationally. The reasons for such immediate dismantling differ from country to country. It may be, for example, that there is a need to use the site for other activities. Other reasons may be so that the expertise that exists at the plant can be utilized, or to demonstrate that decontamination and dismantling can be carried out safely and economically.

Dismantling is assumed to take place after a relatively thorough decontamination of the facility's process systems. This is done to reduce radiation to the dismantling 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 carried out, it is assumed in SKB's studies that system dismantling is done first and that this takes at least three years. Decontamination of buildings and dismantling of contaminated building parts then follows. Finally, the conventional inactive systems and buildings are dismantled and demolished. This is estimated to take about two years, after which the plant site is restored to an industrial site for other activities. A total dismantling and demolishing time of about six years after removal of the spent fuel, which takes about two years, is judged to be the shortest possible decommissioning period.

24.2 Technology for dismantling

Quite a bit has been done here, mainly in other countries, but SKB is also pursuing its own technology studies, and the power companies will also eventually conduct studies aimed at planning for the decommissioning of their own facilities. The decommissioning projects that have been and are being carried out in various countries have shown that technology exists for decommissioning and disposal of the waste from all types of nuclear installations. What remains to be done is optimization and adaptation of existing technology for decommissioning of the Swedish NPPs.

The technology studies being carried out by SKB are aimed at presenting a possible scenario for decommissioning of the Swedish NPPs based on technology that exists, and is in use, today. With the chosen technology as a base, an estimate is also made of what times, costs and waste quantities are associated with the decommissioning.

When a nuclear power plant has been taken out of service, the site must be restored so that it can be used for other industrial activities without any radiological restrictions. This must be done in such a manner that neither the personnel engaged in the decommissioning and dismantling work nor the general public are exposed to unnecessary irradiation.

The design and licensing process for disposal of the radioactive waste from decommissioning requires planning on the national level. This planning must be done in cooperation between the power companies and SKB. Such planning offers advantages with regard to access to special equipment and specially trained personnel, as well as an opportunities for experience feedback. The point of departure for planning is that no unit is decommissioned as long as a nearby unit is still operating. Taken together, this means that the first decommissioning will not be commenced until some time after 2015, and probably not until a few years into the 2020s. If the operating time of the NPPs is extended, or if the power companies decide to allow the radiation from the reactor to decay for a period, dismantling will begin at a later time.

The power companies bear primary responsibility for planning and execution of the dismantling work. Their responsibility also includes determining which strategy is to be applied regarding the timing of dismantling and the technology to be used. Treatment of the radioactive waste will be planned and carried out in cooperation with SKB.

SKB is responsible for management and disposal of the radioactive waste that arises from decommissioning (the non-radioactive waste is taken care of by the power companies). For this, the transportation system needs to be modified and final repositories built. The short-lived decommissioning waste is planned to be disposed of in an extension of SFR. The waste that has been close to the reactor core is highly neutron-irradiated and is regarded as long-lived. This waste is first placed in interim storage before it is finally disposed of in a repository similar to SFR but at greater depth. This repository can be built adjacent to either SFR or the deep repository for spent fuel. A third alternative is to build the final repository for long-lived waste at a separate site.

Conclusions in RD&D 2001 and its review

No review of RD&D 2001 indicates that any authority has any objections to SKB's method descriptions regarding decommissioning. On the contrary, they point out that the work is being done in an ambitious manner. Like SKB, the authorities conclude that decommissioning technology exists today that can be adapted to Swedish conditions.

Newfound knowledge since RD&D 2001

Experience from development of decommissioning methods is received continuously from the international groups in which SKB and the power companies are participating. Technology development in Sweden for rebuilds and modifications in the NPPs is also a source of experience for planning of decommissioning of the NPPs. Newfound knowledge since RD&D 2001 is summarized in /24-2/.

24.3 Waste from decommissioning

The greatest quantity of waste obtained during decommissioning of a nuclear power plant consists of conventional building material that is not radioactive.

Of the radioactive material, a large portion is very low-level. Following decontamination and/or melting, quite a bit will be able to be reused. How much depends partly on how reliable the available measurement methods are and partly on what rules for free release are applied. Today there are no general rules for free release of material from decommissioning; instead, the regulatory authorities decide this from case to case, since no major decommissioning projects have been started yet. For small quantities, there are rules for removal from the NPPs.

The waste that is not released for unrestricted use will be disposed of in special repositories. The short-lived decommissioning waste is planned to be disposed of in an extension of SFR. This extension must be built so that the first phase is finished when dismantling of the NPPs begins. A final repository for the short-lived waste will not be needed until 2020 at the earliest, see Figure 25-1.

Long-lived waste from decommissioning consists primarily of the reactor internals, which were exposed to considerable neutron irradiation during operation. They comprise a small volume (when packaged, less than 1,000 m^3 for an NPP), but need to be managed separately. They are highly radioactive and therefore require extra shielding, and they contain large quantities of long-lived radionuclides, which means that they should be disposed of at greater depth than the short-lived waste. SKB plans to keep this waste in interim storage until most of the NPPs have been decommissioned. The waste will then be emplaced in a special repository, which is planned to be built e.g. at SFR but at greater depth. The long-lived waste from research etc that is packaged and kept in interim storage at Studsvik will also be disposed of here.

Conclusions in RD&D 2001 and its review

SKI considers it reasonable to demand that all types of decommissioning waste must be able to be managed from 2015. According to SKI, there is a risk that the long-lived waste will be a bottleneck if planning and design of an interim storage facility is not started soon. According to SSI, development of a system for interim storage of the long-lived waste from decommissioning, as an alternative to Clab, should be given priority.

Newfound knowledge since RD&D 2001

The short-lived waste from decommissioning of NPPs will be disposed of in an extension to SFR, which must be finished before a major decommissioning programme starts. This is estimated to occur no earlier than 2020. The power companies bear overall responsibility for obtaining the permits required and planning for decommissioning of their own plants.

Since RD&D 2001, the following activities have been carried out:

- Development of method for dry interim storage of core components as an alternative to storage in Clab.
- Establishment of register of decommissioning documentation.
- Introduction of system for registration of waste intended for disposal in future repository for low- and intermediate-level waste.

24.4 Programme

The overall goals of SKB's activities in the decommissioning field are to:

- Ensure that knowledge and technology for decommissioning are developed in good time before detailed planning of the decommissioning work begins. Is is, however, the owners of the nuclear installations who are responsible for ensuring that the necessary permits are obtained and for carrying out decommissioning of their own installations.
- Carry out cost calculations as a basis for determining the need for allocations to a sinking fund for future decommissioning costs.
- Ensure that the radioactive waste from decommissioning can be properly managed, transported and disposed of.

These goals are being met by keeping track of international development efforts and applying this experience to Swedish conditions, as well as by conducting independent studies and following the rebuilding and repair work being done in the Swedish nuclear installations.

A final repository for the short-lived waste must be ready to receive waste when decommissioning is begun on a large scale. The plan is to add an extension to SFR and license the entire facility for short-lived waste from both operation and decommissioning. Final disposal of the long-lived core components is planned to take place at a later stage, when most of the Swedish NPPs have been decommissioned. This means that the waste has to be kept in interim storage for some time. This is possible today in Clab, but an extension of Clab is required if all long-lived decommissioning waste is to be placed in interim storage there. SKB has therefore studied alternative interim storage alternatives.

The main thrust of the work during the upcoming six-year period will be:

- Studies regarding disposal of whole reactor pressure vessels and other large components. This should be possible, with savings in the form of both reduced dose load and time savings, but the consequences for transport and deposition need to be studied.
- An update of historical decommissioning studies is being carried out where various questions are examined in the light of present-day knowledge. A more comprehensive decommissioning study is being conducted.
- Estimation of dose budget for decommissioning of NPPs.
- Management of inactive waste (quantities, disposal, reuse).
- Overview of decommissioning logistics. Examine the consequences of extending operation from 40 to 60 years. Plan for the phase-out considering the fact that the resources for the phase-out will be limited.
- Preliminary safety assessments of final repository for short-lived waste (coordination of final repository for operational waste with final repository for short-lived waste).
- Work on a preliminary safety evaluation of long-term safety in the final disposal of long-lived low- and intermediate-level waste will begin at the end of the period.

25 Low- and intermediate-level waste

Most of the waste from operation and decommissioning of the nuclear power plants is short-lived and low- and intermediate-level. During operation and decommissioning of the NPPs also long-lived low- and intermediate-level waste arises.

25.1 Components of the LILW system

The system for managing low- and intermediate-level waste (LILW) handles all radioactive materials from the NPPs, with the exception of the spent fuel. Waste that is so low-level that it can be disposed of by on-site shallow land burial at the NPPs is not included either.

The LILW system can also manage the radioactive waste obtained from Studsvik, or waste from other use of radioactive materials in e.g. research and education and 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. Studsvik takes care of the institutional waste.

SKB's facilities for LILW today include the final repository for short-lived LILW from operation and maintenance of the NPPs (SFR), the interim storage facility for intermediate-level long-lived waste, core components, in Clab and the transportation system for LILW (Sigyn with transport casks, ATB).

The LILW system will later be augmented with a final repository for radioactive waste from decommissioning of the Swedish NPPs and phase-out of other nuclear activities.

The short-lived waste from decommissioning of NPPs is planned to be disposed of in an extension of SFR-1. In conjunction with the extension, a rearrangement is planned so that the entire SFR facility can be utilized for optimal disposal of waste from both operation and decommissioning.

Long-lived LILW is interim-stored today at Clab, at the nuclear power plants and at Studsvik. The long-lived waste has a relatively small volume so far, but this will increase with the decommissioning of the NPPs. An extended operating time will also presumably result in increased volumes from maintenance and repairs. SKB is therefore planning for a dry interim storage of core components to relieve the load on Clab.

The final repository for other long-lived waste is planned to be ready to receive waste in around 2045, when most of the waste will be available for deposition, see Figure 25-1.

SKB's activities in the LILW field are financed in part with money from the Nuclear Waste Fund (the repository for decommissioning waste and the repository for other long-lived waste) and in part directly by the owners (existing repository for short-lived operational waste). The parts of SKB's activities in this field that relate to Studsvik and other waste suppliers are financed separately.

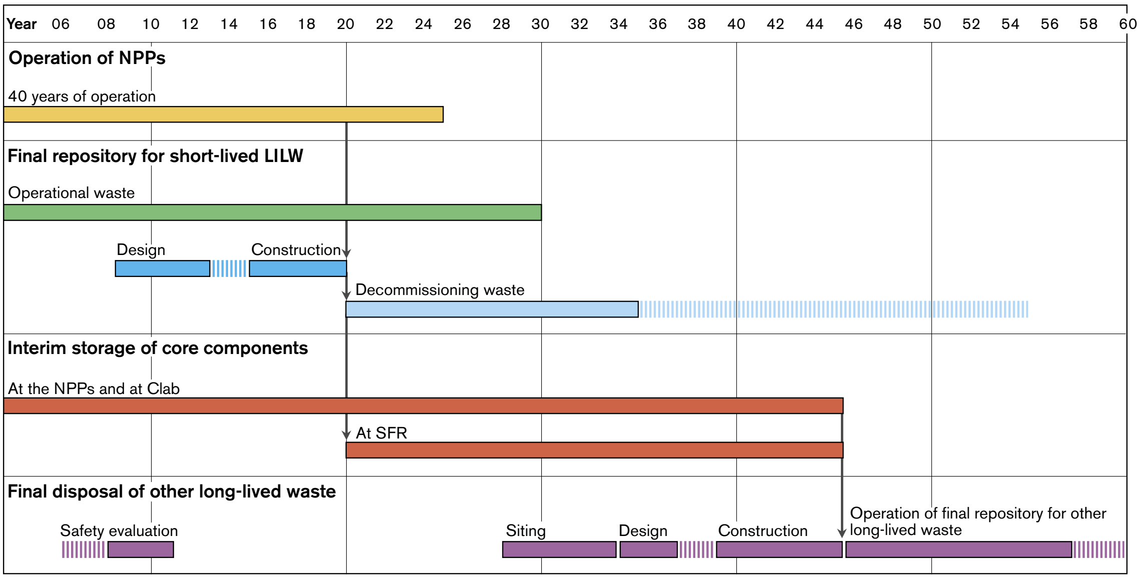


Figure 25-1. *General timetable for management and disposal of LILW, including waste from decommissioning of the NPPs.*

25.2 Short-lived LILW

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. Disposal of the portion for which SKB is responsible has been going on in SFR since 1988. In the future, 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 arise in the operation and maintenance of the NPPs, but in different proportions. These waste types will be able to be treated, transported and deposited in the same way as the operational waste. The decommissioning waste is dominated by scrap metal and concrete residues.

Conclusions in RD&D 2001 and its review

The review of RD&D 2001 called for a better clarification of how the waste from decommissioning will be managed, in particular the large quantities of low-level waste that are expected.

Newfound knowledge since RD&D 2001

SKB is striving for a more coherent planning and handling of issues related to the low- and intermediate-level waste. This is being done by e.g. recurrent waste forecasts as well as new and updated studies regarding quantities and types of waste.

As far as management of LILW is concerned, SKB is responsible for the waste that will be disposed of in SKB's facilities. Other kinds of waste, for example materials released for unrestricted use and low-level materials intended for onsite disposal at the NPPs, are also the responsibility of the NPPs. The whole problem can be addressed and optimal solutions found by cooperation between SKB and the power companies.

Programme

See section 25.5.

25.2.1 Repository for short-lived LILW

Final disposal of short-lived LILW takes place today in SFR. When the phase-out of the NPPs has reached the start of decommissioning, SKB must have a final repository for the short-lived waste ready to receive the waste. This repository is planned to be an extension of SFR. An extension for operational waste will be needed in the mid-2020s if many of the NPPs are operated for more than 40 years.

Conclusions in RD&D 2001 and its review

The regulatory authorities consider it reasonable that a final repository for decommissioning waste should stand ready to receive waste in 2015.

Newfound knowledge since RD&D 2001

The phase-out planning in effect today indicates that large-scale decommissioning will not take place until after 2020 at the earliest. In conjunction with the extension of SFR to receive decommissioning waste, SKB will re-license the facility so it can accommodate short-lived waste, regardless of whether it comes from operation or decommissioning.

Programme

See section 25.5.

25.2.2 Safety evaluation

No formal safety assessment has been carried out for the final repository for short-lived decommissioning waste since the preliminary safety assessment for SFR in 1982. The intention is to conduct a new preliminary safety evaluation during the period. A safety assessment will be submitted in connection with the publication of a preliminary safety report for the extended final repository for short-lived decommissioning waste in 2013.

25.3 Long-lived low- and intermediate-level waste

The long-lived LILW consists mainly of two categories:

- Long-lived waste from research, medical care and industry.
- Core components and some reactor internals (highly neutron-irradiated) from maintenance and decommissioning of the NPPs.

The first category is packaged and interim-stored in a special rock cavern in Studsvik in moulds or drums for subsequent disposal. The material from the NPPs is interim-stored today in storage canisters in Clab, or at the NPPs. Final packaging is done in conjunction with disposal.

Decommissioning of the NPPs will give rise to large quantities of long-lived scrap (reactor internals and core components). Alternatives to interim storage in Clab will be investigated.

An inventory of the long-lived LILW that exists and is expected to arise was done in 1998 as a basis for the preliminary safety assessment of a final repository for other long-lived waste, which was carried out the following year /25-1/. The total volume of long-lived LILW from Studsvik was estimated at 1,850 m^3. Core components and reactor internals from the NPPs were estimated to total 7,800 m^3 for BWRs and 1,800 m^3 for PWRs. The volumes are calculated from the outside dimensions of the waste packages that already exist or will be produced.

A system for documentation of the long-lived waste has been developed by SKB. The system resembles the one for SFR waste, but also takes into account the fact that documentation takes place progressively. This is due to the fact that the waste is in some cases stored as raw waste for a long time before being given its final form for disposal.

Conclusions in RD&D 2001 and its review

SKI concludes that it is reasonable to focus the work on the radionuclides that contribute most to the calculated dose, such as chlorine-36 and molybdenum-93, but that SKB should also be prepared to study other nuclides that may be important at the next safety assessment.

Newfound knowledge since RD&D 2001

The long-lived LILW will be kept track of by SKB in a similar way as the waste destined for SFR. With time, this will give us a better picture of the radionuclide inventory in the waste.

Studies have been conducted on behalf of SKB at the Division of Nuclear Physics at Lund University to reduce the detection limit for nickel-59 in steel material. An earlier measurement method was mainly developed with regard to specimen preparation. The detection limit has been reduced by a factor of 20 compared with the previous level. In recent years, measurements have been performed on both steel material from BWR reactors and reactor water from PWR reactors.

A project has been started at the same division at Lund University to measure carbon-14 in ion exchange resins from Swedish reactors. Previously, carbon-14 has been measured in graphite from the decommissioned research reactor at KTH in Stockholm. Literature reviews have been conducted for the purpose of identifying suitable measurement methods for carbon-14 measurements in ion exchange resins.

SKB has also had measurements performed of the chlorine content of steel material at Imperial College in London. The purpose of these measurements was to permit more accurate calculation of the content of chlorine-36 in steel material from the Swedish reactors. The detection limits in these measurement series varied between 0.14 and 1.5 mg/kg (ppm). The majority of the specimens that were analyzed lay below the detection limits. The project entailed that an earlier method for cleaning of specimens had to be modified to prevent the chloride content from being affected in cases where the specimens contained quantities of molybdenum and tungsten.

Programme

See section 25.5.

25.3.1 Final repository for other long-lived waste

A layout for the final repository for other long-lived waste was prepared in 1996. This repository was to be able to receive long-lived LILW /25-1/.

Conclusions in RD&D 2001 and its review

The authorities /25-2/ note the lack of a coherent account of design studies and design requirements as well as requirements that must be made on a candidate site in order for it to meet the requirements made on the design of the final repository for other long-lived waste.

Newfound knowledge since RD&D 2001

SKB has not conducted any new studies of this nature.

Programme

Work on the design of the repository, and thereby coherent requirements on a candidate site, will be resumed in conjunction with the preparations for a new safety report for the final repository for other long-lived waste. At present, this work is planned to be commenced at the end of this decade. See also section 25.5.

25.3.2 Safety assessment

An initial safety assessment of a final repository for other long-lived waste was performed in 1999 /25-1/.

Conclusions in RD&D 2001 and its review

The safety assessment was thoroughly reviewed by SKI and SSI with the aid of an international team of experts. The conclusions from the review by both the international team of experts and the regulatory authorities have been reported in /25-3, 25-4/. Both the regulatory authorities and the team of experts draw the conclusion "that a great deal of research and development work remains to be done before the level of knowledge in this field is comparable to that associated with the final repository for spent fuel."

In the review of RD&D 2001, SKI also points out that the account of what will be included in the coming safety assessment is too scanty and difficult to assess, and that SKB needs to update the (previous) safety assessment, and that the work should begin immediately so that SKB can perform a renewed safety assessment after completion of the site investigations.

SKB's plans, which were presented in RD&D 2001, entail that the repository will not be sited and built for more than 30 years, and we wish to make use of this time to conduct the necessary research and development.

Newfound knowledge since RD&D 2001

No new safety assessment has been done; efforts have instead been focused on research and development, see further 25.4.

Programme

After the site investigations, we will have the time and the data necessary for a new safety assessment. The fact that the investigations are geared towards the repository for spent nuclear fuel is of no great importance, since basically the same type of site data are needed. The exact point in time for a new safety assessment will be chosen with reference to other safety assessments and resources. Figure 25-1 shows that according to current planning, a safety assessment will be submitted to SKI and SSI in 2011, see also section 25.5.

25.4 Research

The investigations that are being done are mainly aimed at furnishing data and models for assessing the long-term safety of a final repository for other long-lived waste. This knowledge is being built up partly through the research supported by SKB and partly by international studies in the field. We have found that among the most important processes that can affect the properties of the barriers in the long term are the following:

- Corrosion of steel and aluminium in a concrete environment (formation of gas and corrosion products).
- Concrete degradation in saline waters.

- Reactions between high-pH leaching products from cement and surrounding gravel fill.
- Precipitation of calcite and brucite (calcium carbonate and magnesium hydroxide).
- Alkaline degradation of cellulose in the waste (formation of complexing agents).
- Microbial and alkaline degradation of other organic material in the waste.
- Build-up of gas pressure in the waste packages and concrete enclosure.
- Influence of organic additives in cement on radionuclide sorption.
- Sorption properties of fresh and aged concrete.
- The importance of isotope exchanges and co-precipitation for retardation of low-sorbing radionuclides.

Metal reactor internals comprise an appreciable portion of the waste. Some radionuclides are present in crud on the surface of contaminated metal parts, but most of the activity derives from induced activity. Then the metal must first corrode to render the radionuclides accessible. The most common metal in waste with induced activity is stainless steel.

In contrast to the reactor internals, waste from research contains a large quantity of organic material.

Radionuclides, as well as hazardous substances dissolved in water entering the waste packages, can be transported out through the near-field barriers by diffusion and with water flowing through the barriers. This outward transport is retarded by sorption in cement, concrete and backfill gravel. Sorption is mainly dependent on the composition of the water, where pH, Eh and the presence of organic complexing agents are important parameters.

Conclusions in RD&D 2001 and its review

SKI believes that better process models are needed that describe the long-term degradation of concrete, and that should include a more detailed account of the influence of saline groundwater.

Newfound knowledge since RD&D 2001

Degradation of cellulose to ISA

Cellulose is broken down at high pHs and thereby forms a relatively large proportion of isosaccharinic acid, ISA. This product is in turn a strong complexing agent at high pHs. Since cellulose is a common material in LILW, this has been studied since it was noticed for the first time more than ten years ago. The phenomenon was recently thoroughly investigated, with support from SKB, at the Paul Scherrer Institute in Switzerland /25-5/ and previously in a doctoral thesis at Linköping University /25-6/. ISA is formed with high yield (70–85 percent), but the reaction ceases when approximately 20 percent of the cellulose has been broken down. These reactions are influenced by the temperature. ISA decomposes in contact with calcium hydroxide, one of the components in cement, and this reaction will be investigated more thoroughly.

