Technical Report

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RD&D-Programme 2001

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

September 2001

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Preface

The Nuclear Activities Act requires a programme for the comprehensive research and development and other measures that are required to manage and dispose of nuclear waste in a safe manner and to decommission and dismantle the nuclear power plants. To meet this requirement, SKB is now presenting RD&D-Programme 2001. The programme presents SKB's plans for the period 2002–2007. The period of immediate concern is 2002–2004. 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.

In December 2000, SKB presented proposals for sitings of the deep repository and the background material on which the choice was based, as well as programmes for investigations on these sites. In June 2001, SKI and Kasam submitted their statements of opinion to the Government following an extensive review. Pending the Government's decision, SKB has nothing new to add as far as the siting process is concerned.

This RD&D-Programme differs from the preceding ones in that it concentrates on questions relating to research and technology development. Questions pertaining to siting of our facilities will be elaborated on in greater detail in conjunction with applications to authorities and related environmental impact statements. This programme is also structured differently than the previous programmes. We take our point of departure in the regulatory requirements on long-term safety and link them to the development of the safety assessment methodology and the research on the long-term processes in the repository. The programmes for safety and research are then linked together with the programmes for development of methods and instruments for the site investigations and the design of the deep repository, the encapsulation plant and the canister. In conclusion, the programmes for alternative methods, decommissioning and other long-lived waste are also explained. It is our hope that such a structure and such an approach will provide a clearer picture of which factors are most important for safety in the repository and in which areas we are concentrating our efforts.

Stockholm in September 2001

Swedish Nuclear Fuel and Waste Management Company

Peter Nygårds
President

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Head of Safety and Technology

Summary

The preceding RD&D-Programme from 1998 was supplemented in December 2000 by an integrated account of method, site selection and programme prior to the site investigation phase. Since the latter account lies close in time, SKB has chosen to concentrate RD&D-Programme 2001 on research and technology development. Viewpoints offered on previous RD&D-programmes and comments from the review of the SR 97 safety assessment comprise important input for RD&D-Programme 2001. It has not been possible or appropriate in this report to take into account all the viewpoints that have emerged in the regulatory authorities' statements regarding the supplement to RD&D-Programme 98 presented in June. Many of the review comments will therefore be dealt with in the continued work with the site investigation programmes.

An overall goal for SKB is to start the initial operation of a deep repository for spent fuel in 2015. This presumes that site investigations have been commenced at the beginning of 2002 and that the different phases have been executed without major changes. Regular operation should then be able to commence in the early 2020s before the storage pools in CLAB are full, thus avoiding further expansion. The encapsulation plant should be ready to start roughly one year before the deep repository is finished.

Future RD&D-programmes will probably place the emphasis slightly differently depending on different phases and permit applications. RD&D-Programme 2004 is expected to give a central role to the canister and the encapsulation technology. In RD&D-Programme 2007, the deep disposal technology and continued work on alternative disposal methods may be important topics. All of this is shown by the overall timetable presented in Chapter 1.

The timetable also includes conducting safety assessments of the deep repository when data from the site investigations are available. These assessments should provide a basis for site selection and will be preceded by preliminary safety judgements based on data from the initial site investigation phase. The methods used to analyze long-term safety are being developed based on the lessons learned from SR 97. Central parts of the safety assessment are system descriptions, along with choice and analysis of scenarios. This is now being further adapted and developed for the purpose of dealing with data from the site investigations. SR 97 used a simplified method for risk calculations, which has now been evaluated and improved with the aid of newly-developed analytical models.

Safety assessment, research and repository design are closely interrelated. The design of the repository is a premise for safety assessment. The research contributes knowledge regarding what changes may take place in the long term in the repository. Conversely, the results of a safety assessment can be used to improve the repository design and – not least – to prioritize different research areas. We have used this to build up the structure in large parts of the report. Instead of presenting the research arranged according to discipline, as is customary, we have tied it to the processes that are of importance for the long-term safety of a deep repository for spent fuel. It is our hope that it will be easier to determine why research is being done, where sufficient knowledge already exists, and which areas require further studies.

The spent fuel is the waste that is to be isolated in the deep repository. Various processes will with time alter the conditions in the fuel and in the voids of the canister. Many of these process only occur if the isolation of the canister is breached and water enters the canister. Radiolysis of water is an example of such a process, which can in turn influence the chemical conditions in the canister. Water in the canister can also cause corrosion of the fuel's cladding tubes. If water comes into contact with the fuel it can lead to dissolution of radionuclides. Dissolved radionuclides can diffuse in the water and thereby escape from a damaged canister. Fuel dissolution is therefore an important process for showing what might happen if a canister fails to isolate the fuel, which is a part of the safety assessment. Fuel dissolution is a priority area in RD&D-Programme 2001.

The canister is an important barrier in the repository. It consists of different parts. Outermost is a shell of copper, and the insert is of cast iron – outer corrosion resistance combined with inner strength. Corrosion resistance and strength are important properties. Processes that affect these properties are therefore urgent fields of knowledge. Large resources are being devoted to studies of copper corrosion and stress corrosion cracking (SCC) in the copper canister. Corrosion inside a canister is also dealt with in the event that water should enter. The study of strength that was used for SR 97 needs to be brought up to date. Strength needs to be calculated using more realistic material data for the cast iron insert. SKB will also investigate the long-term safety of a canister type with a slightly thinner shell but a heavier-duty insert.

The buffer of bentonite clay is supposed to protect the canister mechanically against minor rock movements. It is also supposed to retard solute transport. Corroding substances should be kept from reaching the canister, and if the canister is damaged the buffer is supposed to retard the migration of radionuclides. After the buffer and canister have been placed in the deposition hole, the buffer will reach a stable water-saturated state. This may take ten years or so. At the same time, the canister emits heat which has to be conducted out to the rock via the buffer. It is important to be able to predict the state of the buffer after it has been saturated with water, which is the stable state in the very long term. The initial evolution of the buffer is therefore studied in the Äspö HRL and by means of models. The water-saturated state is also investigated. Important processes in the latter case are effects of saline water and gas transport. Excessively high salinities can influence the swelling of the bentonite clay, and gas must be able to travel through the buffer without damaging it.

The backfill is supposed to stabilize the tunnels mechanically, keep the buffer in place in the deposition holes and prevent water flow through the tunnels. Different mixes of crushed rock and smectite clays will be tested. The long-term evolution of the backfill is controlled by largely the same processes as in the buffer. Important processes that must be further investigated are the importance of swelling in the tunnels and the influence of saline water. The backfill is more sensitive to saline water than the more compacted buffer.

The geosphere is supposed to protect the canisters and constitute a barrier to the migration of radionuclides if the canister should be damaged. Several processes in the geosphere are important for the safety assessment, such as groundwater flow, earthquakes, microbial processes and matrix diffusion. The models for groundwater flow will be further refined in order to handle the heterogeneity of the rock in the best manner and to serve as a basis for selecting suitable rock for location of deposition tunnels and holes. A model for earthquakes was used in SR 97 which overestimates the risk of movements along fractures in the rock. The earthquake analysis is therefore being further refined to make it more realistic and less conservative. The chemistry of the groundwater at repository depth has been thoroughly studied, and SKB has developed practical methods for investigating a future site. When it comes to determining how stable the conditions are, microbial studies occupy a special position. Microbes contribute towards keeping the environment oxygen-free. Microbial processes are a relatively new field that we are continuing to investigate. Matrix diffusion describes how dissolved radionuclides penetrate into the microfractures in the rock, thereby retarding the migration of radionuclides along large water-bearing fractures in the rock. Diffusion in microfractures has been thoroughly investigated, but its relationship with the water flow and the geometry of the system of major fractures in the rock needs to be further studied.

Colourful descriptions of earthquakes following the retreat of the continental ice sheet are sometimes offered as arguments against building a deep repository. The Boda caves, in the Iggesund district, have been held up as examples of the violence of this process. SKB has had the Boda caves investigated by drilling and geophysical measurements. The phenomenon is superficial, and no traces of fracturing at depth have been found. The results rather suggest that the caves were formed by the erosion caused by the ice sheet. We know that very large earthquakes have occurred in conjunction with the continental ice sheet, for example the Pärvie and Lansjärv faults. But we also know that the effect of earthquakes on underground structures is small and that a deep repository can be designed to withstand even very large quakes in the immediate area. To acquire further knowledge in the area, all known postglacial faults that have been documented in Scandinavian and Canadian bedrock are being compiled and examined. Swedish and foreign experts will have an opportunity to evaluate this material in the light of our safety requirements.

The biosphere is an essential part of what the safety assessment must treat. It is in the biosphere that people live and it is here that the consequences of a release become manifest. We must also expect that the biosphere will change in the future. Postglacial land uplift and climatic variations are examples of processes that influence the evolution of the biosphere in the long term. The turnover of radionuclides in the biosphere is calculated with models (compartment models). They have been developed considerably in recent years and further improvements will be made to bring the models even more closely in line with reality. Knowledge of the mechanisms for transfer of radionuclides between different parts of the biosphere has improved, and the models will be based on this new knowledge. Examples of ecosystems that are studied and dealt with in the models are forest, mireland and sediment.

The climate will change in the future. Different climatic conditions will succeed one another during the period of hundreds of thousands of years or more we deal with in the safety assessment. It is therefore necessary to analyze how different types of climate – if they occur – would affect the repository and its safety. Permafrost is an example of a climatic state that will be more closely investigated, and a project aimed at this is currently planned. Another example is the glacial state.

Natural analogues – examples in nature – make it possible to investigate processes that have proceeded for a much longer time than can normally be followed by experiments in the laboratory or field. Natural analogues are often difficult to evaluate in detail, but they can nevertheless be a good complement to purely experimental investigations. Material analogues occupy a prominent position in the upcoming programme. Typical material analogues are natural deposits of copper or bentonite, but concrete will also be investigated. Specimens of old concrete will be examined, as well as sites where cement minerals occur naturally.

The Äspö HRL is a place for research, development and demonstration. Most of the research is focused on processes of importance for long-term safety. The technical development is focused on the deep repository. The different steps in building the repository, emplacing the canisters and the buffer, and backfilling and closure are tested on Äspö. Site investigation methods are also developed there. Several organizations in other countries are participating in the work at the Äspö HRL. Both the research and the technical development on Äspö are described at different places in this report. The research is dealt with where the processes are described, for example in the chapters on buffer (Chapter 6) and backfill (Chapter 7). Development and demonstration of technology is dealt with in the chapters on instrument development (Chapter 13) and the deep repository (Chapter 14). Since the Äspö HRL is such an important part of SKB's RD&D-programme, it is also described separately in a chapter of its own. The Äspö HRL will continue to play a vital role at least until the Prototype Repository has been opened and evaluated in the early 2020s.

Instruments and methods for handling measurement results are needed to carry out the site investigations. Existing and commercially available technology is used where possible, but for special needs SKB develops both instruments and methods. Many of the measurement methods that will be used are well-tested and documented. Others still require some development, or at least some revision and streamlining, such as seismic measurements, rock stress measurements, GPS networks, seismological networks, measurements while drilling (MWD), hydrological measurements, chemical measurements and measurements of the transport properties of the rock. The preparations also include looking farther ahead. Preliminary programmes are being worked out for both measurements and observations in the detailed characterization phase, during operation and after closure.

The deep repository for spent fuel is being developed with the KBS-3 concept as a basis. Full-scale tests are being performed at the Äspö HRL of drilling of deposition holes, emplacement of canisters and bentonite, and backfilling. The Prototype Repository in the Äspö HRL will contain six deposition holes with canisters, and the test will proceed for 20 years. Electric heaters will be used instead of spent fuel, but otherwise real repository conditions will be simulated to as great an extent as possible. Equipment for depositing buffer and canisters will be further developed. The goal is to demonstrate the deposition technique in its entirety prior to initial operation in the deep repository. Material and methods for backfilling, closure and sealing of boreholes are also being developed at Äspö. KBS-3 is the basis, but we will also examine variants of the concept. Such a variant is Medium Long Holes (MLH), whereby the canisters are deposited horizontally. The study will show whether horizontal deposition can offer practical, environmental or economic advantages compared with vertical deposition.

The encapsulation plant, where the spent fuel is to be placed in copper canisters, is still on the drawing board. The technology for welding on the copper lid is being developed at the Canister Laboratory in Oskarshamn. Electron Beam Welding (EBW) is the method being developed today at the Canister Laboratory. The alternative technique, Friction Stir Welding (FSW), is also being tested and will later be transferred to the Canister Laboratory and developed on a full scale. The technology for examining the weld joint is also being developed there. Elsewhere, different fabrication methods for the different parts of the canister are being tested. The assignment is being given to several different suppliers so that we can then decide which method is best suited. Some of the canisters that are fabricated are used for experiments in the Äspö HRL.

Alternative methods. Even though we in Sweden have in practice already chosen the method of deep geological disposal for the spent fuel, SKB has decided to monitor the development of the two alternatives partitioning and transmutation (P&T) and deposition in Very Deep Holes (VDH). The future of both methods is uncertain to say the least, but it may nevertheless be worthwhile to devote some interest to keeping track of what is being done internationally in these two areas.

Decommissioning. The owner is the one who is responsible for ensuring that a nuclear installation is ultimately decontaminated, decommissioned and dismantled when it has been taken out of service. SKB is conducting general studies of decommissioning to ensure that competence exists and that the costs are correctly estimated. The nuclear power plants themselves are responsible for planning, permit application and execution of decommissioning of their own plants. Disposal of the waste is coordinated with SKB, and a final repository for the short-lived waste must be ready to receive waste when decommissioning is begun on a large scale. The aim during the coming six-year period is to develop methods for dry interim storage of core components, introduce systems for registration of the waste, review the decommissioning logistics, estimate doses in conjunction with decommissioning, and carry out preliminary safety assessments of final disposal. An important element in this work is monitoring of foreign activities.

Long-lived waste from decommissioning in the form of reactor internals and core components also have to be disposed of in a final repository. This repository must also accommodate long-lived LILW (low- and intermediate-level waste) from research, industry and medicine (the short-lived waste is already being disposed of today in SFR). A preliminary design of the repository for long-lived LILW has been studied and a safety assessment has been conducted. The repository does not have to be put into operation for another 45 years. The aim during the upcoming six-year period is mainly to prepare for future safety assessments by conducting research on the waste and processes in the repository.

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1 Introduction

1.1 The Swedish system

Sweden has been producing electricity by means of nuclear power for nearly 30 years. The nuclear power industry was given responsibility for managing and disposing of all radioactive waste from its plants in a safe manner back in the 1970s. The owners of the nuclear power plants jointly formed Svensk Kärnbränslehantering AB (SKB, the Swedish Nuclear Fuel and Waste Management Company) for this purpose. The Nuclear Waste Fund was also established to ensure funding.

Over the past few decades, SKB has built up a system for management and disposal of different types of radioactive waste, see Figure 1-1. The system includes a specially-built ship for transport, a final repository for different types of operational waste (SFR) and a central interim storage facility for spent nuclear fuel (CLAB). However, three important components are lacking to manage the spent nuclear fuel: an encapsulation plant for encapsulating the spent fuel in copper canisters, a canister factory for fabricating the copper canisters, and a deep repository where the encapsulated waste can be disposed of in a safe long-term manner. A transportation system designed to serve these facilities is also needed. Moreover, repositories are needed for disposal of the waste that arises when the nuclear installations are decommissioned and for other types of long-lived waste than nuclear fuel, such as core components.

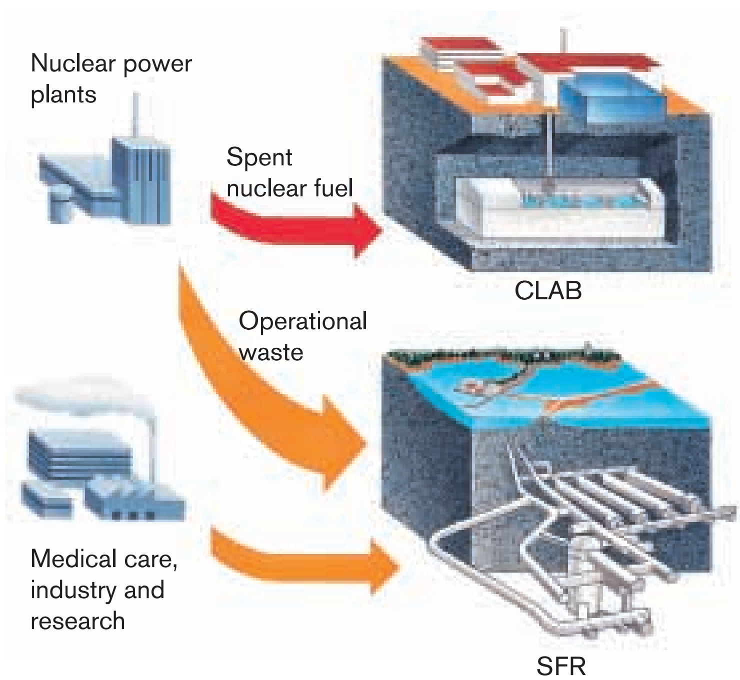


Figure 1-1. *Today's Swedish system for managing and disposing of different types of radioactive waste.*

In the mid-1970s, SKB started development of a concept for encapsulation and final disposal of the spent nuclear fuel and other long-lived waste from the Swedish NPPs. The work resulted during the period 1977 to 1983 in a series of reports that were progressively concentrated on encapsulating the spent nuclear fuel in copper canisters. The canisters are then deposited, embedded in bentonite clay, in vertical deposition holes in a tunnel system at a depth of approximately 500 metres in crystalline bedrock, see Figure 1-2. The method, known as KBS-3, has since then comprised the reference concept in the Swedish programme /1-1/.

1.2 SKB's long-term plan

The overall goal of SKB's work of managing and disposing of the spent nuclear fuel is that the first stage of the deep repository should be finished in 2015 and that initial operation can be commenced at that time. This goal presumes that all decisions and consents from national and local authorities have been made and given, so that the site investigations can be initiated at the beginning of 2002. 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. When sites have been selected for investigations, data will be available for making more detailed and site-specific timetables for the construction of the deep repository.

The reason for the overall goal of starting deposition in 2015 is so that responsibility for the final disposal of the spent fuel will not be shifted to future generations. The different steps in the realization of the deep repository should be carried out at a pace that takes advantage of the competence and the resources that have been built up and are now available. This promotes quality and safety of execution. The goal is also that the regular operation of the deep repository should be able to be commenced before the storage chambers in CLAB are full, thus avoiding the necessity of a further expansion of CLAB.

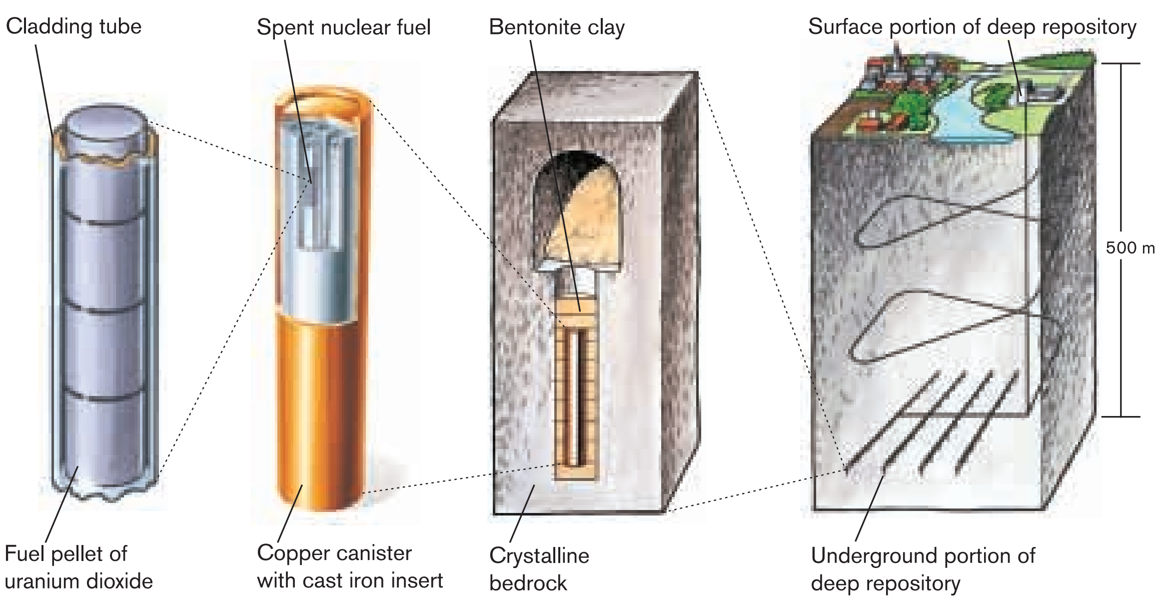


***Figure 1-2.** The KBS-3 method is SKB's reference method for disposal of spent nuclear fuel.*

The coming years' work with the deep repository will lay claim to large resources. The competence that exists in Sweden when it comes to site investigations, analysis of investigation results and safety assessments will be fully engaged in this effort. SKB's intention during the period covered by this RD&D-programme is therefore to prioritize the work with safety assessments and design of the deep repository and the encapsulation plant in relation to corresponding work with the final repository for other long-lived waste. The long-term timetables for the deep repository and the encapsulation plant are shown in Figure 1-3.

Such a prioritization is possible, since the final repository for other long-lived waste is not needed before decommissioning of the NPPs is in its final phase. Siting and construction will therefore not take place until after 2035, according to the current timetable (Figure 17-1). The technology used then is already applied in large part in SFR. The work of developing methods to condition the waste and to fabricate waste packages will be pursued in parallel with the development of methods for the decommissioning work. The design of barriers and research on long-term processes will continue during the ensuing six-year period. The point of departure here is the preliminary safety assessment that has been performed /1-2/.

Encapsulation of the fuel should start approximately one year before the deep repository is put into operation. With reference to the timetable for execution, construction of the encapsulation plant should therefore commence before the deep repository. However, it is not appropriate to start construction before the safety assessment for the deep repository has been completed and reviewed. The application for a permit for the deep repository is assumed in the timetable (Figure 1-3) to be based on the reference design of KBS-3 with deposition in vertical holes. A possible later changeover to horizontal deposition requires a supplementary system and safety account and a renewed decision by the authorities.

1.3 Adaptation of deep disposal and encapsulation

SKB's principal task during the next few years is to adapt deep disposal, encapsulation and canister fabrication to the sites where we will conduct site investigations, and later also to the site where we will conduct a detailed characterization. Work on this has already come quite far and is being pursued for different parts with the following basic subdivision into stages:

1. Overall choice of system (finished).
2. System analysis and optimization (under way).
3. Siting (under way).

1.3.1 Overall choice of system

Internationally, there are two principal strategies for management of the spent fuel: reprocessing (with or without subsequent transmutation) and direct disposal. The choice between these alternatives is determined by whether a country chooses to regard the fuel as waste or as a resource. In several states with large nuclear power programmes, reprocessing has been viewed as a necessity for sustainable management of the earth's resources. Other countries have, for political or economic reasons, chosen to regard the fuel as waste. Regardless of whether the waste consists of spent fuel or

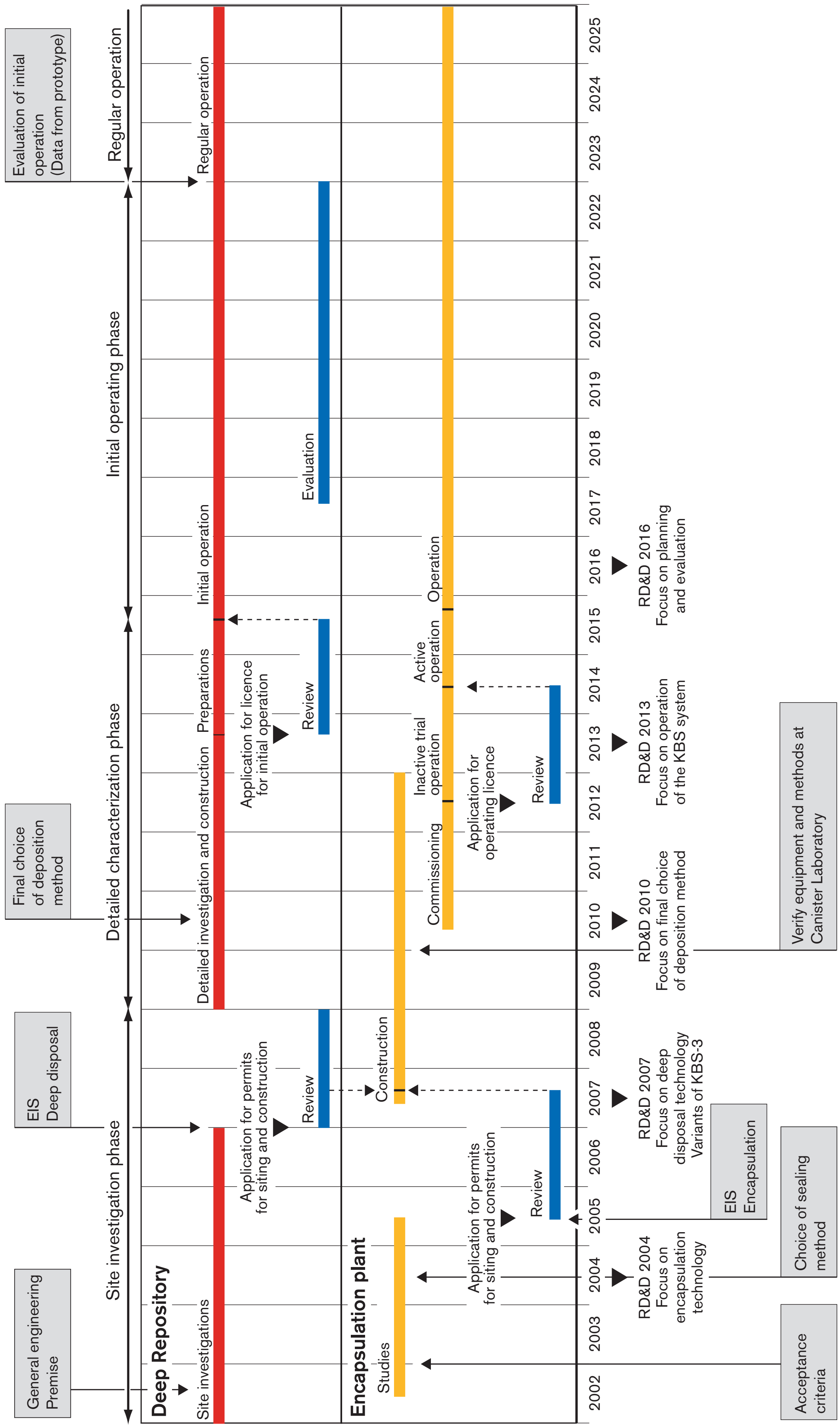


Figure 1-3. *SKB's reference timetable for the deep repository and the encapsulation plant.*

has been partitioned in a reprocessing plant, the idea is that it should be deposited in some type of geological formation. Multiple barriers will then prevent the radionuclides from reaching the biosphere.

The idea of geological disposal was first proposed back in the 1950s. Since then it has survived all other more or less realistic proposals, such as launching the fuel into space, disposing of it beneath the seabed or burying it in the continental ice sheet. The reason is that geological disposal fulfils all requirements that are made on a safe final disposal and that it can be implemented with adaptation of currently available technology.

SKB carried out a comparative system analysis during 2000 /1-3/. The purpose of the report was to compare different strategies for disposing of spent nuclear fuel. In it we also studied different methods for designing a deep repository in crystalline rock. The methods included in the comparison are the reference method KBS-3, Very Long Holes (VLH), WP-Cave and Very Deep Holes (VDH), see Figure 1-4.

In an integrated evaluation vis-à-vis the stipulated requirements, both ethical and technical, KBS-3 was deemed to be the most advantageous alternative. One argument in particular in favour of the KBS-3 method is that the operating phase provides individual control over both canisters and buffer. The repository is also easier to adapt to conditions on a particular site.

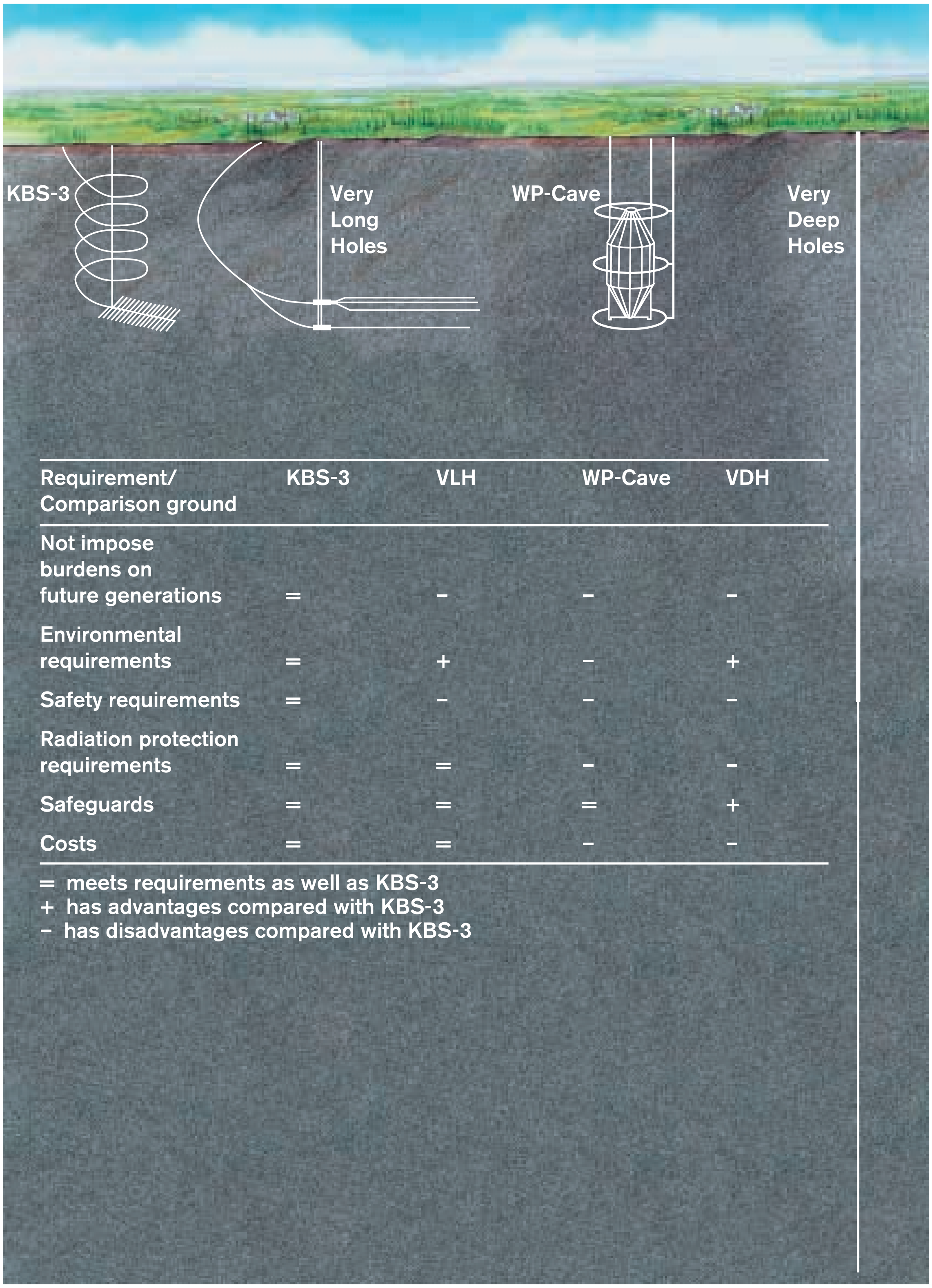
1.3.2 System analysis and optimization

The technical solutions for managing and disposing of different types of radioactive waste 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. We must meet all of society's requirements on protection of human health and the environment. Our existing facilities meet these requirements with good margin. The deep repository, the encapsulation plant and the canister factory must do the same.

The capacity of the facilities has previously been calculated based on the assumption that nuclear power in Sweden will be phased out by 2010. This assumption was based on the premise that approximately 200 canisters could be fabricated, sealed and deposited per year. SKB is now basing its long-range plans and cost calculations on the assumption that the NPPs will be operated for 40 years This means that an average of 165 canisters per year will be deposited over a 25-year period. In light of this, we judge that a capacity of 200 canisters per year is still a reasonable design basis for the different parts of the system.

The build-out of the KBS-3 system will proceed in steps. This means that decisions on individual facilities or system parts will be made progressively. This in turn means that the freedom of choice for each individual facility, and thereby for the whole system, will gradually be narrowed. This narrowing of the freedom of choice will proceed at different paces for different facilities. Different designs of the deep repository may, for example, be retained even after decisions on the design and siting of the encapsulation plant, while the main features in the design of the transportation system are fixed when the decision on the encapsulation plant is taken.

SKB has two tools for this gradual system adaptation: the system analysis and optimization studies. The purpose of the system analysis is to design a deep repository with associated buffer store, encapsulation plant, canister factory and transportation system in the best possible manner. The prerequisites for performing a system analysis are that there is a question or problem to be solved, and that the requirements on the system



Requirement/ Comparison ground	KBS-3	VLH	WP-Cave	VDH
Not impose burdens on future generations	=	–	–	–
Environmental requirements	=	+	–	+
Safety requirements	=	–	–	–
Radiation protection requirements	=	=	–	–
Safeguards	=	=	=	+
Costs	=	=	–	–

= meets requirements as well as KBS-3
+ has advantages compared with KBS-3
– has disadvantages compared with KBS-3

Figure 1-4. *Different technical solutions for a deep repository in crystalline bedrock.*

and the grounds of comparison for the analysis have been specified. The alternative solutions to the question or problem are then presented in the analysis. The different solutions are then evaluated against the stipulated requirements and comparison grounds. The alternative that best satisfies the requirements is chosen as the main alternative.

Variants of the KBS-3 method will be evaluated during the coming years. MLH (Medium Long Holes), where the copper canisters are deposited horizontally, is one such variant, see section 14.4. Deposition of two canisters in vertical holes that are made deeper than in the reference design is another. The final choice of deposition method will be based on an evaluation of safety, technology, costs and environmental aspects.

The methodology of the system analysis is thereby the same as in optimization studies, see section 14.2. The system analysis, however, treats the whole KBS-3 system (deep repository, encapsulation plant, canister factory and transportation), in contrast to the optimization studies which treat individual system parts and details. The system analysis also covers the range of variation and how it is gradually narrowed down as the system is built out. The system analysis comprises the technical basis for the environmental impact assessment.

SKB recently presented a system analysis that sheds light on different variants as regards both design and siting of the facilities included in the KBS-3 system /1-4/. SKB plans to conduct two system analyses during the coming six-year period. The first will be submitted in conjunction with the permit application for the encapsulation plant and deal with its design and siting. The second system analysis will be submitted in conjunction with the permit application for detailed characterization and deals with the design of the deep repository on the sites being considered for site investigations and the consequences of siting the deep repository on these sites.

In parallel with the overall system analyses, constant improvements are also being made in the technical detailed design of the deep repository, the encapsulation technology and canister fabrication.

Deep repository

A deep repository of the KBS-3 type 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 long term after closure of the repository.

The current reference design is based on generic data on Swedish bedrock at a depth of 400–700 metres. The layout is general and will be adapted to conditions on the site. In the further work with the KBS-3 concept we will study how different repository designs and different buffer and backfill materials affect safety and the external environment on the site to be investigated. Questions on which SKB must take a position are e.g. whether the descent leading down to the underground part of the repository should take the form of a shaft or of a ramp, and whether the repository should be built in one or two levels. 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 new technical advances.

The repository cannot be designed in detail until we have commenced detailed characterization. According to plans, initial operation will begin in 2015, when 200–400 canisters will be deposited in an initial stage. The final locations of deposition tunnels and holes cannot be determined until after detailed characterization.

Encapsulation

When it comes to sealing of the copper canisters, SKB is working with two parallel welding methods today: electron beam welding (EBW) and friction stir welding (FSW). The idea is that there should be two developed sealing methods to choose between. EBW is being tested at the Canister Laboratory today. FSW has not yet reached the same level of technical development as EBW, but plans call for FSW to be implemented at the Canister Laboratory during 2003.

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 improvements and simplifications will be made where possible.