Sorption of radionuclides in concrete

Concrete comprises an important barrier to the dispersal of radionuclides in a repository with LILW. Structural concrete is sufficiently dense to prevent the flow of water, but transport of dissolved radionuclides by diffusion is possible. Nevertheless, concrete is an effective barrier for most radionuclides in the waste, since radionuclides are sorbed on the concrete are thereby retained. SKB is subsidizing researchers at Chalmers University of Technology and the University of Linköping in their investigations of the influence of isosaccharinic acid and other organic compounds on sorption of radionuclides in concrete /25-7, 25-8/. An important observation is that isosaccharinic acid itself is strongly sorbed in concrete, which mitigates the effect which complexation with ISA can have on the mobility of the radionuclides. The effect of additives in concrete on radionuclide sorption has also been studied at the Paul Scherrer Institute and at Linköping University /25-9, 25-10/.

Degradation of concrete

The waste will be encased to a large extent in concrete containers. The enclosure with its backfill also consists of concrete. This concrete is an important barrier in the near field. Even though we don't believe that the concrete can prevent groundwater from entering the repository after closure, it will retain radionuclides, partly by virtue of its low hydraulic conductivity and partly by sorbing dissolved radionuclides. It is therefore important to understand how concrete ages. It is not so critical if some new cracks should form with time. We assume that the structure may have some cracks from the start. The hydraulic cage will work nevertheless, and the predominant transport mechanism will be diffusion. However, it is important that the structure does not collapse entirely and that its chemical properties are not completely altered during the time the repository's barriers are important for safety.

Water in contact with concrete will dissolve some of the components contained in the concrete. This could lead to degraded properties in the long term. Models exist for calculating leaching from concrete /25-11/. An urgent task has been to test these models. Samples of old concrete that has been in a water-saturated environment have been collected and investigated for this purpose /25-12, 25-13/. Although none of the samples is older than 90 years, it is nevertheless possible to follow the changes by means of microscopic examination.

Cement analogue

Hyperalkaline water (pH about 12) and primary and secondary cement minerals present naturally in certain areas in Jordan are being investigated in the Maqarin Project. The investigations have been under way since 1990 and the project is now into its fourth phase. Several organizations in different countries support the project. The final report for phase III was published in 1998 /25-14/, and the final report for Phase IV is planned to be finished in late 2004. The following points are examples of valuable observations:

- Minerals formed in cement paste remain for more than 100,000 years, provided that the hyperalkaline conditions persist.
- Hyperalkaline water reacts with the minerals in the rock. Secondary minerals are thereby formed, which tend to clog fractures and prevent the flow of water.
- The surfaces of the water-bearing fractures react with hyperalkaline water, but the porosity in adjacent rock is still available for inward diffusion of solutes (matrix diffusion).
- The colloid concentrations are low (like in ordinary deep groundwater) and we see no tendency towards production of colloids.
- Solubilities of different trace metals can be calculated at high pHs with the aid of thermodynamic constants, but the uncertainties are greater than otherwise. In general, however, the calculated values are conservative.
- Microbes can grow and be active under aerobic and anaerobic hyperalkaline conditions, but their growth and activity are very low.
- In Kushaym Matruk (in central Jordan), the illite and smectite minerals are more amorphous, i.e. they have a lower swelling capacity, close to the cement limit. High pH has spread a few metres into the sedimentary matrix by diffusion.

Experiments in situ

The laboratory experiments /25-15/ and the observations in Jordan indicate that water from leaching of concrete will react with the minerals in the rock. The scientific literature contains measurements of kinetics for reactions between minerals (for example quartz or feldspar) and water with very high pH. It is found that reactions can occur, but are sensitive to temperature. For this reason, most of the experiments are done at high temperatures.

In order to see how concrete pore water reacts with rock minerals in an actual repository environment and how this can affect radionuclides, experiments are being conducted in situ. SKB is participating together with Nagra, Andra, JNC and Sandia in the project HPF (Hyperalkaline Plume in Fractured Rocks) in Grimsel, Switzerland. Simulated cement pore water has been injected into fractures in the rock together with dissolved radionuclides. The fractures will be overcored and investigated afterwards. The project is being led by Nagra. It started in 1997 and will continue until 2004. A fracture has been selected in the underground facility in Grimsel, boreholes have been drilled and thoroughly investigated. Tracer tests in general, and with radionuclides in particular, require extensive preparations, but the results that have been obtained are valuable /25-16/. The field test has run into special experimental difficulties due to the use of highly alkaline solutions. Laboratory experiments and calculations have been performed as a complement to the field test /25-17, 25-18/.

Programme

See section 25.5 below.

25.5 Programme for low- and intermediate-level waste

Many of the studies concerned with the waste are applicable to all categories of low- and intermediate-level waste – both short-lived and long-lived – since the same materials and radionuclides occur in all waste types, to a greater or lesser extent. The same applies to packaging and handling, with the difference that long-lived waste must for the time being be packaged so that it can be reconditioned if the final design of the repository should require this.

A final repository for the short-lived decommissioning waste must be ready to receive waste when decommissioning is begun on a large scale. The plan is to add an extension to SFR and license the entire facility for short-lived waste from both operation and decommissioning. Final disposal of the long-lived core components is planned to take place at a later stage, when most of the Swedish NPPs have been decommissioned. This means that the waste has to be kept in interim storage for some time. This is possible today in Clab, but an extension of Clab may be required if all long-lived decommissioning waste is to be interim-stored there. SKB has therefore studied different alternatives for interim storage of this waste. The overall goals of the work with LILW during the period 2005–2010 are to:

- Put into operation a system for dry interim storage of core components in order to relieve the load on Clab.
- Prepare for future safety assessments.
- Develop handling and storage of the waste in cooperation with the NPPs.
- Carry out preliminary safety evaluations for final disposal of short-lived operational and decommissioning waste in SFR.
- Study the prospects for a shallow repository for very low-level decommissioning waste.

The experience gained from the safety assessment of the final repository for other long-lived waste and the update of the safety report for SFR (Safe) has given us valuable guidance for this. We now know what we should attach importance to and what type of information needs to be stored so that the material can be used for future reports and safety assessments. Furthermore, we are devoting particular attention to some long-lived nuclides which have proved to be important for long-term safety. For some of these we are trying to develop methods to analyze the content (by means of chemistry and calculations). A system for routine documentation of the composition, radionuclide content and properties of the waste is being developed at SKB. Documentation will take place in a similar way as for other LILW.

Research on processes in the repositories is important as preparation for future safety assessments. Many of the questions that need to be addressed are of a chemical nature and specific for the high pHs generated by the concrete in the repository and its near-field. The goals of the planned activities for the period 2005–2010 are as follows:

- Continue the studies of diffusion and sorption of radionuclides in high-pH concrete and rock. We do not intend to limit ourselves to studying actinides, but will also include activation products, such as activated molybdenum. An important aspect is the influence of organic compounds on radionuclide sorption at high pHs, in particular isosaccharinic acid and cement additives.
- Develop the models for concrete degradation, including the effects of saline water.
- Study the reactions between leachate from concrete and the surrounding gravel in the repository.
- Field studies and investigations of natural analogues of alkaline concrete environments.
- Corrosion of metals in a concrete environment.

So far we have used roughly the same model as in SR 97 for calculating radionuclide transport in the near-field, but a model more adapted to LILW would probably have been better. Different ways to better models will be tried.

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Appendix A

SKB's master plan

A1 Introduction

A1.1 Background

The political framework for the current stage of the spent nuclear fuel programme was established by the Government decision in November 2001 regarding SKB's integrated account of method and site selection (RD&D-K), followed by the concerned municipalities' decision processes regarding whether or not to participate, completed in April 2002. With the external framework in place, but still with a great deal of planning flexibility within this framework, SKB decided to carry out a review and revision of its programmes and plans. Attention was first directed towards the site investigation phase, i.e. the stage up until the permit applications for the encapsulation plant and the deep repository have been approved. However, in view of the many links, in terms of timing and activities, to longer-term planning and to other parts of the programme, the review was extended to include all of SKB's activities.

The regulatory review of RD&D-Programme 2001 occasioned additional programme revisions. In the review statement regarding RD&D-Programme 2001 which SKI submitted to the Government in March 2002, the Inspectorate called for a document from SKB that would explain more clearly SKB's plans for the remainder of the spent nuclear fuel programme. As a reason for this request, SKI said that the authorities concerned need to know which regulatory reviews are anticipated over the next ten years and how they depend on each other. This was considered above all necessary for the authorities' own planning, but also to describe in other contexts how SKB will achieve the goal of a safe final disposal of the nuclear waste. In its review statement on RD&D-Programme 2001, SSI had previously offered similar viewpoints but had given reasons that more emphasized the need to clarify links between SKB's RD&D activities and the implementation of the nuclear fuel programme so as to better be able to judge whether the research and development described by SKB is appropriate and adequate.

In its statement to the Government, SKI recommended that SKB be required to compile the requested material and present it no later than in connection with SKB RD&D-Programme 2004. Based on this, the Government stated in a decision from December 2002 that they "assume that SKB is conducting a dialogue with concerned authorities and municipalities and that an account of SKB's timetable with associated plan of action concerning a safe final disposal of the nuclear waste will be included in RD&D-Programme 2004". As has emerged from subsequent consultations and on other occasions, SKB essentially shared the opinions of the authorities regarding the need for clearer plans of action.

Against this background, SKB began the work of clarifying and updating its own short- and long-term planning and compiling the material requested by the regulatory authorities. A milestone was passed in the spring of 2003, when the board of SKB decided to revise the timetable for the spent nuclear fuel programme. A similar revision has since been done of the programme for management of low- and intermediate-level waste (LILW). The revised plans have been presented on different consultation occasions. This includes the aforementioned timetable for the whole deep repository project, as well as the planning for encapsulation, the remaining site investigations, and coming system and safety assessments. Figure 1 shows the main features of the long-term plan which SKB is now following.

This appendix is the requested plan of action. It presents and comments on SKB's planning for a safety final disposal of the nuclear waste and other radioactive waste from the Swedish nuclear power plants. The focus lies on the implementation of the spent nuclear fuel programme and the period up to 2008, including timetables, interim goals and links between the different parts of the programme. The LILW programme is described schematically. With regard to ongoing or planned research and development work aimed at making implementation possible, reference is made to the main report.

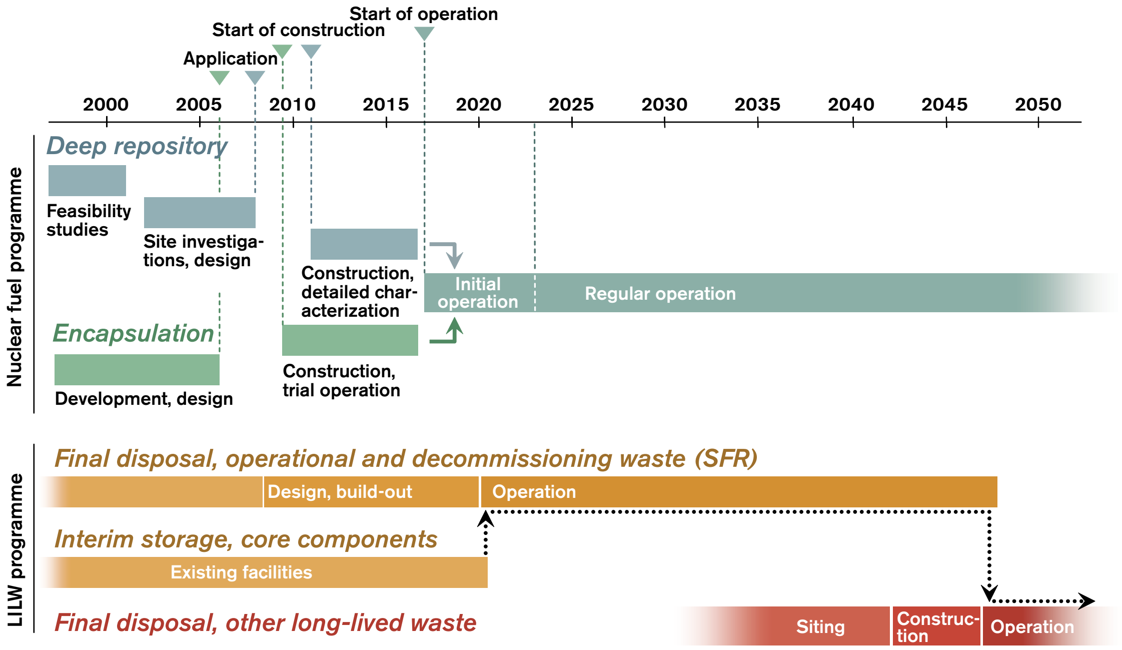

***Figure 1.** Main features of SKB's long-term plan.*

A1.2 Points of departure

The nuclear waste programme of today is the result of nearly 30 years of continuous work. During this period, a large part of the nuclear waste management system needed in Sweden has been built and put into operation. This has been done with the support of a broad R&D programme, and extensive knowledge capital has been accumulated. Concrete plans, as well as resources and commitments, exist for the rest of the programme. Regular payments to the Nuclear Waste Fund will ensure stable financing of the future programme, unlike anything existing in any other sector of industry. Administratively, the programme has gradually found its 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 municipalities that are particularly affected. Finally, the programme enjoys broad support.

What has been achieved so far can be regarded as painstakingly accumulated "capital", which is now contributing in several respects to driving the programme forward. With many years of unbroken progress to look back on, this driving force tends to be taken for granted. However, this capital could be lost, for example if the continuity is broken and the knowledge capital is squandered. A vital aspect of the strategy for moving forward is therefore to nurture and protect what has already been achieved. The importance of this can be seen clearly when a comparison is made with the situation in many other countries.

Siting of the remaining facilities in the system is based on a stepwise process with well-underpinned and firmly anchored decisions. The process is fully transparent and allows concerned municipalities to decide freely whether they wish to participate or not. This model has proved to lead forward, albeit at a somewhat slower pace than foreseen when the programme was initiated. The conclusion as far as SKB is concerned is that the established work model will be of great value now that the programme is entering the siting phase. An important lesson is that sufficient time must be set aside to gather a solid factual basis for decisions. This applies to both the big decisions regarding the siting and subsequent commissioning of the facilities, and the many smaller decisions that have to be made regarding e.g. details in the design of the facilities. The timetable must also allow time for public insight, consultation with concerned stakeholders, and anchoring of the problem in a democratic decision process. At the same time, implementation must proceed at a sufficiently intense pace to meet SKB's basic requirement that the waste from the nuclear energy programme should not burden future generations unnecessarily. Another reason for the high pace of work is the ambition to exploit existing knowledge and skills and thereby promote quality in implementation.

A guiding principle for SKB's planning of the remainder of the programme is to strive for a reasonable balance between, on the one hand, justified requirements on sufficient time for proper decision processes and, on the other hand, the continuity and intensity that are required if the programme is to be implemented with good results. This attitude continues to permeate the way all the stakeholders work, including those who play a leading role in the licensing processes.

Spent nuclear fuel programme

The KBS-3 method, which is SKB's main alternative for final disposal of spent nuclear fuel, has stood the test of time, having been subjected to repeated regulatory review and comparison with alternative methods. This applies to both the crucial safety-related aspects and aspects such as technical feasibility and resource-effectiveness. SKB's strategy is therefore to optimize and realize a final repository in accordance with the KBS-3 concept. Implementation will be based on tried-and-tested technology, but technical advances made during the course of the work will also be put to use. Progress with regard to alternative concepts and disposal methods will continue to be monitored and evaluated in relation to SKB's main alternative.

The nuclear fuel programme must manage all spent fuel generated by nuclear energy production in Sweden. It must therefore be adjustable to different outcomes as regards the remainder of the nuclear energy programme. The scenario on which SKB's planning is based is that the reactors that are still in operation, i.e. all except Barsebäck 1, will be shut down after 40 years of operation. This gives a total fuel quantity of about 9,300 tonnes of uranium, which is equivalent to a deep repository for about 4,500 canisters of the type that will be used according to the current reference design. The programme permits both larger and smaller fuel quantities to be managed, the only consequences being that the total operating time of the management system, and the space requirement in the deep repository, are affected.

LILW programme

Parts of the system for management of low- and intermediate-level waste (LILW) have been in operation since the 1980s, including final disposal of various types of operational waste at SFR in Forsmark. This means that a good knowledge base exists for the remaining steps, including extensions of SFR and, as the last step in the process, a final repository for other long-lived waste.

Of the waste types which the LILW programme will manage in the future, waste from decommissioning of the nuclear power plants represents the dominant fraction in terms of volume. This will require extensions, in accordance with a timetable that can be adjusted to future decisions that will determine the pace of the phase-out and subsequent decommissioning of the NPPs.

A2 Programme for spent nuclear fuel

A2.1 Overview

The current situation in the spent nuclear fuel programme can be summarized in the following points:

- The development of the disposal method that is SKB's main alternative is in a phase featuring pilot- and full-scale tests and demonstrations of system components. The Canister Laboratory and Äspö HRL are the main venues for these activities. In many cases the activities require access to resources and experimental settings which only SKB's own laboratories can offer.

- An encapsulation plant co-sited with Clab is planned. Design of the plant is under way and development of the encapsulation technology is proceeding. As an alternative, a siting at a deep repository in Forsmark will be examined.
- Two candidate sites are being investigated for the siting of the deep repository: Forsmark in the municipality of Östhammar and Simpevarp/Laxemar in the municipality of Oskarshamn. These sites were prioritized after a decision process based on broad information gathered from general siting studies and feasibility studies. The intention is that one of the candidate sites will be chosen later on as the site of the deep repository.
- The selection pool for siting of the deep repository that is currently available also includes other sites that remain as possible alternatives, in the event the investigations of the candidate sites do not yield satisfactory results. Furthermore, a large body of comparison material is available from the study site investigations conducted previously at some ten sites in various parts of the country, as well as from investigations in the Finnish nuclear waste programme.
- Both the encapsulation plant and the deep repository require permits under the Environmental Code and the Nuclear Activities Act. Statutory consultation procedures for this have been commenced, and the coming decision processes are well defined.

On this basis, SKB has updated the plans of action for the remainder of the programme. The main goal is to be able to put the entire system, including the remaining facilities, into operation. The more immediate goal is to obtain the permits needed to establish the encapsulation plant and the deep repository.

Time horizon 2017

The current timetable for the two remaining nuclear facilities in the programme, up to the start of operation of the entire system, is shown in Figure 2. The plan has been revised slightly compared with the one presented in RD&D-Programme 2001. It shows the best estimate SKB can make at the present time. A prerequisite for implementation is that the broad political support enjoyed by the deep repository programme today is sustained.

It is projected that the waste management system, including an initial stage of the deep repository, will be able to be put into operation in 2017. The initial operating phase includes 200–400 canisters, and is intended to serve as a final trial and demonstration of the method. Initial operation will last for several years and be evaluated before a decision is made whether or not to proceed to regular operation of the system. If the evaluation provides support for a transition to regular operation, the latter can be commenced almost immediately. How long regular operation then needs to continue is directly dependent on the operating times of the NPPs. SKB's planning assumption is that all reactors except Barsebäck 1 (shut down in November 1999) are operated for 40 years. With an average deposition pace of about 160 canisters per year, this would mean that the deep repository would continue to operate until the early 2050s and that the whole programme could be wound up in around 2060. The capacity requirement for the deep repository system at full operation is set at 200 canisters per year.

At the end of 2003, just over 4,000 tonnes of spent nuclear fuel were in interim storage at Clab. Plans call for the completed extension to Clab to be commissioned in the autumn of 2004. The space that will thereby be freed for interim storage is judged to be sufficient for the needs of the entire nuclear fuel programme, provided that the system for encapsulation and deep disposal becomes available according to the timetable in Figure 2. If this is delayed, an additional extension of Clab may be necessary.

Time horizon 2008

The goal for the period up to the end of 2008 is to be able to submit permit applications for the system's remaining two nuclear facilities. Crucial prerequisites for being able to realize this goal are:

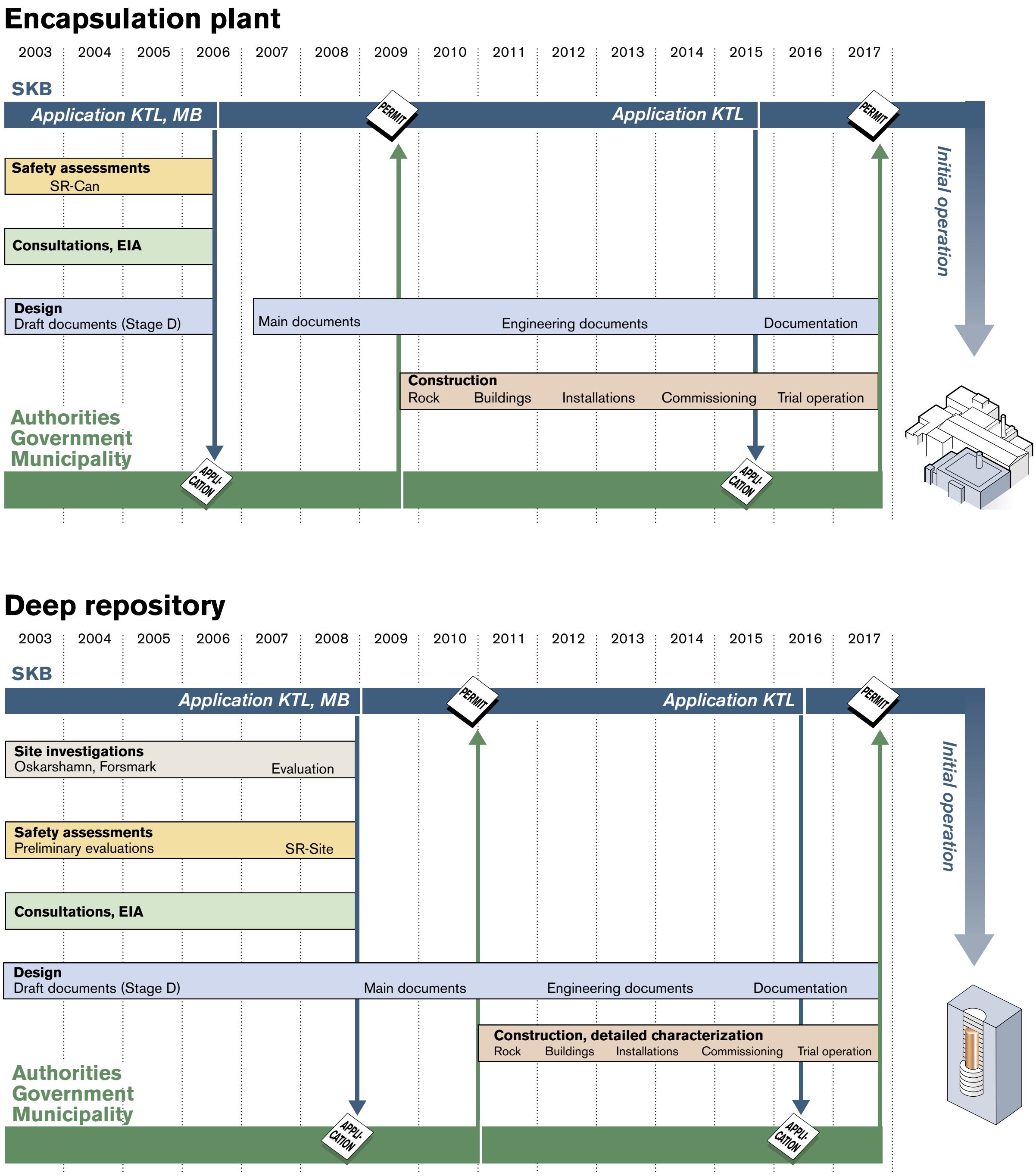

Figure 2. *Timetable for the encapsulation plant and the deep repository, 2003–2017.*

- Application for a permit to build an encapsulation plant assumes co-siting at Clab. If the Clab siting is rejected as the main alternative, the timetable must be revised. The second-choice alternative is a siting at Forsmark, which assumes that the deep repository is also located on this site.
- The initiated site investigations for the deep repository can largely be carried out within the planned timeframe (by the middle of 2007), and with results favourable enough to warrant an application for a permit to build the deep repository on one of the sites. An outcome where additional candidate sites for the deep repository must instead be added to the siting programme would require revision of the timetable.

- Development and optimization of the technology for encapsulation and deep disposal of spent fuel can continue at roughly the planned pace and with the anticipated results. Unexpected problems at some critical point may lead to delays and revisions.

Collecting, compiling and presenting the supporting material required for the permit applications is a large-scale and high-priority activity for SKB. The planning of this work is presented in greater detail in sections A3 and A4. Figure 3 illustrates schematically the supporting material that needs to be produced for each application and how the material is fed into the decision process, along with the planned times for submission of the permit applications. SKB's timetable is governed by the time required to complete the site investigations and the site-specific supporting material (facility design, safety assessment, EIS) that is based on these investigations. With this in mind, it is estimated that the permit application for the deep repository can be submitted by the end of 2008, while the permit application for the encapsulation plant is planned to be submitted in mid-2006.

The time required for the ensuing licensing process is governed by several factors:

- The quality of SKB's supporting material.
- The resources and capacity of the regulatory authorities and the Environmental Court to process and coordinate the matters.
- The readiness and will of the political bodies to make the final decisions.

Figure 3 reflects what SKB judges to be a reasonable plan and timetable for the licensing process. The process begins with SKB's permit application for the encapsulation plant in mid-2006, and the total estimated time for the process is 4.5 years. Besides a detailed description of the encapsulation technology, the plant, its safety and environmental impact, the permit application for the encapsulation plant will also include:

- An account of alternative methods for spent fuel disposal.
- A comprehensive system analysis for encapsulation, transportation and deep disposal.
- An analysis of the long-term safety of encapsulated fuel in a deep repository.

It is assumed that the decision on the encapsulation plant will not be able to be made until some time (around nine months) after the application for the deep repository has been submitted, at which point SKB's choice of site and a complete safety assessment for this site will be available to all concerned. In SKB's view, the licensing process for the deep repository should be greatly

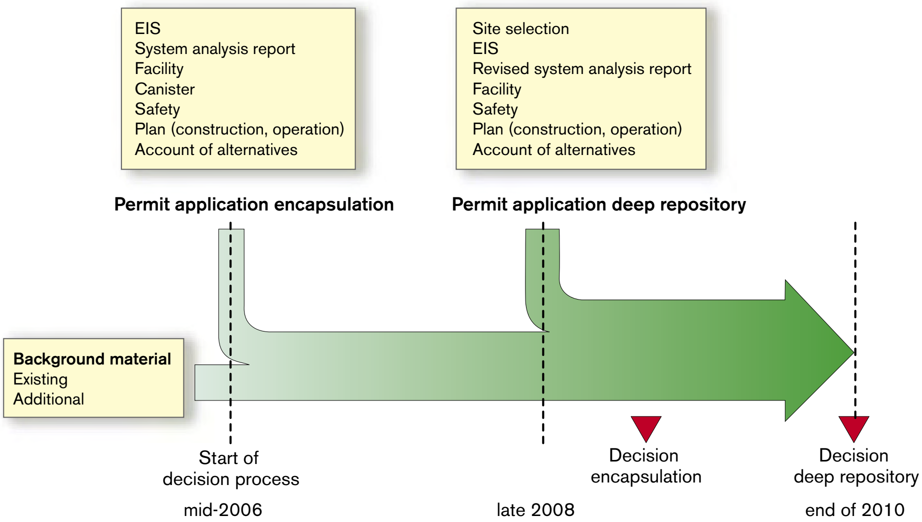

Figure 3. Permit applications and decision process for the deep repository system.

facilitated by the fact that the review of the encapsulation plant (which delivers the product to be emplaced in the deep repository) will have been under way for two years when the licensing process for the deep repository is begun.

Furthermore, it should be noted that according to the reasons given for the Government's decision regarding SKB's integrated account of method, site selection and programme prior to the site investigation phase (RD&D-K), the KBS-3 method is a planning premise for the site investigations, while final approval of a method for final disposal will not be given until a final decision is announced on the permit applications. In order to provide the necessary supporting material for such a decision, SKB will, as is explained above, include in the permit application for the encapsulation plant and associated environmental impact statement a description and evaluation of alternative methods for management and final disposal of spent nuclear fuel. This will enable the regulatory authorities and the Government to take a stand on SKB's choice of method when they consider the application for the encapsulation plant.

A2.2 Consultations and environmental impact statement

Licensing and permits

Three different permits are required for the deep repository and the encapsulation plant:

- Permit under the Environmental Code.
- Permit under the Nuclear Activities Act.
- Building permit under the Planning and Building Act.

The licensing processes under the Environmental Code and the Nuclear Activities Act proceed in parallel. The supporting material for each application must include an environmental impact statement, EIS, prepared in accordance with the rules in Chap. 6 of the Environmental Code. The EIS must show what consequences the planned activity may have for man and the environment, and how they can be prevented or mitigated. The scope of the EIS is determined within the framework of the established consultation processes.

Consultations

Early consultations should be held with the County Administrative Board and those individuals likely to be particularly affected. Early consultations have been carried out for both the encapsulation plant and the deep repository, in both Oskarshamn and Forsmark.

According to the Ordinance on Environmental Impact Statements (SFS 1998:905), a nuclear installation is always assumed to cause significant environmental impact. This was also the implication of the decisions made by the county administrative boards in Kalmar and Uppsala after SKB had submitted consultation reports from the early consultations. This means that extended consultation with environment impact assessment is required for both the encapsulation plant and the deep repository before the applications can be submitted. Extended consultations should be held with the County Administrative Board, other government agencies, the municipalities, the citizens and the organizations that are likely to be affected. The consultation shall relate to the location, scope, design and environmental impact of the activity or measure and the content and structure of the environmental impact statement.

The extended consultations began during 2003 and are being coordinated for the encapsulation plant and the deep repository on each site. The extended consultations can be divided into three phases:

- Scope of EIA.
- Investigation.
- Verification.

Initially the extended consultations have mainly dealt with the scope of EIA. Preliminary scoping reports have been prepared as a basis for discussion. They deal with what the EIA work should cover and what investigations are planned as a basis for the EIS. Viewpoints and proposals that emerge will be taken into account in the planning of the continued EIA process. The intention is that final versions of the reports will be written during 2004.

In the subsequent investigation phase, results from investigations and studies as well as proposals for facility design are presented at the consultation meetings, and the participants are given an opportunity to state their views. This phase continues for as long as investigations, facility design work and studies are pursued, i.e. until the end of 2005 for the encapsulation plant and until 2008 for the deep repository. Figure 4 illustrates the interaction between SKB and other parties in the consultation processes.

When the necessary investigations have been completed, a preliminary EIS is compiled. Before the permit application is submitted, SKB intends to verify major conclusions with the concerned consultation parties. The consultation process is concluded when SKB submits permit applications with supporting EISs for licensing under the Nuclear Activities Act and the Environmental Code. A consultation report will be appended to each application. This report will contain a summary of the viewpoints offered and will tell how these viewpoints have been taken into consideration.

In addition to the formal consultations, extensive information activities are aimed at municipalities, organizations and the public. These activities will continue to be pursued in parallel with the statutory consultation meetings.

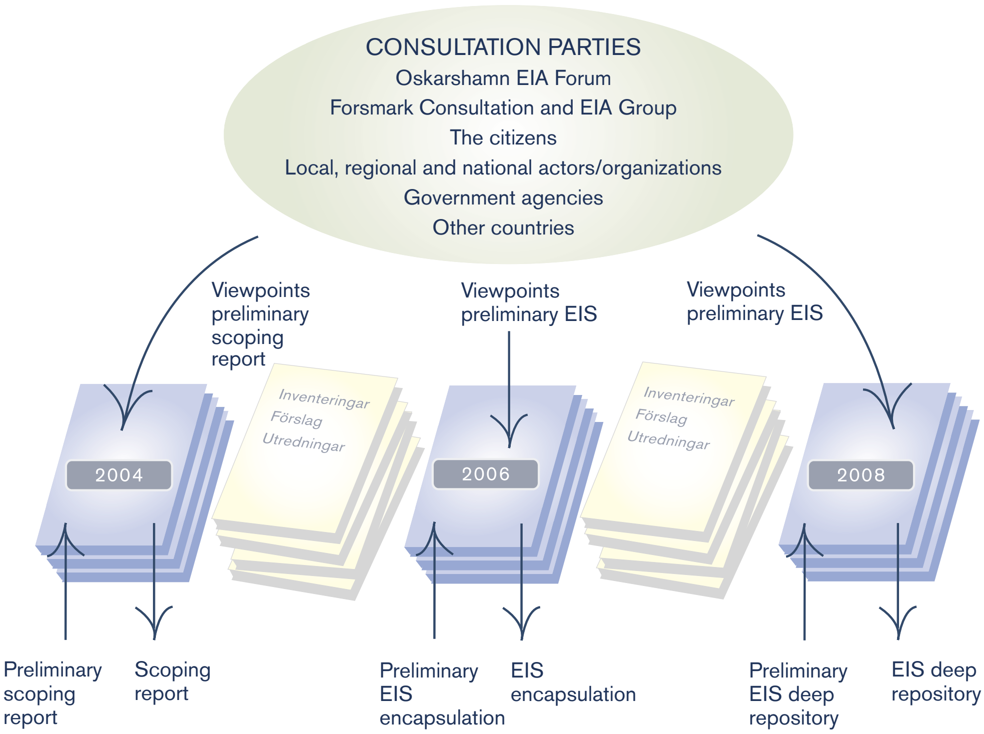

Figure 4. *Interaction between SKB and other parties in the consultation processes.*

A2.3 System design

A2.3.1 Fundamental requirements, design premises

At a general level, the premises for designing and engineering the management system for spent nuclear fuel are derived from Swedish laws and regulations, other requirements on safety, and SKB's own and other parties' requirements on technical feasibility and efficiency. These requirements are as a rule generally formulated and not directly applicable to optimization or more concrete design work. They therefore have to be translated into performance requirements on the system or its parts.

Performance requirements mainly apply to safety and radiation protection, other environmental protection, construction and operation, and aspects that derive from international agreements. The design and execution of the facilities must be shown to fulfil all of these requirements under the design-basis stresses and loads. These stresses and loads are determined by analyzing the situations and processes that occur or might occur during construction and operation, and in the case of the deep repository after closure as well. They include e.g. static loads, deformations and movements, corrosion, etc.

The work sequence in the waste programme, with regular accountings in the form of RD&D programmes and safety assessments, has entailed a gradual development of the system, accompanied by regular cross-checking with the requirements. In 2002, SKB submitted a status report on the work of preparing design premises, see Chapters 5 and 11 with references. The report covers the entire deep repository system and its parts, and also includes the sequence of derivations that has been gone through to arrive at a useful design basis from general requirements. The degree of precision and quantification provided by the report for the parameters, loads etc that govern design and execution corresponds to the status of the work at the time of the report.

A2.3.2 System analysis and optimization

The overall strategy for designing and optimizing a repository system according to the KBS-3 concept has been presented in many contexts, most recently in RD&D-Programme 2001. The principle is to gradually work out, in defined steps, an increasingly detailed design of the facilities, requisite infrastructure and technical supply systems. Execution of construction and operation are more precisely defined in the same way. As the design becomes increasingly detailed, decisions are made which narrow down the range of options, first for general system selection, then for technical solutions for facilities and subsystems, and finally for the details. This mode of working has been successfully applied in many industrial projects, including SFR, Clab and the NPPs.

Decisions and choices during the course of the process are made systematically by producing possible alternatives and evaluating them against established requirements or other criteria with regard to:

- Post-closure safety and performance.
- Safety during construction and operation.
- Environment.
- Feasibility and efficiency.
- Resource needs.

Final choices of system and technology solutions will be made as late as possible to in order to take full advantage of technical advances and, in some cases, site-specific data as well. However, the decisions must not be delayed so much that the development of other parts of the system is held back or otherwise impaired by unclear premises. Striking a balance between the advantages of retaining freedom of choice on the one hand and the need to drive the design process towards the final goal at a reasonable pace on the other hand is a central consideration in SKB's strategic planning.

Overall system optimization is handled within the framework of the concept of system analysis. The purpose of system analysis is to evaluate how alternative ways of designing, building and operating a facility or subsystem affect other facilities or subsystems as well as the whole system. System analysis thereby also provides the necessary overview of how different decisions and choices affect the degrees of freedom in the whole system.

The effects of disturbances and mishaps are also analyzed. The baseline from which the consequences of variations, disturbances or mishaps are measured is the applicable reference design and timetable. The results of the system analysis are vital for being able to choose design alternatives and justify these choices.

The level of detail in the system analysis is limited in that only variations and disturbances in one facility or subsystem that have effects on another facility or subsystem are studied. Questions where alternatives, choices of solutions, disturbances etc only concern individual facilities are handled as components in the design of the facility in question. Due to this limitation, the deep repository's capacity to receive canisters for deposition is, for example, a question for system analysis, while the mode of transporting canisters down into the repository is not.

Important system variants that will be dealt with in future system analyses are:

- Siting alternatives for the deep repository (Forsmark or Simpevarp/Laxemar).
- Siting of the encapsulation plant (reference at Clab, alternative Forsmark).
- Total fuel quantity (reference 40 years' operation of the NPPs, alternative 60 years' operation).
- Deposition method (reference KBS-3V, alternative KBS-3H).
- Retrieval (reference no retrieval, alternative retrieval after initial operation).
- Closure (reference closure shortly after end of operation, alternative extended period with open repository).

Examples of disturbances that will be analyzed are stoppages in different parts of the handling chain. Studied variants and disturbances are evaluated with respect to the aforementioned general criteria. Other comparison factors may also be considered, such as system availability as well as safeguards and physical protection. The cost aspects of different variants of system design and implementation are studied within the framework of the ongoing Plan work and are therefore not included in system analysis.

There are certain mutual system dependencies between the programmes for spent nuclear fuel and LILW. The system analyses for the nuclear fuel system will therefore also shed light on the consequences of design variants for the LILW system.

Accounting prior to permit applications

In conjunction with the integrated account of method, site selection and programme prior to the site investigation phase (RD&D-K), SKB presented a system account of the KBS-3 method and a consequence analysis of the zero alternative, defined as continued storage in Clab.

During the remainder of the site investigation phase, accounts of revised system analyses are planned on two occasions. The first, called Sysinka, will be included in the supporting material for the permit application for the encapsulation plant. Aside from Clab and the encapsulation plant, the material available regarding the deep repository will then be presented. The second system analysis, called Sysdjup, will be appended in a corresponding manner to the application for the deep repository, whereby the complete system with selected sitings is described.

The system analyses will be largely based on other supporting material that is collected and documented in preparation for the applications. The most important supporting documents are:

- System descriptions.
- Facility descriptions.
- Preliminary safety reports (PSRs) for the facilities.
- Alternative studies regarding technical solutions for encapsulation, transportation and deep disposal.
- Safety assessment.

The execution of the safety assessments, especially Sysinka, has been planned in detail and the work has begun. Their initiation has been carried out in dialogue with the authorities, within the framework of the established consultation process.

A2.3.3 Long-term safety

The ultimate purpose of large parts of the implementation programme for spent nuclear fuel is to bring about a safe repository for spent nuclear fuel. Since the development work on the KBS concept started in the late 1970s, SKB has established a number of principles which together can be said to comprise the safety philosophy for achieving this purpose. These principles are summarized below, in accordance with the wishes expressed by the authorities in conjunction with the regulatory review of RD&D-Programme 2001. In addition, a summary is given of the plans for reporting of safety assessments in conjunction with the permit applications for the encapsulation plant and the deep repository. The method for SKB's safety assessments is dealt with from a more technical perspective in Chapter 14.

Safety principles

Spent nuclear fuel is hazardous for a very long time. The first principle is therefore to find a long-term stable environment for a repository. Natural variations in the climate mean that we can expect dramatic changes with permafrost and continental ice sheets in Sweden within time frames on the order of thousands of years. Society is changing at a much faster rate. Far-reaching and unpredictable changes cannot be ruled out, even in comparatively short time frames. Human-induced climate changes may also occur much sooner than the expected natural variations. In view of considerations such as these, geological environment at depths of hundreds of metres are seen as being the most realistic for a repository. Geological conditions in Sweden have led to the selection of granitic crystalline bedrock as the most suitable geological environment.

The repository will be built on a site where the bedrock can be assumed to be of no economic interest to future generations. For example, it must not contain minerals that might become economically attractive in the future.

Another principle is to surround the spent fuel with multiple protective barriers. The purpose of the barriers is primarily to isolate the fuel, and, if this isolation should be breached, to retard the dispersal of any radionuclides that might be released. The fuel is placed in corrosion-resistant copper canisters with a cast iron insert that lends the canisters mechanical strength. The copper canisters are surrounded by a buffer of bentonite clay in deposition holes at a depth of approximately 500 metres in the crystalline bedrock. The bentonite protects the canisters from minor rock movements and retards the ingress of the corrosive substances that are present in low concentrations in the groundwater. The rock in itself comprises a mechanically and chemically long-term stable environment for canisters and bentonite. The canisters are therefore an isolating barrier with a very long lifetime in the environment offered by the buffer and the rock.

The fuel, the canister, the buffer and the rock all contribute towards retarding any escaping radionuclides in the event a canister is breached. The fuel in itself is very stable in the environment prevailing at a depth of hundreds of metres in the crystalline bedrock. Many of the most hazardous radionuclides have such low solubility in groundwater that this renders them inaccessible for further dispersal. Even if they should be breached, both the copper canister and the cast iron insert impair the ingress of groundwater and the escape of radionuclides. The buffer retards both ingress of water to a damaged canister and escape of radionuclides. The groundwater moves slowly in the fracture system in the rock, and many radionuclides have a strong tendency to adhere to fracture surfaces in the rock.

The canister and buffer materials have been selected based on the principle that they should be naturally occurring and stable in an environment similar to that in deep Swedish bedrock. The buffer clay SKB wants to use in the deep repository was formed around 100 million years ago, after which it remained in an environment resembling Swedish groundwater for about 50 million years. Copper is an extremely durable metal in the chemical environment that exists in Sweden's deep groundwater.

Spent nuclear fuel emits radiation which is converted to heat in a repository. Temperatures above approximately 100°C can cause changes in the canister and buffer whose long-term consequences can be difficult to predict. The repository is therefore designed to avoid high temperatures. This is accomplished by interim storage of the fuel in Clab for 30–40 years to allow the radiation to decline, by restricting the quantity of fuel in each canister, and by not spacing the canisters too closely in the repository.

The system of barriers must also be passive, i.e. it must work effectively in its natural state without human intervention and without input of energy or materials.

In summary, the principles behind SKB's safety philosophy 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.

Accounting prior to permit applications

Each of the two applications foreseen in Figure 3 requires an assessment and account of the long-term safety of the deep repository system. The requirement of a safety assessment for the permit application for the deep repository is self-evident. The permit application for the encapsulation plant will also require an account of long-term safety, since it must be shown in the application that a deep repository with the sealed canisters that will be delivered from the encapsulation plant meets the requirements on long-term safety stipulated by the Swedish regulatory authorities.

Two safety reports will therefore be produced, one for each application. In Figure 2 and hereinafter, the reports are called SR-Can and SR-Site. The focus of these reports and the planning of the work of producing them has been discussed with the authorities on a number of consultation occasions. The intention is that SR-Can should be based on site data from the ongoing initial site investigations, while SR-Site should be based on data from the complete site investigations.

The main purpose of SR-Can is to assess the safety of a KBS-3 repository at the sites now being investigated, given canisters according to the application for the encapsulation plant. Another purpose is to provide feedback to further canister development, the design of the deep repository, and to future safety assessments and SKB's programme for research on issues of importance for long-term safety.

A planning document for SR-Can was published by SKB in 2003. A preliminary methodology for the assessment was also outlined there. In addition, the focus and planning of SR-Can has been discussed with the authorities on various consultation occasions. Recently an interim report from the work was published for the main purpose of presenting and demonstrating the methodology used, including updates based on the viewpoints of the authorities from their review of SR 97. The interim report will be subjected to thorough expert review arranged by the regulatory authorities. SKB will take into account the findings of this review in completing SR-Can and later SR-Site.

Accounts of the preliminary safety evaluations of the sites where the site investigations are being conducted are also planned to be published during 2004 (see section A4.5). The main purpose of these evaluations is to determine whether previous evaluations of the suitability of the site with respect to the long-term safety of a deep repository hold up in the light of borehole data, and to provide feedback to the continued investigation activities and the design of site-adapted repository solutions.

The safety assessment SR-Site will be based on data from the complete site investigations. Most of the methodology and the presentation structure for SR-Can will also be used in SR-Site. Certain interim assessments may also be published as references for SR-Can, while most interim assessments based on site data will need to be repeated with the more refined models of the sites that are developed during the latter part of the site investigations. To the extent that viewpoints from the regulatory review of SR-Can are available, they will be taken into account in the design of SR-Site.

A2.3.4 Horizontal deposition, KBS-3H

In its basic version, KBS-3 entails that canisters are deposited in holes with a diameter of 1.8 metres bored vertically downward from tunnels. The reference design entails depositing one canister in each hole, which then needs to be made about eight metres deep. Alternative variants with several canisters in the same hole and/or deposition in horizontal holes or tunnels have been studied over the years. Comparative analyses have resulted in a decision to retain the reference design with vertical deposition.