Canister design

The current design and size of the canister are based on the assumption that it will hold twelve fuel assemblies from a boiling water reactor or four fuel assemblies from a pressurized water reactor. This optimization has been done based on present-day assumptions regarding burnup and requirements regarding highest permissible temperature on the surface of the canister. Other enrichment or other types of fuel, e.g. MOX fuel, have higher decay heat outputs and can therefore lead to sub-optimal utilization of the space in the canisters.

Fabrication of copper tubes for the canisters has so far been demonstrated with three different methods: roll forming, extrusion and pierce and draw processing. SKB does not have to make a final decision on which fabrication method is to be used until the time for submission of a permit application for the encapsulation plant. Other questions that remain to be answered are the thickness of the copper shell and the design strength of the cast iron insert.

1.3.3 Siting

Deep repository

The work of finding a suitable site for the repository is proceeding. We have conducted feasibility studies in a total of eight municipalities: Storuman, Malå, Östhammar, Nyköping, Oskarshamn, Tierp, Hultsfred and Älvkarleby. A feasibility study is a general study of the prospects of siting a deep repository in a municipality with regard to the bedrock, the land use and the industrial establishment, as well as how such an establishment affects the environment and society. The results of the feasibility studies are presented in final reports from each municipality /1-5 to 1-12/. SKB has also conducted county-specific general siting studies and a survey of the advantages and disadvantages of a siting in northern versus southern Sweden /1-13/. The latter report also compares a siting on the coast with a siting in the interior. In December 2000, SKB presented its supporting material and reasons for choosing the KBS-3 method and priority sites for site investigations /1-14/.

SKB's account was circulated for comment during the spring of 2001 and reviewed by the Nuclear Power Inspectorate (SKI), which submitted its statement of comment to the Government on 19 June. The Ministry of Environment's scientific committee, Kasam, has also submitted its own statement of comment to the Government. Both SKI and Kasam say in their statements that:

- The supplement of RD&D-Programme 98 presented by SKB is satisfactory.
- The KBS-3 method can serve as a planning premise for the continued siting work.
- Site investigations can be commenced in three of the areas specified by SKB in the municipalities of Oskarshamn, Östhammar and Tierp.

SKI and Kasam have thereby given their clear support for moving the siting work into the next phase: site investigations. The Government is expected to take up the matter for consideration during the autumn of 2001, after which the selected municipalities can decide whether or not to continue their participation in the programme. Information and consultation activities are continuing with the municipalities, nearby residents and the general public. No crucial changes in or additions to the siting material presented have occurred, so the siting work for the deep repository is not further dealt with in this report.

Encapsulation plant

The encapsulation plant can be sited either at CLAB, at the deep repository, at an existing nuclear installation or somewhere else. It is an advantage if the facility can be coordinated with an existing activity and if it has access to personnel with the necessary competence and experience. Other factors to be taken into consideration in siting are spent fuel transport, resource utilization, environmental impact and societal aspects.

SKB's main alternative is to build the encapsulation plant adjacent to CLAB. Then we can benefit from the aforementioned advantages. We have also investigated a scenario where the encapsulation plant is co-sited with the deep repository /1-15/.

When an application for a permit to build the encapsulation plant is submitted, we must have revised and updated the existing facility documentation /1-16/ and decided which sealing technology is to be used. Advantages and disadvantages of different sitings will also be dealt with in the environmental impact statement submitted together with the permit application.

Canister factory

The site of the canister factory has not yet been determined. Questions that must be taken into consideration in siting include transportation to and from the factory and access to labour. We will study the possibilities of locating the canister factory in the same region as the encapsulation plant or the deep repository. Other alternatives may also be considered.

Final repository for other waste

In addition to the spent nuclear fuel, operation and decommissioning of the NPPs also gives rise to small quantities of other long-lived waste, such as core components. These are being temporarily stored today in CLAB. In order to relieve the load on CLAB (and to avoid a further expansion), SKB plans to interim-store core components under dry conditions. This can be done adjacent to CLAB or in a rock cavern in SFR. Special packages and transport casks need to be developed for this purpose.

Immobilization of the waste for final disposal takes approximately 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 Co-60, to decay. 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 such a repository is therefore not necessary until around 2035. Rock vaults for this type of waste can be located either at SFR, the deep repository or another site for spent fuel.

1.4 Current and future focus of the RD&D-programme

In this RD&D-programme, SKB has focused on the safety assessment and the long-term processes in the repository. There is a constant interaction 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 to improve the repository design.

The purpose of the structure in this report is to clarify how the needs of the safety assessment are reflected in the research and development work that is being done. Instead of presenting the research arranged according to discipline, as is customary, we have where possible tied it to the long-term processes that are of importance for the long-term safety of a deep repository for spent fuel. It is our hope that this will make it easier for the reader to understand why different research and development work is done, within which areas sufficient knowledge already exists, and which areas require further work.

Future RD&D-programmes will similarly be focused on different parts of the activities, depending on which phase of the activities SKB is in at the moment. As is evident from Figure 1-3, the focus in the future programmes will be on the following disciplines:

RD&D 2004	Encapsulation technology – choice of sealing method
RD&D 2007	Deep disposal technology.
RD&D 2010	Final choice of deposition method.
RD&D 2013	Operation of the KBS-3 system.
RD&D 2016	Planning and evaluation.

2 Safety assessments

2.1 Background

The long-term safety of a deep repository for spent nuclear fuel 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 repository at some initial point in time, for example at closure, second predicting what changes might take place in the repository over the long term, and finally describing the consequences for man and the environment. SKB recently carried out a comprehensive assessment based on bedrock data from three different sites in Sweden /2-1/. None of the sites is being considered for siting of a deep repository, but together they provide good coverage of the different conditions that can be expected at other sites. The assessment is called SR 97 and has been reviewed during 2000 by Swedish authorities /2-2/ and, at SKI's initiative, by international experts /2-3/.

There is a constant interplay between safety assessment, research and repository design. The safety assessment is based on a given repository design and on knowledge of the long-term changes in the repository environment furnished by research. The results of the safety assessment can be used to prioritize new research efforts and to improve the repository design. New materials or manufacturing methods can give rise to a further need for research or assessments. The results of SR 97 and its reviews comprise important background material for this programme of research, development and demonstration, as will be made apparent in both this chapter and those to come.

The regulatory authorities stipulate in their regulations both criteria against which the results of the assessment are to be compared and requirements on the contents of the assessment. In 1998, SSI published "Regulations concerning the protection of human health and the environment in connection with the final management of spent nuclear fuel and nuclear waste," SSI FS 1998:1 /2-4/. SKB interpreted and applied these regulations for the first time in SR 97, and via the review of SR 97 and direct discussions with SSI a dialogue is being pursued concerning the application of these regulations. SKI intends to issue regulations concerning "safety in connection with the final disposal of nuclear waste" during 2001, which are expected to influence the design of future assessments.

The next major safety assessment for the deep repository will be conducted when data from the site investigations are available. These analyses will comprise an important basis for selecting a site for a deep repository. The assessment will be appended to the application for a permit for siting and construction of the deep repository, planned for 2007. Before then, preliminary safety judgements will be made based on data from the initial site investigation phase. In conjunction with this, method development as regards e.g. scenario analyses, handling of uncertainties and risk calculations can also be reported and partially applied, along with newfound knowledge concerning canister and buffer. The account also comprises a basis for the safety assessment that will accompany the application for a permit for siting and construction of the encapsulation plant, planned for 2005. At later stages, assessments are planned that will comprise supporting material for applications for a permit to commission the repository and a permit for closure. The repository section for other long-lived waste will not be sited until around 2035 according to current plans. The research programme for questions related to this repository is presented in Chapter 18. A preliminary safety assessment has recently been presented /2-5/. When the next safety assessment for the deep repository is completed, it may be suitable to perform a renewed, more comprehensive safety assessment for the final repository for long-lived waste. Wishes to this effect were expressed by SKI and SSI in their joint review of the preliminary safety assessment /2-6/. The safety assessment for the final repository for low- and intermediate-level operational waste, SFR-1, was recently renewed /2-7/, and renewed assessments are planned every ten years.

This chapter describes SKB's programme for further development of the methodology for assessments of the long-term safety of the deep repository for spent nuclear fuel. The programme is based in large part on SKB's experience from SR 97 and on viewpoints from the reviews of SR 97.

The structure of the chapter is influenced by the steps into which the SR 97 safety assessment was divided, namely:

1. System description.
2. Description of initial state.
3. Choice of scenarios.
4. Analysis of chosen scenarios.
5. Evaluation.

The format for the system description is discussed in section 2.2. A documentation of the processes that influence and change the repository in the long term is also included in step 1. The research programme for the processes is extensive and is presented separately in Chapters 3 to 10. Questions concerning step 2, the initial state, are discussed in these chapters. The programme for steps 3 and 4 is presented in sections 2.3 and 2.4, respectively. Step 5 mainly concerns a discussion of the results of the assessment and is not a direct method question. It is therefore not dealt with here.

Method questions related to the biosphere are dealt with entirely in Chapter 9. This includes e.g. the role of the biosphere in future assessments and measures of the repository's capacity for health and environment protection.

Where possible, a systematic survey is done of different issues with the following subheadings:

- Conclusions in SR 97 and its review.
- Conclusions in RD&D-Programme 98 and its review.
- Newfound knowledge since RD&D-Programme 98 and SR 97.
- Development programme.

An account of how data from the site investigations will be processed and transferred to the safety assessment is provided in section 13.3.

2.1.1 Method report

The results of much of the work outlined in this chapter will be presented in a Method Report for the safety assessments that will be based on data from the site investigations. The report will be concerned with:

- Format for the system description and plans for a modernized Process Report.
- Scenario development.
- Method for choice of data for consequence analyses.
- Method for probabilistic calculations, including role division between analytical and numerical models.
- Role of natural analogues in future assessments, see also Chapter 11.
- Possibilities for feedback from the safety assessment to the site investigations and the repository design.
- Programme for future safety assessments, including interim assessments in preparation for the comprehensive assessments that will be based on data from the site investigations.

The report will be finished prior to the start of the future assessments. SKB is considering having international experts review the report.

2.2 System description

Conclusions in SR 97 and its review

SR 97 describes the repository system with THMC diagrams for the subsystems fuel, canister, buffer and geosphere. The processes that cause long-term changes in the repository and the variables that describe the repository over time are gathered in the diagrams. The associated Process Report /2-8/ summarizes knowledge of the processes. SR 97 drew the conclusion that the method is usable, but also that it needs to be refined.

The authorities express a similar view in the review of SR 97 and offer several viewpoints on what needs to be improved:

> "In the authorities' opinion, the newly developed THMC diagrams are a good complement to previously developed methods for system description and for the visualization of processes in the repository. However, SKB should develop the method in order to improve the inclusion of time-dependent effects and structural changes. SKB should also continue its work on developing a systematic description of the processes in the biosphere.
>
> SR 97 contains a systematic review of the processes and data used in the consequence analysis for the canister defect scenario. Although this documentation represents a major step, SKB should develop the methodology, mainly in view of supporting the reasons for eliminating unfavourable processes from the consequence analysis. Alternatively, these processes should be included in the calculations so that the risk contributions can be evaluated. Colloidal transport of radionuclides and the impact of microbes on canister corrosion are two examples of such processes that have been identified in this review."

> "In the authorities' opinion, SR 97 provides a good review and description of the processes that can affect repository performance and of the data used to calculate radionuclide transport in the canister defect scenario. However, prior to future safety assessments for licence applications, SKB should develop procedures for the documentation and implementation of the expert judgements used to select models, data and other premises for the safety assessment that are well defined and that have been subjected to quality assurance. The authorities would also like to recommend that SKB subject the most important data and assumptions to independent peer review before the safety assessment is completed."

Conclusions in RD&D 98 and its review

The system description for SR 97 was not finished when RD&D-Programme 98 was written and was therefore not discussed in detail.

Newfound knowledge since RD&D-PROGRAMME 98 and SR 97

See equivalent heading in section 2.3.

Development programme

A desirable, but difficult-to-achieve, attribute of a system description is that it should describe the time-dependent evolution of the system for different initial and boundary conditions. This is e.g. valuable in the choice of scenarios. The description would not have to be detailed, but focus on what is essential for long-term safety, which can often be formulated by saying that the state of the barriers must be kept within certain limits. This can in turn be stipulated as limitations on the variables that describe each barrier.

The THMC diagrams show qualitatively with arrows how different variables control a process which in turn influences other variables. If the method is to be used to quantitatively illustrate the time-dependent evolution of the system, these relationships must be quantified in one way or another. A complete coupled model that includes thermal, hydraulic, mechanical and chemical aspects for the entire repository system would seem to be beyond the realms of possibility. Such a model would also be far too complex and unmanageable to be of any practical use in a safety assessment.

On the other hand, many parts of the system can be modelled in detail, which is also a necessary feature of a safety assessment. Many modelling results can be expressed by means of simple empirical relationships between impacting variables on the one hand and time-dependent changes in one or more impacting variables or properties on the other. If such simplified relationships could be worked out for most processes, a simplified form of time-dependent coupled model could be devised and then provide a rough picture of the course of events for different scenarios. Different boundary conditions would then have to be quantified. The performance of the system would be expressed as requirements that certain values for the barriers, such as thickness of the copper shell or density of the buffer, remain within stipulated intervals over time.

The possibilities of accomplishing all this will be studied. The task is demanding and its feasibility is hard to judge. Some form of feasibility study is therefore necessary. If the method works, one of the original intentions with the THMC description – with its strict differentiation between subsystems, variables and processes – would be met and the tool is then judged to be very useful in a safety assessment, not just to provide a structure for the assessment, but also to describe the evolution of the system. If the method proves useful, it will probably need to be developed and refined over a long period of time.

In any event, the system description also needs to be developed in a number of other respects. The following development needs were noted in the SR 97 report:

- Storage of system description with appurtenant process documentation on electronic medium, coupled to existing databases.
- A revision of the process selection based on available databases.
- Augmentation of the process documentation where new knowledge has emerged.

Furthermore, it is obvious from the comments of the authorities on SR 97 that procedures for and documentation of several steps in the safety assessment need to be improved or described more clearly, which can be done prior to and in a future version of the Process Report:

- A clearer justification for excluding potentially unsuitable processes.
- A better description of how different processes are handled in models.
- Documented choices of experts for updating subsections in the Process Report.
- Procedures for describing uncertainties.
- Procedures for internal review.

The format for the developed system description, including the format for a new Process Report, will be given in the Method Report mentioned in section 2.1.1.

It can also be pointed out that this research programme, RD&D 2001, as well as the results of its regulatory review, comprises in itself one step in the revision of the system description and the Process Report.

Finally, the question of whether all essential processes and couplings have been identified must be kept alive, among other things by critical review of the system description and discussions with both national and international experts.

2.3 Choice of scenarios

Conclusions in SR 97 and its review

In SR 97, the choice of scenarios is largely based on previous work and experience. It is also observed there that future work should include "A more systematic choice of scenarios based on the format for system description and available FEP databases".

The evaluation of SR 97 notes:

> "In the authorities' opinion, the scenarios analyzed in SR 97 provide an acceptable coverage of the internal and external events that could affect the protective capability of the repository. However, in future scenario work, SKB should ensure that these provide a good basis for, and are logically coupled to, both the system description and the risk calculations. One deficiency of SR 97 is that couplings

between different events are not adequately analyzed. For example, SKB has not adequately investigated the impact that future climate changes could have on the engineered barriers, on radionuclide transport as well as on how the frequency and magnitude of earthquakes can affect the protective capability of the repository. In the authorities' view, SKB should consider analyzing more comprehensive scenarios that, in a more integrated manner, handle events and processes that can affect repository safety. SKB should also conduct a more extensive analysis of scenario uncertainties, such as climate evolution alternatives and alternative assumptions on defects in the engineered barriers."

In SR 97, SKB discussed scenarios based on human actions. The authorities observed in their review that "SKB's analysis is evaluated as satisfactory, based on the premises that apply at the present time".

Conclusions in RD&D 98 and its review

RD&D-Programme 98 did not describe any final method for choice of scenarios. The authorities therefore offered only general comments.

Newfound knowledge since RD&D-PROGRAMME 98 and SR 97

SKB has participated in an international workshop under the auspices of the OECD/NEA for the purpose of evaluating methods for scenario development in safety assessments. Two principal remaining difficulties emphasized in the report from the meeting /2-9/ are the description of time dependencies and the problem of clearly and traceably documenting the technical material and the results of scenario development. Both of these problems have been pointed out before.

Development programme

An improved method for scenario selection is needed prior to future safety assessments that will be based on data from site investigations. At the same time, both SKB and the regulatory authorities note that the choice of scenarios in SR 97 provides acceptable coverage of the repository's possible evolutionary pathways. Different methods that have been used historically for scenario selection by SKB and others have given scenario sets similar to the one in SR 97. Nor is the method development outlined below expected to lead to any great changes in the scenario set.

A systematic choice of scenarios can be done directly with available THMC diagrams. If the development of time-dependent relationships for the diagrams that is outlined in section 2.2 is successful, this is expected to become yet another tool for scenario selection. The evolution and performance of the system could then be studied at a general level for a variety of initial and boundary conditions within the framework of the validity of the time-dependent model. The choice of scenarios could thereby be systematized more thoroughly than before.

Another, more qualitative method for scenario selection is the so-called morphological field analysis, which was used to define human-caused scenarios in SR 97. The method was useful in that application and could be made even more widely useful.

Furthermore, several organizations in other countries have developed and published methods for scenario development /2-9/ that could in part be useful for SKB, along with an examination of the scenarios actually chosen in other assessments.

A more systematic analysis of the initial state with associated uncertainties than that done in SR 97 will be conducted prior to the choice of scenarios in future assessments. In this way, scenario selection will be dependent on the special conditions on the site.

The different approaches outlined above need to be tested and evaluated before a method for scenario selection in future safety assessments can be finalized.

Earthquakes were dealt with in their own scenario in SR 97, after which a discussion was pursued regarding couplings to e.g. the climate scenario. The reason for separating earthquakes from other scenarios was in part practical, since model development was under way for earthquake calculations. The intention in future assessments is to integrate earthquakes site-specifically in all relevant scenarios.

SKB intends to continue the work with scenarios based on human actions, for example in international fora and in dialogue with the authorities as regards the forms of accounting.

The scenario methodology in future assessments will be described in the Method Report, see section 2.1.1.

2.4 Analysis of chosen scenarios

Most of the account in SR 97 falls under this heading, as does therefore most of the regulatory authorities' comments in the review report. Large parts of the account and the comments are concerned with individual processes, models or data and are therefore dealt with in Chapters 4 to 11. Other parts are concerned with concrete choices of calculation cases and presentation forms, which can only be dealt with in a renewed safety assessment or in the Method Report which is planned to precede future assessments, see section 2.1.1.

Some points that generally concern either models and data or risk assessments and calculations are dealt with below.

2.4.1 Data and models

It is noted in the review of SR 97:

> "In the authorities' opinion, prior to conducting SR 97, SKB developed a comprehensive set of models for the needs of the safety assessment. However, the documentation and the justification of models must be improved in future safety assessments. The evaluation of alternative hydrogeological models in SR 97 is a valuable initiative for understanding model limitations and conceptual uncertainties. A similar approach should also be considered for other parts of the model chain, such as the evolution of the near field and radionuclide transport."
>
> The authorities find the Process Report to be "a laudable initiative to document the scientific understanding of the underlying processes in the models. However, in future safety assessments, SKB should be clearer in its presentation of how the process descriptions are used in the selection of conceptual models."
>
> "In the authorities' opinion, the background report, Data and Data Uncertainties (where SKB's selection of data for the canister defect scenario is justified) generally provides a good discussion of the scientific basis for the selection of param-

eter values. However, in the authorities' view, SKB should use well-defined procedures that have been subjected to quality assurance to select data, since it is often not clear in SR 97, how the judgements have been made and which experts have been involved ... The authorities also recommend that, before future licensing, SKB should supplement this background report with the required data for analyzing other scenarios besides the canister defect scenario."

Conclusions in RD&D 98 and its review

SKB's account and SKI's comments concern almost exclusively individual models and are therefore dealt with in Chapters 4 to 10.

Newfound knowledge since RD&D-PROGRAMME 98 and SR 97

See Chapters 4 to 10 for development of individual models.

In SR 97, the results of numerical calculations of radionuclide transport in the entire repository system were compared with results from preliminary, simple analytical models. This work has been carried further, and today all essential parts of the numerical results in SR 97 can be recreated with the analytical models.

Among the purposes of developing analytical models are:

- Permit rapid preliminary probabilistic calculations.
- Improve the understanding of transport phenomena in canister, buffer and rock.
- Quickly and simply put the focus on dominant nuclides and the most important parameters in the transport models.
- Validate and verify the numerical models.
- Give others, e.g. the regulatory authorities, access to a tool that does not require special training in user interfaces, use of mainframe computers, etc.

The mathematical derivation of the analytical model, including comparisons with numerical results in SR 97, is described in /2-10/.

The results of the transport model for the near field are presented in section 7.3, for the geosphere in section 8.2.28. Figure 2-1 shows maximum annual doses in the time interval up to one million years after closure calculated with numerical and analytical models. The figure includes all uncertainty cases in SR 97 /2-11/, as well as cases where all parameters are simultaneously given either consistently reasonable or consistently pessimistic values. In most cases, the deviations lie within a factor of ten. The deviations are generally less for higher doses than for lower; for doses over 10^{-8} Sv/y, the deviations lie within a factor of three. If the maximum total dose is instead compared, i.e. the maximum aggregate dose from all nuclides in a calculation case over a million years, all deviations lie within a factor of 1.4. Since this is the quantity that is determined in the probabilistic dose calculations, it can be expected that the probabilistic results will also be similar with the two model sets.

This is confirmed in Figure 2-2, where the probabilistic results for a peat bog from SR 97 have been recreated with the analytical model. The calculation times in the probabilistic case were about three weeks with dual SUN Ultra SPARC II processors for the

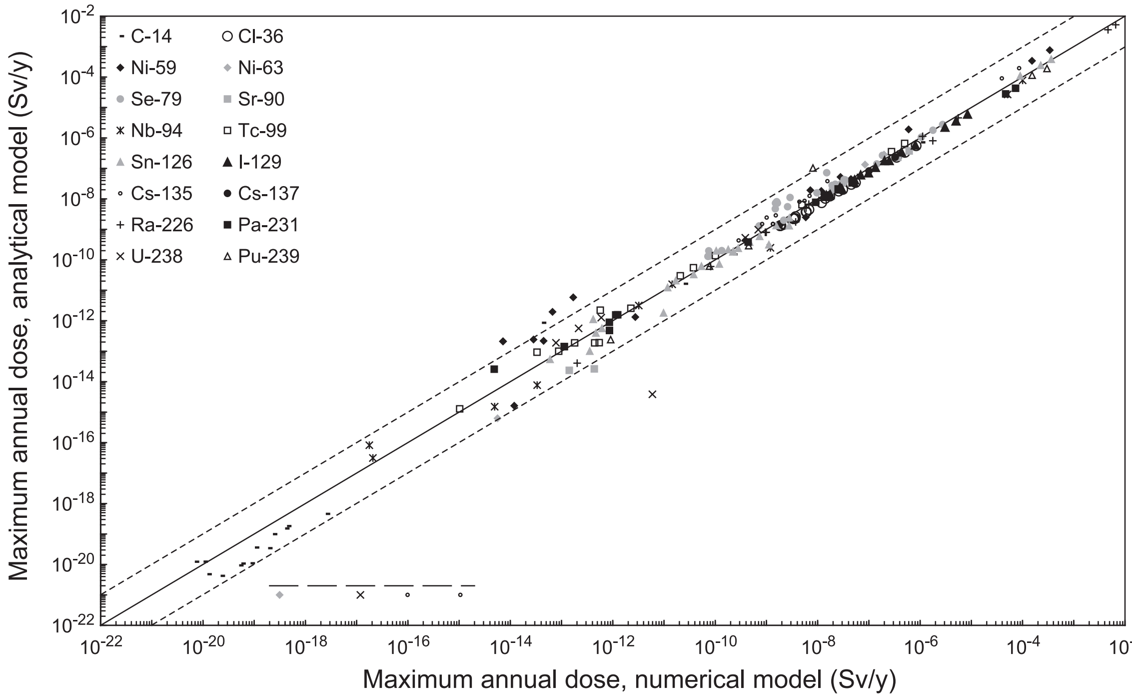


Figure 2-1. Comparison of maximum annual doses for the three sites in SR 97 and the 16 most important nuclides in SR 97, calculated with numerical and analytical models. The figure shows the results of nine different calculation cases for each of the three sites and is further explained in /2-10/.

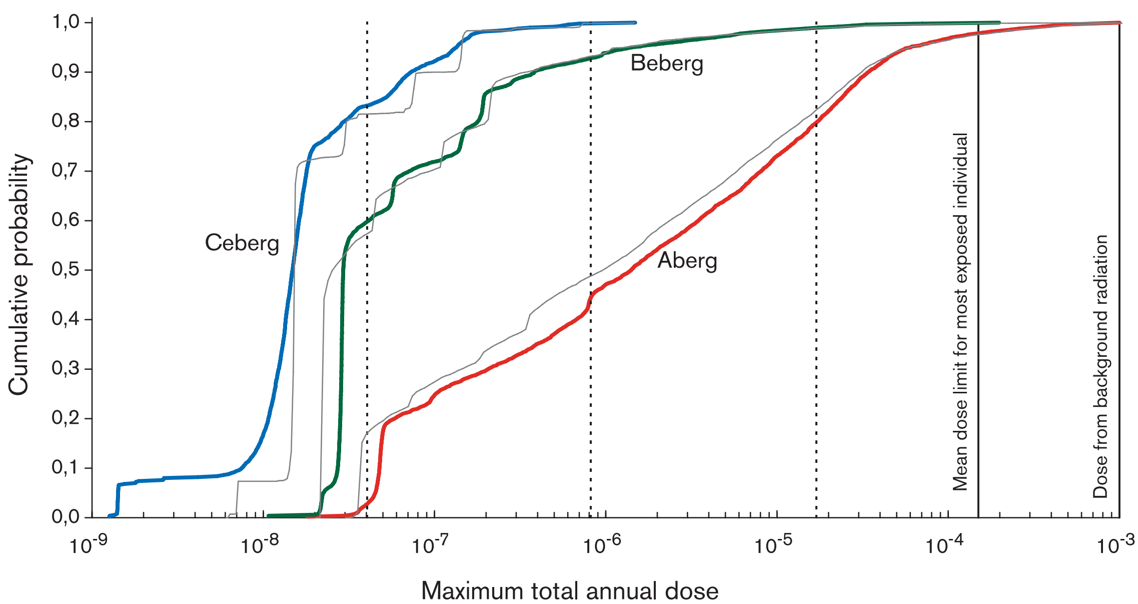


Figure 2-2. Probabilistic results for the three sites in SR 97, calculated with numerical (thick lines) and analytical (thin lines) models. The dashed vertical lines show the mean values of the distributions for the three sites (nearly identical results with the two models).

numerical models, while the corresponding analytical calculation required less than one hour with an ordinary 450 MHz desktop PC. The analytical calculations were done with commercially available software. Both calculations use the results of extensive hydrocalculations for the three sites, something which is not deemed possible to recreate with a simple analytical model.

The results show that the analytical model should be useful for the purposes formulated above. Data for the model comparisons cover three different sites and relatively wide uncertainty intervals for both near field and geosphere. It is therefore reasonable to expect that numerical results from future analyses based on data from site investigations can also be recreated with the analytical model, provided that the fundamental understanding of transport phenomena and how they are represented in the numerical model does not change.

It is not SKB's intention to use the analytical approximations as a principal instrument in future analyses. The validity of the approximations must be determined by comparisons with numerical models in each safety assessment, after which it should be possible to use the model for the outlined purposes. The numerical models will always comprise the "yardstick" and be the most important calculation tool for radionuclide transport; they must continue to be maintained and developed with full force in the future.

Development programme

See Chapters 4 to 10 for development of individual models.

As for as the documentation of choices of conceptual models is concerned, a more explicit description is planned in the Process Report of how different processes are dealt with in the models that are used in the safety assessment, and special validity documents are planned for the most important models for consequence calculations, i.e. the models for groundwater flows in the geosphere and for radionuclide transport in the near field, geosphere and biosphere.

The Data Report will be broadened in future versions to include input data to more models than those for groundwater flow and radionuclide transport, as well as more scenarios. It will also be developed to include probabilistic data for at least the parameters that give the dominant uncertainties in the risk calculation, see section 2.4.2. The methodology for handling expert choices of data in SR 97, in brief by means of instructions to co-authors and then a balanced expert appraisal at SKB, will be clarified and developed as needed.

The plans for this, as well as for how data are to be quality-assured in future assessments, will be elaborated on in the Method Report, see section 2.1.1.

The results of the broadened probabilistic calculations have been published in the proceedings of a conference /2-12/, and the intention is to broaden the study at a later time and publish the results in an international scientific journal. More results need to be compared with the results of numerical models. Transferral of the model to other software needs to be considered. The role of the models in future safety assessments needs to be established. This can suitably be done in the Method Report, see section 2.1.1.

2.4.2 Risk analyses and calculations

Conclusions in SR 97 and its review

In SR 97, a simplified method for risk calculations was employed and it was noted that the method needs to be evaluated and further developed.

It is noted in the review of SR 97:

> ”In the opinion of the authorities, in its canister defect scenario, SKB has developed a set of calculation cases that describe the interactions of the various barrier functions and illustrate the possible consequences of leakage from a defect canister. However, it should be possible to considerably develop the uncertainty and sensitivity analyses for example by including variations of more than one parameter or parameter group at a time as well as hypothetical examples that more stringently test individual barrier functions.
>
> In the authorities' opinion, the risk calculations in SR 97 are a first step in adapting to the use of a risk criterion. However, SKB should develop a less arbitrary method of representing probabilities for the many parameters that are included in the risk analysis. Correlations between different parameters in the risk analysis should also be studied in greater detail, since these could have a considerable impact on the final result. In the view of the authorities, a specific account of the protective capability of the repository in the short term (0 – 1,000 years after closure), as stipulated in SSI's regulations on the final management of nuclear waste, is also lacking.”
>
> ”In the view of the authorities, SKB should develop its method for data selection for the risk calculations, since SKB has not shown that the bimodal distributions, with a probability of 0.9 and 0.1 for reasonable and pessimistic values, is a conservative choice. The authorities also agree with the external reviewers that there is a measure of arbitrariness in SKB's way of representing a parameter and the related uncertainty with the bimodal distributions, which means that the analysis could be difficult to evaluate and the statistic implications would be unclear.”

Conclusions in RD&D 98 and its review

This section deals with the specific risk analyses and calculations that were presented in SR 97, so the subject is not treated in RD&D-Programme 98.

Newfound knowledge since RD&D-PROGRAMME 98 and SR 97

With the aid of the newly-developed analytical models, the sensitivities of the results of the risk calculations in SR 97 have been analyzed with regard to:

- Correlations between input data.
- Details of the assumed distributions.
- Variations in the hydromodelling at Aberg, Beberg and Ceberg.
- Risk as a function of time.

Furthermore, the simplified uncertainty analyses in SR 97 have been supplemented with a rank correlation analysis, an established method for this purpose. Some of the results can be found in /2-12/.

Figure 2-3 shows how the calculated risk distribution is affected by assumptions of details in the input data distributions. In the base case, i.e. the risk calculation presented in SR 97, most of the distributions are bimodal with probabilities of 0.9 and 0.1 for reasonable and pessimistic values, respectively. Advective travel time and groundwater flow at repository level comprise exceptions where calculated, correlated distributions are obtained from the results of hydrocalculations with HYDRASTAR. Figure 2-4 shows how the mean value and the 5th and 95th percentiles of the resulting risk distribution are affected by exchanging the bimodal distributions for log-normal ones with unchanged mean values and variances. The changes in the resulting distributions are undramatic, which is gratifying since knowledge of the details of distributions of this kind will always be imperfect.

Figure 2-3 also shows how the calculated risk distribution is affected by assumptions concerning correlations between input data. In the base case, i.e. the risk calculation presented in SR 97, all data are uncorrelated, with the exception of advective travel time and groundwater flow at repository level, where pairs of correlated values are taken from the results of hydrocalculations with HYDRASTAR. Figure 2-3 shows how the mean value and the 5th and 95th percentiles are affected by first the assumption that all parameters correlated with the geochemical conditions (solubilities and sorption and diffusivity data in buffer, backfill and geosphere) are assigned either reasonable (probability 0.9) or pessimistic (probability 0.1) values. It is clear that this full correlation also has a limited impact on the result. In a second example, the base case was varied by assigning either reasonable or pessimistic values to the ecosystem-specific conversion factors for all nuclides. Such a correlation should exist at least in part, since many conditions in the biosphere affect all nuclides in a similar manner. This is true, for

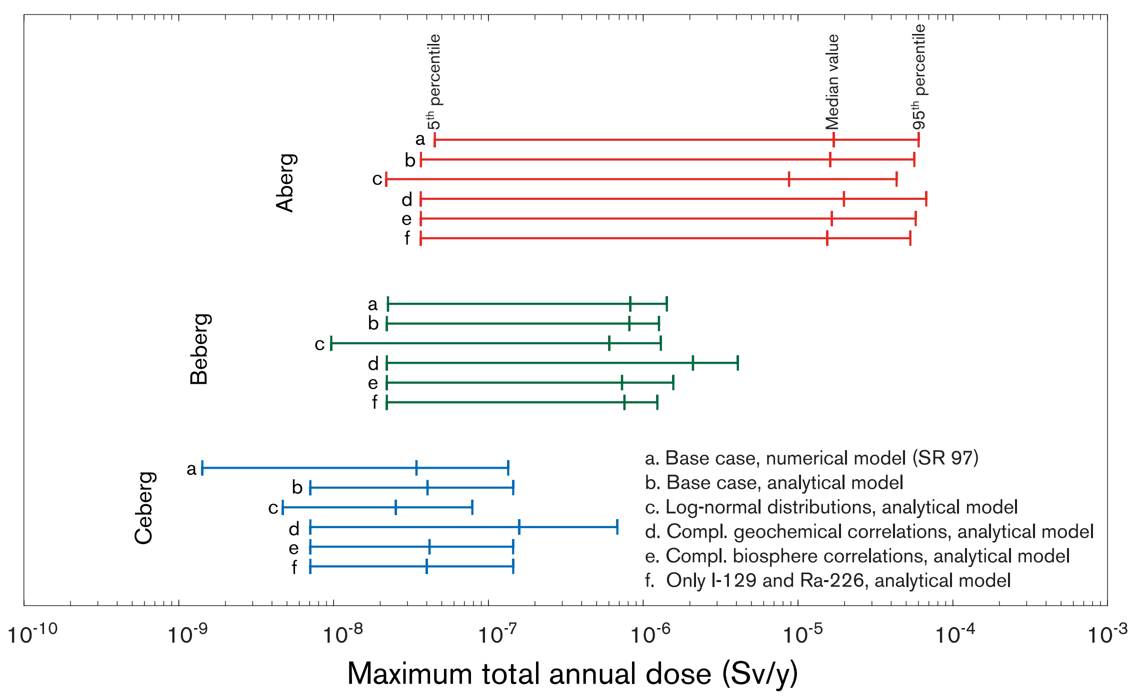


Figure 2-3. *Results of probabilistic calculations with alternative distributions and correlations.*

example, of the surface area of the peat bog to which the calculations apply. In this case as well, not even a full correlation had any appreciable effects on the result. The results of this example are gratifying, since correlations can be difficult to quantify.

The lowermost dose distribution for each site in Figure 2-3 is calculated with only I-129 and Ra-226. Since these distributions are virtually identical to the base case, it is clear that these two nuclides completely dominate the total dose when the biosphere is assumed to be a peat bog. For Ceberg, only I-129 actually contributes.

Figure 2-4 shows the properties of dose distributions calculated with all the variants that were analyzed in the hydromodelling with HYDRASTAR for the three sites, see Figures 9-15, 9-18 and 9-20 in SR 97 Main Report Volume II. It is obvious that the spread in the base case (or any of the variants) is much greater than the differences between the variants. (In SR 97, the consequence calculations were only done for the three base cases.)

Figure 2-5 shows dose distributions calculated with hydrodata from three different conceptual models for Aberg in SR 97, see section 9.8.4 in SR 97 Main Report Volume II. The figure shows that the differences between the distributions are much less than the spread within a distribution. All conceptual hydromodels have thereby been used in the consequence analysis, which was recommended in e.g. the international peer review of SR 97.