Horizontal deposition is not judged to offer any advantages compared with the reference design when one canister is deposited in each hole. However, an alternative is to make much longer horizontal holes (on the order of 100–300 metres) so that many canisters can be deposited in a row. A prerequisite is that a canister and its surrounding bentonite can be deposited as a unit surrounded by a perforated steel casing. This variant has in previous contexts been called MLH (Medium Long Holes), but is referred to hereinafter as KBS-3H (Horizontal).

A KBS-3H repository offers advantages from an environmental and cost point of view. The reason is that the long holes fill the double function of deposition tunnels and deposition holes, or to put it differently, the need for deposition tunnels is eliminated. This reduces both the total rock volume that needs to be excavated and the tunnel volumes that need to be backfilled. The technology for boring the long, large-diameter holes that would be needed has been improved considerably in recent years. If such a design can be regarded as being equivalent to the reference alternative, vertical deposition, in terms of overall technical feasibility and safety, KBS-3H can therefore offer interesting optimization possibilities.

In view of this, SKB has decided to further develop horizontal deposition in holes with lengths on the order of several hundred metres. A stepwise development programme has been devised, and the work was commenced in 2002. The intention is to pursue the development work to the point where KBS-3H can either be dismissed or substituted for the present-day reference design.

Much of the knowledge that is needed to evaluate KBS-3H can be taken directly from the development work for vertical deposition. The repository's surface facilities, descents and central area are not affected at all, or only marginally, by how deposition is carried out. The same applies to the deposition density and thereby the overall dimensions of the repository, provided that the requirements on the rock are comparable. The encapsulation technology and canister dimensions are the same as for the reference design. The same general knowledge concerning the bedrock is applicable, and the site investigations being conducted now are judged to provide the data needed concerning the rock on the site, regardless of which deposition alternative (-3V or -3H) is chosen. The properties and function of the buffer material are additional areas where existing R&D results are largely applicable to KBS-3H as well.

There are, however, other issues where present-day knowledge is not directly applicable to KBS-3H and where extensive development work is required, with large-scale testing and demonstration. It will take time before a comprehensive evaluation of the method is possible. Key issues identified by SKB regarding the technical feasibility of KBS-3H are:

- Boring of deposition holes (equipment and execution).
- Need and technology for sealing and rock stabilization in deposition holes.
- Fabrication of the deposition units.
- Deposition equipment and deposition sequence.
- Function of the buffer material (development during the initial water saturation phase after deposition).
- Ability to meet the requirements on long-term safety.
- Possibility of retrieval.

SKB's development programme is focusing on these issues, see Figure 5. A feasibility study and the first of three main stages (basic design) were carried out in cooperation with Posiva during 2002 and 2003. The results of completed technical studies and practical trials have warranted the more ambitious stage which is now in progress. Besides studies of technical key issues and preparations for a safety assessment, it also includes full-scale demonstration trials at the Äspö HRL. Two holes are planned to be bored and deposition equipment will be designed, built and tested. The first goal is to demonstrate that the method is practically feasible. If so, a full-scale performance test will be arranged, with preliminary start in early 2006. The safety assessment will be carried out by Posiva, preliminarily in 2006.

If the plans illustrated in Figure 5 can be implemented according to schedule with clear results, RD&D-Programme 2007 will be a suitable occasion for a summarizing status report on KBS-3H. The technology development and demonstration phase will then be finished and the safety assessment completed. What may be lacking, however, are complete data from the full-scale trial that is planned to be under way at that time, but will be at a relatively early stage. Furthermore, it can be assumed from experience that those parts of the development programme that will have been completed by then will have raised questions that require additional work.

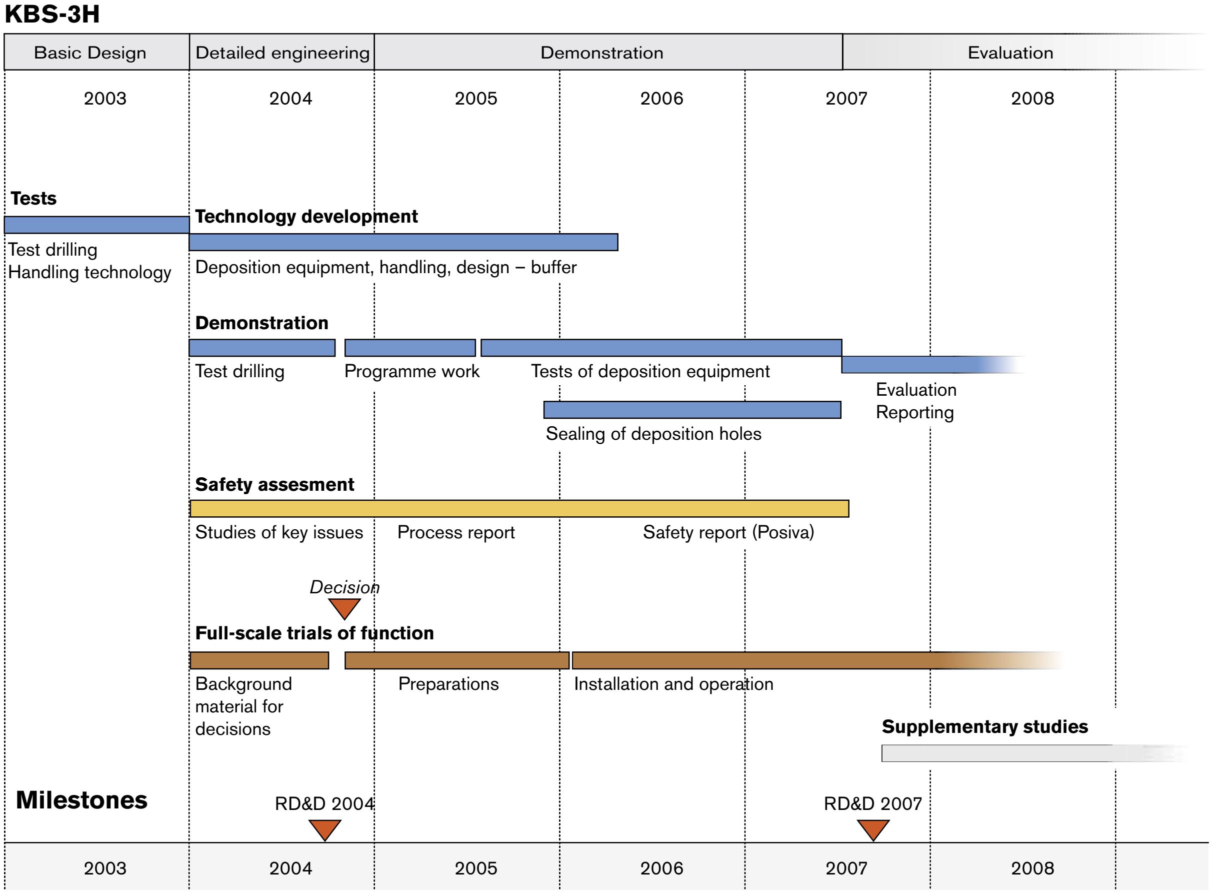

Figure 5. *Plan for development of KBS-3H.*

At the time of the permit application for the deep repository (2008 according to the timetable), an extensive body of data will presumably be available on KBS-3H with regard to technical feasibility, environmental aspects, costs, etc. This means it will be possible to evaluate relatively thoroughly the potential advantages from an environmental and cost point of view. However, it is not likely that KBS-3H will by that time have reached the developmental maturity that is required for a decision to make this variant the reference design. The judgement SKB makes today is that such a decision should be seen as being more long-term. This would entail that SKB would, in conjunction with the application (which is thus based on vertical deposition), describe the development status of KBS-3H, as well as the possibilities and consequences of switching to this deposition method at a later phase.

In order to justify a switch to KBS-3H at a later phase, the method must be shown to be equivalent to the reference design in terms of long-term safety, and to offer clear advantages from other viewpoints as well. If the development work leads to this conclusion, the procedure should be that SKB files a facility modification application, which is then examined by the regulatory authority (SKI).

An important question is how much flexibility in the design of the deep repository remains in various phases, in relation to what is reasonable to achieve when it comes to background material on KBS-3H. SKB's assessment is that a switch to horizontal deposition is possible even in a phase when construction of the deep repository has begun, since the choice of deposition alternative is of little consequence for those parts that are built early on, i.e. surface facilities, descents and underground central area. This provides a time perspective which, based on present-day knowledge, is reasonable in order to drive the development of KBS-3H so far that a comprehensive evaluation stands on a stable foundation.

A3 Encapsulation

A3.1 Overview

Development of the technology for encapsulation is in an intensive phase. The work is now focused on the supporting material for the permit application for the encapsulation plant. After a permit has been granted, the focus will shift to construction, commissioning and trial operation. According to SKB's timetable, it should be possible to obtain a licence for operation of the encapsulation plant by 2017.

The basic requirements on encapsulation are that the canisters to be deposited must be leaktight, possess long-term corrosion resistance in the environment existing in the deep repository, and be able to withstand the loads predicted to arise after deposition. They must be functionally unaffected by the handling chain from sealing to deposition. The work of deriving quantitative requirements regarding material quality and dimensions, as well as tolerances in fabrication and sealing, from these basic requirements has been under way for a long time.

Figure 6 is a simplified illustration of the flow in the encapsulation process. There are different methods for fabrication of the canister's components. In cooperation with suppliers, SKB has refined and tested several methods on a full scale. This work will be pursued further in order to arrive at a finished industrial-scale fabrication process.

A key component in the production process is sealing, which takes place directly after fuel assemblies have been placed in the canister. Sealing consists of welding a copper lid on the copper tube that comprises the canister's outer shell. Extensive development work is required in order to be able to weld with sufficiently high reliability in the relevant materials and thicknesses. SKB is developing two methods – EBW (electron beam welding) and FSW (friction stir welding).

In parallel with the development of fabrication and sealing methods, techniques are being developed for quality inspection by means of nondestructive testing. In order to ensure that the quality goals are achieved, a quality assurance system is being developed. The system stipulates quality requirements and how they are to be satisfied and documented. It includes procedures and quality plans, as well as requirements on testing methods and associated acceptance criteria. Methods and suppliers for fabrication, sealing and inspection will be qualified, and a dialogue is being held with SKI regarding the forms for this qualification.

Even though the production process is being developed towards the goal of very high reliability, the risk that canisters that fail to satisfy the specifications will nevertheless occasionally be produced and pass the inspection system must be taken into consideration. This risk must be quantified and taken into account in the safety assessments. This quantification will be based on trial production and statistical evaluation of the resulting quality. The risk that a canister will fail to satisfy the specifications is dependent on the reliability of both the welding process and the quality control system.

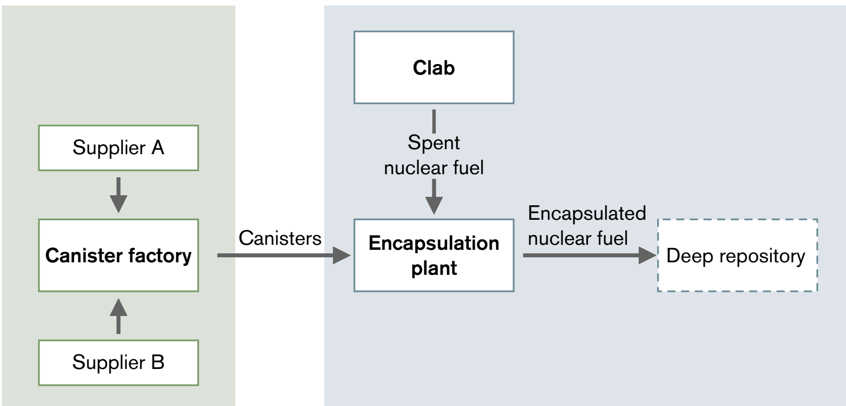

Figure 6. *Overview of the production process.*

Time horizon 2017

The current phase in the implementation of encapsulation is dominated by development and testing of technology and processes, which will gradually phase into qualification of established systems and procedures. Within a time horizon of 2017, the programme will also undergo design, construction and commissioning phases, after which an operating phase will commence in 2017. Figure 7 shows an implementation plan for encapsulation, up to the start of operation.

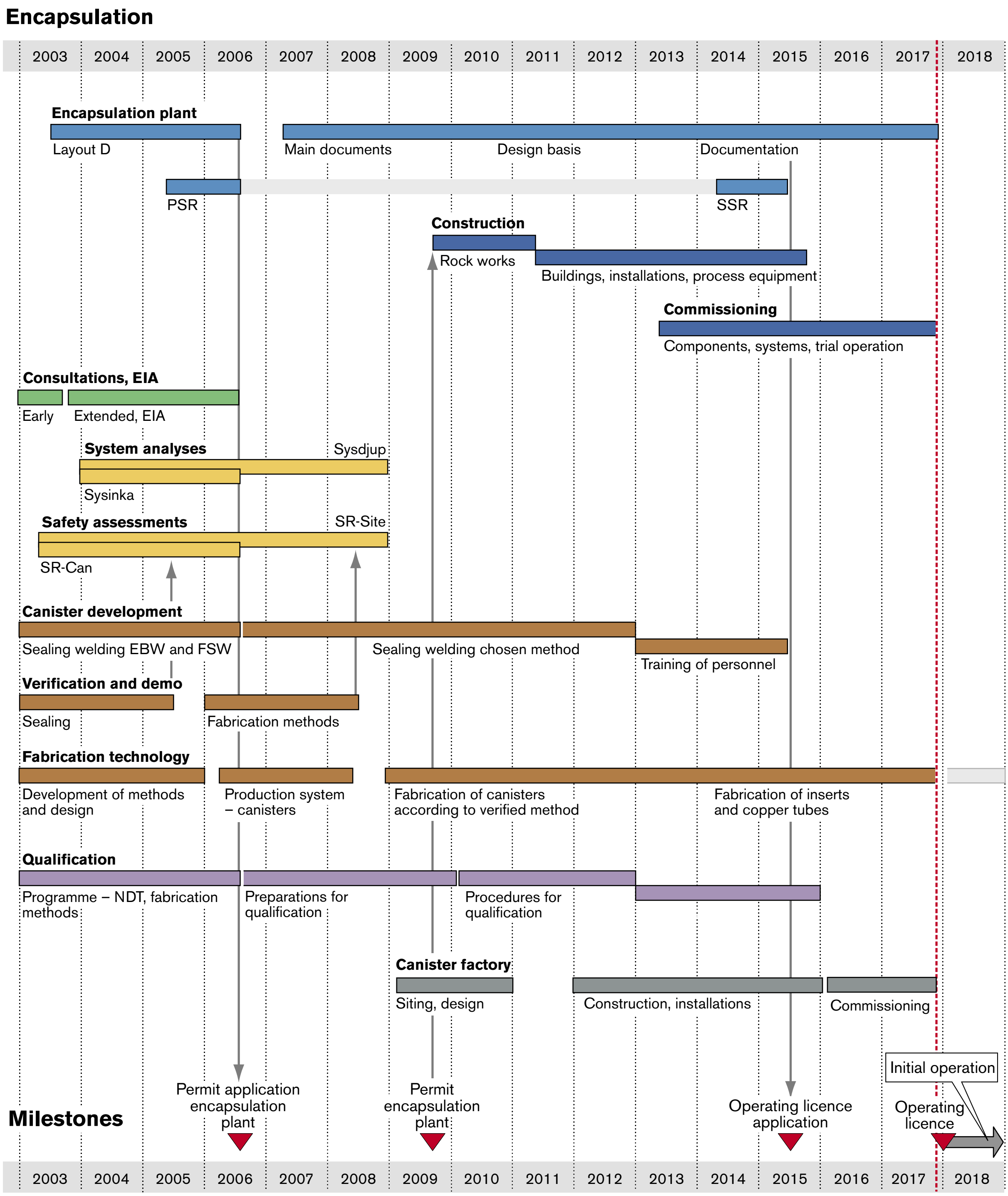

***Figure 7.** Plan for encapsulation, 2003–2018.*

The important milestones are:

- Applying for a permit for siting and construction of the encapsulation plant.
- Obtaining a permit for siting and construction.
- Applying for a licence for operation of the encapsulation plant.
- Obtaining an operating licence.

Once a decision has been made on the siting of the encapsulation plant, the following phases are detailed design, construction, installation and commissioning. During the commissioning period, SKB intends to apply for a licence for operation of the encapsulation plant.

Time horizon 2008

During the next few years, efforts will be focused on gathering supporting material for an application for a permit for siting and construction of the encapsulation plant, assembling this application and submitting it to the authorities – according to the timetable, in mid-2006. The application will be for a co-siting with Clab. The alternative siting is Forsmark. A prerequisite for siting the encapsulation plant at Forsmark is that the deep repository is also sited there, but even in this case co-siting the encapsulation plant with Clab is SKB's main alternative.

In order for the application to be submitted, the development work must have come so far that encapsulation can be shown to be feasible with safety and reasonable efficiency. Figure 8 shows the implementation plan for this, and also indicates mutual links between activities and important accounting occasions. The main activities during the period are as follows, with the addition of activities besides the technical development work that are required before a permit application can be submitted:

- Establish acceptance criteria for canister components and sealing welds.
- Refine welding methods for sealing of canisters and choose a main alternative.
- Refine and verify methods for nondestructive testing of fabrication and sealing of canisters.
- Draw up a plan for qualification.
- Fabricate and seal copper canisters on a scale and with a quality that can serve as a basis for the safety assessment that is to accompany the application.
- Produce a revised system analysis in which an account of alternative methods for disposal of spent nuclear fuel is given ample space.
- Produce a safety assessment (SR-Can) including revisions of methodology and taking into account new findings from the development work regarding encapsulation.
- Design an encapsulation plant co-sited at Clab to a level that can serve as a basis for the facility description that is to be included in the application.
- Produce supporting material for an encapsulation plant sited at Forsmark to a level that permits a comparison, in accordance with the requirements of the Environmental Code, with the applied-for co-siting with Clab.
- Carry out statutory consultations.
- Produce an environmental impact statement.
- Assemble the application.

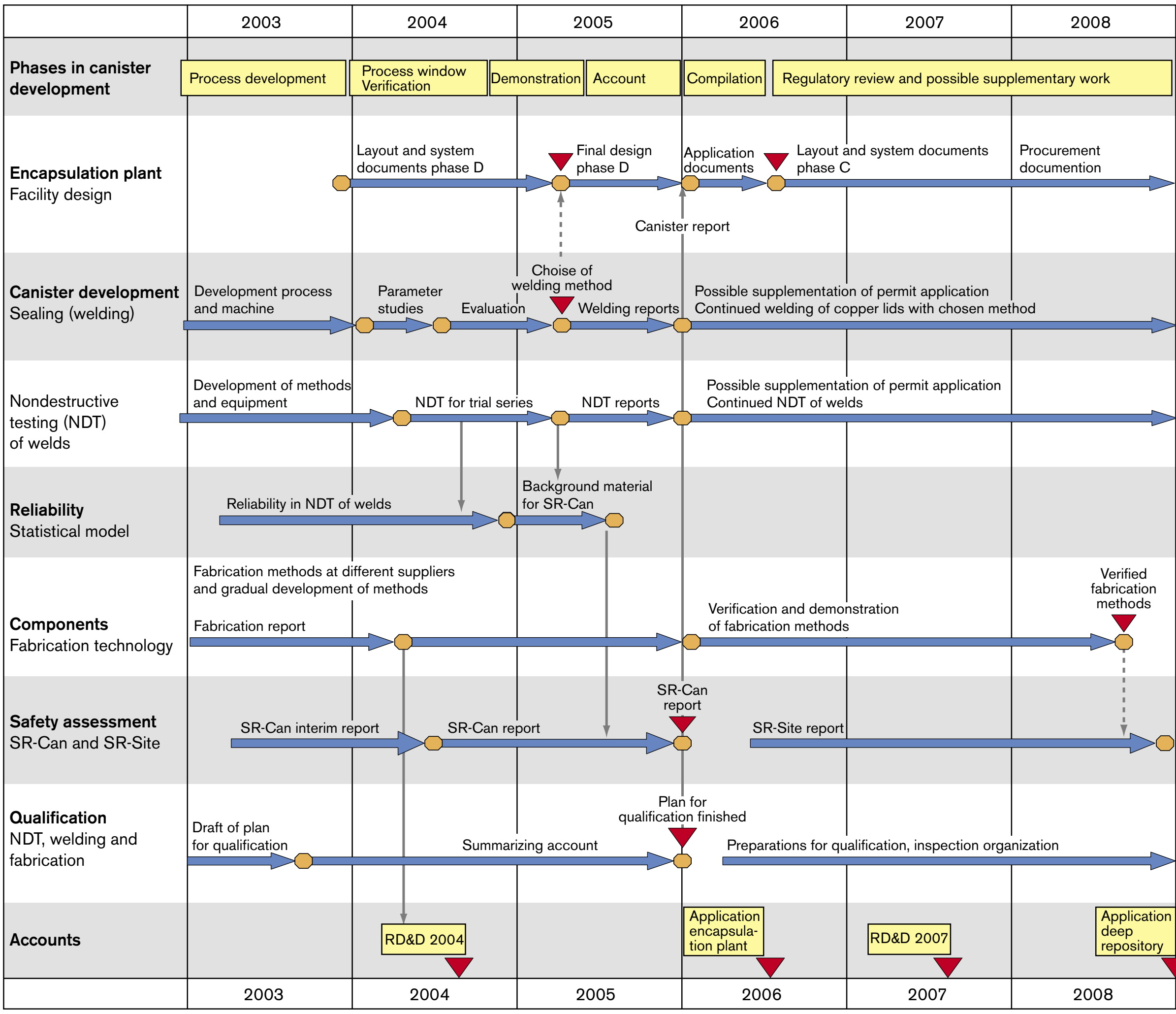

Figure 8. *Plan for encapsulation, 2003–2008.*

During the period 2006–2008, the principal emphasis will be on supporting the submitted application with whatever clarifications and supplementary material the authorities may request, to continue working with design and technology development, and to adapt the encapsulation to resource-effective production. A status report on encapsulation is planned in conjunction with the permit application for the deep repository.

Granting of a permit entails that the site for the encapsulation plant and the main features of its design are approved. As far as technical optimization on the detailed level and adaptation of the process to resource-effective production are concerned, considerable degrees of freedom will remain even after a siting decision. An example is serial production and assembly of canister components. How this is organized and where it will take place are questions that will be decided later on.