The uncertainty analyses in SR 97 were carried out as a number of variation cases where one or a few parameters at a time were varied. An accepted method for uncertainty analyses is to determine so-called rank correlations for the parameters involved, based on the results of a probabilistic calculation /2-13/. The rank correlation is a measure of to what extent the uncertainty in the parameter in question is related to the

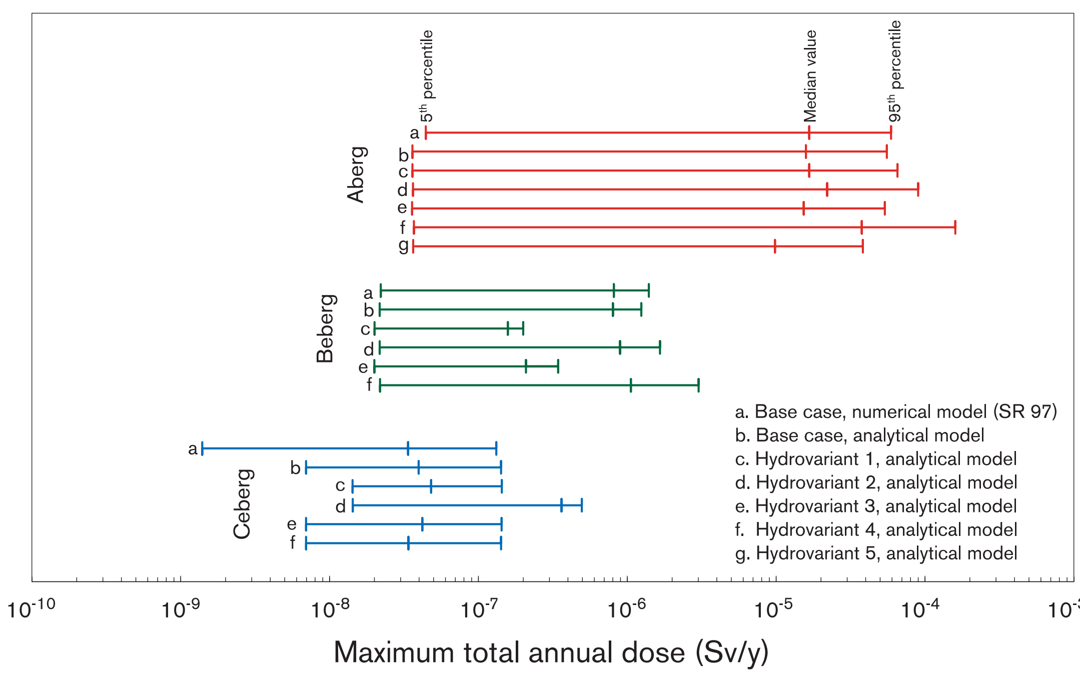


Figure 2-4. *Results of probabilistic dose distributions where all variants of the stochastic continuum model for Aberg, Beberg and Ceberg in SR 97 have been used.*

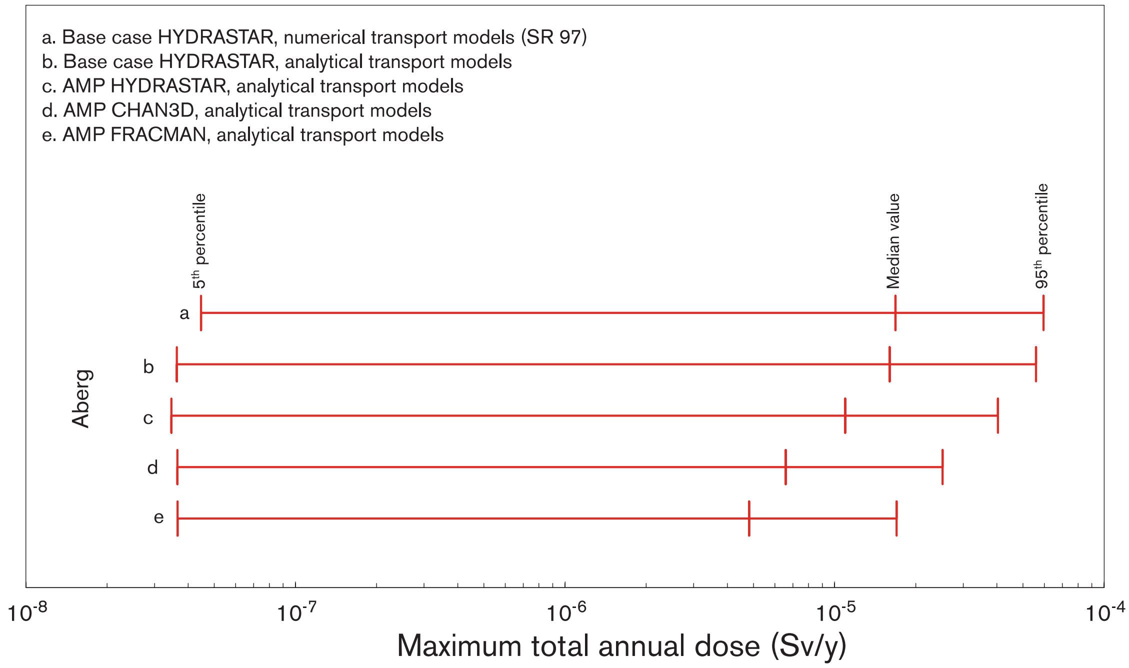


Figure 2-5. *Results of probabilistic dose distributions carried out with hydrodata from three different conceptual models for Aberg, Beberg and Ceberg.*

uncertainty in the calculation result (the spread of the dose distribution). Figure 2-6 shows rank correlations calculated with the aid of the results of the risk calculation with the analytical model for Aberg, Beberg and Ceberg. The results confirm the picture from the simple uncertainty analyses in SR 97, namely that the uncertainties/variability in advective travel time t_w, flow-wetted surface a_w, number of broken canisters, NCAN, and ecosystem-specific dose conversion factors, EDF, make the greatest contributions to the uncertainty in the resulting dose distribution. The method could just as well have been applied to the results of the numerical calculations in SR 97.

The analytical models are judged to be a valuable aid for illustrating the importance of different aspects of the risk calculations in the safety assessment. The above results indicate that great resources should not be devoted to trying to determine details in assumed distributions for a probabilistic calculation or to quantifying correlations between different input data to the calculations, at least not for the parameter relationships that have been investigated here. Furthermore, the general conclusion in SR 97 – that the natural variability in hydroconditions on a site causes a greater spread in the calculation results than the conceptual uncertainties that are covered by the hydrovariants – can be broadened to include the results of dose calculations as well. The valuation of which parameter uncertainties make the greatest contributions to the spread of the calculated risk curve is also confirmed by the calculation using the more sophisticated method above.

Finally, in Figure 2-7 the analytical model has been used to calculate risk (expressed as mean dose) as a function of time for the three sites in SR 97, as recommended in the international peer review. In subsequent discussions, SSI has explained that this is the quantity they expect in future accounts, rather than the risk measure based on the

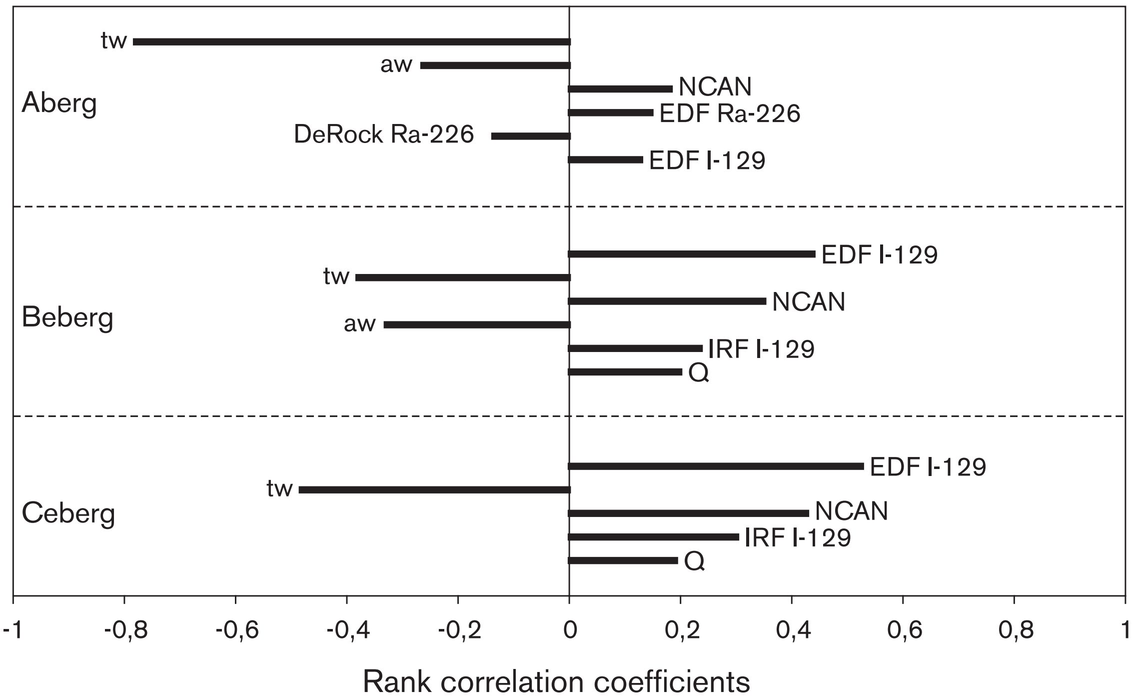


Figure 2-6. *Rank correlation coefficients for Aberg, Beberg and Ceberg.*

maximum dose in the time interval up to one million years after closure that was used in SR 97. The figure shows the mean dose as a function of time, calculated with the same distributions in input data as in SR 97.

Research programme

Several questions concerning probabilistic risk calculations need to be further examined. The analytical model has proved to be useful in several respects, but the most important results above need to be confirmed with the numerical models for radionuclide transport.

The above results suggest that the forms of the assumed distributions are not of crucial importance; as simple forms as bimodal distributions should also be able to be used to illustrate the safety of the repository, even though this is not SKB's express intention for future assessments. On the other hand, great attention must be devoted to central values and spread measures for the distributions. Reasonable and pessimistic values with probabilities of 0.9 and 0.1, respectively, were routinely used in SR 97. In future assessments, this needs to be replaced with more rigorously determined central values and spread measures, especially for those parameters that are of importance for the spread of the calculated dose distribution. This will be documented in the future equivalent of the Data Report in SR 97, see further section 2.4.1.

In the planned Method Report, section 2.1.1, a strategy will be presented for both non-probabilistic and probabilistic calculations in future safety assessments, as well as how data for these calculations are to be established.

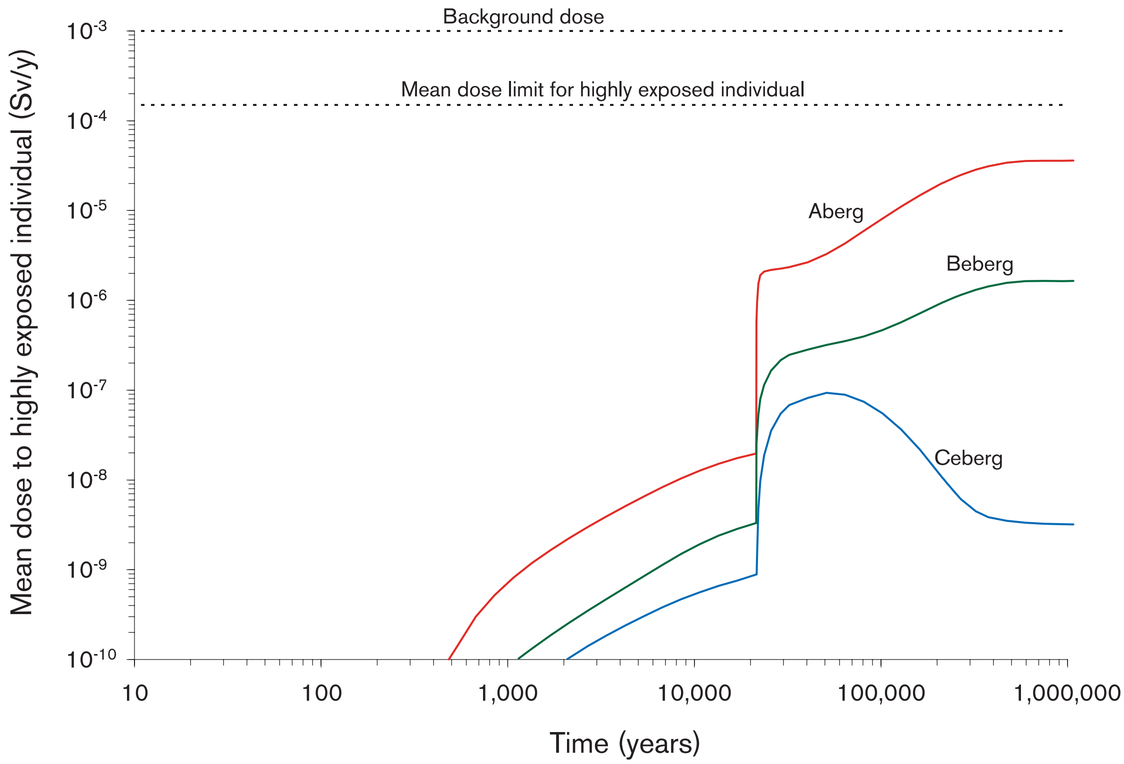


Figure 2-7. *Mean dose as a function of time at Aberg, Beberg and Ceberg.*

Estimates of uncertainties in input data according to defined procedures are included in many activities that precede a safety assessment, for example in the development of the site-specific models, see section 13.3.

SKB's handling system for probabilistic calculations, PROPER, will be further developed so that, for example, risk can be calculated as a function of time in future assessments. A graphical user interface called Monitor2000 also belongs to PROPER. The interface has proved to be demanding to maintain and has yielded moderate efficiency gains in the execution of calculations. Nor has Monitor2000 been decidedly better for documentation of calculations than the internal documentation produced by PROPER. Moreover, the new analytical models offer a powerful method to check the results of PROPER calculations with a completely independent system. SKB therefore intends to freeze the development of Monitor2000 during a transition period, possibly deciding to terminate it at a later date. The development of the individual models used in PROPER is described in sections 7.3 (near field) and 8.2.28 (geosphere).

3 Research on long-term safety

A considerable portion of SKB's programme for research, development and demonstration concerns the processes that are of importance for the long-term safety of a deep repository for spent fuel. The recently completed SR 97 safety assessment documented the state of knowledge concerning all known long-term processes in a special Process Report. The report dealt with processes for fuel, canister, buffer/backfill and geosphere, in that order. Uncertainties concerning each process and their importance for long-term safety were discussed in the Process Report. This is also done in the Main Report of SR 97, where the combined effects of the processes on the long-term safety of the repository are examined for a number of scenarios.

The coming chapters deal with the research programme for all processes in the Process Report, based on the uncertainty discussions in SR 97 as well as the viewpoints SKI, SSI and the International Review Team (IRT) had on the account in SR 97. SKB's account in RD&D-Programme 98 and the review statement on the report are also taken up where relevant. The form of the following account thus links the results of the safety assessment to the design of the research programme, even though many of the conclusions can be drawn without a complete safety assessment. The structure is also in line with the IRT's viewpoint that SKB should "enhance the role of safety assessment as a means to integrate different parts of the final disposal programme". In their review of SR 97, the Swedish regulatory authorities have also called for accounts of couplings between results of safety assessments and SKB's research programme.

Because all known processes are dealt with in a similar manner, the account is necessarily something of a catalogue, where small and big questions are mixed. To give some idea of the main outlines of the research programme rooted in the need for long-term safety, this chapter therefore provides an overview of the most essential questions to be explored during the upcoming period.

Detailed accounts of the programmes for fuel, canister, buffer, backfill and geosphere follow in Chapters 4 to 8. 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, regardless of where they are located in the repository and thereby regardless of when they arise in the gradual build-out of the repository. It is therefore natural to use the time of deposition as the initial time for the description of fuel, canister, buffer and backfill. Other analyses concern the repository as a whole. Here there are great differences between different parts of the repository due to the gradual build-out. The problem of finding a starting time is, however, simplified by the fact that many essential variables in the geosphere, such as fracture geometry, do not change appreciably on this timescale. For the geosphere it isn't just the initial state immediately after construction that is important to describe. The natural state that prevailed prior to repository construction is often of greater interest for long-term safety, since such conditions as groundwater flow and groundwater composition can be expected to return to their natural state some time after closure of the repository. This is also discussed in section 8.1.

After the discussion of research and development needs for the initial state, all processes are dealt with in the Process Report. The processes are divided into radiation-related (R), thermal (T), hydraulic (H), mechanical (M) and chemical (C), plus processes related to radionuclide transport. In some cases a treatment of individual processes is not sufficient for understanding the course of events. The subdivision of processes has therefore sometimes been augmented with descriptions called integrated studies. An example is the hydro-mechanical-chemical (HMC) evolution of a damaged canister, and the thermo-hydro-mechanical (THM) evolution of an unsaturated buffer. The following subheadings are used as far as possible in each section:

- Conclusions in SR 97 and its review.
- Conclusions in RD&D-Programme 98 and its review.
- Newfound knowledge since RD&D-Programme 98 and SR 97.
- Research programme.

The biosphere, which is not dealt with in the Process Report, is then presented in Chapter 9 with a freer format than other parts. Finally, states of knowledge and research programmes for climatic evolution and natural analogues are presented in Chapters 10 and 11, respectively.

Table 3-1 shows all processes of importance for long-term safety that are dealt with in Chapters 4 to 8. 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. Large resources have often already been devoted to the most important processes. The corresponding information for the initial state is found in Table 3-2. The following sections provide a brief overview of the most important research areas for the different parts of the repository, as well as for the biosphere and climate change.

3.1 Fuel

If a canister is damaged and groundwater comes into contact with the spent fuel, the fuel will eventually be dissolved. Fuel dissolution was pointed out in SR 97 and its review as an important area where knowledge needs to be improved by means of further research. SKB's programme for research concerning this process and some new findings are presented in section 4.2.12.

3.2 Canister

For an initially intact canister, it was concluded in SR 97 that the uncertainties above all relate to strength at loads during a glaciation and during earthquakes. Strength under isostatic loads needs to be calculated with realistic material data for the cast iron insert, see section 5.2.4. Strength in connection with rock movements has only been calculated for a weaker canister than SKB's current reference canister and with incomplete mechanical data for the buffer. The study needs to be updated, see section 5.2.4. Great resources will also be devoted to studies of copper corrosion, section 5.2.12, and stress corrosion cracking in the copper canister, section 5.2.13.

Table 3-1. Research on long-term processes.

	Fuel	Canister	Buffer	Backfill	Geosphere
R	Radioactive decay 4.2.2				
	Radiation attenuation 4.2.3	Radiation attenuation 5.2.2	Radiation attenuation 6.2.2	Radiation attenuation 7.2.3	
	Induced fission 4.2.4				
T	Heat transport 4.2.5	Heat transport 5.2.3	Heat transport 6.2.3	Heat transport 7.2.4	Heat transport 8.2.2
H	Water/gas transport 4.2.6		Water transp. unsatur. 6.2.4	Water transp. unsatur. 7.2.5	Groundwater flow 8.2.3
			Water transp. saturated 6.2.5	Water transp. saturated 7.2.6	
			Gastransport/dissol. 6.2.6	Gas transport/dissol. 7.2.7	Gas flow
M		Deformation insert 5.2.4	Swelling 6.2.7	Swelling 7.2.8	Movement intact rock
		Outer deformation Cu 5.2.5	Mech. int. buf./backf. 6.2.8	Mech. int backfill/rock7.2.9	React. (earthquake) 8.2.7
		Inner deformation Cu 5.2.7	Mech. int. buf./canister 6.2.9		Fracturing
			Mech. int. buffer/rock 6.2.10		Time-dependent deform
	Thermal expansion 4.2.7	Thermal expansion 5.2.6	Thermal expansion 6.2.11	Thermal expansion 7.2.10	Thermal movement
					Erosion
C	Advection/diffusion 4.2.8		Advection 6.2.13	Advection 7.2.11	Advection/mixing 8.2.11
			Diffusion 6.2.14	Diffusion 7.2.12	Diffusion 8.2.12
	Residuel gas radiolysis 4.2.9	Corrosion insert 5.2.8	Osmosis (salt effects) 6.2.15	Osmosis (salt effects) 7.2.13	Reactions GW/rock 8.2.13
	Water radiolysis 4.2.10	Galvanic corrosion 5.2.9	Ion exch./sorption 6.2.16	Ion exch./sorption 7.2.14	Dissolution/prec. fracture min. 8.2.14
	Metal corrosion 4.2.11	SCC insert 5.2.10	Montmorillonite transf. 6.2.17	Montmorillonite transf. 7.2.15	
	Fuel dissolution 4.2.12	Radiation effects 5.2.11	Dissolution/prec. impurities 6.2.18	Dissolution/prec. impurities 7.2.16	Microbial processes 8.2.15
	Dissolution gap invent. 4.2.13	Copper corrosion 5.2.12	Colloid release/erosion 6.2.19	Colloid release/erosion 7.2.17	Inorganic decomp. 8.2.16
	Speciation radionucl. 4.2.14	SCC shell 5.2.13	Radionuclides-induced transf. 6.2.20	Radionuclides-induced transf. 7.2.18	Colloid turnover 8.2.17
	Helium production 4.2.15	Grain growth copper 5.2.14			Gas formation/dis. 8.2.18
			Radiolysis pore water 6.2.21	Radiolysis pore water 7.2.19	Methane turnover 8.2.19
			Microbial processes 6.2.22	Microbial processes 7.2.20	Salt exclusion 8.2.20
Integration		HMC evolution damaged canister 5.2.16	THM evolution unsaturated 6.2.12		HC evolution 8.2.21
			THMC evolution saturated 6.2.23		
Radionuclide transport			Advection 6.2.24	Advection 7.2.21	Advection/disperion 8.2.22
			Diffusion 6.2.25	Diffusion 7.2.22	Matrix diffusion 8.2.23
			Sorption 6.2.26	Sorption 7.2.23	Sorption 8.2.24
			Speciation 6.2.27	Speciation 7.2.24	Speciation 8.2.25
			Colloid transport 6.2.28		Colloid transport 8.2.26
					Gas phase transport 8.2.27
		Radionuclide transport near field 7.3			RN transport geosphere 8.2.28
Code:		Great efforts	Moderate efforts	Small efforts/monitoring	during coming 3-yr period

Table 3-2. Research on the initial state of the repository.

Fuel	Canister	Buffer	Backfill	Geosphere
Geometry 4.1.2	Geometry 5.1.2	Geometry 6.1.2	Geometry 7.1.2	
Radiation intensity 4.1.3	Radiation intensity 5.1.3	Pore geometry 6.1.3	Pore geometry 7.1.3	
Temperature 4.1.4	Temperature 5.1.4	Radiation intensity 6.1.4	Radiation intensity 7.1.4	
Hydrovariables 4.1.5	Mechanical stresses 5.1.5	Temperature 6.1.5	Temperature 7.1.5	
Mechanical stresses 4.1.6	Material composition 5.1.6	Smectite content 6.1.6	Smectite content 7.1.6	
Radionuclide inventory 4.1.7		Water content 6.1.7	Water content 7.1.7	Site investigations
Gap inventory 4.1.8		Gas contents 6.1.8	Gas contents 7.1.8	
Material composition 4.1.9		Hydrovariables 6.1.9	Hydrovariables 7.1.9	
Water composition 4.1.10		Swelling pressure 6.1.10	Swelling pressure 7.1.10	
Gas composition 4.1.11		Smecitite composition 6.1.11	Smectite composition 7.1.11	
		Pore water composition 6.1.12	Pore water composition 7.1.12	
		Impurity levels 6.1.13	Impurity levels 7.1.13	
Code:	Great efforts	Moderate efforts	Small efforts/monitoring	during coming 3-yr period

As far as the canister's initial integrity is concerned, it is urgent to obtain greater knowledge concerning types and probabilities of leaks or defects, particularly in the canisters' lid weld. The programme for this is mentioned in section 5.1.2 and is further elaborated on in Chapter 15.

For canisters with an assumed initial defect, it is urgent to further explore the coupled chemical, hydraulic and mechanical evolution that results if water enters the canister. The chemical corrosion of the cast iron insert is dealt with in section 5.2.8, and the mechanical stresses of the corrosion products on the copper shell in section 5.2.7.

As a step in the optimization of the canister, long-term safety will also be examined for a variant where the thickness of the copper shell has been reduced from 50 to 30 mm and the thickness of the insert has been increased accordingly. The basis of this study is that the canister's corrosion protection (copper thickness) is judged today to be much more overrated than its mechanical strength, which is determined by (among other things) the thickness of the insert, see further Chapter 5.

3.3 Buffer

After deposition, the buffer undergoes a complicated thermo-hydro-mechanical (THM) evolution when it becomes saturated with water. The process proceeds for some ten or so years, and our knowledge of the coupled processes during this time is not complete. Nor is such knowledge necessary for the safety judgements. It is, however, important to understand and be able to predict the state of the buffer after completed water saturation, since this comprises the point of departure for the analysis of its long-term evolution. That is why the buffer's initial THM evolution is studied in the field and with models, see section 6.2.12.

The evolution of a water-saturated buffer is much slower and the couplings are simpler to handle. Studies are being conducted here as well, both in the field and with models, section 6.2.23. Individual processes where further research is urgent are the effects of saline groundwater, section 6.2.15, and colloid release/erosion, section 6.2.19. As far as radionuclide transport is concerned, the phenomenon of surface diffusion may require further studies, section 6.2.25.

3.4 Backfill

The backfill has been treated less thoroughly than other parts of the repository in SR 97 and earlier safety assessments, in part because its properties have not been definitively specified in the KBS-3 concept. SR 97 observed that "a more detailed analysis of the evolution of the backfill" both with today's climate and with climate changes is required in future assessments.

Different compositions of the backfill (smectite clays mixed with crushed rock in varying proportions) will be tested during the period, in terms of both practical usefulness and long-term properties, see section 7.2.2. The long-term evolution of the backfill is controlled largely by the same processes as that of the buffer. This means that a large knowledge base is available, even though the relative importance and scope of the processes may be different in the backfill compared to the buffer.

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Processes of particular importance to investigate are the swelling and the backfill's subsequent long-term mechanical evolution, as a consequence of e.g. saline water, sections 7.2.9 and 7.2.13, other chemical transformations, section 7.2.15, and colloid release/erosion, section 7.2.17. Furthermore, an analysis of whether the backfill might comprise a preferential transport pathway for radionuclides is also required, section 7.2.21.

3.5 Geosphere

The modelling of earthquakes was not fully developed in SR 97. SKB concluded that this development work needs to be carried further and a number of points for further studies were mentioned. Section 8.2.7 describes how several of these points have now been addressed and presents plans for further development. The goal is that the earthquake analyses should be used in the deployment of canister positions so that earthquake-induced canister damage can be avoided completely. Another intention is that earthquakes should not be studied in a separate scenario as in SR 97, but integrated in all scenarios.

The purpose of model development for groundwater flow is to make the main alternatives, the continuum models, more flexible and to further develop alternative, discrete models, see section 8.2.3.

SR 97, like previous assessments, shows that the transport resistance, which is dependent on flow conditions and geometric properties of water-bearing fractures, is decisive for how radionuclides are transported in the geosphere. It is also observed in SR 97 and its review that a better understanding is needed of the transport resistance and how it should be handled in the safety assessment. The programme for this is presented in section 8.2.23.

The most essential questions concerning future hydrochemical conditions have largely been clarified, see further section 8.2.21. The single major area that remains concerns microbial processes, an area where research started relatively late. It is known today that microbes occur at repository depth and much deeper. The microbes affect redox conditions and can be of great importance as a redox buffer if e.g. oxygenated glacial water should penetrate down into the bedrock, see further section 8.2.15.

Long-term interaction between groundwater and bentonite can affect the groundwater chemistry in the near field. Basic research continues to be pursued in this area, see section 8.2.13. Readiness will be maintained to investigate new hydrogeochemical questions that arise during the site investigations.

In the review of SR 97 it is stated that infiltration of oxygenated water during a glaciation is not dealt with thoroughly enough. The authorities also call for a more thorough treatment of radionuclide transport with colloids. The programme for these two points is presented in sections 8.2.14 and 8.2.26, respectively.

A methodical handling of all geosphere information from the site investigations will also require considerable efforts during the period, see section 13.3.

3.6 Biosphere

The evolution of the biosphere will always comprise an essential part of a safety assessment, mainly because the consequences of a possible release from a deep repository become manifest in the biosphere. Unlike the geosphere, the biosphere can be expected to change greatly during the time the safety of the repository is to be judged, above all as a result of future climate change. This means that a series of different biospheres can be expected to exist in the future on a given site. The consequences of possible releases from the repository must be acceptable in all of these if the repository is to be considered safe.

Radionuclide turnover in the biosphere is usually described in the safety assessment with compartment models, where the biosphere is divided into a number of relatively homogeneous subunits between which radionuclide transfers are calculated. In previous assessments, the description of these transfers has been based on rough empirical measurements and estimates. At present there is a trend towards more realistic so-called process-oriented descriptions, where the calculation of transfers is based on knowledge concerning the underlying mechanisms, see further sections 9.3 to 9.5. Among the ecosystems being studied and modelled are forest, mire and sediment, see sections 9.6 to 9.8. Long-term variations in e.g. climate, land uplift and salinity are crucial for the evolution of the biosphere, see section 9.9. The site investigations require extensive methodology development as regards the biosphere, which is described in section 9.12.

3.7 Climate change

Climate change can undoubtedly be expected to occur in the more than hundred thousand year timespan over which the safety of the deep repository is to be assessed. A description of climate change and the impact it may have on the repository is therefore necessary in a safety assessment. The uncertainties surrounding future climate change are great, and any description of how different climate states succeed each other will necessarily be sketchy. On the other hand, it can be said with greater certainty that certain climate states will prevail during at least some era in the future, even though the era cannot be exactly pinpointed. The safety assessment is therefore focused on describing a number of climate states and the effect they have on the repository. The research programme for describing future climate change and the different climate states is described in Chapter 10.

4 Fuel

Several types of fuel will be deposited in the repository. For one alternative with 40 years of reactor operation, the quantity of BWR fuel is estimated at approximately 7,000 tonnes and the quantity of PWR fuel at approximately 2,300 tonnes /4-1/. In addition, 23 tonnes of MOX fuel and 20 tonnes of fuel from the reactor in Ågesta will be deposited. The fuel's burnup may vary from approximately 15 MWd/kgU to 55–60 MWd/kgU.

In SR 97, it was assumed in most subanalyses that all canisters contain BWR fuel of type SVEA-96 with a burnup of 38 MWd/tU. The hypothetical repositories were designed for 8,000 tonnes of fuel, equivalent to 4,000 canisters.

PWR fuel differs marginally from BWR fuel when in comes to radionuclide content. Other aspects of importance in the safety assessment, for example the geometry of the fuel cladding tubes, are as a rule handled so pessimistically in analyses of radionuclide transport that differences between different fuel types are irrelevant. MOX fuel has a higher decay heat than uranium fuel, which means that less fuel can be placed in each canister.

Differences between different fuel types are more important for criticality assessments. BWR fuel of type SVEA-64 and PWR fuel of type FA17x17 were dealt with in SR 97, since these types are most unfavourable with regard to criticality.

4.1 Initial state fuel/cavity

4.1.1 Variables

In SR 97, the fuel was 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 to 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 cavity could thus be included in either the fuel or the canister subsystem, and has been included in the fuel here. The variables are defined in Table 4-1.

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 6.2. The research programme around the initial state for the different variables in the fuel is described in the following.

Table 4-1. 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 stress 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.

4.1.2 Geometry

Conclusions in SR 97 and its review

In most subanalyses in SR 97 it is assumed for simplicity's sake that all canisters contain BWR fuel of type SVEA 96. The actual repository will contain fuel of several different types and geometries. The geometry of the fuel assemblies is of subordinate importance for long-term safety.

During operation, the originally cylindrical fuel pellets crack, leading to surface enlargement. The extent of this surface enlargement, which can be of importance if the fuel comes into contact with water in a deep repository, is incompletely known.

Conclusions in RD&D 98 and its review

The fuel area that is accessible for corrosion attack by groundwater is an essential parameter in the determination of absolute corrosion rates. This is particularly true in the treatment of data from flow-through leaching of spent fuel, recently started in Studsvik. Previously, the specific area of the fuel has been determined using the BET method for two of the reference fuels used in SKB's experimental programme /4-2/. In measurements with krypton adsorption, reproducible values of the area in the range 70–120 cm^2/g were obtained. Several PWR fuel fragments have been ground and screened for the flow leachings, after which the area of two fractions (0.125–0.25 mm and 0.25–0.50 mm) has been determined with the Kr-BET method. The fuel specimens to be used in the flow leaching experiments are stored in an argon atmosphere.

Newfound knowledge since RD&D 98 and SR 97

No new knowledge has been forthcoming.

Research programme

SKB, together with other organizations, has been granted funds for an EU project called "Spent fuel stability under repository conditions, 2001–2004", which includes research on long-term changes in the structure and geometry of the fuel. Among other things, the temporal evolution in the immediately accessible fraction of the radionuclide inventory will be studied. The project embraces:

- A statistical analysis of all available literature data.
- Diffusion calculations for transport of radionuclides to fuel grain boundaries before the fuel comes into contact with water.
- An estimate of long-term changes in the size of the fuel surface.

4.1.3 Radiation intensity

Conclusions in SR 97 and its review

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 98 and its review

No questions for further research were identified in RD&D-Programme 98 or its review.

Newfound knowledge since RD&D 98 and SR 97

No new knowledge has been forthcoming.

Research 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.

4.1.4 Temperature

Conclusions in SR 97 and its review

The greatest uncertainty in the calculations of the temperature of the fuel and in the cavity, as well as in the different parts of the canister were the uncertainties surrounding the heat transfer between the different components in the canister and between the canister and the bentonite during the water saturation phase. The critical interface in the canister is the boundary between the cast iron insert and the copper shell. The copper's emissivity is of crucial importance.

The authorities believe that a more detailed study of the importance of the surface properties for the heat transfer is needed to be able to formulate the design requirements for the canister and insert surfaces, with respect to both machining and storage of canisters prior to deposition. Experience regarding the properties acquired by the surface of the canister during fabrication should reduce the uncertainty regarding emissivity.

Conclusions in RD&D 98 and its review

Not dealt with in RD&D-Programme 98.

Newfound knowledge since RD&D 98 and SR 97

No new knowledge has been forthcoming.

Research programme

SKB plans to conduct studies of the importance of the surface properties for the heat transfer during the coming three-year period. The purpose is to formulate design requirements for the canister surfaces. New calculations of the initial temperature distribution in a canister will then be performed.

4.1.5 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.

4.1.6 Mechanical stresses

Conclusions in SR 97 and its review

The fuel pellets have inherent stresses caused by grain growth etc. as a consequence of nuclear fissions and irradiation. The crystals in the pellets may change slightly during irradiation, depending on temperature and burnup. The fuel rods and structural elements have inherent stresses due to pressure from fission gases and gas filling. These stresses vary with the make and burnup of the fuel. The stress distribution in the assemblies is affected in an unpredictable manner by irradiation in the reactor, which can lead to dimensional changes in the structural materials. This affects the surface of the fuel pellets, which is of importance for how rapidly radionuclides can be released if the fuel comes into contact with water. Data for the safety assessment are based on surface determinations of spent fuel affected by the above processes and conditions, see section 4.1.2.

Conclusions in RD&D 98 and its review

Not dealt with.

Newfound knowledge since RD&D 98 and SR 97

No new knowledge has been forthcoming.

Research programme

Work will be done within the EU project "Spent fuel stability under repository conditions," see section 4.1.2.

4.1.7 Total radionuclide inventory

Conclusions in SR 97 and its review

The uncertainty in calculations of the inventory of radionuclides in the fuel is at most ten percent or so and is related to the fuel's burnup, among other things.

In SR 97, data on nuclide content, decay heat and radiation were calculated with the program ORIGEN. SKI points out that this type of calculation has not been validated for certain nuclides, e.g. Cl-36, Se-79 and Sn-126.

The authorities consider SKB's description of the properties of the fuel to be acceptable, but believe the uncertainties in the composition of the fuel need to be studied more closely. The authorities would also like to see a clearer analysis of the importance of other burnups and fuel types (MOX).

Conclusions in RD&D 98 and its review

No own development of calculation programs for inventories will be done. The internal documentation of the reliability, verification and validation of the programs needs to be strengthened.

Newfound knowledge since RD&D 98 and SR 97

No new knowledge has been forthcoming.

Research programme

A new calculation of radionuclide inventory and decay heat will be performed. In conjunction with this, the calculation model for individual nuclides (such as Cl-36, Se-79 and Sn-126) will be validated.

Prior to the next safety assessment, a study will be made of all the fuel types to be deposited in the repository. The intention is to shed light on differences in inventories, decay heats, readily soluble fraction, etc.

4.1.8 Gap inventory

Conclusions in SR 97 and its review

Certain radionuclides accumulate on the surface of the fuel pellets and are thereby rendered more accessible for transport. The estimation of this fraction is based on experimental data from above all Canadian CANDU fuel. Uncertainties in the gap inventory included in the Data Report were discussed in SR 97, but no concrete questions for further research were identified in SR 97 or its review.

Conclusions in RD&D 98 and its review

SKI proposed studies of the distribution of relatively readily soluble radionuclides in the spent fuel.

Newfound knowledge since RD&D 98 and SR 97

In general there is good agreement between the fractions of readily soluble nuclides proposed by SKB and those used in an EU project that deals with safety in the final disposal of spent fuel /4-3/.

The readily soluble fraction of nuclides in spent fuel is usually estimated indirectly by means of measurements of fission gas release. Direct leach measurements are difficult, since a portion of e.g. cesium is also present in the fuel matrix and goes into solution together with e.g. the grain boundary fraction. New results suggest that fuel matrix dissolution is very limited in the presence of hydrogen gas (pressure and temperature conditions remain to be determined), see further section 4.2.12. This makes it possible to determine the readily soluble fraction with greater accuracy than was previously possible. Preliminary results from such attempts /4-4/ show that uranium contents and the fraction of readily soluble nuclides (e.g. cesium and iodine) are lower than expected. Less than one percent of the total cesium or iodine inventory in fuel powder is measured in solution after 15 days.

A study of leaching and the electrochemical behaviour of synthetic metal particles similar to those formed in spent fuel /4-5/ has shown that molybdenum is leached selectively at a rate that is 3–4 orders of magnitude higher than ruthenium, rhodium and palladium under both anoxic and oxidizing conditions. This agrees well with data from fuel leaching (see e.g. Figure 4-4 in section 4.2.12).

Research programme

Experiments in a hydrogen gas environment with fuel pellets of varying burnup and irradiation history are planned. If possible, such pellets will be used where the release of fission gas has already been determined.

Metallic particles containing platinum group metals as well as molybdenum and technetium will be extracted from spent fuel with a non-oxidizing reagent (phosphoric acid) instead of nitric acid, in order to avoid dissolution of smaller grains. The dissolution rate of different components from these particles under different redox conditions will be determined in future experiments.

4.1.9 Material composition

Conclusions in SR 97 and its review

The uncertainties with regard to material composition are small, partly because the quality requirements in the fabrication of fuel assemblies are very strict.

The authorities point out that effects of non-radioactive fission products such as xenon would have needed to be described in greater detail, since they can have both positive and negative effects on safety.

Conclusions in RD&D 98 and its review

Not dealt with.

Newfound knowledge since RD&D 98 and SR 97

No new knowledge has been forthcoming.

Research programme

SKB will conduct a study of the importance of non-radioactive fission products prior to the next safety assessment. The study intends to go through all fission products and document their properties and what importance they might have in the repository.

4.1.10 Water composition

The temperature and pressure in the cavities in the fuel and canister at deposition are such that water occurs in vapour form, see gas composition below.

4.1.11 Gas composition

Conclusions in SR 97 and its review

Fuel-clad gap

The fuel rods are filled with helium to a pressure of 0.4 MPa during fabrication. There are also fission gases from operation, of which mainly Kr-85 is left at the time of deposition.

Canister cavity

The canister will be sealed at atmospheric pressure or under vacuum, which means that the pressure in the canister cavity may be a couple of atmospheres if the initial temperature is as high as 400ºC.

Water vapour

The maximum quantity of water in a canister is estimated at 50 grams. This amount is equivalent to the void in a fuel rod and thus presumes that a Zircaloy cladding tube is defective during operation or interim storage.

Conclusions in RD&D 98 and its review

Not dealt with.

Newfound knowledge since RD&D 98 and SR 97

No new knowledge has been forthcoming.

Research programme

Besides what is said in section 4.1.9 about the importance of non-radioactive fission products, 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.

4.2 Processes in fuel/cavity

4.2.1 Overview of processes

A number of processes will with time alter the state in the fuel and in canister 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.

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 means of 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 to which the alpha radiation gives rise, 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 be transported into 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 dissolution or transformation of the fuel matrix with 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.

4.2.2 Radioactive decay

Conclusions in SR 97 and its review

SKB considers that there is a good understanding of the radiation-related processes. The availability of data and models of good quality is also judged to be good.

The authorities concur with these conclusions. The processes in question (radioactive decay and absorption of radiation) are, in the view of the authorities, among the best known of the processes that must be taken into account in a safety assessment.

Conclusions in RD&D 98 and its review

Not dealt with.

Newfound knowledge since RD&D 98 and SR 97

No new knowledge has been forthcoming.

Research programme

The half-lives of the radionuclides in question are generally known with good accuracy. However, new data concerning the half-lives of Se-79 and Sn-126 emerged during the work with SR 97. For this reason, SKB intends to conduct a quality review of data on the half-lives of all radionuclides of interest in the safety assessments. It will be finished in good time before the next safety assessment.

4.2.3 Radiation attenuation/heat generation

Conclusions in SR 97 and its review

The conclusion is drawn in SR 97 that our understanding of the radiation-related processes is good as far as radiation attenuation and heat generation are concerned. The availability of data and models of good quality is also considered to be sufficient.

The authorities concur with these conclusions. The processes in question (radioactive decay and absorption of radiation) are, in the view of the authorities, among the best known of the processes that must be taken into account in a safety assessment.

Conclusions in RD&D 98 and its review

Not dealt with in RD&D-Programme 98.

Newfound knowledge since RD&D 98 and SR 97

No new knowledge has been forthcoming.

Research 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.

4.2.4 Induced fission (criticality)

Conclusions in SR 97 and its review

SKB observes that with the current design of the canister, criticality cannot arise if water enters the canister, provided that the fuel assemblies are intact and the fuel's burnup is taken into consideration. SKB further claims that the probability of criticality outside the canister due to leakage of fissionable material is very small, and that the consequences of any possible criticality would be small.

The authorities agree that criticality is not probable, provided that the fuel is sufficiently spent and that the geometry does not change. The authorities also consider it a weakness that burnup has to be taken into consideration.

Conclusions in RD&D 98 and its review

SKI would like to see an updating of the criticality analyses for the canister.

Newfound knowledge since RD&D 98 and SR 97

SKB has initiated a study of the safety margin to criticality. A comparative study has been conducted of the criticality calculations performed by SKB, Posiva and Nagra, since they have arrived at different results /4-6/. The conclusions were that the differences in k values between SKB's and Posiva's results can be fully explained by differences in fuel types, enrichments, canister material and canister dimensions in the two calculations. The differences in k values between SKB's and Nagra's results could not be explained in the same way. Subsequent analyses have shown that in Nagra's scenario, an infinite number of canisters were packed densely in air (vacuum), while SKB assumed an infinite number of canisters in bentonite. When this had been allowed for, the differences between Nagra's and SKB's results were acceptable.

Research programme

SKB is continuing the initiated programme with an evaluation of the uncertainty in necessary data in order to be able to take into account the lanthanides in the fuel in judging the risks of criticality. The next step will be to identify realistic accident scenarios, for which the calculations may need to be checked. It is projected that the programme can be completed during the three-year period.

4.2.5 Heat transport

Dealt with in section 4.1.4.

4.2.6 Water and gas transport in canister cavity, boiling/condensation

If the copper canister is not intact, water can enter the canister cavity as liquid or water vapour. Transport of water, water vapour and other gases in the canister is then determined by the detailed geometry of the canister cavities, the presence of water/vapour in the cavities, and temperature and pressure. Boiling/condensation comprises an integral part of water/gas transport. The process is strongly coupled to several other processes. The processes are dealt with collectively in section 5.2.16.

4.2.7 Thermal expansion/cladding failure

Conclusions in SR 97 and its review

The process is of no importance for long-term safety as long as the copper canister is intact. For initially damaged canisters it can be pessimistically posited that all cladding tubes are damaged, but that they still constitute physical protection for the fuel and that the fuel assemblies retain their original geometry. The same line of reasoning can be posited for canister retrieval.

The question is not discussed by the authorities.

Conclusions in RD&D 98 and its review

Not dealt with in RD&D-Programme 98.

Newfound knowledge since RD&D 98 and SR 97

No new knowledge has been forthcoming.

Research 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.

4.2.8 Advection and diffusion

It is observed in SR 97 that 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 is dealt with in section 7.3.

The process has not been commented on in the review of SR 97, or in RD&D-Programme 98 or its review. SKB intends to pessimistically simplify this process in future safety assessments as well.

4.2.9 Residual gas radiolysis/acid formation

Conclusions in SR 97 and its review

Residual air, water and radiolytically formed nitric acid will be consumed by corrosion reactions with the canister insert. The total scope of general corrosion is negligible. The process can therefore be neglected in the safety assessment. Consequences of stress corrosion cracking (SCC) are judged to be of no importance for canister life.

The question is not discussed in the regulatory review.

Conclusions in RD&D 98 and its review

The question is not discussed.

Newfound knowledge since RD&D 98 and SR 97

No new knowledge has been forthcoming.

Research 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.

4.2.10 Water radiolysis

This process concerns radiolysis of water in the space between the fuel cladding and the cast iron insert. Radiolysis of importance for fuel dissolution in the space inside a damaged canister cladding is dealt with in section 4.2.12.

Conclusions in SR 97 and its review

SKB's conclusion was that our fundamental understanding of the gamma radiolysis of water that has entered the cavity between fuel and canister is sufficient for the needs of the safety assessment. SKI notes that one of their reviewers questions whether the aerobic corrosion mechanisms that are caused by the formation of oxygen and other oxidants from the radiolysis of spent nuclear fuel have been adequately taken into account, see further section 4.2.12.

Conclusions in RD&D 98 and its review

The question is not discussed.

Newfound knowledge since RD&D 98 and SR 97

No new knowledge has been forthcoming.

Research programme

Iron corrosion in initially oxygen-free water under gamma irradiation will be studied during the period, starting in 2002 at the earliest. The investigations tie in with the corrosion studies discussed in section 5.2.8.

4.2.11 Metal corrosion

Conclusions in SR 97 and its review

Our fundamental understanding of the process is sufficient for the needs of the safety assessment. The uncertainties principally concern whether the corrosion rates that have been observed in short-duration experiments are relevant for very long periods of time. Available data suggest that the cladding tubes have a life of at least 100,000 years. The tubes can pessimistically be assumed to be damaged or corroded, but largely retain their mechanical integrity for more than 100,000 years and act as a mechanical support for the column of fuel pellets.

The question is not discussed in the regulatory review.

Conclusions in RD&D 98 and its review

The question is not discussed.

Newfound knowledge since RD&D 98 and SR 97

No new knowledge has been forthcoming.

Research 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.

4.2.12 Fuel dissolution

Conclusions in SR 97 and its review

Fuel dissolution was identified in SR 97 as the area where the greatest uncertainty remains in our knowledge.

The authorities conclude that the results from SKB's spent fuel dissolution model must be considered to be inadequately documented to be directly useful in supporting a consequence analysis. Since it can be questioned whether the knowledge base is adequate, the authorities consider that SKB in SR 97 should have used more robust assumptions to estimate an upper bound for the fuel dissolution rate. SKB is urged to devote more attention to the results from the extensive spent fuel experiments carried out at Studsvik's Hot Cell Laboratory.

Conclusions in RD&D 98 and its review

SKI and Kasam find that SKB's experimental work is adequately focused on issues which are important to resolve and which are of importance for safety assessments. In SKI's opinion, SKB's work is generally of good scientific quality and makes a significant contribution to the international research. Studies of the mechanism that controls release from metallic inclusions in spent fuel are recommended by both SKI and Kasam. Kasam underscores the need for high quality in the analysis results. SKI recommends studies of the distribution of relatively readily soluble radionuclides in the spent fuel.

Newfound knowledge since RD&D 98 and SR 97 and research programme

A part of SKB's fuel programme during the period 2001–2004 will be carried out within the framework of two EU projects. The project "Rates and mechanisms of radioactive release and retention inside a waste disposal canister" has been under way since the autumn of 2000, where SKB is coordinating the work on thermodynamic and quantum mechanical modelling of the chemical reactions in the canister cavity. The project "Spent fuel stability under repository conditions" will commence during 2001, where SKB will coordinate the experiments in fuel dissolution and radiolysis. SKB's own research initiatives are presented below.

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A. Analytical methods

Nowadays, researchers at Studsvik are able to quickly separate dissolved oxidized U(VI) from reduced U(IV) and analyze very low uranium concentrations (10^{-9} M) /4-7/. The method has been used to study the oxidation kinetics when U(IV) transforms to U(VI). The measured oxidation rates have been published /4-8/ and agree well with data in the literature. Investigation of the redox kinetics of plutonium with the same technique has also been concluded and presented /4-9/. By determining the oxidation numbers of different nuclides in fuel leachates in this manner, the dissolution of fuel in contact with water can be more easily understood and calculated.

Research programme

A better method for iodine analyses will be developed to determine the readily soluble fraction in fuel (the uncertainties with the current ICP-MS method are great). Further development of plutonium speciation in leachates is also planned. In order to be able to achieve better accuracy in analyzing the low concentrations of radionuclides obtained in the leaching of spent fuel under reducing conditions, the purchase of an ICP-MS with sector magnet is planned for Studsvik. A sector magnet provides much better mass resolution than the quadrupole that is used in the current instrument.

B. Redox conditions in fuel dissolution

For more than two years, pH and E_h have been measured continuously in spent fuel leaching experiments. The goal is to understand how the fuel corrodes in contact with water. These measurements have contributed to a better understanding of the concept "anoxic conditions". In a strictly geochemical sense, "anoxic" is synonymous with "completely oxygen-free", as for example in deep groundwaters. In research on the long-term safety of the repository in general, an attempt has often been made to simulate deep repository conditions by continuously allowing an inert gas such as argon or nitrogen to pass through the system. Measurements /4-10/ show that in such cases the concentration of oxygen that diffuses into the system is sufficient to create highly oxidizing conditions, corresponding to an E_h greater than +600 mV at pH = 8. Figure 4-1 shows the difference between the pe-pH ranges for "anoxic" laboratory conditions and the deep repository in a predominance diagram for plutonium.

Since the difference in oxygen pressure between atmospheric conditions and at best a fraction of a ppm of oxygen in a measuring vessel is six to seven orders of magnitude, it is very difficult to avoid inward oxygen diffusion. This means that even if the oxygen concentration is relatively low, oxygen constantly enters from the surroundings, since existing oxygen is consumed by fuel oxidation. However, since the oxygen concentrations produced by radiolysis are on the order of 10^{-7} M /4-11, 4-12/, the level of oxygen diffusing in can be kept two to three orders of magnitude lower than the level of radiolytic oxygen. This means that investigations of fuel dissolution under anoxic conditions can still be relevant. They would then correspond to an upper limit for the fuel dissolution rate in groundwater which is not redox-buffered by components from the near field such as Fe^{2+} or hydrogen gas (see next section). The results also clearly show that the traditional experiments in open vessels (oxygen concentrations greater than 10^{-4} M, i.e. more than three orders of magnitude higher than radiolytically produced oxygen) give far too pessimistic values of the leaching.

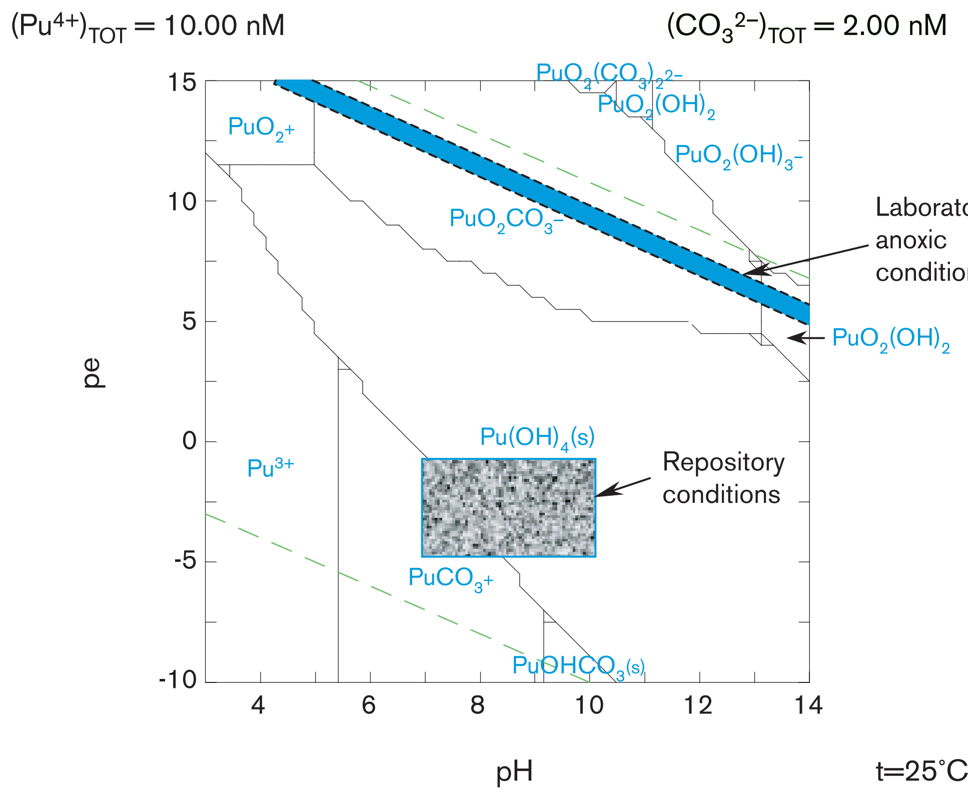

***Figure 4-1.** Predominance diagram for plutonium, where the pe-pH ranges for deep repository conditions and anoxic conditions are also shown.*

Research programme

Redox potential will continue to be measured in experiments with fuel pellets in a hot cell, into which argon is introduced via metal tubes and with better seals to minimize oxygen diffusion. Gold and platinum electrodes are used to distinguish the effects of dissolved gases on the platinum electrodes. The same applies to planned flow-through leaching experiments.

C. Dissolution rate of the fuel matrix under different redox conditions

The project with leaching of radionuclides from spent fuel and diffusion in bentonite has been concluded. The results of studies of actinide dissolution and transport in bentonite clay have been published /4-13/, along with a compilation of the methods for analysis of the radioactive substances /4-14/.

The redox conditions are crucial for fuel dissolution. Processes and reactions that influence and are influenced by these conditions must therefore be characterized. Autoclave experiments involving fuel leaching with hydrogen under 5 MPa pressure (the water pressure at 500 m depth) are described first here, and then flow leaching experiments under oxidizing, reducing and anoxic conditions at atmospheric pressure.

Autoclave experiments at 5 MPa hydrogen pressure

A potential reductant is hydrogen gas, which is formed in large quantities in a damaged canister, above all by corrosion of the canister's cast iron insert. At room temperature hydrogen can only reduce in the presence of a suitable catalyst. There are, however, reports in the literature from other fields of research (see /4-15/ for a compilation) that the UO_2(s) surface itself could activate hydrogen. Preliminary data from the influence of a 5 MPa hydrogen pressure on fuel dissolution /4-4/ are shown in Figure 4-2.

The experiment was carried out in a one-litre autoclave with 2 grams of powdered spent fuel (0.25–0.5 mm; 295 cm^2/g) in simulated groundwater with 5 MPa hydrogen gas pressure. Water samples of 10 ml were taken at different times during a period of more than a year and analyzed. The measured uranium concentrations agree well with the lowest published data for UO_2(s) solubility at the equivalent temperature /4-16, 4-17/. This is interpreted as indicating that all uranium in the solution is U(IV). This is remarkable, since the fuel continuously radiolyzes the water, producing oxygen. If uranium and other redox-sensitive elements were first dissolved from the fuel by the influence of radiolytic oxygen and then reduced at e.g. the surface of the autoclave, the concentrations of non-redox-sensitive elements such as cesium and strontium from the fuel matrix should increase with time. This is seen clearly in Figure 4-3, where data for leaching in a hydrogen gas atmosphere are compared with data from leaching under anoxic (argon) conditions. In this experiment, argon at atmospheric pressure was used instead of hydrogen and fuel pellets instead of fuel powder. The constant measured concentrations of all fuel components during a period of more than one year indicate a high stability of the fuel matrix in the presence of dissolved hydrogen.

Data for anoxic conditions indicate a relatively rapid dissolution, close to that for oxidizing conditions. Note, however, that the experimental set-up is not oxygen-tight (see above), which means that the figure may be an overestimate. Under hydrogen gas conditions, no dissolution can be detected after the first measurement point. Given the

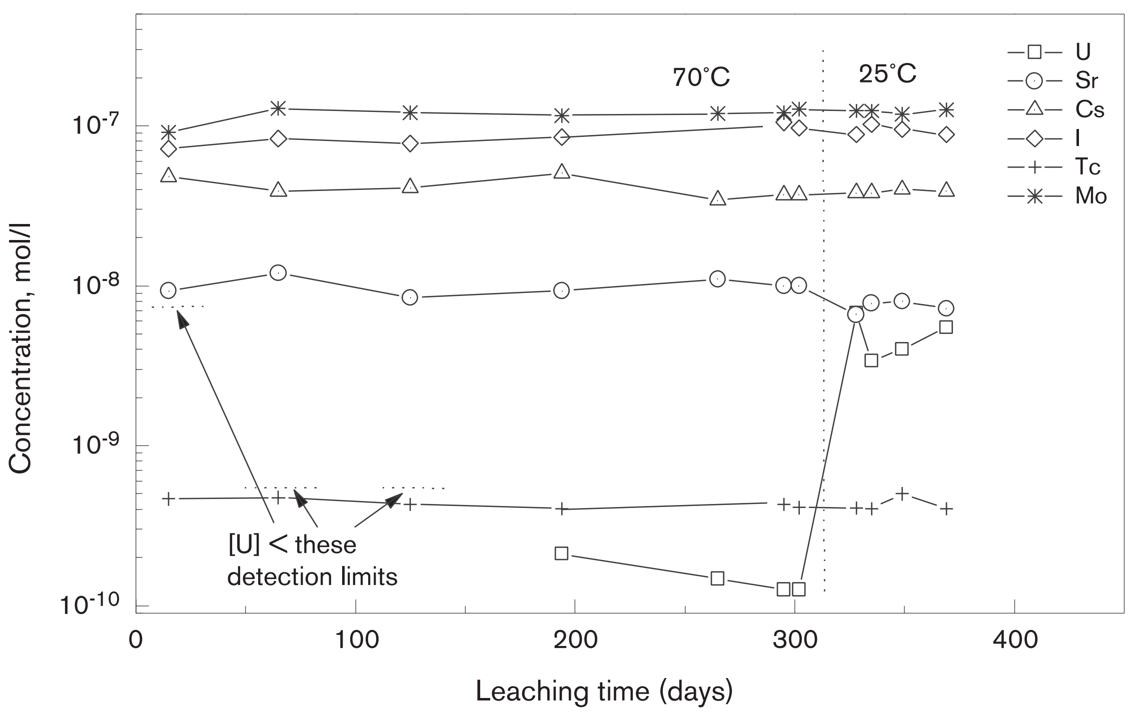

Figure 4-2. *Measured concentrations of U, Sr, Cs, I, Tc, and Mo as a function of leach time for hydrogen leaching under high pressure (5 MPa H_2) of spent fuel powder in a 10 mM NaCl, 2 mM HCO_3^- solution at 70°C and 25°C.*

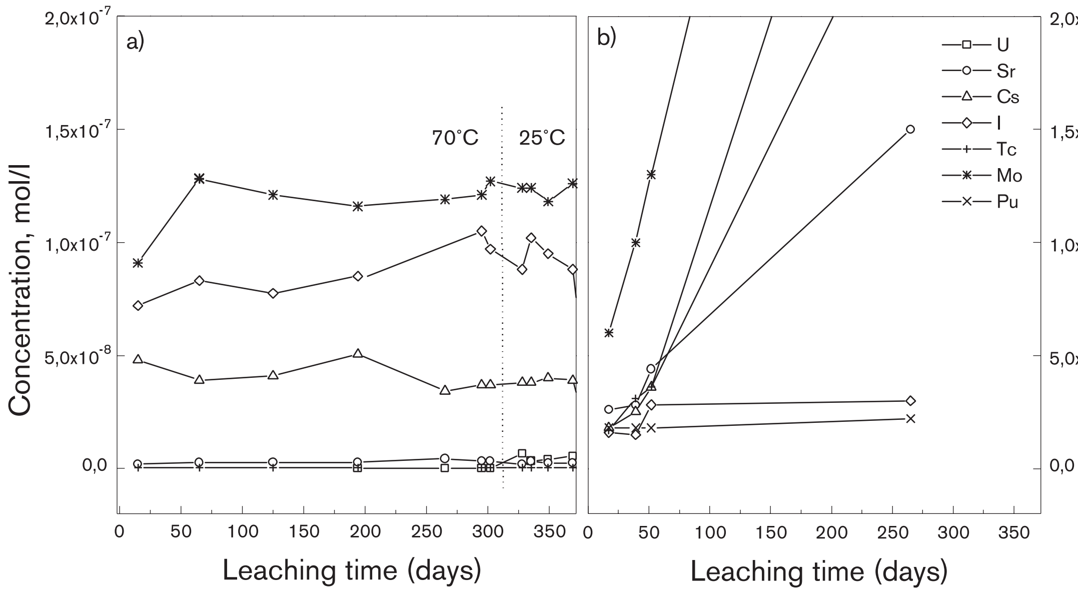

Figure 4-3. Comparison of concentration changes with time for leaching at 5 MPa hydrogen gas pressure (2a) and leaching (2b) of spent fuel under anoxic conditions. Data are shown on a linear scale to simplify the comparison.

time for the experiments and the accuracy of the concentration determination, a preliminary analysis of data suggests an upper limit for the fuel dissolution rate as being a fraction of $5 \cdot 10^{-8}$ per year. However, the figure is based on a single experiment with an autoclave of stainless steel whose surfaces were not completely clean. To verify the results and determine whether fuel matrix dissolution proceeds very slowly or stops completely, the accuracy of the analyses must be improved and the experimental time increased further.

At the pH values in question, oxygen is expected to oxidize U(IV) rapidly to the considerably more soluble U(VI). The experiment thus shows that the presence of hydrogen gas seems to prevent this. The stability of the fuel matrix in the presence of dissolved hydrogen may have several causes.

One possible explanation is that radiolytic oxidants are neutralized in solution /4-18, 4-19/, which was assumed in the fuel dissolution model used in SR 97.

Another possible explanation is a catalytic activation of hydrogen at the fuel surface. More sophisticated experiments are required to prove such an effect. Experiments with leaching of uranium dioxide, Gd-doped uranium dioxide or SIMFUEL in the presence of hydrogen gas, where small quantities of $^{18}O_2$ are introduced and followed in the system, are planned, along with experiments with uranium dioxide and low concentrations of oxygen and hydrogen in the gas phase of the type that have been conducted to demonstrate the catalytic effect of PuO_2(s) /4-20/.

A study of the influence of gamma radiolysis on uranium dioxide in 0.1 M NaCl solutions under 5 MPa of hydrogen or argon gas has been carried out at AECL in Canada /4-21/. Measurements of the corrosion potential of UO_2(s) electrodes show that hydrogen not only protects uranium dioxide from radiolytic oxidation, but also creates more reducing conditions than without radiation. The very negative corrosion potentials

(< –800 mV vs. SCE) mean that it is impossible for a positive ion to leave such a negatively charged surface (i.e. no corrosion of uranium dioxide by release of uranyl ions). These conclusions are also supported by XPS (X-ray Photo Electron Spectroscopy) analyses of the uranium dioxide surface before and after the experiment. These show a decrease in the oxidation state of the surface after contact with hydrogen-saturated solutions in the presence of gamma radiation.

Flow leaching experiments under varying redox conditions at atmospheric pressure

In another series of experiments, flow reactors have been used to study fuel dissolution under oxidizing, anoxic and reducing conditions. Flow reactors have previously been used in studies of dissolution kinetics for poorly soluble substances, including studies of UO_2(s) and spent fuel. This method has been improved and tested at Studsvik /4-22/. First a critical review was done of all literature data on dissolution rates for uranium dioxide, SIMFUEL and spent fuel /4-23/. All dissolved fuel components in the leachates were analyzed with ICP-MS, see above under "Analytical methods". This provides a better understanding of the fuel dissolution kinetics compared with other fuel studies, where only uranium and cesium have been analyzed. An HPLC dual piston pump was used instead of a peristaltic pump; oxygen-tight materials were used for the reactor, tubes and packings in order to minimize oxygen diffusion. Redox potential and pH were measured continuously before and after the fuel reactor during the experiment. In order to get a better understanding of the influence of carbonate and pH on the fuel dissolution kinetics, experiments were performed in the pH range 3 to 9.2.

The measured fuel dissolution rates under oxidizing conditions (air-saturated solutions) agree well with published data. The results also make it possible to draw some conclusions /4-22/ regarding congruence in conjunction with matrix dissolution for different fuel components, see figure 4-4.

The measured fuel dissolution rates decreased by up to four orders of magnitude in simulated groundwater solutions saturated with 1 atm hydrogen (Figure 4-5). Since hydrogen at room temperature is chemically inert, this suggests that dissolved hydrogen is activated in the presence of spent fuel, which was one of the possible explanations for the stability observed in the fuel in the above high-pressure experiment.

In other flow leaching experiments with uranium dioxide instead of spent fuel /4-24/ and hydrogen-saturated solutions, much higher uranium concentrations were obtained. One reason may be that in that case a peristaltic pump and plastic tubing were used, so that oxygen diffusion was probably much higher. It is also possible that the difference is due to the effect of the combination of the radiation from spent fuel and hydrogen. In order to ascertain this, the flow experiments with spent fuel will be repeated with uranium dioxide.

In the Studsvik experiments, the dissolution rates increased markedly at low pH and oxidizing conditions, but were nearly pH-independent for pH > 4 at reducing conditions. The dissolution rates could be fitted well to a kinetic expression of the type

$$R_{red} = k\ [U_{max}],$$

where $[U_{max}]$ is the solubility of UO_2(s) at a given pH. This indicates a non-oxidizing dissolution of the fuel matrix, which is explained more exhaustively in /4-22/.

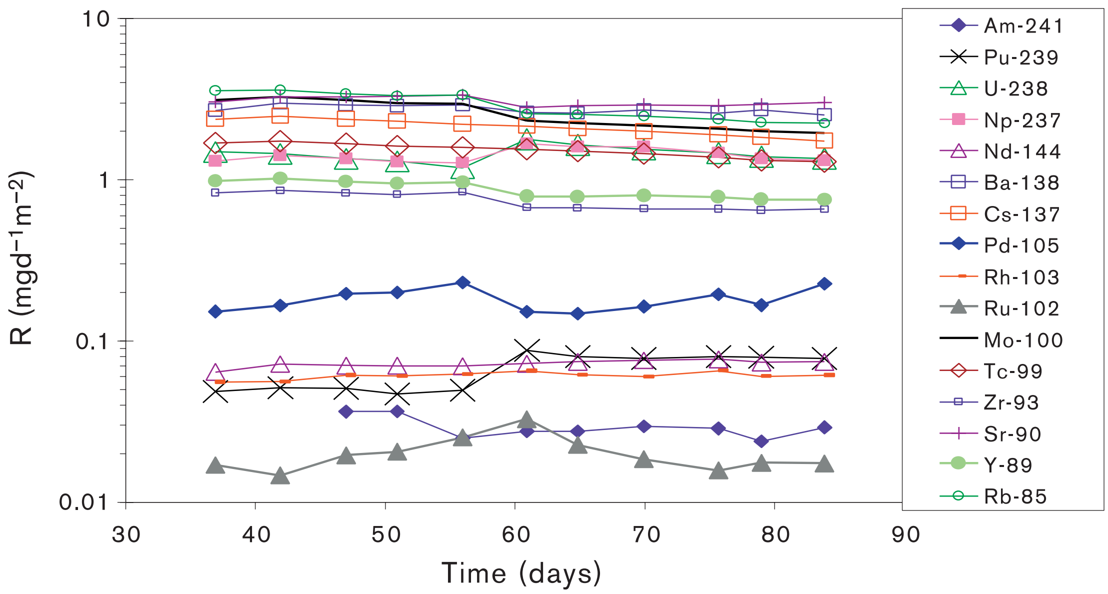

Figure 4-4. *Inventory-normalized dissolution rates (R) for different fuel components in 10 mM $NaHCO_3$ solutions under oxidizing conditions (air-saturated solutions).*

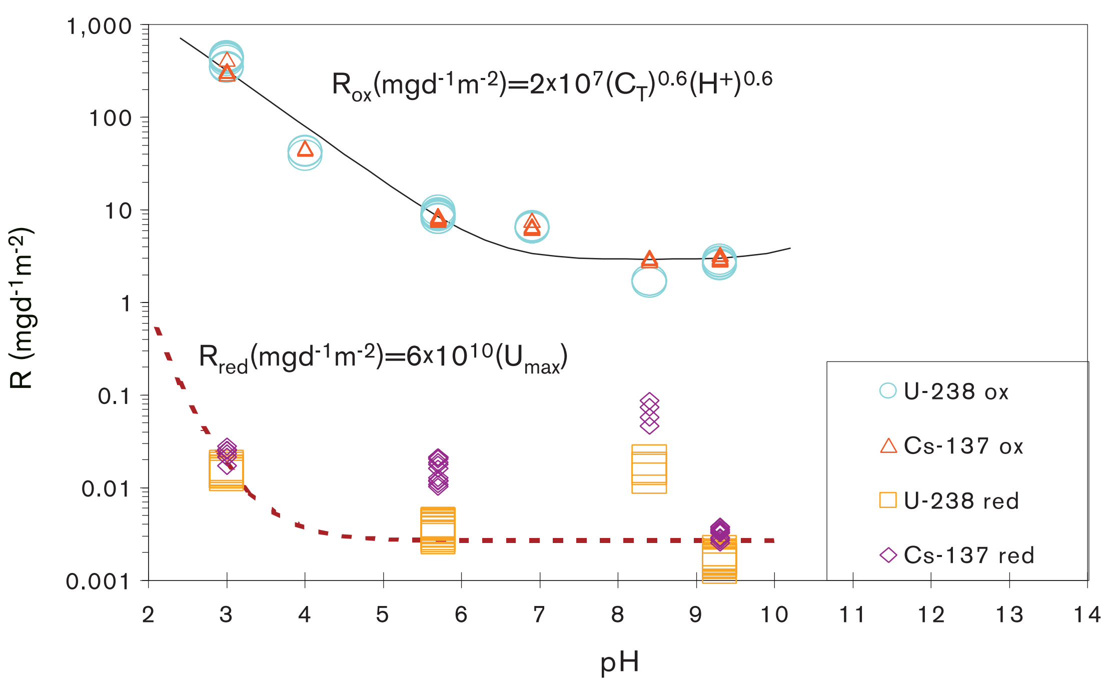

Figure 4-5. *Dissolution rates based on U-238 and Cs-137 for different pHs, under oxidizing (air) and reducing (hydrogen) conditions. C_T refers to the total carbonate content.*

The measured concentrations of certain fuel components in the presence of dissolved hydrogen were so low (less than 0.001 ppb) that it was impossible to analyze e.g. neptunium after a given leach time, see Figure 4-6. In Figure 4-7, data are compared from fuel leaching at pH 8.2 for oxidizing (air), reducing (H_2) and anoxic (Ar) conditions. The hydrogen effect can be clearly seen, especially after hydrogen is switched to argon. Then oxygen from radiolysis and diffusion takes over and the fuel matrix is dissolved at rates approaching those measured under oxidizing conditions.