A3.2 Facility design

A3.2.1 Encapsulation plant

As early as RD&D-Programme 92, SKB stipulated a siting adjacent to Clab as the main alternative for siting of the encapsulation plant. During the period 1994–1996, planning and preliminary design of the plant was carried out for this siting. To some extent, further planning has awaited the results of the siting work for the deep repository. With the start of the site investigations, however, the design of an encapsulation plant at Clab could be resumed as a part of the work of compiling supporting material for a permit application, see Chapter 8.

There are several advantages of a location directly adjacent to Clab, for example that the experience of fuel handling that exists at Clab can be taken advantage of, and that several of the existing systems and plant components at Clab can be utilized. As an alternative, a siting at a deep repository in Forsmark will be examined.

In view of the development situation and the plans for canister sealing technology, a decision on a welding method will probably not be able to be made before early 2005. This choice affects the design of the encapsulation plant. For the time being, the plant will therefore be designed for both methods. Design of the encapsulation plant will continue after an application has been submitted.

A3.2.2 Canister fabrication

Capacity for serial production of canisters should exist approximately one year before the encapsulation plant is put into operation, i.e. about 2016. Most of the background material for the crucial decisions as to where canister fabrication is to be located will become available in 5–6 years, according to the current timetable, i.e. after the application for the encapsulation plant. Some background material on the planned canister factory will, however, be appended to the permit application for the encapsulation plant, including a technical description. But the siting work is not expected to have begun at the time of the application.

A3.3 Canister development

A3.3.1 Sealing

SKB is currently working on two alternative methods for sealing of the canister: EBW (electron beam welding) and FSW (friction stir welding). A detailed description of the methods and the development work is provided in Chapter 6. Full-scale equipment for both is on hand at the Canister Laboratory. The intention is to decide in early 2005 which method is to comprise the main alternative in the application. It is believed today that both methods can be used successfully.

Development of the welding methods is taking place at the Canister Laboratory with the support of TWI (The Welding Institute) in the UK. The main stages in the work are:

- Process development.
- Process verification.
- Demonstration.
- Presentation/reporting of results.
- Compilation.

The most important steps in process development have already been taken for both welding methods. The work has entailed building up an understanding of both welding processes, modifications and improvements of equipment, and studies of how individual parameters control and affect the welding results.

In the subsequent phase, verification, the intervals in which the welding parameters must lie to ensure the desired quality of the weld are being studied. The intervals must be large enough so that small, unforeseen or normal changes in welding parameters, equipment or ambient conditions will not affect weld quality. This phase will be concluded in 2004.

This will be followed by demonstration of the welding methods, to such an extent that the results can comprise input data to the safety assessment SR-Can. Results and experience are presented and reported. During this phase, the possibilities of running the process under conditions equivalent to serial production are studied.

Development of methods for nondestructive testing of the canister's sealing weld is also pursued at the Canister Laboratory. Procedures for testing of canisters sealed by EBW have been developed, and similar work is being pursued for FSW. In order to determine the reliability of non destructive testing (NDT), development work is being conducted at BAM (Bundesanstalt für Materialforschung und -prüfung) to quantify the risk that a canister weld that does not satisfy the acceptance criteria will escape detection.

The criteria for the choice of welding method will include experience from the development work, evaluation of the robustness of the welding methods, data on achieved quality in serial welding, and expected rejection frequency in production. If for some reason it is not possible to select a main method at the planned point in time (2005), the choice can be postponed. If both welding methods are deemed suitable at the time of application, it is possible to specify one method in the application but continue to pursue development work for both. The final choice can then be made later, provided that the design of the encapsulation plant is kept open for both alternatives.

A3.3.2 Canister components

Fabrication technologies for the canister components (canister insert, steel lid for the insert, copper tube, copper lid and bottom) have been under development for a number of years. The work has mainly been pursued at suppliers inside and outside Sweden, with support from trade associations, universities and research institutes, see Chapter 5.

Four methods have been tested for fabrication of copper tubes. The development status of the methods varies, but all are judged to have potential for meeting the quality requirements. In order to guarantee future deliveries and stimulate supplier competition, the aim is to continue the development of different methods in parallel. There is also an ambition that future serial production will engage several suppliers and perhaps also different methods.

Development of fabrication technology for the canister's nodular iron insert is proceeding with different casting methods at different suppliers. As is the case with the copper tubes, the aim is that the future serial production of inserts will engage several suppliers and methods.

A large number of copper lids and bottoms have been fabricated by forging. This part of the fabrication chain works very well, and the components meet the stipulated quality requirements. Work on the canister's lid and bottom has thus come far. In the reference design, the wall thickness of the copper tube is 5 centimetres. Thinner copper shells have been discussed. The choice of copper thickness is a question of optimization with respect to e.g. short- and long-term safety, technology, environment and resource-effectiveness. Trial welding of the bottom onto the copper shell by means of EBW has previously been conducted at TWI, and quite recently FSW trials were conducted at the Canister Laboratory. A welding method that satisfies the quality requirements for lid welding can also be used to weld bottoms. Compared to lid welding, bottom welding is simpler to perform and inspect, since it is done at an earlier fabrication stage without insert or fuel. If the copper tube is made by pierce and draw processing, bottom welding can be omitted.

The development work on nondestructive testing (NDT) of the canister's components is based on the testing activities of different suppliers, as well as the experience being accumulated at the Canister Laboratory. An inventory has been made of equipment, methods and know-how. So far the work has focused on the copper shell and the insert. There is as yet no NDT of certain parts such as copper lid and bottom, channel tube and steel lid with bolt. Work is planned to clarify which type of testing is required and to develop and apply a methodology. The intention with regard to the canister's copper components and insert parts is to complete studies and specifications during 2004. Approved NDT resources for testing of the most important canister components will be available during 2005.

The aim during 2004 is to prepare descriptions of the defects that can arise in different stages of the production system. Based on these descriptions, together with reliability studies for NDT and probabilistic strength analysis of the insert, preliminary acceptance criteria for the canister (copper shell and insert) will be formulated in 2005. The criteria will stipulate limits for defects in different fabrication processes and the effects these defects have on the canister's properties. Furthermore, the ability of the testing methods to detect these defects will be quantified.

The aim of component fabrication is, by 2006, to fabricate a sufficient number of canister components using a reference method under serial forms, and confirm that these components satisfy stipulated quality requirements, in order to verify that the designs and fabrication methods are reliable. This goal will be achieved by trial fabrication at a supplier and progressive development of the fabrication methods based on evaluation of achieved quality.

Development of other fabrication methods will continue. Qualification of these methods is intended to be done as late as possible to retain flexibility and enable technical advances to be adopted.

A3.3.3 Fabrication

Fabrication of the components for the canisters will be done at different suppliers, both in Sweden and abroad. However, SKB needs to have strict control over the canister components that are delivered to the encapsulation plant. Final adjustment and assembly of the canister components is therefore planned to take place under SKB's auspices, possibly in cooperation with SKB's Finnish counterpart Posiva. A factory for these purpose can be compared to an advanced engineering works. No fuel assemblies will ever be present in the plant. As noted previously, the siting work for canister fabrication has not begun.

A3.4 Safety assessment

The planning for safety assessments during the site investigation phase is described in its entirety in section A2.3.3. The permit application for the encapsulation plant will be based on the safety assessment SR-Can. The recently published interim report from the work with SR-Can describes completed method development, as well as plans to answer the method questions that remain before a final report can be published on the project.

The goal of SR-Can is to show that canisters that have been sealed and tested with the technology that is developed, selected and demonstrated prior to the permit application can ensure a repository that satisfies the safety requirements, given the repository environment offered by the candidate sites. Experimental data from the demonstration phase of the work in particular will therefore comprise an important part of the input data for SR-Can.

Site data from the initial site investigations will be used in SR-Can. The links between the different steps in the investigations, design of the deep repository and the background material for SR-Can are shown in Figure 10.

The canister development work will continue even after the application for the encapsulation plant has been submitted. When SR-Site is prepared prior to the application for the deep repository, newfound knowledge concerning encapsulation will be taken into account. For this application, SKB intends to show that they also have full control over serial canister production, i.e. the work operations performed outside the encapsulation plant. This includes the entire fabrication chain, including associated nondestructive testing (NDT). At this time, it is essential that a reasonable number of canisters have been fabricated, where the only component lacking is the fuel.

A3.5 Qualification

Qualification involves investigating that a fabrication or inspection procedure satisfies stipulated requirements. The quality systems developed by SKB contain qualification requirements on both processes and suppliers of canister components, see Chapter 7. SKB has concluded from studies that the regulations that apply to qualification for fabrication, installation, repair and in-service inspection according to SKIFS 2000:2 are not applicable to the canister. This has also been confirmed by SKI. Nor are the inspection procedure, accredited laboratory, accredited inspection body and approved qualification body that apply to the nuclear power sector currently applicable to the canister. One of the reasons for this is that qualification must apply to the canister's integrity over such a long period of time. The qualification procedure that applies to fabrication, installation and repair does not take this into consideration. Nor will in-service inspection be of relevance for the canister. For SKB, this means that a qualification method, qualification procedure and inspection procedure must be devised and presented to the regulatory authority.

Qualification of the production process covers the different sub-processes fabrication, welding and NDT. SKB will probably be able to carry out certain qualifications in accordance with the quality system's current requirements, while some will be subject to future regulatory requirements. An important part of the work during the next few years will thus be to clarify this.

It should be emphasized that the extensive work being pursued by SKB in research and technical development goes hand in hand with the qualification work. To a great extent, the qualification work involves structuring and compiling existing and new information in a logical fashion.

An important milestone for the qualification work will be passed when SKB applies for a permit for the encapsulation plant. At this point the work will be focused on determining preliminary detection goals, demonstrating the reliability of NDT of the sealing weld, and studying via the SR-Can safety assessment the effects on total safety in the deep repository. SKB will also take a coordinated approach to underlying technical documentation that is of relevance for the requirements on NDT. The principles of technical documentation of the encapsulation and fabrication process will be explained. This work is part of a long-range plan for qualification that is gradually being devised in dialogue with SKI and that will be appended to the application.

A4 Deep disposal

A4.1 Overview

Time horizon 2023

Figure 9 shows the implementation plan for the deep repository project that is guiding SKB's work. The figure also shows the key components of the technology development being pursued in parallel, as well as the most important large-scale tests at the Äspö HRL, with links to the implementation plan.

The important milestones are:

- Applying for a permit to build the deep repository on the selected site.
- Obtaining a permit to build the deep repository on this site.
- Applying for a licence for operation of the deep repository.
- Obtaining an operating licence.
- Transitioning into regular operation after a period of initial operation.

Time horizon 2008

Figure 10 shows in greater detail the plan for the period 2003–2008, i.e. the remainder of the siting phase for the deep repository, up to the planned time of application. In addition to the site investigations, the figure presents the plans for design and the safety assessments of the deep repository, as well as important links between these activities. An equivalent plan for the parallel technology development work for the needs of the deep repository project is presented in section A4.4, Figure 12.

The activities in the site investigation phase are aimed at gathering the material that is needed for a permit application. The main activities are as follows:

Site Investigations

- Complete initiated investigations in Forsmark.
- Complete initiated investigations in Oskarshamn.
- Produce descriptions of the investigated sites as a basis for site-adapted deep repository solutions, safety assessments and environmental impact statements.

Design

- Design facilities, systems and infrastructure for deep repositories on the investigated sites to a level that can serve as a basis for the facility descriptions and safety assessments that are to be included in the application.

Safety assessment

- Produce safety assessments for deep disposal on the investigated sites.

Consultations and environmental impact assessment

- Carry out statutory consultations and other communication with concerned parties and the public.
- Produce the environmental impact statement that must accompany the application.

These activities are described more thoroughly in sections A4.2–4.6.

In the final part of the site investigation phase, an integrated evaluation of all background material is made in order to be able to:

- Prioritize a site for the deep repository and justify this prioritization.
- Assemble the permit application.

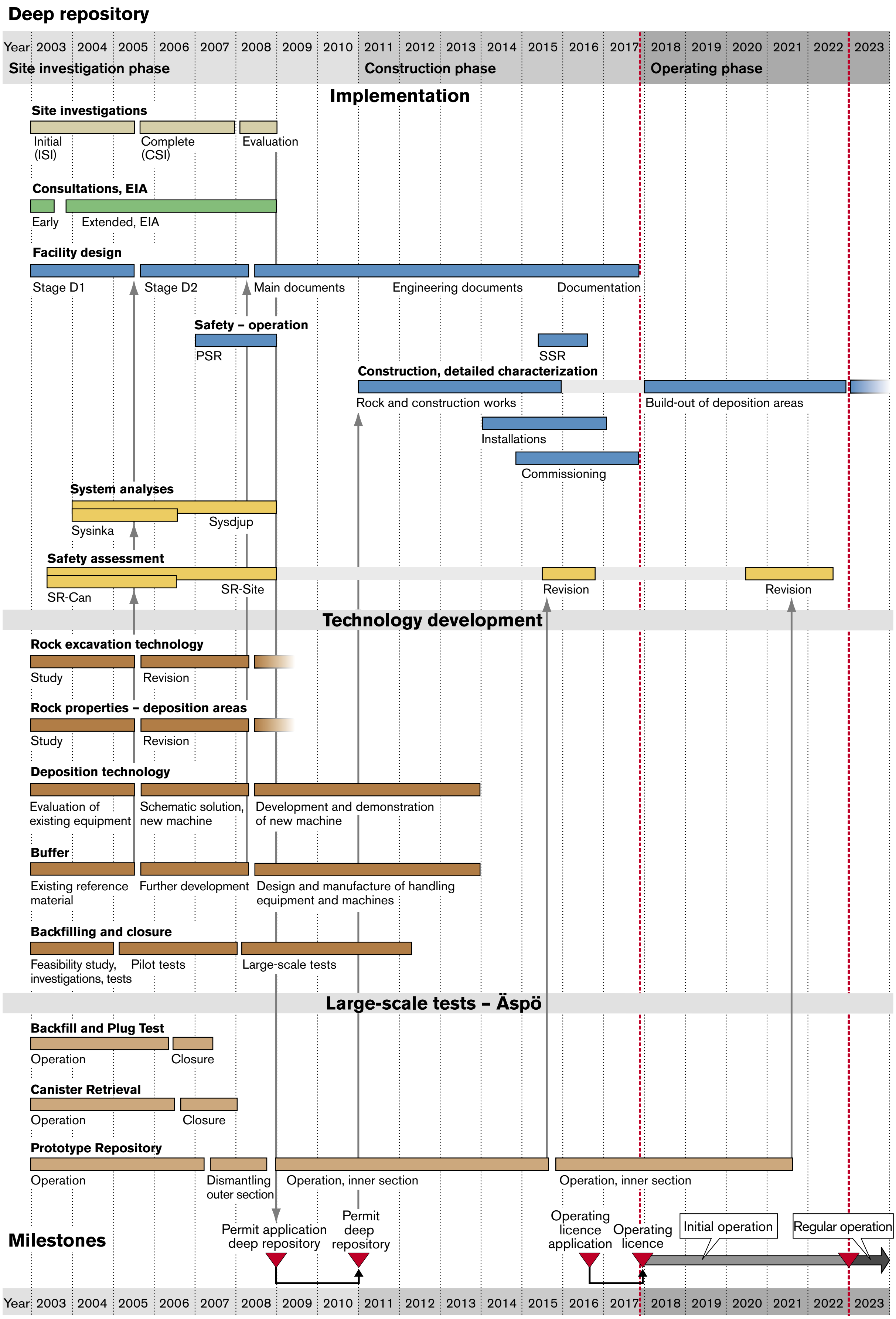

Figure 9. *Plan for the deep repository, 2003–2023.*

As is evident from Figure 10, the work during the site investigation phase is iterative. The current stage is called initial site investigation and is projected to be completed in the spring of 2005. The goal of this phase is to verify the judgement that warranted the choices of candidate sites, i.e. that they have good prospects for meeting the requirements for a deep repository. Collected data concerning conditions on the site are compared with pre-established criteria. Furthermore, the possible configuration of a deep repository with regard to local conditions is studied, and preliminary evaluations are made of the safety of such a repository.

Provided the results confirm the continued viability of the siting alternative, the second stage of the plan (called complete site investigation) is implemented. The purpose then is to gather information to a level that permits an application to be submitted.

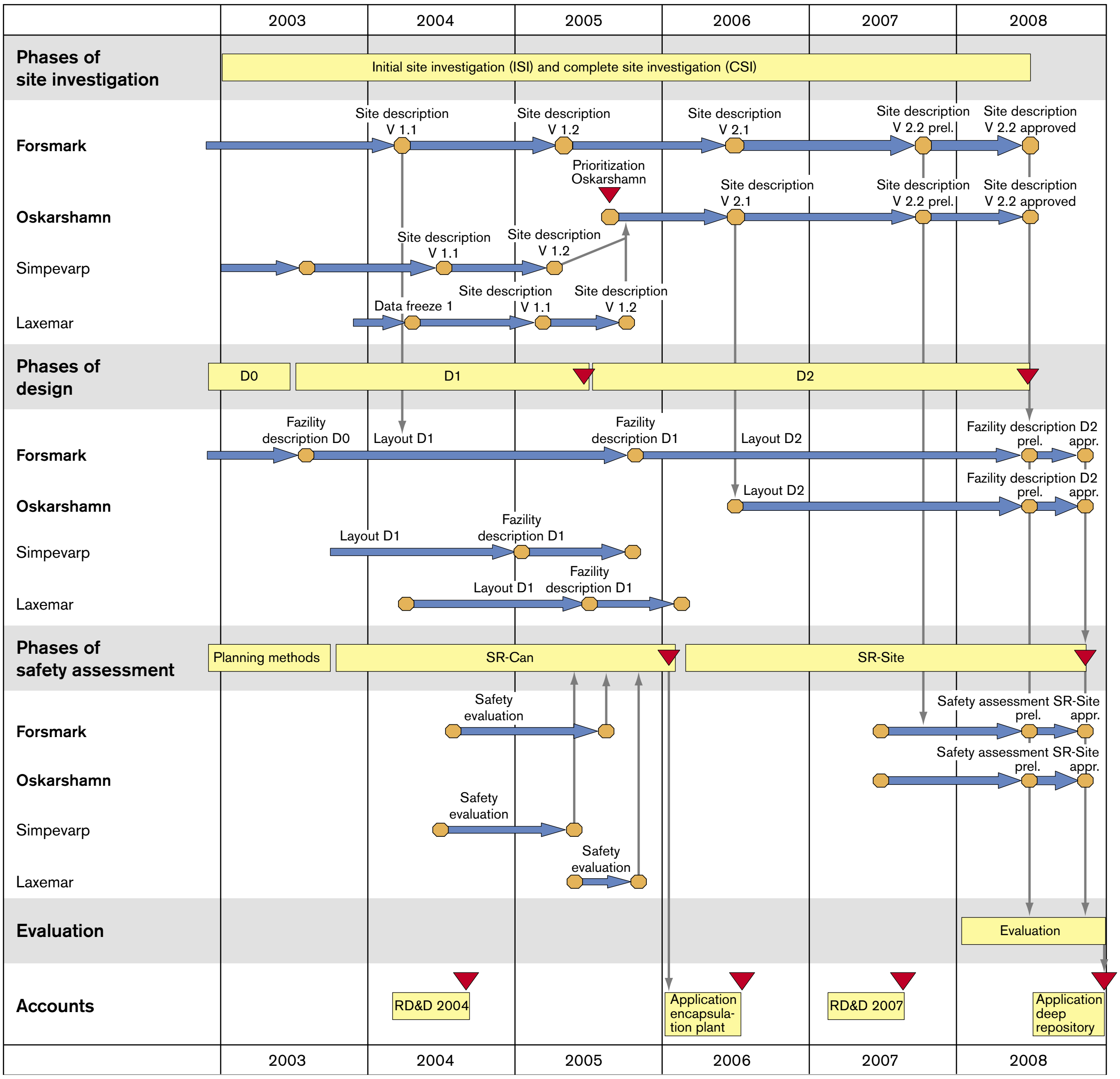

Figure 10. Main activities during the site investigation phase and mutual links between them.

A4.2 Site investigations

Site investigations are now being conducted in two municipalities, Oskarshamn and Östhammar. The work is divided into two stages: initial and complete site investigation. Following the initial stage, an evaluation is made which includes a preliminary safety evaluation where the findings are cross-checked against the requirements made on the rock. If it turns out that any site does not meet the requirements, the site investigation can be discontinued at this stage. SKB's planning assumption is, however, that the site investigations will be completed in both municipalities.

A4.2.1 Forsmark

The site investigation in Forsmark pertains to an approximately 10 km^2 area extending southeast from the nuclear power plant down towards Kallrigafjärden. The area largely coincides with the extent of a so-called tectonic lens, which is a relatively well-preserved bedrock unit surrounded by zones of highly deformed bedrock. The main arguments for the choice of the area were that the bedrock is judged to be favourable, and that it has an advantageous location near the industrial area, SFR and the harbour. The area is situated in a coastal environment with high natural values, which imposes special requirements on both the site investigations and the development of a deep disposal solution on the site.

The site investigation was initiated at the beginning of 2002. The organization and the activities were built up and reached full scope during the first year. The current status of the investigation can be summarized as follows:

- Characterization of the area's geological and ecological conditions on the surface has largely been completed.
- Five deep cored boreholes (1,000 metres) and a number of shallower percussion boreholes (max. depth about 200 metres) have been completed for investigating the bedrock.
- A comprehensive, preliminary site description (version 1.1) has been presented.
- The consultation process for a possible deep repository in Forsmark has been commenced.
- An active information and communication programme has been established for ongoing dialogue with nearby residents, the public, the municipality and other local stakeholders.

The data that have been analyzed so far have led to a focusing of the investigations to the northwestern part of the area. It is not yet possible to make any reliable forecast of the final results. Among other things, the preliminary safety evaluation, based on data after the initial investigation stage, still remains to be done. At present, however, all signs indicate that the site investigation in Forsmark will be completed, and that this will be done in keeping with the timetable in Figure 10.

Before the site investigation was initiated, a number of site-specific geoscientific issues were identified as being particularly important to clarify in order to judge the suitability of the site for a deep repository. Table 1 summarizes the current status of these key issues in terms of how well they are understood.

Besides issues that are specific for the site, there are numerous factors that are generally important to clarify. These factors include the presence and frequency of dykes and fracture zones, the water flow in these zones and the intervening bedrock, and hydrochemical and thermal conditions. In the case of Forsmark, the general picture is that the bedrock near the surface is characterized by unexpectedly high water flow in distinct structures. This contrasts with conditions at greater depth, which are characterized by homogeneous, fracture-poor bedrock with unexpectedly low water flow. As far as hydrochemical and thermal conditions are concerned, the investigations have not revealed any surprises, which suggests favourable conditions at repository depth.

Table 1. Current status of site-specific key issues identified prior to the start of the site investigation in Forsmark.

Key issue	Status
The vertical extent and shape of the tectonic lens.	Several boreholes have verified a depth in excess of 1,000 metres. The presumed steep dip of the margins of the lens has been verified for certain sections, for others investigations remain to be done before the issue can be settled.
Possible ore potential at depth.	The issue has been studied particularly closely in conjunction with the holes that have been drilled. No traces of mineralizations and/or bedrock with ore potential have been detected within the lens. The issue should therefore be able to be dismissed.
Presence of gently-dipping fracture zones.	Highly conductive, gently-dipping fractures and fracture zones are common down to a depth of about 200 metres. Only a few gently-dipping fracture zones have been found at greater depth.
Possible occurrence of high rock stresses.	The measurements made so far have shown relatively high, but not extreme, rock stresses. Additional measurements are planned in order to obtain a better overall picture.

A4.2.2 Oskarshamn

The main argument for a site investigation in the Simpevarp area near Oskarshamn was the combination of bedrock judged to be favourable and the advantages offered by Simpevarp for industrial establishment in the form of available industrial land and infrastructure, proximity to Clab and the Äspö HRL, and the planned co-siting of the encapsulation plant. The site investigation started when the municipal council decided in March 2002 to allow SKB to initiate the site investigation. The consultation process with the municipality and its working groups had already started at that time and is well established today.

The investigations were focused on two subareas: The Simpevarp Peninsula with environs and the Laxemar area west of there. These areas have different geological conditions, and the investigations are based on somewhat different system solutions for a repository. A siting on the Simpevarp Peninsula would mean that the surface facilities would also be located there. A siting in the Laxemar area could entail either that certain above-ground facility parts are located on Simpevarp (connected by tunnel to the repository) or that the entire facility is placed in Laxemar.

Questions existed regarding the bedrock on the Simpevarp Peninsula due to a relatively high frequency of fractures and thereby an uncertainty regarding the space available for a deep repository. Given the advantages offered by the site in other respects, an investigation was nevertheless judged to be warranted. The investigations on and around the peninsula started immediately after the municipality’s decision, and the current situation can be summarized as follows:

- A detailed geological survey has been performed.
- Three deep cored boreholes (1,000 metres) have been completed on the Simpevarp Peninsula.
- The investigation area has been expanded to include Ävrö, Hålö and surrounding water areas.
- A new cored borehole has been completed on Ävrö and an existing one has been made available for measurements.

The results of the drilling on the Simpevarp Peninsula showed good mechanical and hydraulic conditions to a great extent, despite a complex mix of different rock types. Based on these results, it was decided to expand the area in the manner that has been done, since the Simpevarp Peninsula itself is not considered to offer enough volume for a sufficiently flexible deep repository solution.

Already in the feasibility study, large areas were found to the west of the Simpevarp Peninsula that warranted further investigations from a geoscientific point of view. The site investigation was commenced here with geophysical airborne surveys and other studies so that an area could be prioritized for drilling. An analysis revealed a number of areas with what could be judged to be equivalent geological conditions. The Laxemar area just west of Simpevarp was therefore prioritized due to its proximity to existing facilities on the Simpevarp Peninsula. Adhering to the principle that the deep repository project should be pursued on a voluntary basis, SKB started negotiations with the many concerned landowners to obtain access to the area. The negotiations were drawn-out, but were finally more or less completed at the end of 2003. The work could then start, nearly a year later than originally planned.

The aim is still to complete the current stage of the site investigation for both alternatives, Simpevarp and Laxemar. After that an evaluation will be made, with the support of the collected data. Contingent upon the results of the evaluation, the idea is to then carry out a complete site investigation for one of the alternatives, see Figure 10. If the Simpevarp alternative is prioritized, the investigations can be concentrated there. If the Laxemar area is chosen instead, further investigations will be conducted there, and the prospects for a connecting tunnel from Simpevarp will be explored.

In addition to the choice between the two subareas, a number of site-specific geoscientific issues were identified as being of particular importance in the Oskarshamn case as well. Table 2 summarizes the current status of these issues, mainly with regard to the Simpevarp area, since it is there that new borehole data are available.

Table 2. Current status of site-specific key issues identified prior to the start of the site investigation in the site investigation in Oskarshamn.

Key issue	Status
Size and location of bedrock blocks with favourable properties at repository depth.	Drilling, in combination with lineament interpretations, show that the Simpevarp subarea is probably surrounded by deformation zones of such importance that they constitute boundaries for a possible repository area. Within the area are lineaments that can be interpreted as zones of lesser importance. Most of the fractured formations in the boreholes exhibit relatively low hydraulic conductivity.
Presence and importance of dykes of fine-grained granite and fracture zones, particularly with respect to permeability.	Analyses of data from large areas adjacent to and west of Simpevarp show that fine-grained granite is evenly distributed. The dykes of fine-grained granite encountered in the boreholes on the Simpevarp Peninsula have not exhibited elevated permeability, compared with the surrounding rock.

A4.3 Facility design

Design is the collective term for activities where requirements, design-basis criteria, technical solutions and other types of information are collected and processed so that they can eventually be translated into facility descriptions, function descriptions, engineering drawings and construction documents.

Prior to the site investigation phase, the results of the design work to date were compiled into a comprehensive facility description outlining SKB's general reference design of the deep repository. The task during the site investigation phase is to produce site-adapted configuration proposals and plans for detailed characterization and construction for the studied siting alternatives. The starting point is the general reference design, which is progressively adapted to the site conditions revealed by the investigations. At the same time, technical solutions for subsystems and other results delivered by ongoing development work are implemented (see section A4.4).

The requirements on site-specific design are governed by the general goals for the site investigation phase and the subsequent construction phase. They entail that the facility descriptions and plans that are presented must be sufficiently specific in order to:

- Serve as a basis for safety evaluations (PSE after initial site investigations) and ultimately safety assessments (SR-Site after the complete site investigation) which show that a deep repository on the site in question satisfies the safety requirements.
- Serve as a basis for an environmental impact statement showing that the deep repository project can be implemented with acceptable consequences for man and the environment.
- Show that a deep repository on the site in question can be built and operated with known technology and so that requirements on personal safety, occupational safety, efficiency and cost-effectiveness are satisfied.

Design is carried out in steps in the manner illustrated in Figure 11. Up until permit application, the design work is carried out in three steps (D0, D1, D2) for the candidate sites. Then, while the authorities are processing the permit application, work begins on main documents for a deep repository on the chosen site, starting with for the facility parts that come first in the building process after a permit decision.

The process up until permit application ties in with the subdivision of the entire deep repository project into stages according to Figure 10. In step D0 (see Figure 11), possible locations and configurations of facility parts and activities which the deep repository requires on the surface are studied. This step is almost finished. In step D1, which is currently under way, the preliminary layout and dimensions of the facility parts under ground are determined, based on data from the initial site investigation. A key issue in this step is the size (area requirement under ground) a repository on the site would have, in relation to the rock volumes that are available. Schematic solutions and locations for descents (ramp and shafts) and central area are other issues that are dealt with and that are of great importance for the overall result. The preliminary facility description describes locations and extent of facility parts above and below ground. The description is used as a basis for further investigations, for consultations on environmental consequences, and for SR-Can.

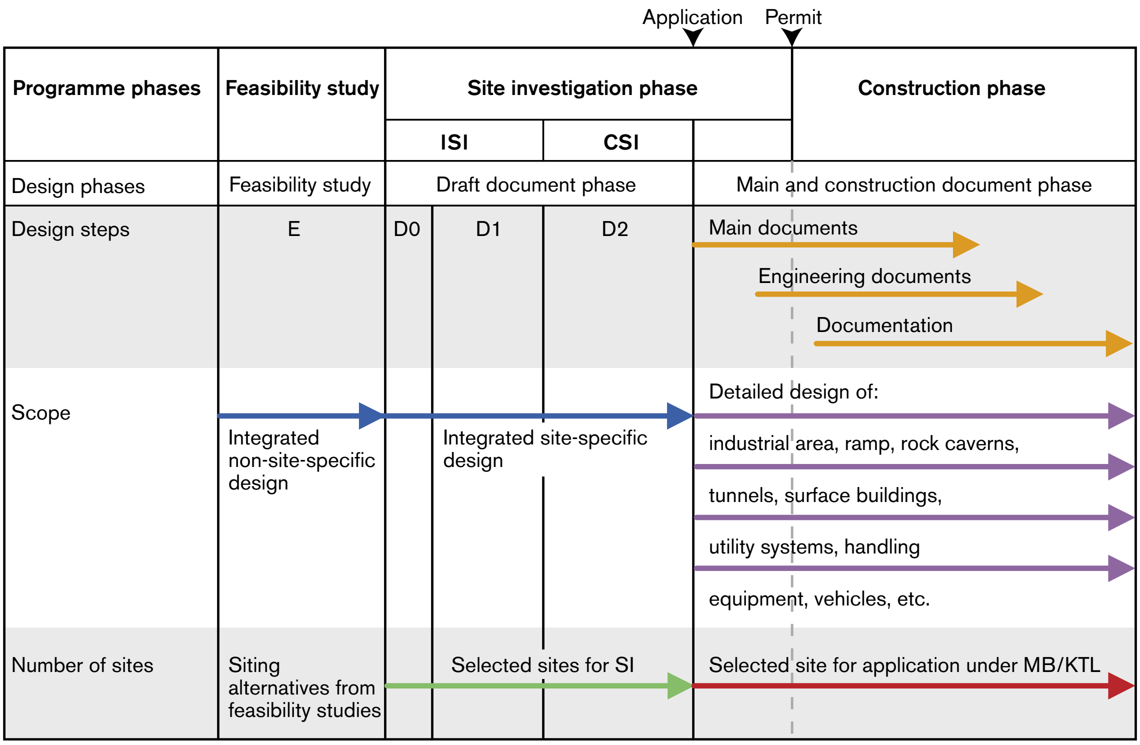

Figure 11. Plan and subdivision into stages of design of the deep repository.

In step D2, the facility description is revised taking into account the information from the complete site investigation. One of the end products is the facility description that serves as a basis for SR-Site and the environmental impact statement, and that is included in the supporting material for the application, see section A4.5.

The design and gradual build-out of the deep repository on the selected site will take many years. The work will be affected by the rock conditions encountered, among other things. It is therefore important that the solutions that are arrived at during the site investigation phase provide sufficient flexibility for possible changes later on. More or less final decisions must nevertheless be made on issues that are of great importance for the site-specific design of certain subsystems as well as for the facility as a whole.

Tables 3a and 3b show design issues that are of central importance during the site investigation phase, in the sense that important choices or prioritizations must be made. Significant links to the design of the facility as such (layout, engineering, construction, operation), and its long-term safety and performance, as well as health and environmental aspects, are indicated in qualitative form. The issues span over a wide field with respect to development needs, and tables 3a and 3b correspond to a rough breakdown into two categories:

- Table 3a pertains to issues or subsystems that can be said to be “conventional” in the sense that they are not unique to the deep repository – equivalent functions can be found in other hard rock facilities, and technology is available.
- Table 3b pertains to issues or subsystems that require extensive development work because they are unique to the deep repository, or because available technology must be modified to a greater extent.

With few exceptions, the design issues or subsystems shown in Table 3a are not related to long-term safety other than indirectly. The required knowledge and technology can therefore be obtained from outside sources, and the work essentially consists of adapting solutions to the requirements of the deep repository and conditions on the site, based on this knowledge and on various analyses and alternative comparisons. As is evident from the table, this applies to:

- Infrastructure and facilities parts above ground (conventional site preparation and civil engineering works).
- Access alternatives (schematic solution and locations).
- Rock spoil (hoisting, handling, treatment).
- Ventilation and drainage of the underground facilities.

Table 4 summarizes interim goals for these issues, for design steps D1 and D2, and documents (main and construction documents) that are needed in the next step. Note that D1 and D2 are facility descriptions that should be submitted at given times according to Figure 11. Main and construction documents, on the other hand, are prepared during the construction phase as they are needed for contract procurements.

The issues or subsystems given in Table 3b are, as noted above, all subject to technology development, in some cases with the support of basic research. The solutions arrived at are implemented during the design process. Section A4.4 gives an overview of interim goals etc linked to the design stages in the site investigation phase. Status and programme for the development work are presented in Chapter 11.

Table 3a. Important issues for site-adapted design. ***Solutions for the deep repository are based for the most part on existing knowledge and technology that is adapted to the requirements of the deep repository and conditions on the site.*** **Interim goals for design are shown in Table 4. A plus sign indicates important links that must be taken into account in the design work.**

Design issue/ subsystem	Configuration/execution			Long-term safety and performance		Health and environment	
	Layout	Constr.	Oper.	Near-field	Far-field	Internal	External
Infrastructure and layout for facility parts above ground	+	+	+			+	+
Access alternatives	+	+	+		+	+	+
Rock spoil	+	+	+				+
Ventilation below ground	+	+	+			+	
Rock drainage		+	+			+	+

Table 3b. Important issues for site-adapted design. ***Solutions for the deep repository are based for the most part on own technology development, cf section A4.4.*** **Interim goals for design are shown in Table 5. A plus sign indicates important links that must be taken into account in the design work.**

Design issue/ subsystem	Configuration/execution			Long-term safety and performance		Health and environment	
	Layout	Constr.	Oper.	Near-field	Far-field	Internal	External
Rock excavation technology							
– Excavation methods	+	+	+	+	+	+	
– Sealing		+	+			+	+
Engineering materials		+	+	+	+	+	
Adaptation to rock properties – deposition areas/ deposition holes	+	+	+	+			
Deposition technology		+	+	+		+	
Buffer		+	+	+		+	
Backfill, closure							
– Deposition tunnels		+	+	+	+	+	+
– Accesses, transport tunnels	+	+		+	+	+	
– Boreholes		+	+	+	+		

Table 4. Current situation and preliminary interim goals for certain design issues, according to Table 3A.

Design issue/ subsystem	Current situation, reference	D1 – permit application for encapsulation plant	D2 – permit application for deep repository	Main and construction documents
Infrastructure and layout for facility parts above ground				
Location and disposition of functions in relation to local conditions.	Generic design basis and reference solutions exist. First site adaptation done during step D0.	Alternative locations and preliminary configurations presented. Environmental aspects preliminarily analyzed.	Main alternative chosen and justified. Configuration presented for this alternative. Environmental aspects analyzed and described.	Requisite documents for procurement of contracts for site preparation and infrastructure.
Access alternatives				
Various combinations of shafts and inclined tunnel (ramp) can be chosen for transport and communications.	Comparative analyses done of alternative solutions. Reference: Separate shafts for personnel transport and rock hoisting, ramp for transport of transport casks with canisters.	Locations for shafts, or route for ramp, preliminarily determined and justified. Environmental aspects preliminarily analyzed.	Locations and dimensions for shafts chosen. Possible execution described. Revised route for ramp described. Environmental aspects described.	Documents for executing the works on the site prepared, checked and approved.
Rock spoil				
Handling procedure for excavated rock from removal to end use. Location of facilities, transport roads.	Handling alternatives, preliminary market situation etc have been analyzed.	Proposals for handling procedure studied, alternative locations of facilities presented. Environmental aspects preliminarily analyzed.	Handling procedure and technical solution presented for prioritized alternative. Environmental aspects analyzed and described.	Handling procedure and technical solutions chosen and approved.
Ventilation below ground				
System solutions and rating.	Preliminary assessment of the ventilation requirement is included in the reference design.	Preliminary rating of the ventilation system based on the requirement for the facility's underground part, including principles for design of fire ventilation and fire cells.	Ventilation system rated for ventilation requirement of the facility's underground part, including principles for design of fire ventilation and fire cells.	Ventilation requirement during construction and operating phases clarified so that requisite procurements can take place as needed.

A4.4 Technology development

Prior to the permit application for the deep repository, the development work should generally have reached a level such that technical solutions – for subsystems and for the whole deep repository on the site in question – can be shown to be feasible and to satisfy the crucial safety and environmental requirements. They must furthermore satisfy reasonable requirements on efficiency and resource-effectiveness in the execution of the deep repository project.

A complete account of status and programme for technology development is given in Chapter 10. The following development issues can be said to be particularly important for the site-adapted configuration of the deep repository that is done during the site investigation phase (cf Table 3b):

- Rock excavation technology (adaptation and development of methods for excavation, rock stabilization and sealing).
- Engineering materials (for sealing, stabilization and underground installations).
- Rock properties for deposition areas and deposition holes (criteria, methodology, adaptation).
- Deposition technology (machines, handling procedure).
- Buffer (materials, fabrication, application).
- Backfill and closure of deposition holes, tunnels and boreholes (materials and application).

Figure 12 shows a general plan for the development work, with a time horizon of 2008. As the figure indicates, the results of the development work find their primary application in the safety assessment and in the stepwise design process. Table 5 provides an overview of the current "delivery plan" vis-à-vis the implementation plan for the deep repository project. The table presents interim goals in the form of preliminary requirements on background material regarding the formulated issues linked to the different design steps. In addition, brief comments are made on the development situation with references to those sections in the main report where the RD&D work is described.

The above development activities pertain to the components in the reference concept, i.e. a repository according to the KBS-3 method with deposition in vertical holes in the tunnel floor. To this can be added the special development programme for the variant of KBS-3 where deposition takes place in long horizontal holes (KBS-3H), which is described in section A2.3.5.

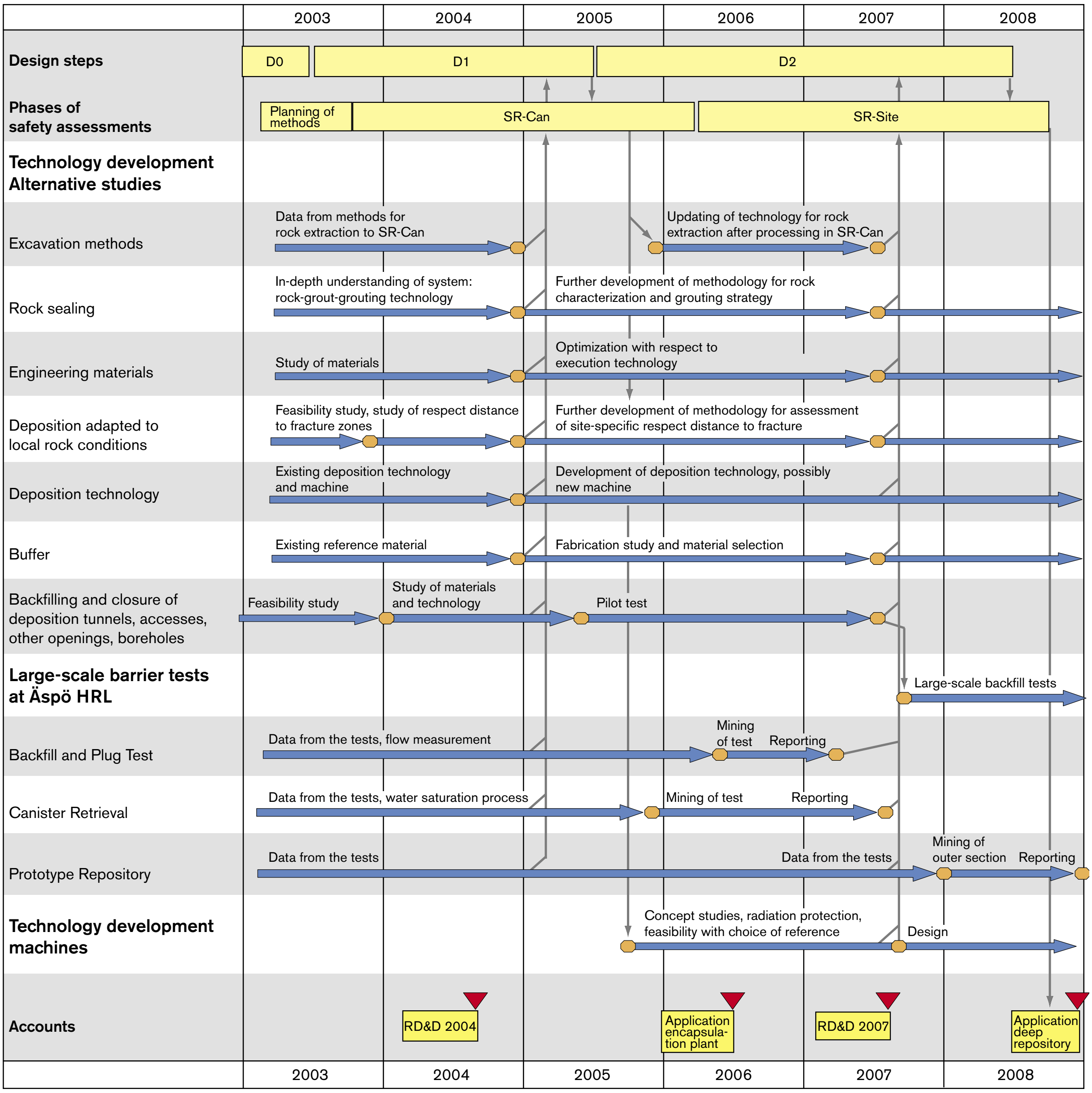

Figure 12. Plan for technology development during the site investigation phase.

Table 5. Important technology development issues – Current status, planned activities and preliminary interim goals linked to design steps (cf also Table 3b).