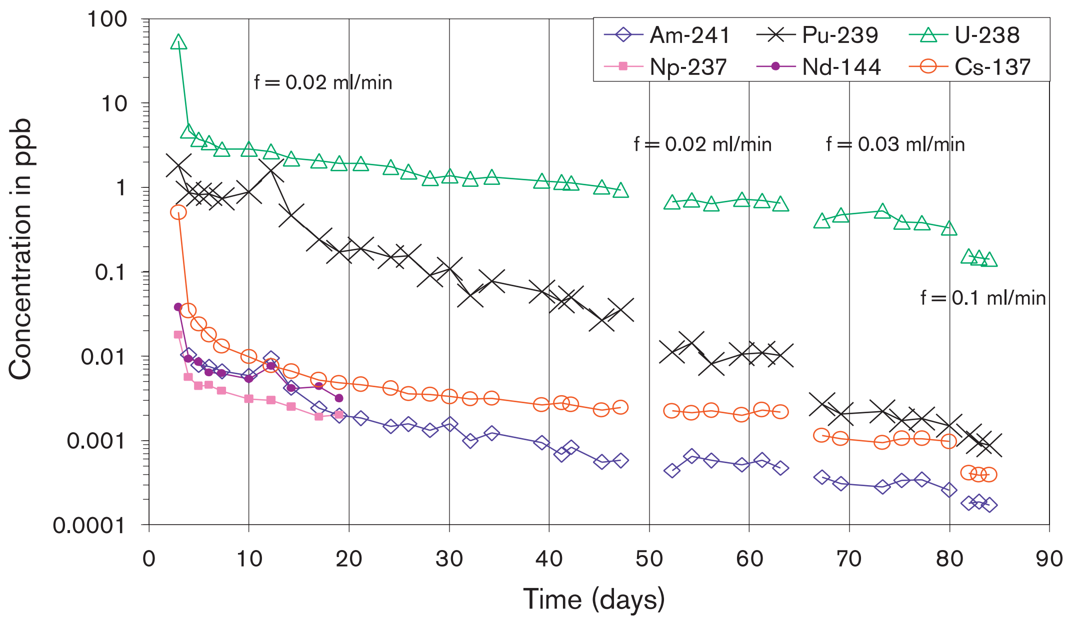

Figure 4-6. *Measured concentrations of different fuel components in flow leaching with a 10 mM $NaHCO_3$ solution saturated with H_2(g).*

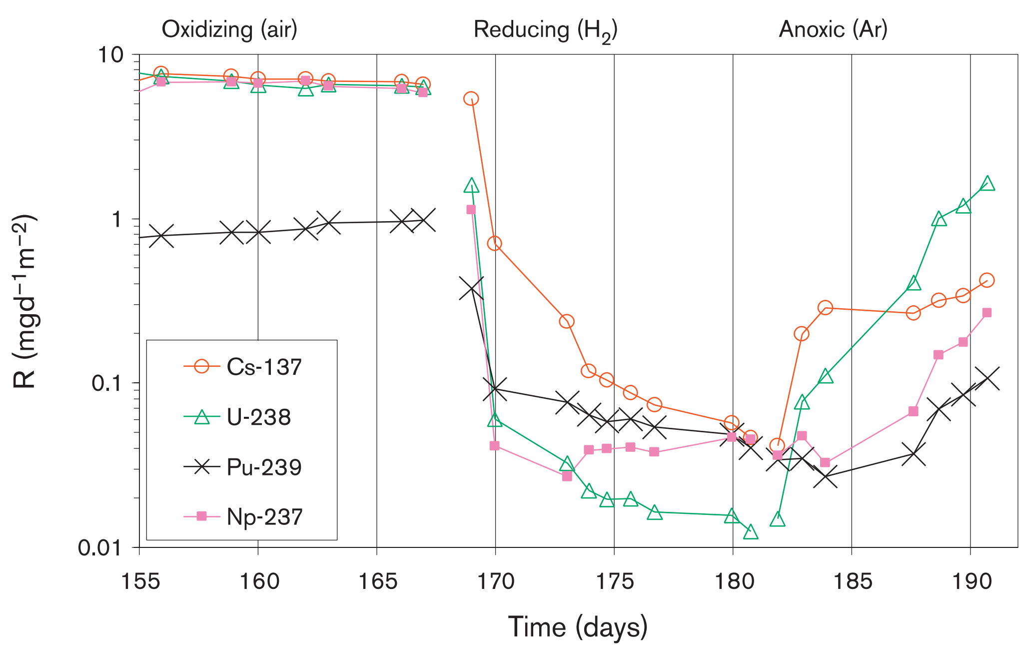

Figure 4-7. *Inventory-normalized dissolution rates (R) based on different radionuclides for a 1 mM $NaHCO_3$ test solution under oxidizing, reducing and anoxic conditions.*

Research programme

In order to rule out the influence of autoclave surfaces, new autoclaves lined with quartz have been purchased for future experiments. A parameter study has been started of the importance of temperature and hydrogen gas pressure in leaching.

The flow leaching apparatus has been installed in an argon-filled glovebox to further reduce oxygen diffusion. Leaching of fuel under anoxic (Ar) and reducing (H_2) conditions, as well as leaching of uranium dioxide under reducing conditions, are planned.

Experiments with Ar + 0.03 percent CO_2 and Ar + 10 percent H_2 + 0.03 percent CO_2 atmospheres will be conducted with fuel pellets in a hot cell. Gas tubes of metal and tighter sealing of the measurement system are expected to reduce the inward diffusion of oxygen. The results are also supposed to show whether such low concentrations of dissolved hydrogen have any effect on the leaching process.

Fuel dissolution under repository conditions will be studied in the CHEMLAB probe at Äspö. The experiments will require careful radiological control during preparation, execution and associated transport. The exact time required cannot be calculated until these matters have been explored. It is reasonable to assume an experimental period of three to five years. The goal is to begin the experiments with spent fuel during 2003.

D. Natural analogues

The natural fossil nuclear reactors in Oklo, Gabon have been studied as natural analogues for spent nuclear fuel in a geological setting. The history of these reactors since they were formed is important for these studies. Geological and geochronological information on the Oklo reactors and the surrounding ore has been published /4-25/. The report describes in chronological order the processes that led to the uranium mineralization in Oklo, the nuclear reactions, and more recent influences on the reactors. A discussion of recent influences is concentrated around the intrusion of dolerite dykes, since this event had a powerful effect on the Oklo reactors. A study of migration of some elements that are natural analogues of radionuclides (REE, Th, U, Zr and Pb) in the far field of the Oklo reactors has also been published /4-26/.

SKB has supported a doctoral thesis within this area that will shortly be presented at Stockholm University.

E. Radiolysis

Mass balance experiments were carried out during the period in which the time dependence for the formation of hydrogen and oxygen was studied in a closed system with approximately 2 grams of fuel fragments and initially oxygen-free solutions. Oxygen and hydrogen in the gas phase were measured at different times with gas-phase electrode detectors. The aqueous phase was analyzed with respect to hydrogen peroxide (luminescence measurement) and uranium at the end of the experiments. The effects of different concentrations of carbonate and chloride ions in the solution were studied. Processing of data from analysis of the solutions indicates that the composition of the solution has a great influence on the uranium concentration.

In order to permit mass balance calculations in the leaching experiments, a new leaching system which permits simultaneous analysis of both gas phase and solution has been designed and tested. The results of time-resolved experiments show that the consumption of oxidants in distilled water takes place by reactions with the fuel surface and formation of an oxidized UO_{2+x} layer, and in carbonate solutions by the formation of soluble U(VI) carbonate complexes. Since analysis of the gas phase during the course of the experiment always entails a risk of leakage and loss of radiolysis gases, particularly as the concentrations grow higher with time, long-term experiments with fused glass vials have also been carried out. The results from the first vials, which were fused with a gas burner, have been published together with time-resolved experiments /4-27/.

Since small quantities of impurities can be introduced into the vials from the gas burner, a new series of vials have been fused by means of a small high-temperature oven. In the experimental series, the size of the fuel fragment (ratio of surface area to volume) and the composition of the solution (chloride and carbonate concentrations) are varied. The vials will be opened and analyzed for radiolysis products (H_2, O_2, H_2O_2) and dissolved fuel components (ICP-MS) after one or two years.

Alpha-doped uranium oxide has been synthesized in cooperation with ITU in Karlsruhe. This material resembles old fuel, where virtually only alpha radiation remains. The first results from leaching of UO_2 doped with alpha activities equivalent to 1,000 to 100,000-year-old fuel show that uranium dissolution was higher at the highest alpha activities, and that redox conditions have a great influence on the leaching of uranium dioxide with lower alpha activities /4-28/. Mass balance experiments similar to those carried out at Studsvik with spent fuel, but with alpha-doped uranium dioxide, are expected to permit a comparison of the effects of different types of radiolysis.

F. Fuel dissolution in the safety assessment – summary

Highly reducing conditions are expected to prevail in the deep repository. If a canister is damaged and water enters, the cast iron insert will probably corrode, producing hydrogen gas. The hydrogen gas pressure can be expected to be at least equal to the water pressure at repository level (around 5 MPa) for a very long time.

This means that the fuel dissolution rates that are observed in autoclave experiments in the presence of 5 MPa hydrogen today are deemed to be the most realistic for the deep repository, as long as hydrogen gas production continues. The results from the first experiment under such conditions point towards a very slow or non-existent dissolution.

When hydrogen can no longer be expected to be produced or remain in the canister, the experimental observations for anoxic conditions with flow reactors will be those that are judged to be able to provide an upper limit for the fuel dissolution rate. A thorough evaluation of experimental results is required prior to future safety assessments for the purpose of finding defensible descriptions of fuel dissolution under different conditions in the interior of the canister.

4.2.13 Dissolution of gap inventory

Conclusions in SR 97 and its review

Radionuclides in materials that have been segregated to the fuel-clad gap will quickly go into solution. The quantity of released activity is determined by the solubility and the availability of segregated material. The activity release from the gap is independent of the dissolution or alteration of the uranium dioxide in the fuel.

In SR 97 it was assumed that the gap and grain boundary inventories are released immediately when the fuel comes into contact with water. This is pessimistic, but was deemed to be fairly realistic on the timescales being considered.

In the authorities' opinion, there are several good reasons to apply the simplified assumption that release from both grain boundaries and metal parts takes place completely instantaneously.

Conclusions in RD&D 98 and its review

Not dealt with.

Newfound knowledge since RD&D 98 and SR 97

No new knowledge has been forthcoming.

Research 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.

Further research will, however, be done to improve the body of data, see section 4.1.8.

4.2.14 Speciation, colloid formation

Conclusions in SR 97 and its review

From the regulatory review of SR 97: "Even if the solubilities calculated in SR 97 are probably conservative, the authorities and several of SKI's consultants consider that the solubility calculation method can be improved. Certain premises for solubility calculations can be clearer in future analyses, such as handling of data, propagation of uncertainties and estimation of pore water compositions in the bentonite buffer. Furthermore, the authorities recommend that SKB evaluate what types of pore water composition can be expected inside a breached canister, since SKB anticipates a very limited exchange between a defective canister and the surrounding buffer. Processes that influence the pore water composition inside a damaged canister include fuel dissolution, radiolysis and corrosion of the iron insert."

Conclusions in RD&D 98 and its review

No questions for further research were identified in RD&D-Programme 98 or its review.

Newfound knowledge since RD&D 98 and SR 97

In the scenario with a damaged canister, redox conditions in the near field are significant. The actinides present in the fuel have, for example, a much lower solubility in the tetravalent state than in the pentavalent or hexavalent state. Radiolysis can influence the redox conditions, and the radiation at the surface of the fuel is intensive. As a result, the uranium oxide in the fuel may be oxidized at a higher valence and go into solution as uranyl ions. The actinides neptunium and plutonium may also be similarly affected and be oxidized to higher valence states, resulting in increased solubility.

At Studsvik it has been shown that uranyl ions are reduced on iron surfaces and precipitated as uranium dioxide /4-29/. The same applies to the mineral pyrite (FeS_2(s)) /4-30/ and other Fe(II) minerals that are present e.g. in the bentonite buffer or in rock /4-31/. It is thermodynamically possible to reduce Np(V) with UO_2(s), i.e. ΔG for the reaction:

$$UO_2(s) + 2NpO_2^{+} \rightarrow UO_2^{2+} + 2NpO_2(s)$$

is negative /4-32/, but there was no proof that this is kinetically possible. During the period it has been shown at Chalmers that Np(V) is reduced and precipitated at the uranium dioxide surface /4-33/. The same should apply to Pu(V or VI), which are less stable than Np(V). In this manner, the iron insert or the redox front (in bentonite or rock) could take care of released actinides and serve as a chemical barrier.

Another component in the near field is cast iron and its corrosion products. In the presence of groundwater, the iron surface is coated with iron corrosion products from reaction with water. A study of cast iron corrosion and its interaction with U(VI) in anoxic groundwater at 20ºC has been concluded /4-29/. After three months, a layer of a dark-green corrosion product was identified by X-ray diffraction as carbonate green rust, $Fe^{II}_4Fe^{III}_2(OH)_{12}CO_3$(s). In another three-month experiment with the same anoxic groundwaters, but initially containing 10 ppm U(VI), UO_2(s) and carbonate green rust were identified at the iron surface by means of X-ray diffraction. SEM-EDS-analyses showed that a thin (0.2 μm) uranium layer was deposited on top of the green rust layer, and some UO_2(s) crystals (3–5 μm) were observed at the surface.

At higher temperatures the stable iron corrosion product is magnetite /4-34/. The interaction between the synthetic magnetite surface and dissolved U(VI) species has been studied as a function of carbonate concentration, total uranium concentration and the surface area to volume ratio at neutral pHs /4-35/. The decrease in uranium concentration in solution is greater at low carbonate concentrations, but there is almost no effect at high carbonate concentrations due to the strong U(VI)-carbonate complex. A magnetite layer formed at the cast iron surface should have stronger reducing properties than a pure magnetite phase, since magnetite has semiconductor properties /4-32/. Preliminary data from experiments with cast iron coupons where magnetite has been identified by X-ray diffraction and XPS, show considerably higher reducing capacity for dissolved U(VI) /4-36/.

In recent years, studies have been conducted at FZK Karlsruhe in which relatively low solubilities of tetravalent actinide dioxides have been determined, e.g. Th(IV), at the pHs where colloid formation is detected in the solution /4-37, 4-38/. This means that the often-discussed actinide(IV) colloids cannot be formed from undersaturation, i.e. in connection with dissolution of spent fuel. They can be formed in the experimental vessel when a relatively concentrated alkali solution is added to a millimolar solution of actinide(IV), because strong oversaturation occurs where a drop of alkaline solution falls into an actinide(IV) solution.

Research programme

A long-term research programme will be started to investigate the solubility of tetravalent actinide oxides from undersaturation. At the same time, oxidation number speciation and characterization of solid phases will be carried out. Solubility calculations for SR 97 suggest that plutonium in certain groundwaters can exist as Pu(III). Since almost no data exist on solubility-limiting phases of Pu(III) in the literature, the solubility of PuO_2(s) in hydrogen-saturated solutions will be studied in the coming years. Studies will also be conducted to identify solubility-limiting phases of Pu(III) and their solubility.

Radiolysis experiments with Tc will be started in the CHEMLAB probe at Äspö during 2001 and are expected to continue until the end of 2002. These experiments simulate how radiolysis caused by radiation from the fuel influences the speciation of Tc(IV).

The same type of solubility calculations as those done for SR 97 are planned for future safety assessments, but with an updated database. For analysis of which chemical conditions can be expected in the canister's surroundings, see section 6.2.23.

4.2.15 Helium production

Conclusions in SR 97 and its review

Alpha particles (helium nuclei) from alpha decay in the fuel form gaseous helium after they have been slowed down in the fuel matrix. This leads to a pressure build-up inside the tube around a fuel rod with an intact cladding tube, which can in turn lead to mechanical tube rupture. If the cladding tubes are damaged, a negligible pressure increase arises in the canister cavity. The pressure increase over 100,000 years lies in the range 10 to 10 MPa, calculated on a void of 20 cm^3. If this overpressure were to lead to rupture of the cladding tubes, the pressure increase in the void in the canister would be on the order of 0.1 MPa, which is completely negligible.

The process was not commented on in the review of SR 97.

Conclusions in RD&D 98 and its review

Not dealt with.

Newfound knowledge since RD&D 98 and SR 97

No new knowledge has been forthcoming.

Research 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.

5 Canister

SKB's reference canister, see Figure 5-1, consists of an inner container of cast iron and a shell of copper. The cast iron insert provides mechanical stability and the copper shell protects against corrosion in the repository environment.

Preliminary design premises for the canister were presented in RD&D-Programme 98 and in /5-1/ and /5-2/. The design premises for the entire deep repository are currently being compiled. The final design premises for the canister may differ slightly from the preliminary ones and thereby lead to modifications of the canister design in some respect. An initial version of the design premises for the entire repository will be presented, see further section 14.2.1.

The reference canister is described in greater detail in Chapter 15, as is the development programme for its fabrication. Following is a brief summary of the most important properties, fabrication and testing methods.

The insert has channels in which the fuel assemblies are placed and is available in two versions: One for twelve BWR assemblies and one for four PWR assemblies. The canister weighs a total of around 25 tonnes filled with twelve BWR assemblies. A canister holds approximately two tonnes of fuel.

The fuel channels in the insert are fabricated in the form of an array (cassette) of square tubes. The walls and bottom of the insert are then manufactured by casting spheroidal graphite iron around the channel array.

50 mm copper

Estimated weight (kg):

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

Figure 5-1. *The copper shell is 50 mm thick and the canister has the shape of an approx. 4.8 metre tall cylinder with a diameter of 1.05 metres.*

The copper canister is fabricated either of drawn seamless tubes or by welding together two tube halves of rolled plate. A bottom is welded on by electron beam or friction stir welding in such a way that the weld can be examined by means of nondestructive testing.

After fuel has been placed in the canister, the insert is closed with a screwed-on lid. The copper shell's lid is then welded on, and leaktightness is tested by means of non-destructive testing.

Three methods are being developed for nondestructive testing. Radiography detects pore defects, ultrasonic testing also detects defects that do not occupy volume, such as incomplete penetration, and eddy-current testing reveals near-surface defects.

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 the welds are satisfied.

During the next few years, the repository design will be adapted to the conditions that prevail on the sites selected for site investigations. In RD&D-Programme 98, SKB gave notice that the thickness of the copper shell is one of the aspects that could be subject to such adaptation.

At the bottom is a requirement on a minimum thickness to ensure that the canister will remain intact for a long time in the face of whatever corrosion processes might be active. RD&D-Programme 98 stipulated that the copper thickness must be at least 15 mm in order to provide the required corrosion protection. Conservative estimates show that this thickness gives a safety factor of three against corrosion in a 100,000-year perspective.

To improve the design of the canister, the requirements on corrosion resistance, mechanical strength and methods for fabrication and handling must be satisfied. In RD&D-Programme 98, a copper thickness of 30 mm was given as a possible result when these factors are weighed together. Fabrication trials have therefore been conducted.

The work on canister development and design during the upcoming period will also include a thinner canister. The thickness of the insert will be increased accordingly. The advantages of a thinner copper shell are:

- The copper thickness that is needed to guarantee sufficient protection against corrosion is less than one centimetre /5-3/. A thicker copper shell contributes marginally to increased safety.
- The mechanical strength of the insert is improved.
- There is a higher degree of reduction in the fabrication of the copper tubes using the pertinent methods, providing better control over the microstructure of the material. One disadvantage is, however, that thinner walls lead to reduced mechanical stability of the copper cylinder. It has not been established whether this might complicate fabrication and handling.
- Sealing of the canister is simplified by thinner walls. Even though the techniques which SKB has developed for welding in thick copper – electron beam welding and friction stir welding – work well for 50 mm copper, the reliability and quality of the weld is expected to be even higher with thinner walls.

- Nondestructive testing with both ultrasonic and radiographic techniques is simplified by thinner materials. The gains for ultrasonic testing are more marginal with electron beam welding, since the microstructure of the weld dominates the background noise in the ultrasonic signal. For radiography, the detectability of discontinuities increases and it may be possible to reduce the x-ray energy and thereby simplify the radiography equipment and reduce the need for radiation shielding in the encapsulation plant.

5.1 Initial state of canister

5.1.1 Variables

Table 5-1 shows the set of variables that was used in SR 97 to describe the copper canister and the cast iron insert.

The initial state, i.e. the value these variables were assumed to have at the time of deposition, was described in section 6.3 of the Main Report, SR 97. The research programme around the initial state of the different variables in the canister is described in the following.

Table 5-1. 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	The 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

5.1.2 Geometry

In addition to the geometric shape of the canister, any initial defects in the seal are also included in the variable "canister geometry" in SR 97.

Conclusions in SR 97 and its review

SKB says that the requirement with regard to initial defects is that no more than 0.1 percent of the canisters may have defects that are greater than what is permitted by the acceptance criteria for nondestructive testing. In the authorities' opinion, however, it remains for SKB to demonstrate that this is an adequate and realistic goal. The authorities also observe that the acceptance criteria are not specified.

Kasam says that SKB should gather evidence for realistic assumptions regarding initial canister defects.

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Conclusions in RD&D 98 and its review

SKI does not believe that the claim that no more than 0.1 percent defective canisters can be achieved with available testing methods has been proved in RD&D-Programme 98. SKI is furthermore of the opinion that SKB must produce a derivation of acceptance criteria for permissible defects. It should be based on the safety assessment; consequences should be demonstrated for what happens if there are more or larger defects in both the canister material and the weld than those allowed by the acceptance criteria.

Research programme

The work on canister fabrication and testing is described in Chapter 15. During the upcoming period, this work will also extend to a canister with a 30 mm copper shell.

SKB has started a research programme for determining acceptance criteria in an initial phase, and in a later phase working towards qualification of equipment for nondestructive testing. The evaluation of welding trials at the Canister Laboratory will provide information on the types of defects, as well as the frequency of defects, to which electron beam welding and friction stir welding can give rise.

In future safety assessments, assumptions concerning initial defects should be more directly linked to the results of the development work at the Canister Laboratory and in connection with the design of fabrication methods. Derivation of input data to the safety assessment from testing statistics from nondestructive testing and the established acceptance criteria should be carried out jointly by representatives of safety assessment, research and technology development. Both frequencies and types of defects need to be treated.

5.1.3 Radiation intensity

Conclusions in SR 97 and RD&D 98 and their reviews

SKB's criterion is that the surface dose rate on the canister may not exceed 1 Gy/h. This criterion is met for both the canister described in SR 97 and for the possibly modified canister, where the lower radiation attenuation in the thinner copper shell is offset by greater attenuation in the thicker cast iron insert.

Newfound knowledge since SR 97 and RD&D 98

No new knowledge has been forthcoming.

Research 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.

5.1.4 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.

5.1.5 Mechanical stresses

Conclusions in SR 97 and its review

The residual stresses in the sealing weld that may remain after a very long time are low and not deemed to be of any importance for the life of the canister. No comments have been noted from the authorities.

Conclusions in RD&D 98 and its review

The question has not been dealt with.

Newfound knowledge since SR 97 and RD&D 98

No new knowledge has been forthcoming.

Research programme

The field is judged today not to require any further research, development or demonstration.

5.1.6 Material composition

Conclusions in SR 97 and its review

The insert consists of spheroidal graphite iron EN-GJS-400-15 and the copper shell of ASTM UNS C10100 with addition of 50 ppm phosphorus. No comments regarding the choice of material are noted from the authorities.

Conclusions in RD&D 98 and its review

SKI finds SKB's description of the choice of copper as a canister material both structured and well-supported. The reasons are described with reference to the requirements on both chemical resistance and mechanical strength and to a discussion of if and how other design requirements influence the choice of material.

There are, however, uncertainties surrounding the mechanisms whereby phosphorus influences the creep properties of the copper. This is further discussed in section 5.2.5.

Newfound knowledge since SR 97 and RD&D 98

New results concerning canister design are presented in Chapter 15.

Research programme

Future work concerning canister design is presented in Chapter 15.

5.2 Canister processes

5.2.1 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.

Mechanically, the insert and canister can be deformed 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 7.3.

The research programme for the different processes in the canister is dealt with in the following sections.

5.2.2 Radiation attenuation/heat generation

Conclusions in SR 97 and RD&D 98 and their reviews

SKB is of the opinion that sufficient understanding and data exist for the needs of the safety assessment.

The authorities concur with these conclusions. In the view of the authorities, the physical processes concerned here (radioactive decay and absorption of radiation) are among the best-understood of the processes that need to be considered in a safety assessment.

Newfound knowledge since SR 97 and RD&D 98

No new knowledge has been forthcoming.

Research 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.

5.2.3 Heat transport

Treatment of heat transport in the canister is integrated with treatment of the temperature evolution of the fuel, see section 4.1.4.

5.2.4 Deformation of cast iron insert

Conclusions in SR 97 and its review

The collapse pressure at isostatic load for the PWR and BWR variants of the canister insert had been calculated to be 114 MPa and 81 MPa, respectively, in SR 97. The calculations were carried out for a canister insert of homogeneous cast iron and are judged to be reliable under these conditions. The uncertainties with regard to the strength of the canister came from possible nonconformances, which may have been caused by undetected casting defects or deviations from tabulated values for the material properties of the spheroidal graphite iron.

The discussion of strength in connection with tectonic rock movements around the deposition hole in SR 97 is based on an earlier calculation with incomplete buffer data and for a weaker canister.

The authorities concur with the judgement of the need for calculations of the critical pressure with realistic material data.

Conclusions in RD&D 98 and its review

SKI is of the opinion that the premises for the strength analyses need to be further clarified. They are to some extent dependent on the properties of the bentonite and uncertainties in them, which is why an integration of the canister and buffer programmes is important. Furthermore, the strength analyses need to be updated with the results of investigations of the actual material properties of the fabricated canisters (defects, grain size, dimensions, etc.). Permissible values of stresses/strains and other loads on the design should be clearly specified and justified in the design requirements. Furthermore, safety factors for the individual load cases should be justified with reference to the consequences each individual load case might have on the integrity of the canister. These factors should then be specified in the design requirements. The load cases considered to be less probable and where safety factors are not applied, for example an expected ice load, should be analyzed and specially justified.

Newfound knowledge since SR 97 and RD&D 98

Experience from the trial fabrication of 17 inserts shows that deviations from tabulated values for cast iron quality can be considerable, and the high strength cited in SR 97 cannot always be achieved. Check calculations for a cast iron insert for a canister with a 30 mm copper shell show that high strength can be achieved with EN-GJS-400-15, but that variations in material data, above all the ductility, can be great /5-4/. This means that trial fabrication has not yet shown that canisters able to withstand loads of 80 MPa can always be fabricated. The strength specified in the design premises in RD&D-Programme 98, 45 MPa, can still be achieved however. The body of data from trial fabrication is still small, and it is possible that the castings will be able to achieve more uniform quality in the future.

Research programme

As new material data are compiled, renewed strength calculations will be performed. When material data from the castings are better known, damage resistance calculations will also be carried out to define permissible defects in the casting. SKB may consider trial fabrication in other cast alloys than EN-GJS-400-15 for the purpose of being able to specify a new cast alloy for the canister insert.

When the range of variation in material data becomes better known, along with the frequency and nature of possible defects in the casting, and methods for nondestructive testing of the cast iron have been developed, SKB will investigate which safety factors are to be applied in the design of the canister insert.

As more material data for the insert are gathered, new calculations will also be done of the canister's behaviour in connection with shear movements in the rock. In the earlier calculations from 1992, the rock movement of 0.1 metre during 30 days was simulated for a thinner canister than today's. The purpose of the new calculation is to try to simulate a more realistic timescale with the current canister. Before the calculations are begun, new material data for bentonite must also be gathered, see section 6.2.9.

5.2.5 Deformation of copper canister from external pressure

Conclusions in SR 97 and its review

In the model study of how stresses and strains in the copper canister are built up, SKB assumed that full pressure had developed after an hour. Since the pressure in the repository will probably be built up over the course of years, it is most likely that the copper shell will obtain support against the insert as a result of creep instead of plastic collapse, as the calculations assume. The authorities believe that it should be more clearly explained how this simplification influences how the results of the study can be applied in reality.

Conclusions in RD&D 98 and its review

The mechanism whereby phosphorus affects the creep properties of the material has not been clarified, and SKI believes that this question should be studied and that SKB should find out whether an improvement of the creep properties also includes the creep rupture limit.

Newfound knowledge since SR 97 and RD&D 98

As an initial step, a constitutive model /5-5/ for plastic deformation and creep in copper has been implemented in ABACUS /5-6/.

Modelling by means of *ab initio* calculations of the influence of phosphorus and sulphur on the mechanical properties of copper has been carried out during the past three years /5-7, 5-8, 5-9/. The conclusion from the modellings is that the binding energy of a sulphur-vacancy pair is great (–0.46 eV). The interaction sulphur-vacancy and sulphur-sulphur in the copper matrix appears to favour precipitation of copper sulphide, which is the most likely cause of embrittlement. The influence of phosphorus on embrittlement would be related to the fact that phosphorus competes with sulphur for vacancies and other lattice defects.

Experimental studies have also been conducted since 1998. Andersson et al. /5-10/ have conducted a study of the influence of phosphorus, sulphur and grain size on creep in pure copper. The results show that the favourable influence that phosphorus has on creep ductility is present at an admixture of 30 ppm and does not increase at higher contents.

Research programme

As creep data for canisters and lids becomes available, model calculations will be carried out for realistic load cases.

The theoretical studies will continue for at least the year to come, but are expected to be completed during the period.

A programme where the creep properties of base metals, such as under welds performed by electron beam and friction stir welding, are being studied started during the autumn of 2000 and will extend over a period of 2.5 years.

5.2.6 Thermal expansion (both cast iron insert and copper canister)

Conclusions in SR 97 and its review

The difference in coefficient of thermal expansion between cast iron and copper can lead to strains in the copper canister of less than 0.1 percent. Even if the strains are slightly greater at corners and other discontinuities, this is negligible from the strength viewpoint, since the creep ductility of copper with a grain size less than 800 μm is at least 20 percent /5-10/.

Conclusions in RD&D 98 and its review

Not dealt with in RD&D-Programme 98.

Newfound knowledge since SR 97 and RD&D 98

No new knowledge has been forthcoming.

Research 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.

5.2.7 Deformation from internal corrosion products

The consequences of deformation of the copper shell are in principle the same regardless of the causes. The same knowledge is needed for this process as for the processes discussed in sections 5.2.5 and 5.2.6.

Conclusions in SR 97 and its review

The build-up of corrosion products in the gap between the cast iron insert and the copper shell leads to a pressure build-up that causes strain and eventually rupture of the copper shell.

Conclusions in RD&D 98 and its review

Not dealt with in RD&D-Programme 98.

Newfound knowledge since SR 97 and RD&D 98

See section 5.2.5.

Research programme

See section 5.2.5.

5.2.8 Corrosion of cast iron insert

Conclusions in SR 97 and its review

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 with hydrogen gas and magnetite as corrosion products. Anaerobic corrosion of cast iron has been studied experimentally and the corrosion rate is very low, below one µm/y, even in the most aggressive water tested. The corrosion rate has proved to be independent of both the hydrogen gas pressure and the concentration of Fe^{2+} in the system. This suggests that the corrosion rate is most likely determined by the transport properties in the layer of corrosion products on the iron surface.

The authorities are of the opinion that corrosion of the cast iron insert needs to be studied further. SKI's consultants point out that other corrosion products than magnetite, such as siderite or pyrite, could be formed. Experiments where corrosion products are examined would be of value to verify SKB's opinion that the corrosion rate is controlled by the transport properties of the magnetite layer.

Conclusions in RD&D 98 and its review

Not dealt with in RD&D-Programme 98.

Newfound knowledge since SR 97 and RD&D 98

Some new knowledge of the speciation of iron corrosion products is described in section 4.2.14.

Research programme

Magnetite has been found to be a corrosion product in earlier studies /5-11/. This does not exclude the possibility that other corrosion products may form when iron corrodes anaerobically in other waters. As the water chemistry on SKB's candidate sites for the deep repository becomes better known, experimental studies of anaerobic iron corrosion will be conducted in the relevant groundwaters. The experimental studies will continue during the coming year mainly with systems where bentonite is present. Characterization of corrosion products will be included in all planned studies.

The results of the studies are being used in an integrated modelling of the evolution of a damaged canister, see section 5.2.16.

5.2.9 Galvanic corrosion

Conclusions in SR 97 and its review

If the penetrating water is oxygen-free, the galvanic coupling will not be able to increase the corrosion rate by more than what corresponds to the increased area for reduction of water contributed by the copper canister. This results in a possible doubling of the corrosion rate.

Conclusions in RD&D 98 and its review

SKI finds it urgent that SKB study the course of corrosion in the gap between the iron insert and the copper canister. Questions concerning galvanic corrosion should also be explored in this context, in the event metallic contact can occur in the gap. The work within this field should also be closely linked to the work with safety assessment models for the evolution of a damaged canister.

Newfound knowledge since SR 97 and RD&D 98

No new knowledge has been forthcoming.

Research programme

In 1994, SKB conducted an investigation of the effects of galvanic corrosion when the copper shell was breached /5-12/. An experimental study of galvanic corrosion in the iron/copper system under oxygen-free conditions is expected to start during 2001 and be finished by 2003.

5.2.10 Stress corrosion cracking of cast iron insert

Conclusions in SR 97 and its review

SKB deems the risks of stress corrosion cracking to be small, since only local areas in the insert have tensile stresses.

Conclusions in RD&D 98 and its review

Not dealt with in RD&D-Programme 98.

Newfound knowledge since SR 97 and RD&D 98

No new knowledge has been forthcoming.

Research 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.

5.2.11 Radiation effects

Conclusions in SR 97 and RD&D 98 and their reviews

The conclusion was drawn in SR 97 that the effects of neutron irradiation are insignificant and can be completely neglected in an assessment of the performance of the canister in the repository.

SKI points out that the influence of possible material embrittlement due to radiation on the mechanical strength of the canister should be further investigated (see also section 5.2.5).

Newfound knowledge since SR 97 and RD&D 98

A study of the risks of radiation embrittlement has been completed. The study shows that the risks are negligible and that the effect during 100,000 years is not measurable /5-13/.

Research 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.

5.2.12 Corrosion of copper canister

Conclusions in SR 97 and its review

Under currently known conditions at the deep repository level, the canister is expected to remain intact for a very long time, much longer than the 100,000 years stipulated in the design premises. Even though the uncertainties are great in judgements extending over long periods of time, it is highly likely that general corrosion or pitting could lead to canister penetration during the 100,000 years for which the canister has been designed.

The canister's resistance to corrosion is one of the most important questions in a safety assessment of the KBS-3 method. Among the corrosion issues that needs to be elucidated more thoroughly in future safety assessments is the influence of microbes. The authorities recommend that SKB summarize the state of knowledge when it comes to copper corrosion without further delay.

In the opinion of Kasam, on the basis of present-day knowledge of corrosion in pure copper in the environment in question, there is nothing to indicate that canister penetration would be expected. However, this remains to be verified for welded joints as well.

SKI and SSI also believe that the corrosion analysis for intact canisters needs to be better validated against experiments and other corrosion models. Furthermore, SKB should take the welds on the canisters into consideration in the corrosion analysis.

Conclusions in RD&D 98 and its review

In SKI's evaluation of RD&D-Programme 98, it is observed that the central factor within the corrosion area is how knowledge of the different corrosion processes is used in the assumptions and analyses upon which the thickness of the copper is based. In view of the work done in recent years and the work being pursued within SKB on corrosion, SKI considers that SKB should make a new compilation of how different types of corrosion comprise a basis for the design of the copper canister.

SKI is further of the opinion that SKB should await the results of these ongoing corrosion studies before changing the focus to research with an emphasis on corrosion in the initial phase, before reducing conditions prevail.

SKB believes that sulphate-reducing bacteria and their survival in the repository are one of the most important questions with respect to microbes, but that the results of ongoing experiments will determine what will be done from now on. SKI would like to urge SKB to continue the studies of the influence of microbes on the integrity of the canister.

SKI finds it laudable that SKB plans a programme for corrosion testing in a realistic environment in the Äspö HRL, but notes the lack of a more detailed description of the experiments.

Newfound knowledge since SR 97 and RD&D 98

Since RD&D-Programme 98, SKB has commissioned a compilation of thermodynamic data for copper /5-14/ and a compilation of present-day knowledge concerning copper corrosion /5-3/. The latter was done in cooperation with Posiva.