Technology issue/ subsystem	RD&D – current status	RD&D – planned activities, reference	Reference design	D1 – permit application for encapsulation plant	D2 – permit application for deep repository	Main and construction documents
Rock excavation technology						
– Excavation methods Choice of technology for different repository parts.	Good knowledge base via own rock works and R&D, plus long involvement in sector development.	Extensive investigations with focus on near-field properties and performance of different excavation methods, see section 10.1.	Boring or blasting of descent ramp, transport tunnels, rock caverns and deposition tunnels. Boring of deposition holes.	Excavation methods and execution for deposition tunnels, accesses and other openings preliminarily chosen and explained. Important links to other subsystems described.	Updating of methods and execution described. Renewed analysis performed of links to industrial safety and reliability as well as long-term safety. Environmental aspects described.	Chosen methods are included in the background information for contracts for all rock works, starting with ramp and shafts.
– Rock sealing Rock characterization plus materials and technology for sealing of rock chambers.	Basic and applied R&D for all parts of the sealing issue (characterization, materials, technology) has been pursued for a long time. Low-pH grout under development.	Further development of methodology for rock characterization and grouting. Continued R&D to develop suitable materials, see section 10.1.	Pre-grouting as needed, with conventional cementitious grouts.	Rough estimate of quantity and distribution of grouting material. Theoretical impact on groundwater level described.	Site-specific account of possible sealing technique, material choice, estimated consumption and impact on long-term safety and environment.	Chosen sealing method is included in background information for contracts for all rock works, starting with ramp and shafts.
Engineering materials Materials (quantities, properties, possible consequences) for installations, stabilization, sealing etc brought into the repository and left behind after closure.	Quantities and distributions of engineering materials and materials that will be left behind have been calculated, see reference design.	Re-examination of material choices, with aim of minimizing amounts of cementitious materials left behind, see section 10.1.	Quantity calculations based on reference design of underground facility. Conventional materials are assumed.	Alternative materials examined with regard to construction and operation. Revision performed of quantity and type of engineering materials, and judgements made of impact on long-term safety and environment.	Engineering materials preliminarily chosen and quantities calculated. Impact on long-term safety analyzed. Analyses of industrial safety and reliability as well as environmental aspects presented.	Main and construction documents based on chosen materials and methods.
Adaptation to rock properties – deposition areas and deposition holes Methodology/criteria for determining whether a rock volume can be used for deposition. Includes respect distance.	Considerable R&D conducted on respect distance and requirements on rock conditions in deposition positions. Re-examination of methodology for respect distance under way.	Further development and examination of methodology for respect distance and for choice of deposition positions, see sections 19.2.5–19.2.8.	Preliminary guideline values for respect distance in earlier design steps, methodology for investigations etc in later steps.	Adaptation of configuration based on data from initial site investigation and preliminary design premises.	Adaptation of configuration based on data from complete site investigation and updated design premises.	Criteria and methodology for determination of deposition positions approved, application based on data from detailed characterization.

Cont'd next page.

Table 5. Continued.

Technology issue/ subsystem	RD&D – current status	RD&D – planned activities, reference	Reference design	D1 – permit application for encapsulation plant	D2 – permit application for deep repository	Main and construction documents
Deposition technology						
Schematic solutions, including radiation protection, for handling and deposition of canisters.	There is a demo machine for deposition of canisters at the Äspö HRL. Different types of handling tests have been conducted with experimental equipment.	Re-examination of performance requirements, plus technical and environmental evaluations, possible modification of machine design, see section 10.3.	Like Äspö demo machine, except that the equipment is not planned to be rail-bound.	Like Äspö demo machine, except that the equipment is planned to be wheeled.	Studies of modified version of deposition machine finished and design chosen. Links to other subsystems analyzed.	Detailed engineering, fabrication and testing of deposition machine with chosen design carried out.
Buffer						
Material choice, preparation and application, performance in short and long term.	Continuous R&D to develop knowledge base concerning properties and performance. More than a hundred full-scale blocks have been fabricated by uniaxial pressing and installed in full-scale trials at the Äspö HRL.	Additional research concerning materials and processes prior to choice of buffer material. Testing of isostatic pressing of blocks, see section 10.2 and Chapter 17.	Sodium bentonite (MX 80). Blocks are fabricated by isostatic pressing.	Current knowledge base for reference material (MX 80) or other equivalent materials presented.	Updated knowledge base presented. Material chosen and explained. Methods for fabrication and application studied and requisite tests performed. Feasibility demonstrated and environmental aspects analyzed.	Chosen system (materials, press equipment etc) fabricated and tested prior to preparation of construction documents for deposition tunnels and production building for compaction of buffer.
Backfill and closure						
– Deposition tunnels Material choice, application, function	Extensive alternative studies conducted of materials and handling concepts. Technology and function tested in large-scale tests.	Continued evaluation of alternative materials and methods for handling and application, see section 10.4 and Chapter 18.	MX 80 mixed with crushed rock in ratio 30/70.	Alternative materials examined. At least one optional material that meets the requirements specified. Links to other subsystems described.	Site-adapted reference material chosen and shown to meet requirements. Interaction with other subsystems (excavation method, sealing) investigated and described. Environmental aspects analyzed.	Chosen system for backfilling (materials, equipment, application) fabricated and tested prior to preparation of construction documents for deposition tunnels and production building.
– Accesses, other chambers	As above.	As above.	As above.	As above.	As above.	As above.
– Boreholes	Inventory of feasible materials completed.	Continued studies of materials. Compilation of concepts for sealing and field test, see section 10.5.	Compacted bentonite blocks in perforated copper tubes.	Sealing requirements analyzed. Current knowledge base for sealing concept described.	Site-adapted reference concept that meets the requirements chosen.	Detailed engineering, fabrication and testing.

A4.5 Safety assessment

The integrated planning for safety assessments during the site investigation phase is described in section A2.3.3. Figure 10 shows in greater detail the links between safety assessment, the versions of site descriptions produced by the investigations, and corresponding repository layouts from design.

Preliminary safety evaluations for the investigated sites are planned as a first step. For Oskarshamn, this means separate evaluations for the Simpevarp and Laxemar areas. In all cases (Forsmark, Simpevarp and Laxemar), the site-specific background material for the safety evaluations consists of site-descriptive models, version 1.2. The main purpose of the safety evaluations at this relative early stage of the site investigations is to determine whether the early judgements of the sites as being suitable with respect to long-term safety still hold, taking into account the borehole data from repository depth that will be available. If the results suggest difficulties meeting the safety requirements, the investigations of the site in question may be discontinued. Furthermore, the work is expected to provide valuable feedback to the planning of the continued investigations and to future safety assessments, mainly SR-Can.

The safety report SR-Site will be based on the total body of material that is available when the site investigations with associated design work are finished. SR-Site will show whether the entire system with encapsulation according to the described technology and deep disposal on the site that is ultimately chosen satisfies the regulatory requirements regarding long-term safety.

The planning for SR-Site is still at an early stage. The intention is to perform safety assessments for two sites, with equivalent deep repository solutions. Other details of the implementation will depend on the ongoing process of determining the methodology for the site investigation phase's safety assessments, experience from the preliminary safety evaluations and SR-Can, and the outcome of the remaining site investigations.

A4.6 Evaluation and site selection

The ongoing site investigation phase concludes the siting process for the deep repository that has been going on since the beginning of the 1990s. Since the start, the guiding principles for the siting work have been:

- The repository shall be located in crystalline basement on Swedish territory.
- It must be possible to satisfy environmental, safety and radiation protection requirements.
- Active siting studies are only conducted in municipalities that have good geological and technical conditions and that wish to participate in the siting work.

These principles are based on knowledge gained from study site investigations, general siting studies and safety assessments which SKB has conducted since the late 1970s. One main conclusion from the studies is that there may be sites in many of Sweden's municipalities that satisfy the requirements for a deep repository.

After feasibility studies in eight municipalities, an integrated evaluation of all the findings was made in 2000. On the basis of this evaluation, SKB prioritized areas in Oskarshamn, Tierp and Östhammar for site investigations and proposed further investigations of the siting prospects in Nyköping Municipality. The facts and evaluations on which SKB based these choices were presented in detail in the so-called RD&D-K report. In the subsequent decision process, the Government gave the go-ahead to SKB's proposals. After approval by the concerned municipalities, site investigations were commenced in Östhammar (Forsmark) and Oskarshamn (Simpevarp area), while Tierp and Nyköping declined further participation in the siting process.

A4.6.1 Siting factors

Before prioritizing sites for site investigations, SKB presented general siting factors for the deep repository and a basic structure for their application. These factors are still points of departure for the future choice of site, but the extensive body of site-specific data that is now being collected will provide much better prospects for applying the methodology and evaluating different factors.

The factors are divided into three main categories:

- Bedrock.
- Industrial establishment.
- Societal aspects.

Bedrock

The properties of the bedrock determine the prospects for long-term safety and the technical prospects for building and operating the underground parts of the deep repository. The safety requirements and the requirements these in turn lead to on the rock distinguish the deep repository from other rock facilities. SKB has previously described:

- The requirements and preferences made on the bedrock on the site for the deep repository.
- How these requirements and preferences can be translated into measurable parameters and criteria that provide guidance, especially during the site investigation phase.

The requirements and preferences presented prior to the site investigation phase were based on the reference design for the deep repository and the state of knowledge that existed at that time. Changes in the repository concept or new technical or scientific advances can of course occasion changes in certain requirements, preferences or criteria. During the years that remain before a site selection is to be made, extensive development work and new safety assessments will be carried out. This, together with experience from the investigation work, will in all likelihood warrant revisions in existing requirements, preferences and criteria.

Industrial establishment

The deep repository project must be able to be implemented as an industrial establishment. This means that construction and operation must be technically feasible, that resources must be available, and that all requirements on occupational safety and protection of man and the environment must be met. In these respects the deep repository does not differ essentially from any other industrial activity.

The deep repository's facilities and activities on the surface require land for operating areas and infrastructure. The facilities must be sited on land that is suitable for the purpose, and the siting must not conflict with good long-term management of land and water.

The deep repository is a large and long-term industrial establishment which is in many ways dependent on the community in the locality and the region where the repository is established. With the feasibility of the deep repository as a point of departure, SKB will evaluate what resources the community can contribute to the project in the form of labour, public and private services, etc, and whether these resources meet the requirements to enable the project to be completed with high quality. When it comes to the other side of this mutual dependency, i.e. what the project can contribute to the community, SKB's role is to present the facts, but leave the evaluations to others.

Societal aspects

In order for the deep repository project to be realized, it must have political and popular support. The concerned municipality, as well as the Government, must approve of the siting. In practice, this means that local and national elected officials, as well as the public, and particularly local residents, must have confidence in SKB and the nuclear waste programme.

A4.6.2 Site selection

The investigations in Oskarshamn and Forsmark are expected to be able to be completed during 2007. This will be followed by a period of analysis and compilation of results for both sites. Based on this body of material, the site for the deep repository will then be selected, according to the current timetable in the latter part of 2008.

The factual findings and the overall assessment for the final choice of site will be presented in the environmental impact statement that is supposed to accompany the application for a permit for a specific site for the deep repository. The basic requirement on the site that is selected is that it must satisfy the environmental, safety and radiation protection criteria. The requirements and preferences on the rock presented prior to the start of the site investigation phase will be reviewed and possibly revised. This review will be based on the safety assessment SR-Site, which is in turn based on the complete version of the site investigation data and the technical risk evaluation presented in the facility description. This will be followed by an integrated assessment of whether the safety and radiation protection requirements are met, taking into account the uncertainties in the description of the site and its long-term safety, as well as uncertainties in the evaluation of the technical risks.

The environmental impact statement describes the projected effects and consequences of the impact of a deep repository on the selected site, both during construction and operation of the repository and in the long-term perspective. Furthermore, a cross-check is made with the Environmental Code's rules of consideration, with environmental quality standards, and with local, regional and national environmental objectives in order to show that the site has been selected in accordance with the intentions of the Environmental Code so that its purpose can be achieved with a minimum of damage or detriment to human health and the environment. Monitoring programmes and planned consequence-mitigating measures are also reported.

If both sites satisfy the fundamental criteria – i.e. if the environmental, safety and radiation protection requirements are met – other factors will also be weighed into the site selection decision. The sites are then evaluated and compared with respect to certain of the preferences described in RD&D-K and whatever additional preferences may have emerged from the extensive investigations and consultations that have taken place up until that time. In accordance with the intentions of the Environmental Code, preferences must be evaluated from a holistic perspective, where the benefits of siting the facilities on the site in question are also weighed in.

A4.6.3 Alternative scenarios

Figure 10 and the plan for the site investigation phase presented above pertain to the reference case on which SKB's plan of action is based, i.e. that the two ongoing site investigations are completed, that this is followed by an evaluation after which one of the sites is selected, and that an application for a permit for this site is assembled and submitted. There are, however, alternative outcomes that must be considered. Site investigations and subsequent site selection are judged to be more uncertain in terms of planning than other parts of the programme. There are basically two reasons for this. One is that knowledge of conditions at repository depth on the candidate sites is incomplete in the initial phase. The other is the fact that the entire siting process is heavily dependent on global factors.

A possible alternative scenario is that the investigations gradually make the choice of site obvious, i.e. that one site proves to have such superior merits that the choice becomes given at some point. This does not mean that the requirements on the selected site are changed in any way. However, it can change the procedure and timetable in the final part of the site investigation phase, since data collection on the site that is not being considered does not have to be taken to the level required by a permit application, even though it should be complete enough to permit comparisons in all relevant respects.

Another possibility is that the site investigations are delayed, but otherwise completed and evaluated according to the plan for the reference case. The consequence may then be a corresponding postponement of the entire timetable. Depending on the size of the delay, this may have more or less significant consequences for the other parts of the nuclear waste programme.

A third possible scenario is that the site investigations do not qualify either alternative for a siting application. The programme must then be revised. What this may mean depends to a great extent on the stage at which a revision becomes necessary, for what reasons, and what the prospects are for getting support for a modified programme. The probable way out is to propose additional siting alternatives that can be incorporated into the selection pool and investigated. What is clear is that the whole deep repository programme would then be considerably delayed, with resultant risks and strains for e.g. continuity and personnel recruitment.

A5 Programme for low- and intermediate-level waste (LILW)

A5.1 Current situation

Most of the low- and intermediate-level waste (LILW) that is produced today comes from operation and maintenance of the nuclear power plants. Short-lived waste is disposed of in the SFR facility (SFR-1). Waste containing larger fractions of long-lived radionuclides is temporarily stored by the producers at the NPPs, or by SKB in Clab. Long-lived LILW from research, hospitals etc is interim-stored in Studsvik. Final disposal of this waste lies outside of SKB's undertaking vis-à-vis the owners, however, and requires separate agreements. A small portion, very low-level waste, is disposed of by shallow land burial in near-surface repositories at the NPPs. This is a matter for the power companies and lies beyond SKB's obligations.

The current situation and the programme for research and development concerning LILW are described in Chapter 25. An overview of the planning to implement the remaining parts of the LILW programme is provided in the following.

A5.2 Plan

Figure 13 shows the long-term planning for the whole LILW programme. The main points are continued operation of the SFR facility for final disposal of operational waste, continued interim storage of certain long-lived LILW at Clab, future extensions of SFR to receive waste from the decommissioning of the NPPs, and in the longer term siting and extension of a special final repository for other long-lived waste.

The scope and timetable of the LILW programme are dependent on the plans for operation, phase-out and decommissioning of the NPPs. Figure 13 is based on the reference scenario that the NPPs are operated for 40 years before shutdown, and are then deactivated and decommissioned more or less immediately. There are indications today that the operating times will be as long as 60 years or more. It is also conceivable that the nuclear power companies will choose to let their plants stand a number of years to allow the radioactivity to decline before decommissioning is begun in earnest. Accordingly, the need for space to dispose of decommissioning waste may be postponed.

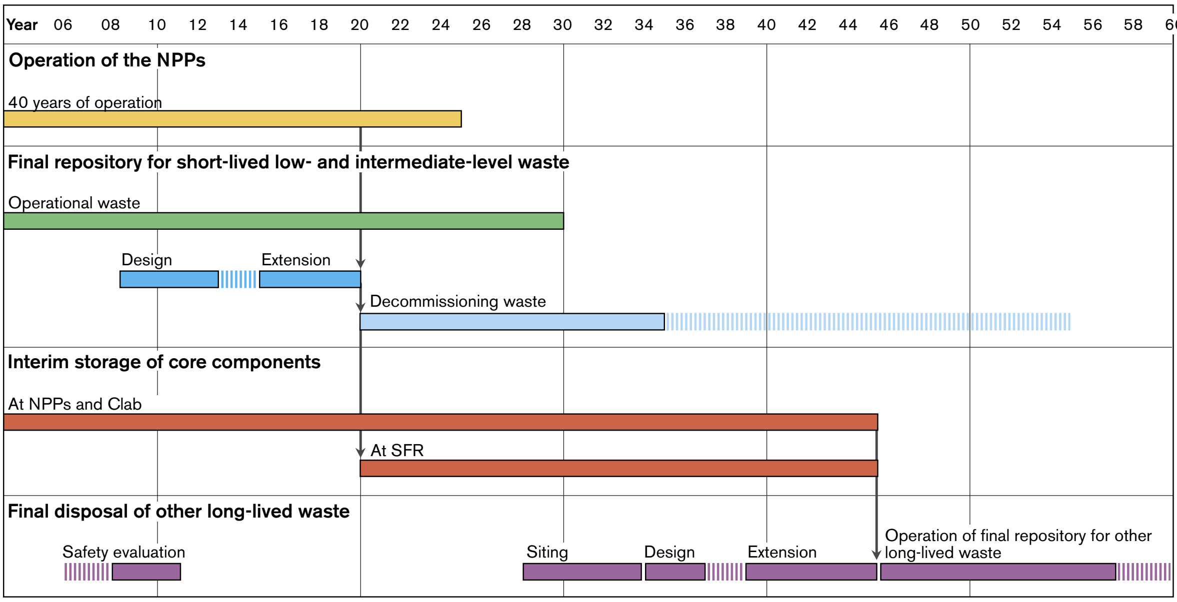

***Figure 13.** Rough timetable for the LILW programme.*

The calculated volumes of decommissioning waste presume that the NPPs are decommissioned and dismantled to slightly below ground level, and that all radioactive material is disposed of in SKB's facilities. This ensures that the need for repository volume will not be underestimated. The actual volumes may be less, however. It is, for example, possible that the power plant owners will choose to dispose of waste containing small quantities of radioactive material by shallow land burial in near-surface repositories, such as is done today with certain types of low-level waste.

A5.2.1 Final disposal – short-lived waste

Operational waste

Assuming that the NPPs are operated for 40 years, the capacity of existing chambers in the SFR facility (SFR-1, volume 63,000 m^3) will suffice for the routinely produced short-lived operational waste. If the operating times are prolonged, an extension may be necessary in around 2025. Waste from research, medical care and industry similar to operational waste is also disposed of in SFR-1.

Decommissioning waste

Decommissioning will generate both short-lived and long-lived LILW. Extensions of the SFR facility consisting of several additional rock caverns are planned for the short-lived decommissioning waste, which is the dominant fraction in terms of volume. Assuming that the NPPs are operated for 40 years, the first of these chambers will not be needed until 2020 at the earliest. Design and other preparations should then start about ten years earlier. The total quantity of short-lived decommissioning waste from the NPPs to be disposed of in SFR is estimated at about 150,000 m^3, i.e. twice as much as the waste from operation and maintenance.

A5.2.2 Interim storage – core components

The interim storage of long-lived LILW, mainly core components, that is required up until about 2020 can be managed in existing space in Clab, in combination with the at-reactor interim storage for which the power companies themselves take responsibility. When decommissioning of the NPPs starts, however, long-lived decommissioning waste must also be dealt with. This requires extra space, separate from Clab, where capacity problems may otherwise arise. That is why the afore-mentioned extensions of SFR are also planned to contain chambers for interim storage of long-lived LILW. After interim storage, the waste will be transferred to the special final repository for other long-lived waste that is planned.

A5.2.3 Extensions at SFR

Disposal of the additional waste types that are planned for at the SFR facility imposes roughly the same requirements on the facility itself as the operational waste that is disposed of there today. The extensions are therefore planned to consist of a number of rock caverns, at the same depth and of the same type as today's. A "re-licensing" of the entire facility is also planned in conjunction with the extension, so that the different parts can receive short-lived waste from both operation and decommissioning. This will enable the facility to be utilized maximally.

Extension is planned to take place in three stages. A total of four rock caverns will be built in the first stage – two for final disposal of short-lived decommissioning waste, one that can be used for interim storage of long-lived waste, and one for final disposal of large, odd components from maintenance and repair of the NPPs. As mentioned above, these chambers are planned to be put into use no earlier than 2020. In a second stage, 10–20 years later, additional rock caverns for decommissioning waste will be added. The cavern that is planned to be utilized for interim storage of long-lived LILW will be emptied when the waste is transferred to the final repository for other long-lived waste. This cavern can then also be used for deposition of short-lived decommissioning waste. If needed, additional chambers for operational waste may also be built in this time perspective.

A5.2.4 Final repository for other long-lived waste

The construction of a final repository for other long-lived waste is planned to start at a stage when most of the NPPs have been phased out. The facility will thereby be the last one in the entire nuclear waste programme. According to present-day plans, the repository should stand ready for deposition in around 2045. Long-lived LILW produced before then will be interim-stored as described above.

Plans for an early safety evaluation as well as supportive research regarding the final repository for other long-lived waste are described in Chapter 25. Site selection for this facility requires its own siting process. In order to allow sufficient time for this process, but nevertheless ensure that it is still relevant when the time comes to build the facility, it should, by SKB's reckoning, be started some time around 2025–2030. Thus, site selection is an open question today, and neither co-siting with SFR (but at greater depth) or with the then-existing deep repository, nor siting at an entirely new site, can be ruled out.

The long-lived LILW that will be disposed of in the facility can be described most simply as waste in which a large fraction of the radionuclides have half-lives in excess of 30 years. The sources are both the parts of the NPPs located in or close to the fuel, known as core components, and Studsvik (own activities and management of waste from industry, medical care and research). The idea is also to utilize the repository for the short-lived waste that arises when Clab and the encapsulation plant are decommissioned. The design outlined above includes rock caverns (similar to those in SFR but at greater depth and with important differences in technical design) that divide the facility into three parts, corresponding to the three categories of waste to be disposed of.

A6 Management, quality and competence

A6.1 Organization and management system

Current situation

SKB's organization currently includes more than 220 employees at three locations: Stockholm (head office) approximately 130, Oskarshamn (Clab, Äspö HRL, Canister Laboratory, site investigation) approximately 80, and Östhammar (SFR, site investigation) approximately 15. Counting the contributions of outside agents as well (institutions, consultants, contractors), the nuclear waste programme encompasses around 500 full-time jobs.

The main features of the present-day line organization are shown in Figure 14. Responsibility for the RD&D work, including Äspö HRL and the Canister Laboratory, has been gathered in a technology department. A special department has been established for the site investigations. A third department is responsible for operation of the existing facilities. A fourth department handles administrative duties, and a fifth is in charge of EIA and communications.

Many of the activities are pursued in project form. This includes the planned facilities in the nuclear fuel programme, where two major projects have been organized for the purpose of gathering all the material needed for the permit applications for the encapsulation plant and the deep disposal.

Over many years, SKB has devised and implemented an integrated management system that meets the requirements of ISO. As of 2001 the system is certified to ISO 9001:2000 and ISO 14001:1996. The regulatory authorities have reviewed and commented on the management system on different occasions. The changes in working methods required by the certification process are now well established in the organization.

Future needs

SKB's work force, organization and mode of working are now adapted to the needs of the current phase of the nuclear waste programme. No major changes are planned during the coming years. In the longer term, however, radical changes will take place. After permits are granted for the encapsulation plant and the deep repository, most of the nuclear fuel programme will enter an intensive implementation phase, after having long been dominated by development and planning. The facilities will then be built, to a great extent simultaneously. The activities will thereby both change character and expand greatly. The deep repository in particular is a huge industrial project which is expected to require a work force of around 300 persons during the most intensive part of the construction phase. The construction of an encapsulation plant is a project of smaller scope than the deep repository, but contains unique elements. At later stages, an assembly factory for canisters will be built and certain modifications will be made in the transportation system.

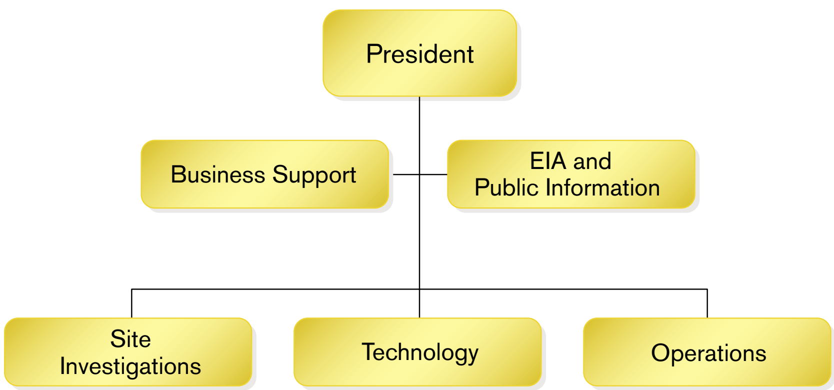

Figure 14. *SKB's line organization.*

Between now and 2008, an organization must be planned and established for the upcoming construction phase, and to some extent for the following operating phase as well. Important questions in this planning work are how management and leadership of the big construction projects are to be organized, and how contract procurement is to be managed. Furthermore, SKB must organize its own safety review and inspection functions under forms that ensure a strong and independent status in relation to the rest of the organization.

Where the future facilities are sited will greatly affect the organization. With the start of the construction phase, the venue of SKB's activities will be shifted more and more towards the community or communities where the encapsulation plant and the deep repository are established. What this will entail organizationally depends, among other things, on recruitment prospects in the communities and the regions, and on SKB's requirements on continuity and competence. Good advance planning based on realistic assumptions is required in order for the organizational transformation process needed for construction of the facilities to be implemented successfully. From SKB's perspective it is therefore essential that the implementation programme be robust and enjoy broad support in order to minimize the risks of major deviations from the overall planning.

The LILW programme also includes future facility construction, with associated organizational and resource needs. But the scope is smaller, and the time perspective longer, than for the nuclear fuel programme's facilities. Coordination of planning between the nuclear fuel and LILW programmes should enable variations in resource needs to be equalized over time. Given the goal that the disposal chambers for decommissioning waste etc should be available by 2020 at the earliest, early planning and design should be started at roughly the same pace as resources for this can be freed from the deep repository project, which will then be in transition from planning to building. Similarly, the extension for decommissioning waste can be started at the same time as the deep repository nears the operating phase. Siting and establishment of the final repository for other long-lived waste come later, at a stage when the other facilities are in operation.

A6.2 Meeting future competence needs

Current situation

SKB's competence profile today reflects both the nuclear waste programme's more than 30-year history and changes in recent years. Continuous activities over many years and a tradition of low staff turnover have led to a considerable accumulation of knowledge and expertise covering all parts of SKB's operations. There are many people in the company, especially in the technical fields, with industry experience stretching back all the way to the early days of the programme. This assembled knowledge capital is of great value and can only be maintained via an organization that ensures active experience feedback.

During the past 3–4 years, SKB's personnel needs have increased considerably. The initiation of the site investigations required a rapid build-up of local site units and to some extent central staff units as well. The systems for quality and environmental management have also required additional resources. There have been staff increases at the laboratories as well, as more full-scale testing has required more and more resources.

These needs have been met by a combination of staff recruitment and contracting of consultants with specialist expertise. The expansion is now more or less complete. The resultant rejuvenation of the organization opens up new possibilities for managing the existing knowledge capital via experience feedback.

Future needs

Compared with other industrial enterprises, SKB is able to predict its future competence needs with good accuracy and can thereby plan ways to meet these needs well in advance.

The programme for the remaining development work and for building and operating the facilities is relatively well defined in terms of content and scope. Financially, there are few programmes with as good long-term prospects as the nuclear waste programme. The planning uncertainties that do exist mainly relate to society's attitudes towards the nuclear waste programme, with the consequences this may have on decision processes and timetables.

In the time perspective of the permit applications for the facilities in the nuclear waste programme (2006–2008), SKB is now well equipped and staffed for its mission. This applies to both key competencies and total manpower needs. There is, however, also a vulnerability in the form of insufficient redundancy within certain strategically important niches where qualified personnel are hard to find and/or take a long time to train. An example is system analyses and safety assessments, but the problem also exists in the geoscience, radiology and nuclear technology. Responsibility for identifying and eliminating such uncertainties in time rests with the company's ongoing strategic human resources planning.

When the permit applications have been submitted, the nuclear fuel programme will enter into a preparation phase prior to decisions regarding the facilities. It is then important to maintain continuity of competence, even though some uncertainty may exist with regard to the duration and outcome of the decision process. SKB's main tasks during this phase will be to continue pursuing those activities that are not primarily affected by the decisions, to remain at the disposal of the decision-makers in different respects, and to make preparations for the establishment phase of both the encapsulation plant and the deep repository.

Prior to the construction of the encapsulation plant and the deep repository, there is a great need for qualified, well-trained and well-prepared personnel for management of major construction projects, procurement and quality control. Building facilities is not in itself anything new for SKB, and the knowledge and skills gained from the construction of SFR, Clab and the Äspö HRL will comprise valuable core competencies. However, the deep repository is a much bigger project than the previous facilities. The construction phase requires competent and qualified contractors from different parts of the building sector, particularly rock construction. The ambitious plans that exist today for development of the country's infrastructure are expected to contribute to a project volume that is sufficient to ensure continuity within this sector. To what extent resources will be available when the deep repository is to be built may determined by the timing of other large rock construction projects.

Long-term development of the sector

The development of key fields such as nuclear technology, radiation protection and geoscience, as well as the corresponding educational sectors, will in the long term be of great importance for the prospects of the nuclear waste programme to meet its future competence needs. Many of the senior positions in these areas (as well as in the entire nuclear power industry) are currently filled by persons with roots from the time when nuclear power was seen as a highly attractive and expansive future industry with a strong position in the educational system. Today this sector is said to be one of the mature industries that are finding it increasingly difficult to attract members of the younger generation. Active training and research programmes are vital in ensuring a future supply of qualified personnel.

In the long run, the prospects of meeting future competence needs are highly dependent on what happens with nuclear power and nuclear engineering in Sweden and the rest of the world. The present-day situation in Sweden, with an unclear phase-out scenario, makes it difficult to judge both future competence needs and the prospects of meeting them. So far, however, fears of a shortage of competencies in the field of nuclear technology have proved unfounded, even though vigilance is certainly warranted. The radiation protection sector has expressed concern regarding the future availability of qualified personnel, especially at a stage when the nuclear power sector will be faced with the task of decommissioning the NPPs and managing the waste.

Appendix B

Abbreviations

Abaqus	Finite-element computer code for strength calculations.
ACL	Active Central Laboratory, Studsvik.
Adopt	EU project. Thematic network on advanced options for partitioning and transmutation.
ADS	Accelerator-driven systems.
AECL	Atomic Energy of Canada Ltd, Canada.
AFCI	Advanced fuel cycle initiative.
Amber	Computer code for safety assessment (biosphere).
Andra	Agence National Pour la Gestion des Dechets Radioactifs (Andra), France.
Apse	Experiments at Äspö HRL, Pillar Stability Experiment.
ASCII	American standard code for information interchange.
ATB	Transport casks for spent nuclear fuel and core components.
ATW	Accelerator-driven transmutation of nuclear Waste.
BAM	Bundesanstalt für Materialprüfung in Germany.
Barra	Enresa project.
Bastra	EU project. Adopt cluster, Transmutation – Basic studies.
BEM	Boundary element method.
Benchpar	EU project. Benchmark tests and guidance on coupled processes for performance assessment of nuclear waste repositories.
Big Bertha	Full-scale test, swelling of bentonite.
Bio42	SKB's computer code for calculation of radionuclide transport in the biosphere (Proper submodule).
Bioclim	EU project. Modelling sequential biosphere systems under climate change for radioactive waste disposal.
Biomass	IAEA project. Programme on biosphere modelling and assessment.
Biomat	Computer code (biosphere)
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.
Bios	Biological iron oxides.
BNFL	British Nuclear Fuels Ltd.
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.
CEA	Commissariat à l'Energie Atomique.
CEC	Cation exchange capacity.
Chan3D	Computer code, channel network model in three dimensions.
Chemlab	Measurement probe for investigations in boreholes, Äspö HRL.
Ciemat	Research Centre for Energy, Environment and Technology in Spain.
Clab	Central interim storage facility for spent nuclear fuel.
Code Bright	Computer code for thermo-hydro-mechanical calculations.
Comp23	SKB's computer code for calculation of radionuclide transport in the near-field (Proper submodule).
Compass	Computer code for thermo-hydro-mechanical calculations.
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.
Coup	Computer code that handles transpiration, growth and nutrient uptake for vegetation.

Crop	EU project. Cluster repository project, a basis for evaluating and developing concepts of final repositories for high-level radioactive waste.
Crud	Chalk river unidentified deposits. Surface contamination.
CTH	Chalmers Tekniska Högskola (Chalmers University of Technology), Göteborg.
DarcyTools	Computer code for groundwater flow calculations.
Decovalex	International project. Mathematical models of coupled THM processes for nuclear waste repositories.
DFN	Discrete fracture network.
EBS	Engineered barrier system.
EBW	Electron beam welding.
EC	European Commission.
Ecoclay	EU project. Effect of cement water on clay barrier performance.
Ecolego	Computer code for safety assessment (biosphere).
Ecopath	Computer code for safety assessment (biosphere).
EDF	Ecosystem-specific Dose Conversion Factor.
EDZ	Excavation Disturbed Zone.
EKG	Technical group within SKB for exchange of information between site investigation, analysis group, safety assessment and research.
Elforsk	Svenska elföretagens forsknings- och utvecklings AB.
Embras	IAEA project.
Eniq	EU project. European Network for Inspection Qualification.
Enresa	Empresa Nacional de Residuos Radiactivos, Spain.
Equip	EU project. Evidence from Quaternary infillings for palaeohydrology.
Erica	EU project. Environmental Risk from Ionising Contaminants.
Esarda	European Safeguards Research and Development Association.
Esdred	EU project. Engineering studies and demonstrations of repository designs.
ET	Eddy current testing.
EU	European Union.
Euratom	European Atomic Energy Community.
Europart	EU project. European research program for the partitioning of minor actinides and some long-lived fission products from high active wastes issuing the reprocessing of spent nuclear fuels.
Examine	Computer code for rock mechanical analyses.
Farf31	SKB’s computer code for calculation of radionuclide transport in the far-field (Proper submodule).
Fasset	EU project. Framework for assessment of environmental impact.
Febex	Full-scale high level waste engineered barriers experiment, Grimsel, Switzerland.
Fep	Feature, events and processes.
F factor	Transport resistance.
Flac3D	Computer code for rock mechanical analyses.
R&D	Research and Development.
Fracman/PAworks	Computer code, discrete fracture network for performance assessment.
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.
Fuetra	EU project. Adopt cluster, Transmutation – Basic studies.
Gambit	International project. Gas migration in bentonite.
Gasnet	EU network. A thematic network on gas issues in safety assessment of deep repositories for nuclear waste.
Geotrap	OECD/NEA project. Radionuclide migration in geologic, heterogeneous media.

GIA	Global isostatic adjustment.
Gis	Geographic information system.
Goldsim	Computer code for safety assessment (biosphere).
Hindas	EU project. Cluster Bastra, High and intermediate energy nuclear data for accelerator-driven systems.
HMC	Hydro-mechanical-chemical.
HPF	International project. Hyperalkaline plume in fractured rocks, Grimsel, Switzerland.
HRL	Hard rock laboratory.
HTGR	High-temperature gas-cooled reactor technology.
HTO	Tritiated water.
IAEA	International Atomic Energy Agency.
Ibeco Deponit CA-N	Calcium bentonite from Milos.
ICP-AES	Inductively coupled plasma – optical emission spectroscopy.
ICP-MS	Inductively coupled plasma – mass spectrometer.
ICRP	International Commission on Radiological Protection.
IJC	International joint committee, Äspö HRL.
InCan	EU project. In can processes.
INF	Department of Neutron Research at Uppsala University.
Inka	SKB project. Design of encapsulation plant.
IPCC	Intergovernmental panel on climate change.
ISI	Initial site investigation.
IRPA	International Radiation Protection Association.
ISA	Isosaccharinic acid.
ISO 14001	International quality standard, environmental management systems.
ISO 9001	International quality standard, quality management systems.
ISTC	International Science and Technology Center.
ITU	Institute for Transuranium Elements, Karlsruhe.
IUR	International Union of Radioecology.
JNC	Japan Nuclear Cycle Development Institute, Japan.
JobFem	Computer code for thermomechanical analyses.
JRC	Joint Research Center in the Netherlands.
KASAM	Swedish National Council for Nuclear Waste.
KBS	Kärnbränslesäkerhet = Nuclear fuel safety.
KBS-3H	Variant of KBS-3, horizontal deposition with several consecutive canisters in medium-long deposition holes.
KBS-3 method	SKB's reference method for disposing of spent nuclear fuel.
KBS-3V	Reference variant of KBS-3, vertical deposition with one canister in each deposition hole.
K_d	Element-specific distribution coefficients.
CSI	Complete site investigation.
K-S-P	Hydraulic parameters. Permeability (K) Saturation (S) Pressure (P).
KSU	Kärnkraftsäkerhet och Utbildning AB (Nuclear Power Safety and Training Company).
KTB	Kontinentales Tiefbohrprogramm der Bundesrepublik Deutschland.
KTH	Kungliga Tekniska Högskolan (Royal Institute of Technology, Stockholm).
KTL	Kärntekniklag (Nuclear Activities Act, SFS 1984:3).
KTS 001	SKB's technical specification – Copper ingots and billets for canister components.
Lasgit	Experiment at Äspö HRL, Large scale gas injection test.
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.
M3	Computer code for hydrochemical analyses, Mixing and mass balance modelling.

Maqarin	Natural analogue. There is natural cement in the rock in Maqarin, Jordan.
Matlab	Commercial computer code for mathematical calculations.
MB	SFS 1998:808 Environmental Code.
MBA	Material balance area.
Microbe	Microbial experiments at Äspö HRL.
Mistra	Swedish Foundation for Strategic Environmental Research.
EIA	Environmental Impact Assessment.
MLH	Medium Long Holes, early name for KBS-3H.
Mock-up	Czech large-scale experiment simulating a vertical deposition hole with canister and buffer.
Mox	Mixed oxide fuel.
MSRE	USDOE project. Molten Salt Reactor Experiment.
Muse	EU project. Cluster Bastra, Demonstration of the physical principles of an external source-driven sub-critical core at near zero power.
MX-80	Sodium bentonite from Wyoming.
Nagra	Nationale Genossenschaft für die Lagerung von Radioaktiver Abfälle, Switzerland.
Nanet	EU project. Network to review natural analogue studies and their applications to repository safety assessment and public communication.
Natt	Project financed by SKB, SKI and the nuclear power companies in Sweden. Neutron data for accelerator-driven transmutation technology.
NDT	Non destructive testing.
NDT Reliability	Research programme at BAM to determine the reliability of the NDT methods.
NEA	Nuclear Energy Agency, Paris.
Net.excel	EU project. Network of excellence in nuclear waste management and disposal.
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.
NGI	Norwegian Geotechnical Institute.
Nimonic 105	Nickel-based superalloy.
Nirex	Nirex Ltd.
NKS	Nordic nuclear safety collaboration.
n-TOF	Neutron time-of-flight facility in Cern.
Nuctran	SKB's computer code for calculation of radionuclide transport in the near-field.
Numlib	Routine library for numerical calculations.
Numo	Waste management organisation of Japan.
OECD	Organisation for Economic Cooperation and Development, Paris.
OECD/NEA	Organisation for Economic Cooperation and Development/Nuclear Energy Agency.
NDT	Nondestructive testing.
Ondraf/Niras	Belgian agency for radioactive waste and enriched fissile materials.
Opalinus	Swiss project. Performance assessment of a high-level radioactive waste repository in Opalinus clay host.
OPG	Ontario Power Generation.
ORNL	Oak Ridge National Laboratory, USA.
Padamot	EU project. Palaeohydrogeological data analysis and model testing.
Particle Flow Code	Computer code for rock mechanical analyses.
Partition	EU project. Adopt cluster, Partitioning.
Partnew	EU project. Cluster Partitioning, New solvent extraction processes for Minor Actinides.
PDS-XADS	EU project. Adopt, Preliminary design studies of an experimental accelerator-driven system.
UDP	Deep Repository, Underground Design Premises.
PFC	Particle flow code. Computer code for rock mechanical analyses.
Phreeqc	Computer code for coupled geochemistry and transport analyses.
Pick51	Proper submodule for communication with ASCII files.

PMMA	Polymethylmethacrylate autoradiographs.
POD	Probability of detection.
Posiva	Posiva Oy.
Prism	Computer code for probabilistic calculations of radionuclide transport in the biosphere.
Proper	SKB's computer code package for handling of probabilistic calculations of hydrology and radionuclide transport.
Prototype	EU project. Full scale testing of the KBS-3 concept for high-level radioactive waste.
PSACoin	OECD/NEA project. Probabilistic system assessment codes intercomparison.
PSI	Paul Scherrer Institute, Switzerland.
PWR	Pressurized water reactor.
PVT	Method for measuring reaction kinetics (pressure-volume-temperature).
Pyrorep	EU project. Cluster Partition, Pyrometallurgical processing research programme.
RedImpact	EU project. Impact of reduction and waste treatment techniques.
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.
RMN bentonite	Czech bentonite.
RNR	Experiment at Äspö HRL. Radionuclide retention experiment.
ROC	Risk of false calls.
RVS	Rock visualisation system.
SAD	ISTC funded project. Creation of sub critical assembly driven by proton accelerator.
Safe	SKB project. Renewed safety report for the final repository for operational waste, 2001.
Safir-2	Belgian project. Belgian programme on high-level and long-lived waste.
SBM	Shaft boring machine.
SEM-EDS	Scanning electron microscope – Energy dispersive spectroscopy.
SFR	Final repository for short-lived low- and intermediate-level waste.
SFS	EU project. Spent fuel stability under repository conditions.
Simulink	Commercial computer code for mathematical calculations.
SKB	Svensk Kärnbränslehantering AB (Swedish Nuclear Fuel and Waste Management Co).
SKB 91	SKB project. Importance of the bedrock for the long-term safety of the KBS-3 repository, 1992.
SKI	Statens kärnkraftinspektion (Swedish Nuclear Power Inspectorate).
SLU	Swedish University of Agricultural Sciences, Uppsala.
Soil	Computer code that handles transpiration, growth and nutrient uptake for vegetation.
Spire	EU project. Cluster Testra, Irradiation effects in martensitic steels under neutron and proton mixed spectrum.
SQC	SQC Kvalificeringscentrum AB.
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	SKB's safety assessment as a basis for an application for a permit to build an encapsulation plant.
SR-Site	SKB's safety assessment as a basis for an application for a permit to build a deep repository.
SSI	Statens strålskyddsinstitut (Swedish Radiation Protection Authority).
Sum41	SKB's computer code for weighting and summation of time series in the biosphere (Proper submodule).
SveBeFo	Stiftelsen svensk bergteknisk forskning (Swedish Rock Engineering Research Foundation).
Sweclim	Mistra project. Swedish regional climate modelling programme.
Sysdjup	SKB's system analysis as a basis for an application for a permit to build the deep repository.

Sysinka	SKB's system analysis as a basis for an application for a permit to build the encapsulation plant.
TBM	Tunnel boring machine.
TBT	Experiment at Äspö HRL. Temperature buffer test.
TDB	OECD/NEA project. Thermodynamic data bases.
TDS	Total dissolved solids.
Tecla	EU project. Cluster Testra, Technologies, materials and thermal-hydraulics for lead alloys.
Tecplot	Computer code for postprocessing of results.
TEF	Technical Evaluation Forums, Äspö HRL.
TEM	Transmission electron microscopy.
Tensit	SKB's computer code package for numerical calculations of radionuclide transport.
Testra	EU project. Adopt cluster, Transmutation – technology studies.
THM	Thermo-hydro-mechanical.
THMC	Thermo-hydro-mechanical-chemical.
TN17-2	Transport cask for spent nuclear fuel.
TN17-CC	Transport cask for spent core components.
True	Experiment at Äspö HRL. Tracer retention understanding experiments.
TS01	Proper submodule for communication with ASCII files.
TSL	The Svedberg Laboratory, Uppsala.
TWG	European technical working group of experts on ADS.
TWI	The Welding Institute, Cambridge, England.
UPC	Universitat Politècnica de Catalunya.
URL	Underground Rock Laboratory.
US NRC	United States Nuclear Regulatory Commission.
USDOE	United States Department of Energy.
UU	Uppsala University.
Wave	Computer code for rock mechanical analyses.
WPS	Welding procedure specification.
Xanes	X-ray absorption near edge structures.
XAS	X-ray absorption spectroscopy.
XPS	X-ray photoelectron spectroscopy.
XRD	X-ray diffraction.
Yalina	ISTC-funded project. A sub-critical, thermal facility set up in Minsk.
Zedex	Experiment at Äspö HRL. Zone of excavation disturbance experiment.
α radiation	Alpha radiation.
β radiation	Beta radiation.
γ radiation	Gamma radiation.
σ	Rock stress.
@Risk	Commercial risk analysis program.
3D	Three-dimensional.
3DEC	Computer code for rock mechanical analyses.

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