The studies of the prospects of microbial corrosion have continued since RD&D-Programme 98, and the results to date have been published in a doctoral thesis, as well as in articles in scientific journals /5-15, 5-16, 5-17/. So far, nothing has emerged to contradict SKB's earlier conclusions: sulphate-reducing bacteria are not active in compacted bentonite with the density of the bentonite in the deposition holes.

The corrosion of nearly 200-million-year-old native copper, formed and preserved in mudrocks in southern Devon in England, has been analyzed and the results of the investigations reported. The analyses show that even though copper is affected by corrosion, a large portion of the copper plates have been preserved in the water-saturated compact clay since at least the end of the Jurassic Period, i.e. for nearly 200 million years. Aside from the weathering that has taken place during exposure of the copper in modern time, the changes in the copper are of geological age and took place before the end of the Jurassic Period /5-18/. Further work is under way and will be completed during 2001.

The modelling of pitting on copper under mildly oxidizing conditions has continued since 1998 and a situation report has been published /5-19/. The most important conclusion is that there is a minimum potential below which pitting is not possible. The work is expected to be concluded during 2001 and no continuation is currently planned.

The sensitivity of copper to intergranular corrosion has been studied in an initial stage where no tendencies towards intergranular corrosion have been noted /5-20/.

Research programme

The studies of microbial corrosion will continue during the next three years. They will include laboratory experiments as well as field studies in the Äspö HRL. The question is the same as before: Can naturally occurring populations of sulphate-reducing bacteria in the groundwater and in the bentonite survive under repository conditions and reduce sulphate to sulphide in such quantities that it can threaten the canister's integrity? The programme will start in 2001 and be concluded in 2004.

Field experiments at the Äspö HRL involving exposure of copper for several years to both the atmosphere in the underground laboratory and different groundwaters have been started and will proceed during the coming three-year period. Moreover, copper corrosion in compacted bentonite will be studied in-situ in the Äspö HRL. In these experiments, possible local corrosion will be followed by monitoring and analyzing the electrochemical noise from the copper specimens. These field experiments will be augmented by laboratory studies of anaerobic copper corrosion in waters with high salinities.

The evolution of redox conditions in the bentonite is of importance for the form and development of the corrosion attacks on the copper. Experiments will be conducted to determine the timescale for the redox evolution in the bentonite and to clarify the mechanisms behind oxygen consumption in pure bentonite and in the copper/bentonite system.

The studies of the sensitivity of copper to intergranular corrosion will continue during the next few years and will then also include weld metal.

5.2.13 Stress corrosion cracking of copper canister

Conclusions in SR 97 and its review

In SR 97, SKB observes that there is no evidence that SCC could occur in the repository environment. Even though SCC has not been observed in the repository environment, the possibility cannot be entirely ruled out with present-day knowledge. There are no criteria for under what conditions SCC occurs or under what conditions SCC is impossible.

Tensile stresses in the copper canister are a necessary prerequisite, and since the canister is under external pressure it is not likely that SCC could lead to canister penetration. This would probably require tensile stresses through the whole canister wall, and such a situation is not deemed to be possible under normal repository conditions.

Simple strength calculations performed by SKI show that under normal conditions, parts of the copper canister will be under tensile stresses even though compressive stresses exist in most of the canister surface. The authorities are therefore of the opinion that SKB needs to show that conditions are such that SCC cannot occur in the copper shell, or alternatively that SKB takes into account the possible effects of SCC in its analysis of the life of the canister.

Conclusions in RD&D 98 and its review

Scoping calculations performed by SKI for e.g. the canister lid show that the lid will be deformed plastically at the load that is expected to exist in the final repository. As a result of this deformation, certain parts of the canister and the lid will be subjected to tensile stresses. SKI therefore believes that there is a risk of SCC at these surfaces, and that SKB needs to show that the risk of SCC is negligible in the environment in which the canister will find itself.

Newfound knowledge since SR 97 and RD&D 98

An investigation of the risks of SCC under reducing conditions in the presence of ammonium ions has been carried out in cooperation with Posiva. The results do not indicate that there are any risks of SCC under these conditions /5-21/.

The results of an investigation of crack growth in connection with SCC have been reported. The results so far suggest that there is a threshold value for the stress intensity in order for stress corrosion cracks to grow, but that additional data is needed to provide greater credibility for this /5-22/.

Research programme

The research on stress corrosion cracking of copper in the repository environment will continue with both laboratory experiments and field experiments in the Äspö HRL. At present a pilot study is in progress of the prospects of studying SCC with measurements of electrochemical noise in cooperation with Canada. If the results are positive, the method will be installed and used in the Äspö HRL for studying in-situ the prospects of stress corrosion cracking of copper in a realistic repository environment. These investigations will be supplemented by calculations of the states of stress in the canister at different times after deposition (see section 5.2.5).

The investigations of crack growth due to SCC will also continue during the period to improve the body of experimental data for judging the risks of SCC in the repository environment.

5.2.14 Grain growth in copper

Conclusions in SR 97 and its review

SR 97 quotes Pettersson /5-23/, who drew the conclusion that grain growth in the copper canister will be negligible.

The process was not commented on in the review of SR 97.

Conclusions in RD&D 98 and its review

SKI notes that stress-relief annealing is specified for the rolled tubes. In view of the low and variable stresses that occur, SKB should ask itself if this can lead to critical grain growth.

Newfound knowledge since SR 97 and RD&D 98

No new knowledge has been forthcoming.

Research 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.

5.2.15 Radionuclide transport

Dealt with in section 7.3, which concerns radionuclide transport in the fuel/canister cavity.

5.2.16 Integrated studies – evolution of damaged canister

Conclusions in SR 97 and its review

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 transport of water or water vapour by diffusion 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 completely cease. This will lead to a slow accumulation of corrosion products and a pressure build-up inside the copper canister, which will eventually cause the copper canister to undergo local deformation and ultimately rupture.

Thus, several of the above-described processes in the canister and its cavity affect the course of events and need to be modelled in an integrated fashion to provide a picture of the evolution of a damaged canister. Two studies /5-24, 5-25/ were conducted in SR 97. The conclusions from these studies can be summarized as follows: a small hole in the canister will remain small for a very long time, 100,000 years or more. Eventually, however, the breach will widen and the copper shell will rupture.

In the opinion of the authorities, certain assumptions concerning mechanical effects on the canister can be questioned, for example that the copper shell ruptures when the deformation exceeds the rupture strain of the copper, which is 29 percent /5-24/. Since the process is very slow, creep should instead be the design-basis process. This would mean that the canister can only withstand a creep rupture strain that is expected to be considerably lower than 29 percent. In the authorities' opinion, SKB has not yet shown that the proposed model actually predicts the probable evolution of a defective canister and is not merely an idealized calculation case. SKI deems the difficulty to lie in the fact that SKB's model assumes coupled effects of a number of processes of widely differing character (corrosion, gas transport, groundwater flow, mechanical load). Such a strongly coupled system may be sensitive to small variations in initial conditions, boundary conditions, rate constants and the influence of secondary processes neglected in SKB's analysis.

Newfound knowledge since SR 97 and RD&D 98

Experimental investigations of the mechanical properties of oxides formed on iron and steel under anaerobic conditions have been under way since 1988. A first stage has now been completed and the results published /5-26/. The report describes a "mechanical stress cell" that has been designed to measure the expansion that could be caused by anaerobic corrosion of steel under external pressure. The apparatus consists of a stack of copper/steel plates (200) that are submerged in simulated oxygen-free water. A system of levers amplifies and records changes in the length of the copper/steel stack. No expansion could be observed after more than one years' exposure. The smallest detectable change corresponded to a 1 nm layer of corrosion products per steel plate. In a separate experiment, the modulus of elasticity of corrosion products on iron and steel was estimated to lie in the range $4 \cdot 10^4$ to $2 \cdot 10^6$ Pa /5-26/.

Research programme

The experimental investigations described above will continue for the next few years. The corrosion products will be characterized in a first stage. New experiments will then be started with exposures in a more aggressive environment, where the corrosion rate for iron is expected to be a couple of orders of magnitude greater than the one now being studied. When necessary data have been gathered, new modellings of the kind reported in /5-24/ and /5-25/ will be carried out.

6 Buffer

The buffer is supposed to protect the canister mechanically in the event of decimetre-sized rock movements and prevent groundwater and corrosive substances from reaching the canister. It is also supposed to help retard the release of radionuclides if the canister should be damaged. A number of requirements were stipulated on the buffer material in RD&D-Programme 98:

- The buffer's hydraulic conductivity shall be so low that any transport of corrodants and radionuclides takes place solely by diffusion.
- The buffer's gas permeability shall 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 persistent gas-permeable channels or cavities in the buffer.
- The buffer's swelling pressure shall 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 shall be great enough to absorb rock movements without the canisters being damaged, but small enough to hold the canisters in position.
- Colloidal particles shall be filtered by the buffer.
- The buffer's heat conduction properties shall be such that the heat from the canisters does not lead to unacceptable physical and chemical changes in the buffer.
- The buffer shall not contain anything that has a negative effect on the performance of the other barriers.

SKB has chosen a natural Na bentonite of the Wyoming type as a reference material for the buffer. MX-80 is a natural clay from Wyoming or South Dakota in the USA. The designation MX-80 is a trade name that specifies a given grade and grain size of dried and ground bentonite. Based on the results of investigations, SKB has drawn the conclusion that a buffer consisting of MX-80 should have a density of 1,900–2,100 kg/m^3 after water saturation.

SKB has not made a final choice of buffer material, however. There may be other materials that are as suitable as MX-80, see further section 6.1.2.

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 an MX-80 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.

MX-80 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).

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 therefore be avoided in such a situation.

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 capacity 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.

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.

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.

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 increased solubility of the smectite 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 100ºC.

Fabrication of buffer blocks is described in Chapter 14.5.2. Fabrication aspects are discussed in the following insofar as they have a bearing on the research programme presented.

6.1 Initial state of the buffer

6.1.1 Variables

In SR 97, the buffer was described by a set of variables, see Table 6-1.

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. The research programme around the initial state for the different variables in the buffer is described in the following.

Table 6-1. Variables for the buffer and the backfill.

Variable	Definition
Geometry	Geometric dimensions for 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.
Smectite content	Smectite 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 of 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.
Smectite	Chemical composition of the smectite (including any radionuclides) in time and space composition in buffer and backfill. This variable also includes material sorbed to the smectite surface.
Pore water	Composition of the pore water (including any radionuclides and dissolved gases) in time composition and space in buffer and backfill.
Impurity	Levels of impurities in time and space in buffer and backfill. Impurities also include levels other minerals than smectite. In backfill, crushed rock is an impurity.

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6.1.2 Geometry

Conclusions in SR 97 and its review

The geometry of the buffer is determined by the dimensions of the canister and the thickness of the buffer material that are required to obtain the desired function. In SR 97, 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. Nothing to question these dimensions emerged in either SR 97 or its review.

Conclusions in RD&D 98 and its review

It is pointed out in RD&D-Programme 98 that clays with a lower smectite content than MX-80 could also meet the conductivity requirements made on the buffer. A choice of another clay might lead to an increase in the dimensions of the buffer. Studies of alternative materials were planned in RD&D-Programme 98.

Newfound knowledge since RD&D 98 and SR 97

A part of the study of alternative buffer materials is reported in /6-1/. There the conclusion is drawn that several mineral types are serviceable, but montmorillonite-rich clay is judged to be superior. Other candidates besides Wyoming bentonite (e.g. MX-80) are converted Ca-bentonites and saponite. The continuation of the study is described below.

Research programme

SKB's reference material MX-80 has been studied from different aspects for a long time by a number of organizations. The specific physical and chemical properties of the material with respect to buffer function can be considered to be well known.

It is not realistic to study alternative materials to the same extent as MX-80. Research efforts during the coming period will therefore be focused on correlating desirable physical and chemical properties to fundamental mineralogical properties, e.g. relationships between swelling pressure and the clay mineral's ion exchange capacity, type of ion (sodium or calcium) and charge distribution. The purpose of the research is to describe crucial relationships so well that a relatively limited mineralogical characterization can provide sufficient information regarding the suitability of a material as a buffer material, and regarding what possible modifications of buffer dimensions need to be made in order for the material to be used. Looking ahead, the work can be expected to lead to a basic target specification, which can be used as an initial selection criterion in choosing and purchasing buffer material. Such a specification must then contain requirements that guarantee both fundamental physical and chemical properties and the long-term stability of these properties.

6.1.3 Pore geometry

Conclusions in SR 97 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.

Conclusions in RD&D 98 and its review

In RD&D-Programme 98, it is pointed out that clays with a lower smectite content 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/porosity.

Newfound knowledge since RD&D 98 and SR 97

No new knowledge has been forthcoming.

Research programme

Physical and chemical properties of alternative buffer materials will be correlated to fundamental mineralogical data, see section 6.1.2.

6.1.4 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 to be about 2 mGy/h. The calculations are based on the same assumptions as the material in section 6.2.2.

6.1.5 Temperature

Buffer and backfill are at ambient temperature at deposition. This varies with repository site and disposal depth and is approximately 10–15ºC. The temperature is dependent to some extent on the handling sequence, where the buffer blocks have been stored, heat from the deposition machine, etc. An uncertainty of around 5ºC is reasonable. This was deemed in SR 97 to be of no consequence for the thermal evolution in the repository.

Determination of the initial buffer temperature is of trivial importance, in contrast to the heat transport after deposition, see section 6.2.12.

6.1.6 Smectite content

Conclusions in SR 97 and its review

MX-80 is a commercial product with a given composition. In SR 97 it is assumed that the required smectite content is 75 percent. The delivered product will be quality-tested before being taken to the repository.

Conclusions in RD&D 98 and its review

In RD&D-Programme 98, it is pointed out that clays with a lower smectite content than MX-80 could also satisfy the conductivity requirements that are made on the buffer. SKI called for studies of other materials than MX-80.

Newfound knowledge since RD&D 98 and SR 97

Some of the requested studies have been reported in /6-1/, see further section 6.1.2.

Research programme

The characterizations of MX-80 that have been published are relatively old. A new physical and chemical characterization will therefore be carried out during the upcoming RD&D period.

Regarding alternative materials, see section 6.1.2.

6.1.7 Water content

Conclusions in SR 97 and its review

The compacted bentonite blocks have an initial degree of water saturation of 85 percent, while the pellets in the buffer-rock gaps have 50 percent. The buffer-canister and buffer-rock gaps may be filled with water.

Conclusions in RD&D 98 and its review

Not dealt with.

Newfound knowledge since RD&D 98 and SR 97

Technology has been developed for full-scale uniaxial pressing of blocks, and blocks have been successfully produced in the Äspö HRL. Blocks with a height of 50 cm and a diameter of 165 cm for placement above and below the canister and rings with the same height and outside diameter and with an inside diameter of 107 cm have been pressed to both a natural water ratio of 10 percent and an elevated water ratio of 17 percent. The press pressure can be adjusted so that a mean density in the deposition hole of 2,000 kg/m^3 after full water saturation is obtained if pellets are placed in the block-rock gap. SKB does not, however, intend to commit itself yet to filling the gap with pellets and water. The requirement is that the buffer shall achieve a specified density. Approximately 100 blocks and rings with a water ratio of 17 percent have been fabricated for the full-scale experiments in Äspö.

Research 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 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 aimed at 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.

6.1.8 Gas contents

The bentonite blocks have a degree of saturation of 85 percent, which means that 85 percent of the pore volume is filled with water and the remainder with air. The outer gap is filled with bentonite pellets and water. 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.

6.1.9 Hydrovariables

The hydrovariables are water flow, water pressure, gas flow and gas pressure. Initially it is relevant to describe gas and water pressures. 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.

6.1.10 Swelling pressure

The swelling pressure develops as the buffer/backfill approaches full water saturation, see section 6.2.7. Initially there is no swelling pressure.

6.1.11 Smectite composition

The reference material for the buffer is MX-80 bentonite, which consists of approximately 75 percent Na-montmorillonite. Otherwise, what is said about the smectite content in section 6.1.6 is also applicable to the smectite composition.

6.1.12 Pore water composition

Conclusions in SR 97 and its review

Bentonite in nature contains water. The composition of the clay's pore water depends on the geochemical history of the site and the minerals which the clay contains. After quarrying, 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 85 percent in the finished blocks.

The composition of the pore water has never been analyzed, either in the natural clay or in the finished blocks, but the variations are expected to be small since the material is relatively homogeneous.

The above applies to the initial water composition. The long-term chemical evolution is handled in section 6.2.23.

Conclusions in RD&D 98 and its review

Not dealt with.

Newfound knowledge since RD&D 98 and SR 97

No new knowledge has been forthcoming.

Research 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.

For the long-term evolution, see section 6.2.23.

6.1.13 Impurity levels

Conclusions in SR 97 and its review

Bentonite is a naturally occurring material with natural variations in composition. MX-80 is a commercial product that is blended to meet given specifications. The uncertainties in impurity levels are therefore expected to be small and of no importance for the function of the buffer.

A related question concerns quantities and types of materials left behind in deposition holes and tunnels. This is described in section 14.5.7.

The authorities consider it necessary to shed light on possible negative effects due to the presence of forgotten materials. This is dealt with in section 7.2.16.

Conclusions in RD&D 98 and its review

Not dealt with.

Newfound knowledge since RD&D 98 and SR 97

The results of two one-year tests conducted within the framework of the LOT project at the Äspö HRL have been reported, see section 6.2.23.

Research programme

Regarding characterization of MX-80 bentonite, see sections 6.1.2 and 6.2.23.

6.2 Processes in buffer

6.2.1 Overview of processes

On emplacement, the buffer comes into contact with the hot canister surface, the heat 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 pore water in particular can affect the physical properties of the buffer. By means of ion exchange and sorption, the buffer's original content of ions on the surfaces of the clay particles can be replaced by other ionic species. Chemical smectite degradation can occur, mainly in the form of illitization. Impurities 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 6.2.12 and 6.2.23, which deal with the evolution of the buffer under unsaturated and saturated conditions, respectively.

6.2.2 Radiation attenuation/heat generation

Conclusions in SR 97 and its review

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 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 was deemed in SR 97 to be good enough for the needs of the safety assessment.

Conclusions in RD&D 98 and its review

Not dealt with.

Newfound knowledge since RD&D 98 and SR 97

No new knowledge has been forthcoming.

Research 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.

6.2.3 Heat transport

Conclusions in SR 97 and its review

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.

The heat transfer between the canister and the buffer is also more complicated, since there is a water- and gas-filled gap in this boundary layer 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 the calculations of the heat transport in the rock, SKB uses a model with simplified assumptions concerning 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.

Conclusions in RD&D 98 and its review

SKI was of the opinion that existing knowledge of unsaturated buffer is not of the same class as for saturated buffer. SKI also wanted the THM modelling to be supplemented with simpler calculations for estimating the reasonableness of the results.

Newfound knowledge since RD&D 98 and SR 97

For unsaturated conditions, see 6.2.12.

For saturated conditions, see 6.2.23.

Research programme

For unsaturated conditions, see 6.2.12.

For saturated conditions, see 6.2.23.

6.2.4 Water transport under unsaturated conditions

Conclusions in SR 97 and its review

SKB judges the quality of input data and models used in the calculations of water transport under unsaturated conditions to be good enough for conducting an adequate analysis of the hydraulic evolution in the base scenario. The precision in the calculations would increase with better knowledge of the hydraulic properties around individual deposition holes, which cannot be expected to be obtained until the actual construction of the repository.

The following is noted from the review of SR 97:

> "In the authorities' opinion, the Process Report contains a good survey of the processes that affect resaturation and water transport. However, the authorities question SKB's statement that the present-day understanding of the bentonite buffer water saturation process is adequate for the needs of the safety assessment. SKB itself states that the theoretical knowledge base for water saturation is not comprehensive. Nor is there any definitive experimental evidence to support SKB's assumptions concerning the saturation process in the bentonite buffer."
>
> "The authorities maintain that the single decisive factor for achieving a rapid and homogeneous saturation of the bentonite in the deposition holes is an evenly distributed availability of water in the deposition hole walls, and this has not been demonstrated in SR 97. If this cannot be achieved, the swelling of the bentonite due to uneven water uptake will probably lead to an uneven loading of the canister in the deposition hole. This can in turn affect the mechanical integrity of the copper canister."
>
> "The fact that there is still a great need for better knowledge concerning the resaturation of bentonite clay, for other countries' final disposal concepts as well, is underscored by the extensive research being conducted within the framework of several large international projects. SKB is itself conducting an extensive R&D programme at the Äspö Hard Rock Laboratory, which is expected to provide new insights over the next few decades."

Conclusions in RD&D 98 and its review

Not dealt with.

Newfound knowledge since RD&D 98 and SR 97

The suction potential or negative pore water pressure of bentonite is the primary driving force for water saturation. It is mainly dependent on the water ratio in the bentonite. Laboratory experiments show that the negative pore water pressure is dependent on the external pressure and declines with increasing swelling pressure or applied external pressure. This means that the negative pore water pressure decreases with increasing water saturation in a volume-limited system in a way that deviates from what has previously been assumed. This can influence the final phase of the water saturation process. The phenomenon is being studied in an ongoing doctoral project, see further the research programme for laboratory experiments in section 6.2.12.

The effects of uneven wetting on the canister have been studied since SR 97 by means of scoping calculations and finite element calculations of extreme cases /6-2/. The conclusion of the calculations is that the mechanical integrity of the canister is not affected by uneven wetting. Since the bentonite blocks are compressed at an elevated water ratio of 17 percent, and since the outer gap with pellets is filled with water, the initial water quantity corresponds to a mean water saturation in the buffer of more than 85 percent. As a result of this, along with the relatively low stiffness of the bentonite, the effects that have been analyzed by calculation of extreme cases in accordance with the finite element method are considerably milder than the effects calculated by means of scoping calculations.

Research programme

Several research programmes are being conducted in order to obtain a better understanding of the processes and improve the models that describe resaturation.

- THM model studies, unsaturated conditions.
- Full-scale experiments in the Äspö HRL.
- Supportive laboratory experiments for modelling of the full-scale experiments.
- Laboratory experiments on unsaturated bentonite to obtain a better understanding of hydromechanical processes.
- The full-scale experiment FEBEX II in the Grimsel Laboratory in Switzerland.

The programmes are described in section 6.2.12.

6.2.5 Water transport under saturated conditions

Conclusions in SR 97 and its review

Water transport in a saturated buffer is a complex interplay between a number of subprocesses 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 mentioned in SR 97 concern the effect of transformations, which are expected to result in higher hydraulic conductivity. The effects of very high salinities have also been inadequately investigated, see section 6.2.15.

Conclusions in RD&D 98 and its review

The process is not dealt with explicitly. However, SKI would like to see more experiments concerned with the THM properties of the saturated buffer, see section 6.2.23.

Newfound knowledge since RD&D 98 and SR 97

A study of the risk of liquefaction of the buffer and backfill as a result of earthquakes has been concluded /6-3/. The conclusions of the study are based on empirical relationships between distance to quake and documented cases of liquefaction, on experimental data from JNC, Japan, and on scoping analysis of the sensitivity of the barrier materials to liquefaction. The conclusion is that there is no risk of liquefaction at the densities that will exist in buffer and backfill in the KBS-3 concept.

See also section 6.2.23 for integrated field studies.

Research programme

See section 6.2.23 with regard to the THM model for saturated conditions.

As far as liquefaction is concerned, documented effects of above all pore pressure transients on the water-rock system will be inventoried. This part of the programme will thus be a continuation, or expansion, of the previous study /6-3/ regarding the risk of liquefaction of buffer and backfill.

For integrated field studies, see section 6.2.23.

6.2.6 Gas transport/dissolution

Conclusions in SR 97 and its review

Transport of gas in the buffer can be problematic above all if large quantities of hydrogen gas were to be produced by iron corrosion inside a damaged canister.

A remaining uncertainty in the understanding of gas transport in the buffer material concerns the number, size and spatial arrangement of the gas-bearing fractures as well as the volume behaviour of the clay during gas injection. The experiments done to date indicate that the clay must expand (grow in volume) during gas transport and that changes in gas content must be balanced by an increased total volume.

Furthermore, uncertainties remain concerning at what pressure the gas stops flowing and how this is dependent on the swelling pressure.

Conclusions in RD&D 98 and its review

Remaining uncertainties concern how the boundary conditions influence the gas transport and how the results from gas transport experiments are to be used for the conditions that prevail in a repository.

Newfound knowledge since RD&D 98 and SR 97

The series of experiments that are under way with gas injections through MX-80 have shown that the previous conclusion that the buffer opens when the gas pressure exceeds the sum of the hydrostatic pressure and the swelling pressure does not apply for all types of boundary conditions. It has also been found that the gas breakthrough can be rate-dependent, i.e. dependent on how quickly the pressure is built up.

Research programme

The conclusions drawn in RD&D-Programme 98 remain valid. Our understanding of gas transport in bentonite is inadequate and the area is therefore prioritized. Both model development and the experimental programme will continue. The purpose of ongoing experiments is to answer the questions regarding opening and shut-in pressures as well as what types of transport pathways the gas forms. On the other hand, there will not be time for any experiments on repository scale during the ensuing three-year period, which means that scale dependence will be a remaining uncertainty. The model development project GAMBIT will continue, and the third phase started during 2001. The purpose of this phase is to develop a model that can describe gas on a macroscopic scale, i.e. calculate gas transport in a repository.

6.2.7 Swelling

Conclusions in SR 97 and its review

Water uptake in the buffer and backfill after deposition will lead to swelling. In the buffer, heating will furthermore lead to thermal expansion of the pore water. 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 push up into 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 also lead to changes in the swelling properties, see sections 6.2.16–6.2.17 and 6.2.23.

Swelling is strongly coupled to water transport under unsaturated conditions. It is described with the integrated THM model, see section 6.2.12.

Conclusions in RD&D 98 and its review

See section 6.2.12.

Newfound knowledge since RD&D 98 and SR 97

The model that has been proposed for volume creep has been verified, see section 6.2.8.

The models for coupled THM processes under unsaturated conditions have been tested, see section 6.2.12.

The importance of the salinity for the swelling pressure has been studied for MX-80, see section 6.2.15.

Research programme

The THM processes under unsaturated conditions will be studied both in the field and in the laboratory, see section 6.2.12.

A programme for inventory, evaluation and use of alternative calculation models will be implemented, see section 6.2.12.

Swelling pressure in compacted bentonite at high salinity is being investigated in an ongoing joint project with Posiva, see section 6.2.15.

The research programme for the model for THM development in saturated buffer is reported in section 6.2.23.

6.2.8 Mechanical interaction buffer/backfill

Conclusions in SR 97 and its review

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. The mechanisms for this interaction are well-known and are partially confirmed in Stripa BMT /6-4/. The mechanical interaction between buffer and backfill is coupled to the water transport under unsaturated conditions, section 6.2.12. The uncertainty in the process mainly concerns the achieved density of the backfill.

Conclusions in RD&D 98 and its review

SKI calls for greater knowledge of the buffer under unsaturated conditions, and that the THM modelling be augmented with simple reasonableness calculations, see section 6.2.12.

Newfound knowledge since RD&D 98 and SR 97

In the ongoing research, compression and swelling experiments with water-saturated bentonite are being conducted with a long duration, in part to improve the model of the mechanical behaviour of the water-saturated bentonite, and in part to verify and improve the creep models. The model that has been proposed for volume creep has been verified /6-5/ and new experiments are aimed at providing a better body of data for selection of parameters.

Research programme

See section 6.2.23, the research programme for the model for THM evolution in saturated buffer.

6.2.9 Mechanical interaction buffer/canister

Conclusions in SR 97 and its review

Mechanical interaction between buffer and canister arises from the buffer through the clay matrix, which generates both compressive stresses and shear stresses, through the pore water, which generates only compressive stresses, and through 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 affects the buffer, while the influence of the weight of the buffer on the canister is negligible. 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.

Mechanical interaction between buffer and canister is coupled to water transport under unsaturated conditions, section 6.2.12.

Conclusions in RD&D 98 and its review

SKI calls for greater knowledge of the buffer under unsaturated conditions, and that the THM modelling be augmented with simple reasonableness calculations, see section 6.2.12.

Newfound knowledge since RD&D 98 and SR 97

The settlement of the canister through creep deformations in the buffer has been calculated /6-6/. The total settlement is around a centimetre in 100,000 to a million years, see also section 6.2.8.

Research programme

Dealt with in section 6.2.12 (canister movements during the saturation process) and 6.2.23 (model studies of long-term compression of the buffer). A small series of experiments will also be conducted during the coming three-year period to test the properties of the bentonite in connection with rapid pressure increases or decreases caused by e.g. an earthquake.

6.2.10 Mechanical interaction buffer/near-field rock

Conclusions in SR 97 and its review

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 8.2.9.

Conclusions in RD&D 98 and its review

Not dealt with.

Newfound knowledge since RD&D 98 and SR 97

No new knowledge has been forthcoming.

Research programme

Dealt with in sections 6.2.12 (compressive stresses on the rock) and 6.2.23 (mechanical modelling of effects of rock movements).

6.2.11 Thermal expansion

Conclusions in SR 97 and its review

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 6.2.12.

Conclusions in RD&D 98 and its review

Not dealt with.

Newfound knowledge since RD&D 98 and SR 97

No new knowledge has been forthcoming.

Research programme

Thermal expansion is included in the coupled THM model, see section 6.2.12.

6.2.12 Integrated studies – THM evolution in unsaturated buffer

Conclusions in SR 97 and its review

In the calculations of the heat transport in the rock, SKB uses a model with simplified assumptions concerning 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.

Conclusions in RD&D 98 and its review

SKI was of the opinion that existing knowledge of unsaturated buffer is not of the same class as for saturated buffer. SKI also wanted the THM modelling to be supplemented with simpler calculations for estimating the reasonableness of the results.

Newfound knowledge since RD&D 98 and SR 97

Model studies

The models for calculation of coupled THM processes in water-unsaturated buffer have been refined and tested in some international projects (DECOVALEX II /6-7/ and Catsius Clay /6-8/), where calculated temperature, stress, deformation and water transport have been compared with measured results in both laboratory and field experiments. These projects have succeeded in improving our understanding of the processes and the reliability of the models. One conclusion is that thermal and, to some extent, hydraulic processes can be modelled with good reliability, but that improved models for mechanical and hydraulic processes are in some cases desirable.

Research programme

Model studies

The calculation models used so far for analysis of coupled THM processes in water-unsaturated bentonite have proved to be inadequate on several points. 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 is possible to simulate the effects of temperature-driven vapour transport fairly well with the calculation models that are currently used without explicitly modelling the vapour phase. Effects of other gases cannot, however, be taken into account at all.

A programme for inventory, evaluation and use of alternative calculation models has therefore been started and will continue during the next few years. The main codes that will be used are COMPASS /6-9/, which was developed at the University of Wales in Cardiff, and CODE_BRIGHT /6-10/, 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.

The overarching goal is to be able to describe the process of water saturation of the buffer in a physically correct manner with regard to heat transport, influence of losses of water vapour, build-up of swelling pressure, time for water saturation and hydro-mechanical evolution in the canister-buffer gap, as well as to be able to determine the importance of the different factors that determine the timescale for the water saturation process.

The importance of the microstructure will be evaluated independently of the THM model. The purpose is to make a synthesis of published models and relate them conceptually and quantitatively to all important practical properties of the buffer.

Field studies

Experimental studies of THM processes under unsaturated conditions will be conducted both in the field and in the laboratory. Two full-scale experiments have been started in the Äspö HRL (the Retrieval Experiment and the Prototype Repository).

The Retrieval Experiment is described in section 14.5.6. Its true purpose is to test a method for retrieving canisters after the bentonite has become water-saturated, but the experiment can be used to study THM processes before the canister is retrieved. Canister and buffer with a composition identical to that in the Prototype Repository have been installed in a simulated deposition hole and the hole plugged with concrete anchored with nine braces. The bentonite and the canister surface are provided with sensors to measure temperature, total pressure, water pressure and relative humidity in points that are identical to intended measurement points in the Prototype Repository. What distinguishes the experiment from the Prototype Repository is that the walls of the deposition holes have been fitted with filters for artificial wetting and that the backfill has been replaced with a plug. The buffer's hydraulic and mechanical boundary conditions are determined by measurements.

Since the complex hydraulic interaction between rock and buffer has been eliminated in the retrieval experiment with filters, and similarly the mechanically complex interaction between buffer and backfill has been eliminated with the plug, the experiment is well-suited to evaluation and calibration of the THM models for the buffer. Since the retrieval technique destroys the buffer, sampling in the buffer during some stage is being considered.

The Prototype Repository is described in section 12.3.2. It will consist of an inner section with four holes that will be excavated after about 20 years and an outer section with two holes that will be excavated after about five years. The tunnel is backfilled with a mixture of bentonite and crushed rock, and the sections are sealed off with two plugs. The THM processes are studied in a similar way as for the Retrieval Experiment. Since the two sections are excavated at different times, useful results can be obtained for evaluation of the saturation and homogenization processes in the buffer. The experiment includes six deposition holes. The results will thereby be useful for evaluation of the influence of the rock on the wetting process and the hydraulic interaction between rock and buffer.

Laboratory experiments

In conjunction with modelling of the two field experiments, a number of laboratory experiments will have to be done, partly to determine the parameters that are included in the material models, and partly for studies of certain phenomena in the complex buffer.

In order to obtain a better general understanding of the hydro-mechanical processes in unsaturated bentonite, laboratory experiments will be carried out, in part as a doctoral project. The following hydraulic processes are linked to both mechanical and thermal evolution and will be studied in the laboratory:

- The influence of pressure (swelling pressure and total pressure) on the negative pore water pressure. These studies are conducted e.g. with laboratory experiments in which a sample of unsaturated bentonite is enclosed in an oedometer and the relative humidity in the sample is checked 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, it is expected that the necessary relationships can be obtained.
- The hydraulic conductivity in unsaturated bentonite. The wetting rate is highly dependent on the hydraulic conductivity, which is in turn dependent on both porosity and degree of water saturation. In unsaturated bentonite, the hydraulic conductivity can only be determined by indirect methods, where known negative pore water pressure is an important parameter.
- The redistribution of water by vapour transport in a temperature gradient. This redistribution influences the wetting rate, homogenization and the evolution of the swelling pressure and will be studied.

6.2.13 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 6.2.23. Water flow in the buffer under unsaturated conditions is dealt within detail in section 6.2.4.

6.2.14 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 6.2.23 as regards the chemical evolution of the buffer and in section 6.2.25 as regards radionuclide transport.

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6.2.15 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 material 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 bound water increases. The relationship can be measured and is usually described with a so-called water saturation curve. Other components – such as host rock, salt in the groundwater and bacteria – in a repository system 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 SR 97 and its review

A conceptual description of the swelling pressure in the montmorillonite/saline water system shows that the buffer retains a considerable swelling pressure even in a saturated saline solution /6-11/. There is substantial uncertainty in the quantification of hydraulic conductivity at very high salinities (over 10 percent).

Temperature effects on equilibrium constants for ion exchange are not well documented. Temperature effects on swelling pressure and hydraulic conductivity at very high salinities have not been investigated.

For systems with relatively low salinities (under 3.5 percent) there is both conceptual understanding an a large quantity of measurement data.

Conclusions in RD&D 98 and its review

Not dealt with.

Newfound knowledge since RD&D 98 and SR 97

The importance of salinity for swelling pressure and hydraulic conductivity has been studied for MX-80 and a natural smectitic clay (Friedland). The influence of salt will be small in practice. Two reports have been published describing the microstructure, chemistry and isolating properties of the buffer and showing what the structure of the material means for the function of the buffer /6-12, 6-13/.

The results are also relevant for the backfill.

Research programme

Swelling pressure in compacted bentonite at high salinity is being examined in an ongoing joint project with Posiva, Finland. The project is aimed at further refining the description of the bentonite/water/salt system with respect to ion concentration in the bentonite under given groundwater conditions. Effects of elevated temperature and other types of ions than sodium need to be ascertained with respect to both swelling pressure and hydraulic conductivity.

6.2.16 Ion exchange/sorption

Conclusions in SR 97 and its review

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 Na^+ to Ca^{2+} that can influence the properties of the bentonite to an appreciable extent.

The modelling in SR 97 showed that ion exchange in combination with calcite dissolution affects both pH and the swelling capacity of the buffer. The pH in the groundwater is expected to rise by 1–2 units when the water penetrates into the buffer. The ion exchange will transform some of the sodium montmorillonite to calcium montmorillonite. This affects the swelling capacity. On Äspö, the swelling pressure could fall from around 8 MPa to around 4–5 MPa in a hundred thousand years. This does not affect the performance of the buffer, however.

The authorities have no objections to the description of the long-term changes in the bentonite in the base scenario but observe that the level of knowledge regarding mineral reactions in the bentonite should be further developed. The most important uncertainty is presumably linked to the long-term evolution of the groundwater chemistry, which is commented upon in connection with the climate scenario.

Conclusions in RD&D 98 and its review

The process was not discussed explicitly in RD&D-Programme 98, see also section 6.2.23.

Newfound knowledge since RD&D 98 and SR 97

No new knowledge has been forthcoming.

Research programme

The process is included as a part of the model for the long-term chemical evolution, see section 6.2.23.

6.2.17 Montmorillonite transformation

Conclusions in SR 97 and its review

In SR 97 it is observed that the degree of the most serious montmorillonite transformation, illitization, can be pessimistically limited by regarding the availability of potassium.

The authorities judge that the chemical stability of the buffer and backfill is relatively well known, but that the residual effects of heating at the earliest stage and the influence of the long-term chemical changes in the groundwater need to be described in greater detail.

The authorities are also of the view that the couplings between hydrothermal evolution and mechanical and chemical evolution need to be better illuminated for the early evolution in the buffer, since the long-term properties of the buffer can also be affected by the environment and processes to which it is exposed during an early stage.

Conclusions in RD&D 98 and its review

In RD&D 98, SKB deemed that cementation and permanent contraction of the smectite particles can be a more serious problem than illitization. Natural bentonites that have undergone cementation by precipitation of silicon and aluminium compounds due to the influence of heat exhibit e.g. low swelling pressures due to cementation effects. Verifying experiments are planned in the Äspö HRL.

Newfound knowledge since RD&D 98 and SR 97

Montmorillonite transformation to non-swelling minerals has been investigated in a study of Kinnekulle clay. It is reported in /6-14/ and supports the validity of the general working model presented in 1993 in /6-15/. The conclusion is that cementation by precipitation of dissolved silicon and aluminium is the most important process. The same conclusion is drawn from the study of the effect of vapour /6-16/, which also shows that hydrothermal effects cause some cementation at temperatures above 100ºC.

The effect of high pHs (cement pore water with pHs up to 13.8) on the stability of montmorillonite is currently being investigated within the framework of the ECOCLAY project /6-17/. The ability of the montmorillonite to buffer high pHs is an important question in SKB's part of the project. The goal is to determine whether a high pH reaches the canister quickly with relatively unaffected bentonite, or whether the bentonite slows it down by buffering quickly enough.

The test series LOT (Long Term Test of Buffer Material) is aimed at evaluating models and hypotheses concerning the physical properties and mineralogy of a bentonite buffer under realistic repository conditions. The results of the first tests show that no montmorillonite transformation and no significant change of the physical properties take place during the water saturation phase /6-18/.

The bentonite deposits in the central United States, from which e.g. MX-80 is taken, have been investigated /6-19/. The results show that the sea in which the bentonite was formed and remained for 60 million years exhibits great similarities with the water that is expected to be found in a deep repository in Sweden.

Research programme

The long-term stability of the properties of the buffer material is the most important question in the future research programme for the buffer. Research will be conducted within a number of areas:

- There are very smectite-rich clay deposits in Almeria in southern Spain that have been exposed to various types of influences. They are planned to be studied in the Enresa project BARRA. The most important processes from SKB's point of view are the effect of elevated temperature and the effect of saline pore water.

- Experimental results previously published in work reports and technical reports are being compiled with the intention of publishing the material in article form. The articles will deal with the effects of salt, repeated drying-out and high pH.
- Continued work with the microstructure model for the buffer.

One of the main purposes of the LOT project is to try to verify the conclusion that the transformation to illite is not significantly faster than can be calculated with Huang's kinetic illite conversion model /6-20/, i.e. a check of the laboratory-determined constants as well as the model itself.

It is also possible that studies of the long-term stability of alternative buffer materials will be required.

6.2.18 Dissolution/precipitation of impurities

Conclusions in SR 97 and its review

The buffer material, bentonite MX-80, consists not only of montmorillonite, but also other 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 both in 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. Silicon is the most common element in the buffer and occurs in a number of different minerals and phases. The following processes are not fully understood:

- Release of silicon from the different minerals
- Transport of dissolved silicon driven by the prevailing temperature gradient.
- Precipitation of silicon minerals.

Precipitation of silicon is particularly complex, since it is dependent on several interacting factors and since several conceivable forms occur, both crystalline and amorphous.

The greatest uncertainty concerns the scope of cementation processes as a consequence of dissolution, transport and precipitation of silicon or silicon-aluminium-calcium compounds. The scope and consequences of cementation cannot be predicted with reasonable certainty today.

The authorities conclude that the level of knowledge regarding the bentonite's mineral reactions should be able to be further refined. SKI's consultants /6-21/ are of the general opinion that relatively little attention has been devoted to the evolution of the chemistry in the near field in SR 97, compared with safety assessments from other nuclear waste programmes. They recommend that SKB refine its methods of estimating the pore water composition in bentonite by taking into account the fact that ion exchange reactions also involve tetrahedral and octahedral positions. It is also desirable that parameters in ion exchange and surface complexation models are not based solely on the results of short-term experiments.

The authorities propose that SKB shed light on conceptual uncertainties by evaluating several different methods in parallel for estimating how the pore water composition in bentonite evolves in both the short and long term. The results will then also provide a measure of the uncertainties, and these should be utilized consistently for the modelling of both sorption and solubilities in the buffer. It should be shown that the sorption data that are utilized either are compatible with the entire interval of expected pore water compositions or that several sets of data are available that cover the entire interval. Furthermore, the authorities recommend that SKB taken into account the depletion of the buffer's redox capacity that is caused by radiolysis, which primarily applies to cases where plutonium and americium are retained in the buffer and possibly in the canister.

Conclusions in RD&D 98 and its review

The process was not discussed explicitly in RD&D 98, see also section 6.2.23.

Newfound knowledge since RD&D 98 and SR 97

The test series LOT (Long Term Test of Buffer Material) is aimed at evaluating models and hypotheses concerning the physical properties and mineralogy of a bentonite buffer under realistic repository conditions. The results of the first tests show a minor redistribution of silicon and magnesium along the temperature gradient, precipitation of gypsum on the heater and precipitation of gypsum in the innermost millimetres of the bentonite /6-18/, see further section 6.2.23.

Research programme

Further modelling and model development will be done in order to better be able to describe the geochemistry of the pore water and the near field, see 6.2.23.

6.2.19 Colloid release/erosion

Conclusions in SR 97 and its review

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.

The authorities consider that erosion of the buffer should be taken into account as a potential source of colloids.

Conclusions in RD&D 98 and its review

Not dealt with.

Newfound knowledge since RD&D 98 and SR 97

Release and transport of colloids has been studied and is reported in /6-22/. The conclusion is that aggregates of smectite particles are formed and can be dislodged from the buffer and transported out into the surroundings, but that this requires a water flow rate that will hardly occur when the groundwater table is restored after repository closure. The charge distribution of the aggregates is such that they interact with fracture fillings and rather tend to clog up fractures than move far in them.

Research programme

bentonite erosion is being investigated in a recently started project, COLLOID, see section 8.2.17. First a pilot experiment is being performed so that the experimental procedure can then be optimized. The intention is to investigate whether bentonite clay in contact with various electrolyte solutions forms colloids. The basic assumption is that colloid formation is dependent on the ionic strength of the solution, temperature and bentonite type (Na or Ca). The solutions in contact with bentonite clay are analyzed with respect to the size distribution of the colloids, and as far as possible the concentration of colloids. When the pilot experiment has been evaluated, an optimized laboratory experiment will be started. This will lead to experiments in the Äspö HRL tunnel (planned for the autumn of 2001) and in the Äspö fracture zone (2002).

6.2.20 Radiation-induced montmorillonite transformation

Conclusions in SR 97 and its review

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.

Conclusions in RD&D 98 and its review

Not dealt with.

Newfound knowledge since RD&D 98 and SR 97

No new knowledge has been forthcoming.

Research 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.

6.2.21 Radiolysis of pore water

Conclusions in SR 97 and its review

Gamma radiation emitted by the fuel 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.

The authorities recommend that SKB take into account the depletion of the redox capacity of the buffer that is caused by radiolysis, which primarily applies to cases where plutonium and americium are retained in the buffer and possibly in the canister.

Conclusions in RD&D 98 and its review

Not dealt with.

Newfound knowledge since RD&D 98 and SR 97

No new knowledge has been forthcoming.

Research programme

SKB does not believe it is possible to rely on any redox-buffering capacity in the buffer for extended periods of time and therefore judges that the field does not require any further research, development or demonstration today. New developments are being monitored and will be acted on when appropriate.

6.2.22 Microbial processes

Conclusions in SR 97 and its review

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, the bacteria must be active and have access to water, nutrients and space. Many bacteria are very radiation-resistant, and the radiation intensity in the buffer does not constitute an obstacle to bacterial life there.

Conclusions in RD&D 98 and its review

In RD&D 98 it was stated that studies are under way of whether bacteria are active in a compacted bentonite buffer. The reviewers underscored the importance of studying bacteria.

Newfound knowledge since RD&D 98 and SR 97

The survival and activity of bacteria in compacted bentonite has been investigated in a doctoral project /6-23/.

Experiments with bacteria in bentonite have also been conducted in situ in the Äspö HRL /6-18/. For different reasons, including the energy state of the pore water, bacteria will be dehydrated in the buffer with its high density, while they can survive and reproduce in the backfill.

In parallel with the above studies, the mobility of bacteria in the buffer has also been studied /6-24/. Their survival potential proved to be non-existent in the buffer, while it is a reality in the backfill.

Research programme

The research programme pertaining to microbial processes in the buffer is described in section 5.2.12, which deals with corrosion of copper canisters. The reason for this is that the main safety-related importance microbes could have is their ability to produce copper corrodants.

6.2.23 Integrated studies – evolution under saturated conditions

Conclusions in SR 97 and its review

Integrated model studies for the buffer under saturated conditions were conducted for the integrated chemical evolution.

Conclusions in RD&D 98 and its review

RD&D 98 took aim at carrying out an integrated modelling of the chemical processes in the near field. An initial example of such a modelling was presented in SR 97.

SKI called for experiments on the saturated buffer's THM properties. According to SKI, the Prototype Repository would not be adequate for this purpose.

Newfound knowledge since RD&D 98 and SR 97

Field studies of THMC evolution

The ongoing test series known as LOT (Long Term Test of Buffer Material) at the Äspö HRL aims at evaluating models and hypotheses regarding physical properties and changes in the mineralogy of a bentonite buffer under the conditions that can be expected in a KBS-3 repository. The test series comprises a total of seven test parcels with test time of one, five or 20 years. In each test, parcels containing heaters, copper tubing, precompacted bentonite blocks and instruments are placed in vertical boreholes at the –450 metre level in the Äspö HRL. The heaters are used to simulate the decay heat from spent nuclear fuel and are controlled to provide both KBS-3 conditions (S1 parcels, max. 90ºC) and more adverse conditions (A1 parcels, ~130ºC). The latter is intended to accelerate possible processes in the buffer. Heat output, temperature, pressure and moisture content in the bentonite are recorded during the tests.

Reference and exposed bentonite material is analyzed with respect to physical properties (e.g. swelling pressure, hydraulic conductivity and rheology) and mineralogical properties (e.g. cation exchange capacity, ion content and mineral distribution). Bentonite plugs doped with Cs-134 and Co-60, to an activity of 1 MBq, were placed in the bentonite to study cation diffusion. A large number of microorganisms, between 10^7 and 10^9 cells per gram dry weight of clay, were placed in selected bentonite blocks as starting concentrations. The material is analyzed directly after mixing, after 72 hours and at the end of the test. Small well-characterized copper coupons were placed in the bentonite at selected locations.

Since RD&D 98, two pilot tests (one-year tests) have been concluded and reported with respect to design, field data and laboratory results. /6-18/. Four research groups were engaged in this part of the project working on physical properties and mineralogy, cation diffusion, bacteria and copper corrosion. A millimetre-thick precipitation, mainly gypsum, was found in the warmest innermost part of the bentonite. An overarching conclusion is that no degrading processes, with respect to buffer performance, were found in most of the bentonite as a consequence of water saturation and heating for one year. The diffusion tests confirmed that transport in unsaturated bentonite is insignificant. The apparent diffusivity of cobalt in the saturated bentonite was measured to be about $2 \cdot 10^{-9}$ cm^2/s, which is in good agreement with previous laboratory experiments. The cesium results, on the other hand, were not possible to fit to a diffusion profile, so further laboratory tests will be carried out in parallel with the field tests. All bacteria, except for spore-forming species, occurred below detection limits in the field-exposed parcel material. The mean copper corrosion rate was measured at $3 \cdot 10^{-6}$ m/y, which is in good agreement with previous modelling of oxic conditions. No signs of pitting were found. An elevated copper concentration was measured in the bentonite in the vicinity of the copper coupons.

The LOT project includes extensive measurements of the bentonite's hydraulic conductivity, swelling pressure and rheological properties under saturated conditions. Determinations are made for reference material and material subjected to various exposures in the tests, i.e. material from different positions in the test parcels. The test material is investigated both in the undisturbed field state and after re-preparation according to the same standard method as for the reference material. The results from the laboratory determinations of the concluded one-year tests showed no significant changes of physical properties as a consequence of water saturation under KBS-3-like conditions.

Research programme

Field studies of THMC evolution

An ongoing one-year test at elevated temperature (the A0 test) in the LOT project will be concluded and analyzed during 2001 in accordance with the testing programme. The three ongoing five-year tests will be concluded and analyzed during 2004 /6-18/.

Model studies of chemical evolution

SKB agrees with the authorities that the chemical modelling of the near field should be further developed. The goal of this research field is to further refine the copper model for ion exchange, dissolution-precipitation and diffusion that is used in SR 97 to model the time-dependent evolution of the water chemistry in the near field. The following processes in the buffer will be studied:

- Development of the ion exchange/surface complexation model for bentonite by taking into account the Donnan equilibrium properties of montmorillonite (see section 6.2.15), new knowledge concerning the bentonite's surface properties and the varying hydrological conditions during the saturation process.
- The importance of the quantity, distribution and time dependence of impurities in the buffer and their importance for redox and pH buffering in the near field.
- Determinations of solubilities, sorption and diffusion coefficients for radionuclides as a consequence of the time-dependent evolution of the water chemistry.

The model is being developed and tested with the large quantity of chemical data available from SKB's previous buffer research and new knowledge from the rest of the research programme. New experimental data will be obtained from the FEBEX Mock-up experiment and the BARRA analogue project. Ion exchange is also being studied within the LOT project.

THM model for saturated conditions

The mechanical part of the THM model for water-saturated bentonite is complex and has certain remaining questions, with regard to 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 proceed on the same scale as before for the time being. Moreover, the effect of the strain rate on the stiffness of the buffer will be studied to determine whether the relationships obtained can be extrapolated to very fast processes such as those that could occur in connection with an earthquake. Another phenomenon to be studied is the effect of very rapid compression on the integrity of water-saturated buffer.

6.2.24 Radionuclide transport – advection

Conclusions in SR 97 and its review

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.

Conclusions in RD&D 98 and its review

Not dealt with.

Newfound knowledge since RD&D 98 and SR 97

No new knowledge has been forthcoming.

Research 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.

6.2.25 Radionuclide transport – diffusion

Conclusions in SR 97 and its review

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 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 cesium, strontium and radium.

When bentonite has such high density that the electrical double layers between two planes are superimposed, 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. The effect of anion exclusion becomes less at high salinities, and in crushed rock/bentonite mixtures it is negligible.

Conclusions in RD&D 98 and its review

Laboratory experiments with surface diffusion were described in RD&D 98. No questions for further research were identified.

Newfound knowledge since RD&D 98 and SR 97

Experiments with diffusion of radionuclides have been performed at the Äspö HRL, both in the CHEMLAB probe and in the LOT tests, see section 6.2.23. Both laboratory and CHEMLAB experiments with diffusion of cesium, strontium and cobalt in bentonite have been carried out for SKB /6-25/.

In the CHEMLAB experiment, MX-80 bentonite and the radionuclides R-85, Cs-134, Co-57, I-131 and Tc-99 are used. Table 6-2 shows measured sorption and diffusivity data as well as a comparison with data from laboratory measurements (with groundwater of another salinity) /6-26/.

Table 6-2. Values of K_d and D_a from the CHEMLAB experiments and laboratory experiments.

	CHEMLAB experiments		Laboratory experiments	
	log K_d [cm^3 g^{-1}]	D_a [cm^2 s^{-1}]	log K_d [cm^3 g^{-1}]	D_a [cm^2 s^{-1}]
Cs^+	1.8	$2 \cdot 10^{-8}$	2 ± 0.35	$(2 \pm 1) \cdot 10^{-8}$
Sr^{2+}	1.1	$7 \cdot 10^{-8}$	1.56 ± 0.32	$(9 \pm 1) \cdot 10^{-8}$
Co^{2+}	2.4	$4 \cdot 10^{-9}$	3.3 ± 0.3	$(2 \pm 1) \cdot 10^{-9}$

Research programme

The results of the experiments at the Äspö HRL are in part unexpected for substances that exhibit surface diffusion. This will be further investigated via laboratory experiments.

The process is included in the computer program NUCTRAN/COMP23, which calculates radionuclide transport in the near field. The programme for development of this is presented in section 7.3.

6.2.26 Radionuclide transport – sorption

Conclusions in SR 97 and its review

The surface of smectitic clays has a permanent negative charge. The charge imbalance is neutralized by an exchange of cations between the flakes. When the clay is thoroughly saturated, the exchangeable cations are hydrated and an electrical double layer is formed in the water/clay interface. The charge-balancing cations can easily be exchanged for other cations in the solution that is in contact with the clay surface. The 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. Most actinides and lanthanoids form surface complexes. Nuclides sorbed as surface complexes cannot be transported by surface diffusion.

The distribution coefficient K_d is a measured value which in the strict sense only applies under measurement conditions and cannot be reliably extrapolated to other conditions. The case with sorption in highly-compacted bentonite is particularly complicated, since virtually all water is interlamellar and it can be difficult to define the chemistry. This makes it impossible to apply the results of sorption measurements in batch tests.

Based on comparisons with other programmes, one of SKI's consultants /6-21/ is of the opinion that SKB's realistic K_d values are reasonable. SKB's choice of pessimistic values is, however, considered to be dubious, since K_d values that are two orders of magnitude lower than the realistic values are probably required to cover the entire uncertainty interval.

The authorities propose that SKB shed light on conceptual uncertainties by evaluating several different methods in parallel for estimating how the pore water composition in bentonite evolves in both the short and long term. The results will then also provide a measure of the uncertainties, which should be utilized consistently for the modelling of both sorption and solubilities in the buffer. It should be shown that the sorption data that are utilized either are compatible with the entire interval of expected pore water compositions or that several sets of data are available that cover the entire interval.

According to Kasam, available knowledge of the properties of the bentonite are not being optimally utilized, since only conditions parameters are utilized to describe sorption. More sophisticated sorption models should be developed for the most important nuclides.

Conclusions in RD&D 98 and its review

It was concluded in RD&D 98 that constants for sorption (and diffusion) of radionuclides had been summarized and reported for SR 97. No questions for further research were identified.

Newfound knowledge since RD&D 98 and SR 97

Some sorption measurements of radionuclides on bentonite have been done after RD&D 98 in conjunction with the diffusion experiments in the CHEMLAB probe /6-25/.

Research programme

Detailed knowledge of sorption in bentonite is not of critical importance for the performance of a KBS-3 repository, see e.g. SR 97 Main Report Volume II, Figure 9-41. SKB does therefore not intend to pursue its own studies in the field. The process is of greater importance in concepts with shorter-lived canisters and/or a thicker buffer and is therefore being studied in other countries. SKB will monitor international developments within the field.

The process is included in the computer program NUCTRAN/COMP23, which calculates radionuclide transport in the near field. The programme for development of this is presented in section 7.3.

6.2.27 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 4.2.14 and the evolution of the chemical environment in the buffer in section 6.2.23. The same type of speciation calculations for e.g. the buffer environment are planned in future safety assessments as in SR 97.

6.2.28 Radionuclide transport – Colloid transport through bentonite

Conclusions in SR 97 and its review

One of the requirements on the buffer material is that colloidal particles should be filtered.

The authorities concur with SKB that colloid transport will probably not be of decisive importance as long as the buffer remains intact, and as long as the composition of the groundwater does not change significantly. The influence of colloids should be evaluated for the case where the buffer does not function as intended, for example due to faults in manufacture and emplacement.

Conclusions in RD&D 98 and its review

Colloids in the near field, e.g. from the materials that exist there, are important and have not been quite as fully studied as the natural colloids. Experiments are being conducted to lend further support to the conclusion that bentonite clay acts as a filter for such particles.

Newfound knowledge since RD&D 98 and SR 97

The buffer is supposed to prevent colloids with radionuclides from escaping from a damaged canister. In order to thoroughly test the bentonite in this respect, experiments are being conducted with diffusion of organic colloids in a compacted bentonite buffer as a part of a doctoral project. The organic colloids that are being used are more mobile than mineral colloids, which is what the buffer is really supposed to protect against. Prepared organic colloids work better as test substances for the very reason that they have a greater capability to penetrate into the clay. The results of several years of experiments on this have been reported /6-27/. Organic colloids diffuse through bentonite at approximately the same rate as negative ions such as I^- and Cl^-. The colloids moved slightly faster at high ionic strengths, which was unexpected. The studies are a part of a doctoral project which will continue for a few more years.

Research programme

The studies of colloid transport through the buffer will continue. The most important questions are the importance of the pore geometry for diffusion and the possibility of radionuclide transport with colloids.

7 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 shall have a density that minimizes the upward expansion of the buffer. The density of the buffer is thereby maintained.
- The backfill shall 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 shall exert a given swelling pressure against the roof to resist block breakout and retain a swelling capacity that can seal possible effects of channelling and creep movements in the backfill. In RD&D 98 and SR 97, this swelling pressure was set to at least 100 kPa. Swelling pressure will be the subject of further studies.

The backfill must not have any adverse effect on the barriers in the repository. This imposes some requirements on its chemical composition. Backfill with montmorillonite and crushed rock as main components is considered to be particularly suitable in this respect.

In SR 97, the backfill material was assumed to consist of a mixture of 15 percent MX-80 bentonite clay and 85 percent crushed rock. In actuality, the proportions will be adapted to the chemical conditions (primarily the salinity of the groundwater) on the repository site so that the backfill will have the desired properties.

7.1 Initial state of the backfill

7.1.1 Variables

In SR 97, the same set of variables is used to describe the backfill as for the buffer, see Table 6-1. The crushed rock, which typically comprises 85 percent of the backfill, is included in the variable "Impurity levels".

The initial state, i.e. the value these variables were assumed to have at the time of deposition, is described in the Main Report of SR 97, section 6.4 (together with the buffer). The research programme surrounding the initial state for the different variables in the backfill is described in the following.

7.1.2 Geometry

The dimensions of the backfill are given by the dimensions of the tunnels.

7.1.3 Pore geometry

The initial pore geometry (porosity) of the backfill follows trivially from its material specifications. The porosity of the backfill in SR 97 was 30 percent.

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7.1.4 Radiation intensity

The initial radiation intensity in the backfill is negligible.

7.1.5 Temperature

A determination of the initial temperature in the backfill is trivial. It will be close to the initial temperature of the rock.

7.1.6 Smectite content

Conclusions in SR 97 and its review

The composition of the backfill was not treated in detail in SR 97, in part because it was not adapted to the properties of the site.

Conclusions in RD&D 98 and its review

It was concluded in RD&D-Programme 98 that the requirements on the backfill, choice of material and technology were subject to further research.

Newfound knowledge since RD&D 98 and SR 97

See section 7.2.2.

Research programme

See section 7.2.2.

7.1.7 Water content

The initial water content in the backfill follows trivially from its material specifications. It is a parameter that can be checked during the mixing of the material. In SR 97, the backfill material had an initial degree of water saturation of 65 percent.

7.1.8 Gas contents

The initial gas content in the backfill follows trivially from its specifications.

The porosity of the backfill in SR 97 was 30 percent and its degree of water saturation 65 percent, which means that the air in a tunnel system initially occupies about ten volume-percent.

7.1.9 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 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.

7.1.10 Swelling pressure

The swelling pressure develops as the buffer and backfill approach full water saturation. Initially there is no swelling pressure.

7.1.11 Smectite composition

Conclusions in SR 97 and its review

In SR 97 the clay portion of the backfill had the same composition as the buffer, see section 6.1.11.

Conclusions in RD&D 98 and its review

See section 7.2.2.

Newfound knowledge since RD&D 98 and SR 97

See section 7.2.2.

Research programme

See section 7.2.2.

7.1.12 Pore water composition

The water in the backfill is a blend of water from the crushed rock, the bentonite's original water and water added at deposition. Its composition is mainly dependent on which water is added at deposition.

7.1.13 Impurity levels

Conclusions in SR 97 and its review

The natural impurities in the bentonite are of subordinate importance in the backfill, since it consists of 85 percent crushed rock, which in turn consists of minerals similar to the impurities in the bentonite. See further the mineralogical description of the geosphere.

A related question concerns quantities and types of materials left behind in deposition holes and tunnels. This is described in section 14.5.7.

The authorities consider that possible negative effects due to the presence of forgotten materials need to be elucidated. This is dealt with in section 7.2.16.

Conclusions in RD&D 98 and its review

Not dealt with.

Newfound knowledge since RD&D 98 and SR 97

No new knowledge has been forthcoming.

Research programme

See section 7.2.2.

7.2 Processes in backfill

7.2.1 Overview of processes

Basically the same processes take place in the backfill as in the buffer (see section 6.2.1 for an overview), although sometimes on a different scale. Moreover, the crushed rock (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.

7.2.2 Integrated studies – composition and function

Conclusions in SR 97 and its review

The properties of the backfill are determined not only by its composition, 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. Since the bentonite density is low, the properties are very sensitive to salinity. As a result, the 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 SR 97. 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 98 and its review

It was concluded in RD&D-Programme 98 that the requirements on the backfill, choice of material and technology were subject to further research.

Newfound knowledge since RD&D 98 and SR 97

The composition of the backfill has been discussed in /7-1/. There, a natural clay of the type Friedland Ton is judged to be equal or superior to mixtures of 30 percent MX-80 and 70 percent crushed rock in terms of function. The preliminary conclusion is that the compacting properties of the natural clay are equivalent to those of mixtures of bentonite and crushed rock. Processing and handling are simpler, and costs are competitive.

In an extensive laboratory programme, mixtures of 0–30 percent bentonite and crushed rock have been investigated in conjunction with the installation of the Backfill and Plug Test in the Äspö HRL /7-2/. In this programme, the properties of the backfill under both saturated and unsaturated conditions have been studied and a material model, which is the same for the buffer but with other parameters, has been developed /7-3, 7-4, 7-5/. The following problems have been encountered in application of the models to the field-mixed material that is used in the Backfill and Plug Test:

- Since the backfill material is relatively inhomogeneous and susceptible to channelling under heavy water flow, a large spread is obtained in the results of hydraulic conductivity measurement on a laboratory scale.
- Also due to inhomogeneity and susceptibility to channelling, it seems that the relationship between hydraulic conductivity in the saturated and unsaturated state that was used to model the water saturation phase in the buffer cannot be used for backfills that consist of mixtures of bentonite and crushed rock. Water saturation goes slower, since the conductivity measured in the laboratory is dominated by occasional channels, while water saturation has to take place in the entire backfill, which seems to have much lower conductivity between the channels.

Thus, while the models and the understanding of the hydro-mechanical processes in the buffer are of help in understanding the processes in the backfill, they cannot be applied directly.

Research programme

The research on backfilling with mixtures of bentonite and crushed rock is currently being done to a large extent within the framework of the Backfill and Plug Test in the Äspö HRL.

The objectives of the test are:

- To develop and test different materials and compaction techniques for backfilling of drill-and-blast tunnels.
- To test the function of the backfill and its interaction with the surrounding rock on a full scale in drill-and-blast tunnels.
- To develop technology for building plugs and testing their function.

The backfill and surrounding rock are instrumented with piezometers, total pressure cells, thermocouples, moisture gauges, pressure cylinders, and equipment for measuring the local hydraulic conductivity.

The following tests are performed after the backfill has been saturated with water:

Water transport under saturated conditions is studied by flow tests. Water transport is studied:

- Through the central portions of the backfill.
- In the contact zone between backfill and floor.
- In the contact zone between backfill and roof.

Swelling and mechanical interaction between backfill and near-field rock is being studied by means of swelling pressure measurement and pressure cylinders. The swelling pressure during and after water saturation can be measured with the total pressure cells placed in the roof and on the floor. The mechanical properties of the backfill in the contact zone with the rock can be studied by gradually pressurizing the pressure cylinders (also installed in the roof and on the floor) and measuring pressure and deformation.

After the tests are finished, the plug will be demolished and the backfill dug out at the same time as extensive sampling is performed.

Studies will be conducted of the possibility of using natural clays as a backfill material in the form of both continued field tests on Friedland clay, where above all compaction and compression properties will be tested and evaluated, and tests on bentonite from Milos in Greece. The latter clay is known for its good hydraulic properties, but needs to be tested with regard to both compaction properties and compressibility.

The inventory of alternative backfill materials will continue.

7.2.3 Radiation attenuation/heat generation

The process can be neglected in the backfill.

7.2.4 Heat transport

Conclusions in SR 97 and its review

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.

Conclusions in RD&D 98 and its review

Not dealt with.

Newfound knowledge since RD&D 98 and SR 97

No new knowledge has been forthcoming.

Research programme

The field is judged today not to require any further research, development or demonstration. Temperature calculations and measurement results from the Prototype Repository in the Äspö HRL will be obtained, however. New developments are being monitored and will be acted on when appropriate.

7.2.5 Water transport under unsaturated conditions

Conclusions in SR 97 and its review

It was generally concluded in SR 97 that the function of the backfill needs to be better elucidated. However, no specific questions around this process were identified in SR 97 or its review.

Conclusions in RD&D 98 and its review

Not treated.

Newfound knowledge since RD&D 98 and SR 97

Research on the properties of the backfill in the unsaturated state has been conducted in recent years within the Äspö project on mixtures of bentonite and crushed rock.

Negative pore pressure has been determined as a function of the water ratio, as has hydraulic conductivity as a function of degree of water saturation and bentonite content /7-2, 7-4/.

These relationships have then been expressed in mathematical form and used in calculations of the water saturation process /7-2, 7-4/. The backfill material that has been formulated for the field tests is inhomogeneous, resulting in wide variation in the wetting rate in the laboratory tests. The unsaturated hydraulic conductivity is low, resulting in slow wetting in the absence of external water pressure. See also section 7.2.2.

Research programme

The coupled THM model for unsaturated conditions in the buffer, which will be further developed and described in section 6.2.12, can be used for the backfill as well.

7.2.6 Water transport under saturated conditions

Conclusions in SR 97 and its review

The permeability of the backfill after water saturation is determined by the montmorillonite content and density of the backfill and the composition of the pore water. In contrast to the buffer, the backfill 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.

There are a number of uncertainties for bentonite-mixed backfill. The properties are measured directly after mixing. The risk for 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 are also inadequately explored. The function of the backfill in general was identified as a priority research area in SR 97.

Conclusions in RD&D 98 and its review

No questions for further research were identified in RD&D-Programme 98 or its review.

Newfound knowledge since RD&D 98 and SR 97

Research on the backfill has been conducted in recent years within the Äspö project, involving laboratory and field tests on mixtures of bentonite and crushed rock and laboratory tests on an alternative natural clay material (Friedland clay).

Investigations have been conducted on mixtures of bentonite and crushed rock to determine hydraulic conductivity as a function of bentonite content, density and the salinity of the added water. The results show that salinity has a great influence on the properties, due to the fact that the density of the bentonite fraction in the pore space between the particles of crushed rock is low at bentonite contents of 30 percent and less /7-1/.

At a density of 1,900 kg/m^3 (dry density 1,430 kg/m^3), the conductivity of the natural Friedland clay is around 10^{-10} m/s and the swelling pressure is slightly more than 200 kPa when the salinity is 3.5 percent. This density gives a swelling pressure of at least 100 kPa, i.e. sufficient pressure to support the rock roof in tunnels, regardless of the salt content. With mixtures of 30/70 percent bentonite/sand with a density of 1,900 kg/m^3 in water-saturated condition, the swelling pressure virtually ceases when the pore water is even slightly brackish /7-6/.

See section 6.2.5 regarding the phenomenon of liquefaction.

Research programme

See section 7.2.2.

7.2.7 Gas transport/dissolution

Conclusions in SR 97 and its review

It was generally concluded in SR 97 that the function of the backfill needs to be better elucidated. However, no specific questions around this process were identified in SR 97 or its review.

Conclusions in RD&D 98 and its review

No questions for further research were identified in RD&D-Programme 98 or its review.

Newfound knowledge since RD&D 98 and SR 97

No new knowledge has been forthcoming.

Research programme

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. For gas dissolution, see section 6.2.6.

7.2.8 Swelling

Conclusions in SR 97 and its review

It was generally concluded in SR 97 that the function of the backfill needs to be better elucidated. However, no specific questions around this process were identified in SR 97 or its review.

Conclusions in RD&D 98 and its review

No questions for further research were identified in RD&D-Programme 98 or its review.

Newfound knowledge since RD&D 98 and SR 97

No new knowledge has been forthcoming.

Research programme

See sections 6.2.4 and 7.2.2.

7.2.9 Mechanical interaction buffer/backfill

Conclusions in SR 97 and its review

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.
- Block breakout in the tunnel roof and walls.

The swelling pressure against the roof is dependent on what density can be achieved in compaction. The difficulties of compaction against the roof make it difficult to guarantee a given swelling pressure. The swelling pressure arises from the bentonite in the space between the 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.

Conclusions in RD&D 98 and its review

See section 7.2.2.

Newfound knowledge since RD&D 98 and SR 97

See section 7.2.2.

Research programme

SKB will start a project whose main goal is to establish a design method for quantifying the effect of the mechanical properties of the backfill on a granitic bedrock. See also 7.2.2. Convergence of tunnels as a result of creep movements in the rock is dealt with in section 8.2.9.

7.2.10 Thermal expansion

Conclusions in SR 97 and its review

No questions for further research were identified in SR 97 or its review.

Conclusions in RD&D 98 and its review

Not dealt with.

Newfound knowledge since RD&D 98 and SR 97

No new knowledge has been forthcoming.

Research programme

The importance of this process will be illustrated with simple scoping calculations. This will serve as a basis for the next safety assessment and is projected to be finished during 2002.

7.2.11 Advection

Conclusions in SR 97 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. However, calculations show that even with a very high water flow through the backfill, the outward transport of a given radionuclide is at most twice as great as in the case with diffusion alone /7-7/. See also section 7.2.6 and, regarding radionuclides, section 7.2.21.

Conclusions in RD&D 98 and its review

Not dealt with.

Newfound knowledge since RD&D 98 and SR 97

See section 7.2.6.

Research programme

See also section 7.2.2. Regarding advection of radionuclides, see section 7.2.21.

7.2.12 Diffusion

Conclusions in SR 97 and its review

No questions for further research were identified in SR 97 or its review.

Conclusions in RD&D 98 and its review

Not dealt with.

Newfound knowledge since RD&D 98 and SR 97

No new knowledge has been forthcoming.

Research 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.

7.2.13 Osmosis

Conclusions in SR 97 and its review

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 is therefore swollen 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 increased risk of piping (channel formation 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). The function of the backfill in general was identified as a priority research area in SR 97. See also section 6.2.15.

Conclusions in RD&D 98 and its review

Not dealt with.

Newfound knowledge since RD&D 98 and SR 97

The importance of salinity and its influence on the physical properties of the backfill material as a consequence of e.g. the ion exchange properties of mixtures of MX-80 and crushed rock and of natural Friedland clay has been clarified in /7-6/, see section 7.2.2.

Research programme

See section 6.2.15.

7.2.14 Ion exchange/sorption

Conclusions in SR 97 and its review

Ion exchange from sodium to calcium leads to similar effects as high salinity in the groundwater (see section 7.2.13), 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 98 and its review

Not dealt with.

Newfound knowledge since RD&D 98 and SR 97

No new knowledge has been forthcoming.

Research programme

See sections 6.2.23 and 7.2.13.

7.2.15 Montmorillonite transformation

Conclusions in SR 97 and its review

What is said about the equivalent process in the bentonite in section 6.2.17 is largely applicable to the backfill as well.

Conclusions in RD&D 98 and its review

What is said about the equivalent process in the bentonite in section 6.2.17 is largely applicable to the backfill as well.

Newfound knowledge since RD&D 98 and SR 97

What is said about the equivalent process in the bentonite in section 6.2.17 is largely applicable to the backfill as well.

Research programme

What is said about the equivalent process in the bentonite in section 6.2.17 is largely applicable to the backfill as well. The lower density of the buffer may make the transformation go faster, while the lower temperature may make it go slower. The same model as for the buffer can nevertheless be used.

7.2.16 Dissolution/precipitation of impurities

Conclusions in SR 97 and its review

Natural impurities in the bentonite material (see section 6.1.13) do not have any bearing on the long-term performance of the backfill. The importance of engineering materials and forgotten materials was also dismissed in SR 97, with reference to the small quantities.

The authorities observe the following: "The quantities of organic material that may be left behind after closure, or whether or not it is acceptable to leave large quantities of cement near the deposition holes, is not described in SR 97. In the authorities' opinion, any negative effects that can arise due to the presence of such materials need to be elucidated."

Conclusions in RD&D 98 and its review

Not dealt with.

Newfound knowledge since RD&D 98 and SR 97

No new knowledge has been forthcoming.

Research programme

A critical appraisal of the impurities and stray materials that may remain in the repository /7-8/ and their importance for long-term safety is planned to be conducted during the period.

The importance of cement in the repository needs to be further elucidated, since it is an advantage to be able to use cement and concrete in the construction of the repository. The possibilities of a joint effort with Posiva in this area will be explored. Regarding reactions between bentonite and concrete in a repository, see also Chapter 18.

7.2.17 Colloid release/erosion

Conclusions in SR 97 and its review

The risk of erosion in the backfill is greatest if there is a gap 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 channelling during the compaction phase. When fully wetted, the backfill strives to expand and consolidate the boundary zone. However, at the low density which the backfill will probably have at the tunnel roof, the expansion capacity of the backfill will not be enough, according to repository specifications, to maintain contact with the roof and walls in the tunnels. This gives rise to a risk of considerable erosion and heterogeneity in the backfill. This can be avoided by backfilling with blocks with a higher bentonite content near the tunnel roof.

Conclusions in RD&D 98 and its review

Not dealt with.

Newfound knowledge since RD&D 98 and SR 97

See section 6.2.19.

Research programme

Erosion and colloid formation of the bentonite material in the backfill continue in the same manner as in the buffer, see therefore 6.2.19 for the research programme. The consequences can be greater, however, due to the lower content of montmorillonite, which could lead to erosion of the clay material. This results in higher hydraulic conductivity and lower swelling pressure.

7.2.18 Radiation-induced montmorillonite transformation

The process is judged to be negligible in the buffer and is therefore also judged to be negligible in the backfill.

7.2.19 Radiolysis of pore water

The process is judged to be negligible in the buffer and is therefore also judged to be negligible in the backfill.

7.2.20 Microbial processes

Conclusions in SR 97 and its review

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. Bacterial activity in the backfill can therefore be advantageous, since it will make a significant contribution to oxygen reduction there.

Conclusions in RD&D 98 and its review

No questions for further research were identified in RD&D-Programme 98 or its review.

Newfound knowledge since RD&D 98 and SR 97

No new knowledge has been forthcoming.

Research programme

See section 6.2.22 regarding sulphate-reducing microbes in bentonite and groundwater and 8.2.15 regarding microbes in the bedrock.

7.2.21 Radionuclide transport – advection

Conclusions in SR 97 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, see 7.2.11.

The authorities are of the opinion that it would be of interest for the description of radionuclide transport between buffer/backfill and surrounding rock to evaluate the processes that could lead to changes in the transport properties. For example, it does not appear unthinkable that the backfill might be transformed so that a preferential transport pathway is formed next to the roof in the deposition tunnels. Changes of backfilled boreholes may also have to be taken into consideration.

Conclusions in RD&D 98 and its review

Not dealt with.

Newfound knowledge since RD&D 98 and SR 97

No new knowledge has been forthcoming.

Research programme

The objective is to produce an integrated report that describes the function of the backfill (see section 7.2.2), processes that can affect this function (see section 7.2.13) and the consequences this may have on the performance of the repository. To evaluate the consequences, the computer program for near-field transport, COMP23, will be modified, see section 7.3.

7.2.22 Radionuclide transport – diffusion

Conclusions in SR 97 and its review

Diffusion of radionuclides in the backfill is of subordinate importance for repository safety. No questions for further research were identified in SR 97 or its review.

Conclusions in RD&D 98 and its review

Not dealt with.

Newfound knowledge since RD&D 98 and SR 97

No new knowledge has been forthcoming.

Research 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.

7.2.23 Radionuclide transport – sorption

Conclusions in SR 97 and its review

Sorption coefficients are calculated in SR 97 for radionuclides in the backfill by weighing together K_d values for bentonite and rock in proportion to the composition of the backfill. Otherwise see section 6.2.26.

For conclusions in the regulatory review, see section 7.2.21.

Conclusions in RD&D 98 and its review

No questions for further research were identified.

Newfound knowledge since RD&D 98 and SR 97

No new knowledge has been forthcoming.

Research 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.

7.2.24 Radionuclide transport – speciation of radionuclides

The speciation of radionuclides is of importance for sorption and diffusion in the buffer. It is influenced by what speciation the nuclide had at the boundary to the buffer, i.e. inside the canister, but also by the chemical conditions in the buffer.

The speciation process is discussed in section 4.2.14. The same type of speciation calculations for e.g. the buffer environment are planned in future safety assessments as in SR 97.

Conclusions in RD&D 98 and its review

See section 4.2.14.

Newfound knowledge since RD&D 98 and SR 97

See section 4.2.14.

Research programme

See section 4.2.14.

7.3 Integrated modelling – radionuclide transport in the near field

Conclusions in SR 97 and its review

Radionuclide transport in the near field is calculated in SR 97 with the model COMP23, which handles the processes 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 backfill and out to the surrounding geosphere, and chain decay.

Radionuclide transport in the interior of the canister is simplified in modelling in the following way: After a certain "waiting period" has passed since the 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 waiting period is determined on the basis of the size of the breach in the copper shell and the subsequent water flux and corrosion. After the waiting period, all water in the canister is 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 is 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 waiting period. Sorption of radionuclides to the internal parts of the canister is neglected.

The micropores in the buffer are expected to prevent all outward transport of colloids from the interior of the canister. Colloid transport in the canister interior is therefore not dealt with, provided that the buffer completely surrounds the canister.

Radionuclide transport in the gas phase is handled with scoping calculations.

The following viewpoints emerged from the review of SR 97:

- The authorities were of the opinion that the results from SKB's spent fuel dissolution model are inadequately documented to be directly useful in supporting a consequence analysis. In order to maintain high credibility for models and calculations, it must be possible to judge the quality of the experimental data and the conceptual uncertainties. Conceptual uncertainties can have very great effects when experimental data are extrapolated to very long time periods. Since it can be questioned whether the knowledge base is adequate, the authorities consider that SKB in SR 97 should have used more robust assumptions to estimate an upper bound for the fuel dissolution rate. This is further commented on in section 4.2.12.

- The authorities are also of the opinion that the influence of colloids should be evaluated for the case where the buffer does not function as intended, for example due to faults in manufacture and emplacement. This is further commented on in section 6.2.28.
- Even if the solubilities calculated in SR 97 are probably conservative, the authorities and several of SKI's consultants consider that the solubility calculation method can be improved. This is further commented on in section 4.2.14.
- The international review team finds that the account of COMP23 is unclear. Among other things there is no description of how verification, quality assurance and validation have been handled. A special difficulty that must be addressed is that the code appears to represent a blend of theoretical and empirical equations.

Conclusions in RD&D 98 and its review

The task was to develop and maintain NUCTRAN/COMP23 as principal tools for radionuclide transport in the near field. One of the most important parts of the development programme for NUCTRAN/COMP23 was to combine the variants that existed to a single definitive version.

Newfound knowledge since RD&D 98 and SR 97

The computer model COMP23 has been improved since SR 97. The program is now much faster and requires much less memory. The most important parts from the NUCTRAN version used for SFL 3-5 were transferred to the version used for SR 97.

Since SR 97, an analytical approximation of COMP23 has been developed /7-9/, see section 2.4.1. The agreement with the numerical model for the calculation cases in SR 97 is generally very good. Figure 7-1 shows a comparison of release curves from the near field for one of the calculation cases in SR 97 calculated with the numerical near-field model COMP23 and with the analytical model. The results are very similar for short-lived (Cs-137, Sr-90, Ni-63), long-lived (Cs-135, I-129, U-238 etc.), sorbing (Pu-239, U-238 etc.), non-sorbing (Cl-36, I-129), solubility-limited (Sn-126, Nb-94 etc.) and ingrowth (Ra-226, Pa-231) nuclides.

Figure 7-2 shows a comparison of maximum annual releases in the time interval up to a million years after closure for all uncertainty cases in SR 97 /7-10/, including cases where all parameters are simultaneously given either consistently reasonable or consistently pessimistic values. In most cases the discrepancies lie within a factor of three.

The analytical model will be used as one of the tools in future safety assessments, among other things for preliminary probabilistic calculations, see further section 2.4.

Research programme

SKB intends to keep COMP23 as a principal tool for calculations of radionuclide transport in the near field. However, a study will be carried out to determine if there are other alternatives that could be more suitable. If a new model is to be developed, the study must lead to a target specification for the new model. An inventory of available calculation models will be done to start with. This is expected to be finished by the beginning of 2002.

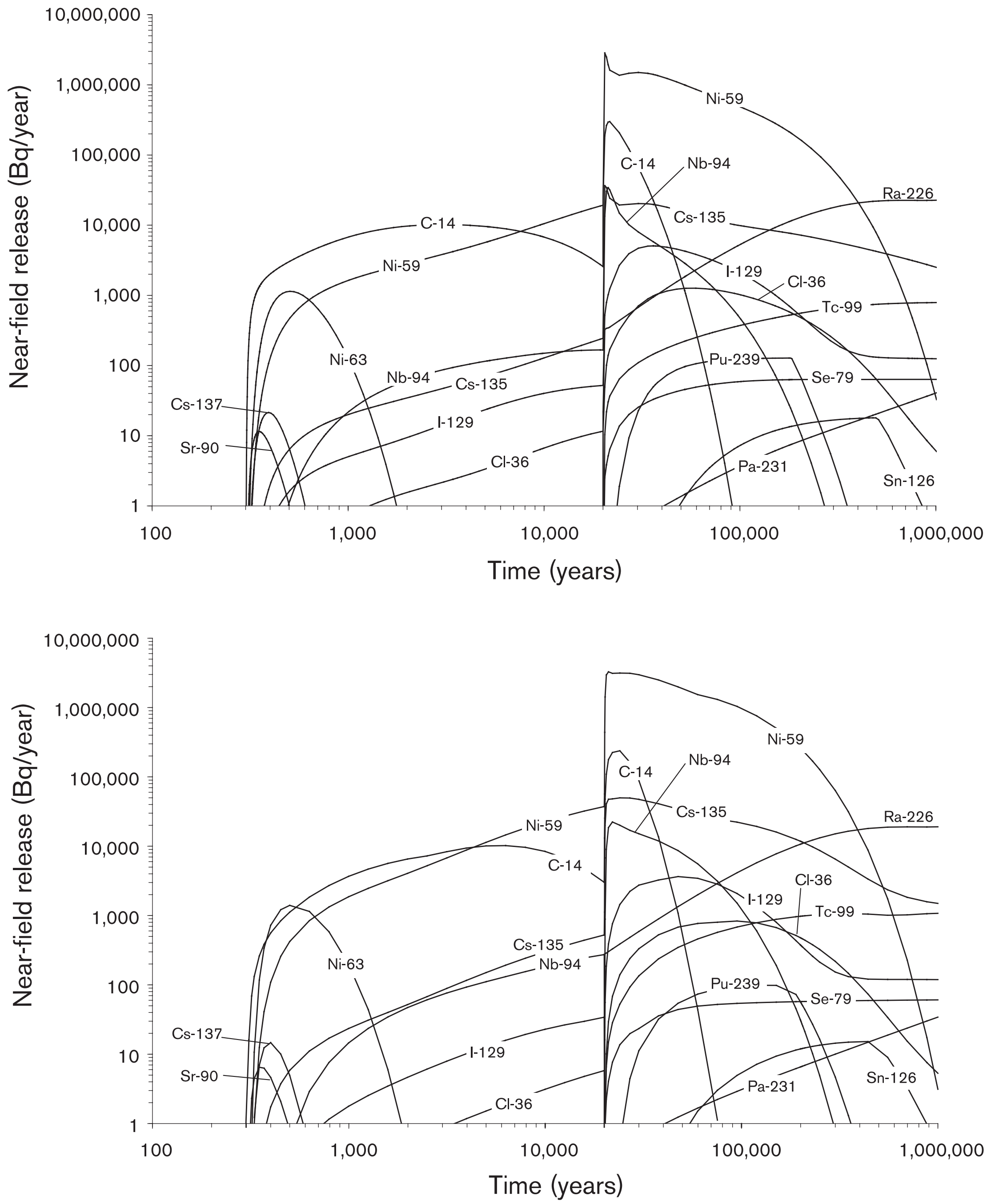

Figure 7-1. *Release curves from the near field for one of the calculation cases in SR 97, calculated with a numerical (upper) and an analytical (lower) model.*

In the meantime, the work with COMP23 will continue with the following main content:

- The verification and documentation work will continue. Today there is a development database where all changes in the code are documented. COMP23 is also entered in SKB's common version management system. An "Assessment Validity Document" /7-11/ will be prepared within the coming three-year period. Among other things, this document will deal with the reviewers' viewpoints given above regarding verification, quality assurance and validation.

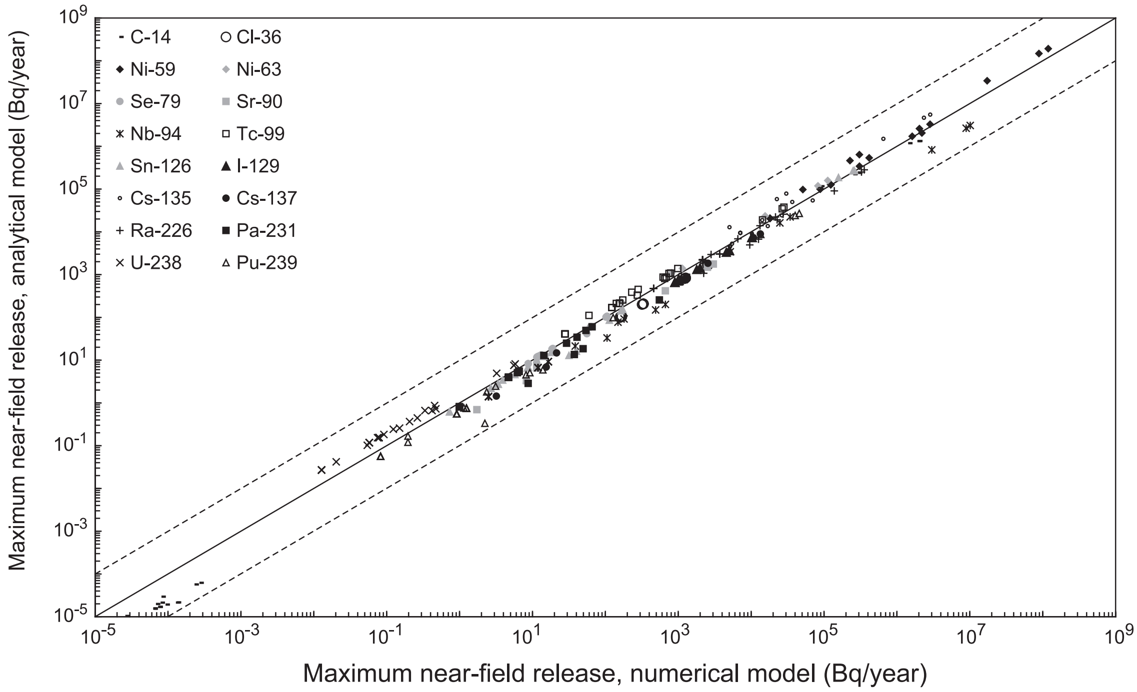

Figure 7-2. *Comparison of maximum annual releases for the three sites and the 16 most important nuclides in SR 97, calculated with numerical and analytical models. The figure shows the results of nine different calculation cases for each of the three sites in SR 97.*

- Shared solubilities will be introduced. This work is expected to be finished during 2001.
- Pulse spread from the Zircaloy tubes and other structural parts will be introduced. In COMP23, radionuclides can either be released immediately or gradually as the matrix is transformed. As a result, the entire inventory in the fuel's metal parts is released immediately. It would be desirable to be able to perform a more realistic modelling of the metal inventory. This has low priority for the time being, however.
- The evolution of the canister breach with time. Today COMP23 can describe different types of canister breaches:

  1. A breach of constant size (hole).
  2. A breach whose size grows at a constant rate.
  3. A breach that grows from one size to another all at once.
  4. Total lack of canister.

  Several courses of events will be introduced if needed, e.g. within the work on the evolution of a damaged canister, see section 5.2.16.
- Transport coupling between buffer and rock. To start with, COMP23 will be coupled to a discrete network model to get a more realistic description of the geometry of the near field. The next step is to try to develop a more realistic description of radionuclide transport between buffer and rock. Today's model describes the fractures in the rock as plane fractures that intersect the entire diameter of the buffer. It is hoped that a description can be developed that is in closer agreement with reality. This work will start at the end of 2001.

- Radionuclide transport in the backfill: COMP23 will be expanded so that it is possible to calculate simultaneous diffusion and advection in the backfill.

The transport of Sr, Cs and I from the bentonite barrier out to a water-bearing fracture will be studied in the CHEMLAB probe. Experiments will be performed to verify theoretical calculations showing that the transition resistance between bentonite and water is a significant retardation mechanism. The nuclides will be chosen to cover different diffusivity values in bentonite. The experiment is projected to take five months during 2003.

8 Geosphere

8.1 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. The hydraulic situation, i.e. groundwater flow and groundwater pressure, is in particular affected by the drainage. The hydrogeochemical situation is also influenced by the altered groundwater flow, as a result of which water of another composition may flow towards the repository. 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 designed and how long the repository 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, including methods to be used and conditions to be determined, is presented in special reports /8-1/. Research and development questions concerning measurement methods are dealt with in Chapter 13. The initial state is therefore not treated here.

8.2 Processes in the geosphere

8.2.1 Overview of processes

The geosphere will be heated up by heat transport from the fuel via the canister and buffer. The groundwater will be 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/backfill, effects of faults 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/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 and reaction processes. 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.

8.2.2 Heat transport

Conclusions in SR 97 and its review

Heat is transported in the bedrock principally by heat conduction in the intact rock. The thermal conductivity and heat storage properties of the rocks, which are both a function of mineral composition, are decisive for the process. To some extent, heat can also be transported by flow with the groundwater. Heat transfer from the buffer to the backfill and to the ambient environment comprises the boundary condition of the process.

In the authorities' opinion, the calculations in SR 97 show that the design criterion can be met by regulating the quantity of fuel or the distance between the canisters.

Conclusions in RD&D 98 and its review

Not dealt with.

Newfound knowledge since RD&D 98 and SR 97

No new knowledge has been forthcoming.

Research 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.

New temperature calculations will be performed for the site or sites in question in the next safety assessment.

8.2.3 Groundwater flow

Conclusions in SR 97 and its review

It is observed in the Process Report that the greatest uncertainties surrounding understanding and modelling of groundwater flow are associated with the natural heterogeneity of the rock. This heterogeneity means that a statistical approach must be utilized for modelling. The heterogeneity also entails scaling problems in the evaluation of field measurements; these scale effects should be taken into consideration when assigning parameters in a model. The most serious problems in modelling of groundwater flow were connected to scaling, which led to mass balance problems between models on different scales. Furthermore, the modelling tool HYDRASTAR's /8-2/ limitation in not being able to handle salinity-driven flow entailed problems in certain applications.

The regulatory review of SR 97 found that the use of a stochastic continuum method (SC) on the site scale is not properly justified. Furthermore, given the chosen discretization, the possibility of handling small-scale fractures, boreholes and plugs is questioned, as is the possibility of optimizing the repository design (layout). These limitations also make it more difficult to achieve a realistic description of repository performance. Furthermore, the authorities considered that a more systematic evaluation of model uncertainties in the regional models should be striven for, that the hydraulic and geochemical evolution should be integrated, and that it should be shown how important parameters in SR 97 can be measured during the site investigation phase. Finally, some criticism was levelled at how oxygen penetration was treated in conjunction with elevated groundwater flow in climate scenarios.

Conclusions in RD&D 98 and its review

It was noted in RD&D-Programme 98 that important goals for the future are to investigate upscaling questions and regional local flow patterns, and to have access to and increase the use of discrete models. An application with a discrete model was used already in SR 97, and development in this area continues, see below. Further, it was observed that the modelling tool HYDRASTAR should be updated on certain points (e.g. handling of hydraulic anisotropy and alternative setting of boundary conditions).

The authorities concurred in their review that upscaling and the role of regional flow for recharge and discharge areas are important factors. They further felt that the interplay between surface and deep groundwaters should be studied more closely to understand the coupling between geosphere and biosphere.

Newfound knowledge since RD&D 98 and SR 97

Many of the problems that were identified in SR 97 and RD&D-Programme 98 with HYDRASTAR have been addressed by development of other modelling tools. SKB is conducting development of the modelling tool NAMMU /8-3/ where the coupling between regional and local models is especially being studied /8-4/. Because the local model is built into the regional model, continuity is guaranteed between the different scales. Since NAMMU is better than HYDRASTAR in setting boundary conditions and can furthermore handle density-driven flow, it is probable that NAMMU will be used in future assessments at the expense of HYDRASTAR. However, this does not entail a change in course, but rather an efficient way to obtain a flexible and versatile modelling tool of high quality.

Incorporating local models in regional models, including explicit modelling of tunnels and rock vaults, has also been done in the hydrogeology modelling within the SAFE project /8-5/. The transient effects of land uplift and sediment accumulation were also analyzed there. The method results and experience from the SAFE project are valuable for future development and use of models within the site investigation phase.

Questions concerning alternative methods for creating hydraulic conductivity fields and upscaling of hydraulic conductivity have been analyzed by means of the modelling tool DarcyTools (previously called PHOENICS). The GEHYCO technique in DarcyTools is used to create conductivity fields based on discrete fracture network models /8-6, 8-7/. The resulting fields have properties that seem to describe conditions on Äspö well; furthermore, the fields seem to have small differences in flow between different discretization scales. This indicates that the method has attractive properties in terms of handling of upscaling. Results from an ongoing task (Task 5) by the Äspö Task Force on Modelling of Groundwater Flow and Transport of Solutes have yielded new knowledge concerning how geochemical data can be used to support models for groundwater flow. Task 5 is further described in section 8.2.21.

Research programme

A number of model studies and projects for model development will be conducted during the coming period.

The projects where NAMMU and DarcyTools are being used and refined will continue. The goal is to have two separate modelling tools that can be used in the site investigation phase for both site understanding and safety assessment. Using the same tools for both site understanding and safety assessment permits coordination of these activities during the site investigation phase. Two SKB reports describe how this coordination takes place in practice and where the responsibility for the coordination rests /8-8, 8-1/.

Interesting questions that can be analyzed with NAMMU and DarcyTools include how to incorporate a discrete description up to block scale (i.e. a scale of about 1–100 metres) in the continuum models. The goal is to have access to models with a discrete representation of fractures and tunnels nearest the repository. The discrete models should in turn be able to be directly incorporated in continuum models on the local and regional scales. Furthermore, the models should be prepared for a coupling to the database SICADA and its visualization tool RVS. DarcyTools will also be used to devise updated models of the Äspö HRL on both the regional and local scales.

In parallel with the above projects, which study how discrete models can be incorporated into continuum models, pure discrete models will also be used. The main purpose of the projects to develop discrete models is to achieve a better understanding of the flow-related parameters that are of importance for retention, see further section 8.2.23. The discrete models can also be used to achieve a better understanding of how optimization of a repository can be done with respect to e.g. layout or safety.

In addition to continuum models and discrete models, the development of the channel network model CHAN3D is also continuing.

Questions concerning upscaling of parameters from a detailed scale to scales relevant to the safety assessment will be elucidated in a modelling task (Task 6) by the Äspö Task Force on Modelling of Groundwater Flow and Transport of Solutes. Models on different time and space scales will be used and evaluated in the task, which is based on data from above all the TRUE-1 and TRUE Block Scale projects at the Äspö HRL. The purpose is to understand how different models, all of which can describe phenomena on small time and space scales, work (or must be modified) when applied to larger scales. This project includes both flow and transport properties.

Projects concerning recharge and discharge areas and the coupling between surface and deep groundwaters are planned. The purpose is to study how watercourses, lakes, local topography and the occurrence and orientation of fracture zones influence the flow pattern, as well as how the surface hydrology influences the discharge conditions for groundwater of deeper origin. Assignment of boundary conditions on the top surface of the models can also be studied in these projects. In modelling with greater realism in the surface hydrology, there may also be reason to consider how the boundary conditions are formulated. Questions surrounding surface hydrological modelling are also discussed in section 9.5. Model calculations will also be performed to judge the influence of the repository on groundwater flow and depth to saline groundwater during the operating period.

Based on the results from Task 5 by the Äspö Task Force on Modelling of Groundwater Flow and Transport of Solutes, the question of utilizing geochemical data for modelling of groundwater flow and radionuclide transport will be pursued further, see also section 8.2.21. Modelling of groundwater flow in different climate scenarios and modelling of oxygen penetration in conjunction with glaciation will also be initiated. Questions surrounding oxygen penetration will be further discussed in section 8.2.14.

The question of whether groundwater flow should be analyzed coupled to other processes, mainly thermal or mechanical, will be kept under surveillance. A forum for such surveillance is DECOVALEX III (BENCHPAR), where the importance of coupled THM processes is analyzed. These questions are also discussed in 8.2.7. Modelling of coupled processes will probably mainly be used in analysis of repository construction and positioning of waste canisters /8-9/.

As far as the coupling between measurements in site investigations and input data to the safety assessment's models is concerned, see section 13.3.

8.2.4 Gas flow/dissolution

Conclusions in SR 97 and its review

No questions for further research were identified in SR 97 or its review.

Conclusions in RD&D 98 and its review

In RD&D-Programme 98, it was noted that knowledge should be compiled and acquired regarding two-phase flow and gas transport. Otherwise, no questions for further research were identified in RD&D-Programme 98 or its review.

Newfound knowledge since RD&D 98 and SR 97

A report on two-phase experiments conducted at the Äspö HRL has been published /8-10/. The results of these experiments are also discussed in section 8.2.18. In this section it is observed that for normal deep repository conditions, two-phase flow is not judged to lead to any appreciable reductions of the water flow in fractures that intersect open boreholes /8-10/. This indicates that gas flow at boreholes and tunnels is not problematic for the safety assessment.

Knowledge of two-phase flow and gas migration has been compiled in a joint project within the EU and the NEA /8-11/. The report identifies problems, conceptualization and still open questions for storage of spent fuel in fractured rock. The report concludes that certain fundamental questions concerning two-phase flow in fractured rock remain to be solved, such as on what scale phenomena are to be described, and how parameters and constitutive relationships are to be determined.

Research programme

The need for the compilation mentioned in RD&D-Programme 98 may be considered to be met by the publication of the EU/NEA report /8-11/. Certain questions have also been addressed in /8-10/.

Aside from specific details identified in /8-11/ which may require further analysis, the field is judged not to require any further research, development or demonstration today. New developments are being monitored and will be acted on when appropriate.

8.2.5 Movement in intact rock

In SR 97, "movement in intact rock" refers to the primarily elastic movements that occur without visible fracturing at moderate loads. No questions for further research were identified for this process in SR 97 or its review.

Conclusions in RD&D 98 and its review

No questions for further research were identified in RD&D-Programme 98 or its review.

Newfound knowledge since RD&D 98 and SR 97

A testing programme has been carried out for determination of the mechanical properties of the diorite that occurs widely in the Äspö HRL /8-12/. The testing programme has yielded additional parameter values for the elasticity properties.

Research programme

Methods for developing descriptive rock-mechanical models for potential repository sites will be developed for the site investigations. The need for any research initiatives when it comes to description and understanding of movements in intact rock will be analyzed within the programme for this method development.

8.2.6 Thermal movement

Conclusions in SR 97 and its review

In SR 97, "thermal movement" refers to the fundamental thermomechanical process of volume expansion in response to temperature increase. No questions for further research were identified for this fundamental process in SR 97 or its review. However, thermal processes generate stresses that can give rise to both reactivation and fracturing. In SR 97, the effects of thermal movement are therefore handled under these process headings.

Conclusions in RD&D 98 and its review

No questions for further research were identified in RD&D-Programme 98 or its review.

Newfound knowledge since RD&D 98 and SR 97

No results that pertain expressly to the process have been reported.

Research programme

Methods for developing descriptive rock-mechanical models for potential repository sites will be developed. The need for any actions when it comes to description and understanding of thermal movement will be analyzed within the programme for this method development.

8.2.7 Reactivation – movements along existing fractures

Conclusions in SR 97 and its review

I SR 97, "reactivation" refers to all types of movements in existing fractures or fracture zones, i.e. both shear movements and normal movements. The process is of potential importance for safety in two ways:

A. Mechanical. The geometry of the deposition holes can be affected so that canisters are loaded to failure.

B. Hydromechanical. The flow conditions, and thereby the retention properties of the rock, can be influenced by aperture changes in fractures and fracture zones.

A. Mechanical effects

For the base scenario, in which earthquakes by definition are not included, it is possible by reference to results from quantitative calculations, where conservative assumptions are made about the thermomechanical load, to draw the conclusion that the process will not cause canister damage. This assumes that no deposition holes are intersected by fractures several hundred metres long and that the canister damage criterion (10 cm shear) that has applied to date also remains valid in the future.

The above also applies in principle to the climate scenario, in which earthquakes by definition were not included in SR 97. There is, however, one uncertainty as regards the load acting on the host rock. Depending on how the interaction between the ice, the earth's crust and the viscous mantle is described conceptually, flexural stresses can vary.

For the tectonic scenario, a risk analysis is done in SR 97 that is based in part on prediction of future earthquake frequencies, and in part on a method for calculation of the mechanical effects of individual quakes in the form of reactivation of the fractures in the host rock. The conclusion of the risk analysis is that the risk of canister damage in the tectonic scenario is so small that no radionuclide transport calculations are warranted. It is emphasized in SR 97 that the risk analysis contains uncertainties, and that not all uncertainties are handled pessimistically. The safety margins that are incorporated in the pessimistically handled uncertainties are deemed to be so large that the conclusion – that the current state of knowledge does not justify conducting radionuclide transport calculations specifically for the tectonics scenario – still holds true. The following important uncertainties are noted:

- The prediction of future earthquake frequencies is based on extrapolation of statistics concerning seismic activity in the Swedish bedrock. The effects of a glaciation cycle, with accompanying elevated seismic activity in the deglaciation phase, are therefore not taken into account. The estimated number and magnitudes of the postglacial fault movements that took place in northern Lapland in conjunction with the most recent ice age indicate that the underestimation may be considerable.
- In the method that is used to calculate the effects on the fractures in the host rock, it is assumed that the dynamic effects can be represented by a static load so that the additional stress is equivalent to the liberated seismic energy. The results need to be compared with results obtained with independent, dynamic calculation methods.

For the tectonics scenario, the authorities comment that the extrapolation to 100,000 years is not relevant, since the seismic activity that can be expected in conjunction with a deglaciation has not been taken into account.

The authorities question the correctness of the assumption that future seismic events will exclusively take place along existing fracture zones. The possibility that future fault movements may take place in part along new lines must be taken into consideration.

The authorities would like to see a stricter definition of the concept of (seismic) "respect distance", and a description of how and when the definition should be applied.

The authorities take the view that the canister damage criterion which now underlies the risk analysis should be verified or modified with new calculations that take into account the current canister design.

B. Hydromechanical effects

The process is of potential importance for the flow conditions in the rock and thereby for the conditions for radionuclide transport from defective canisters. This aspect of the process is only dealt with summarily in SR 97. In the near field, it is assumed that none of the future loads will cause systematic changes in the transmissivity of the fractures, and the effect is therefore not explicitly taken into account in the nuclide transport calculations. Beneath the ground surface, on the other hand, down to a depth of a few hundred metres, a systematic widening of steeply-dipping fractures and fracture zones is obtained during the thermal pulse. This is based on results of quantitative thermomechanical analyses. In view of the moderate depth of the effect in relation to the repository depth and of the fact that fracture zones and fractures at less distance from the repository, including steeply-dipping ones, are compressed during the thermal pulse, the effect is not taken into account in the nuclide transport calculations.

In SR 97, the Process Report, it is stated that the effect of fracture movements on flow conditions, both in the near field and at greater distance, has not been adequately systematically investigated to enable it to be definitively dismissed.

Generally, the authorities point out that the results of coupling effects are not dealt with in SR 97. The authorities further consider that SKB should investigate what requirements may exist on using and possibly developing coupled models.

The effect of the heat pulse on the fracture system, in the form of permanent changes in the fracture system and thereby the flow conditions, should be dealt with more thoroughly.

Conclusions in RD&D 98 and its review

In RD&D-Programme 98 it is pointed out that the positioning of the repository in relation to major deformation zones will be taken into account. The reason is that earthquakes can lead to displacements in the repository. The authorities emphasize that SKB must make it clear what knowledge is sufficient and what additional measures are required, especially with regard to regional plastic shear zones (tectonic lenses) and the prospects of siting in or near such zones.

Newfound knowledge since RD&D 98 and SR 97

A. Base scenario

Another thermomechanical study was completed during 2000 /8-13/. The results confirm that fractures several hundred metres in length would have to intersect a canister hole in order for reactivation to lead to canister failure.

B. Tectonics scenario

A study intended to shed light on the implications of the safety margins that are incorporated in the risk analysis in the tectonics scenario (SR 97) was concluded during 2000 /8-14/. The study shows that above all the assumption that the fractures in the host rock are friction-free has led to a substantial overestimation of risk. The assumption that the host rock is linear-elastic, i.e. that no strain energy goes into fracture formation, also entails overestimations of the risk of canister failure.

The Boda caves in the vicinity of Iggesund have been investigated by drilling and geophysical measurement methods. Hypotheses have previously been put forward that the cave formations were formed by seismic movements in conjunction with the most recent glaciation. No traces of fracturing at depth that would support this hypothesis have been found. The results that have now emerged suggest that the caves were formed by glacial erosion processes /8-15, 8-16/.

Research programme

Methods for developing descriptive rock-mechanical models for potential repository sites will be developed for the site investigations. In general, the need for further research initiatives when it comes to description and understanding of reactivation will be analyzed at an early stage of the programme for this method development. Otherwise, the research initiatives described below are planned.

A. Mechanical effects

Both SR 97 and its review show that research needs as regards the purely mechanical aspects of the reactivation process above all concern the tectonics scenario. The reactivation process includes both the primary movement in the seismically active zone and secondary movements, e.g. in the fracture system in the host rock.

Three prioritized research areas can be distinguished:

- Prediction of future earthquake frequencies.
- Mechanisms behind earthquakes, i.e. whether fault movements will occur along existing structures, or via some form of new fracturing.
- Effects of faulting on the repository.

Prediction of earthquake frequencies

The frequency/magnitude relationships assumed in SR 97 to apply to different regions in Sweden does not include effects of a future glaciation cycle. The relationships are based on the fact that large-scale plate-tectonic movements lie behind today's seismic activity. Effects of slow differential land uplift or of direct load changes in combination with liberation of accumulated strain energy, so-called "postglacial faulting" (PGF), are not included. Various initiatives will be taken to shed light on and increase understanding of what the roles and extent of land uplift and PGF are now and have been historically. The frequency/magnitude relationships are based on regression relationships that have been derived from international databases. The databases used may have to be refined so that regression relationships relevant for areas similar to the Baltic Shield can be derived.

A study of documented postglacial faults is currently under way and will be finished during 2001. The purpose is to compile known postglacial faults that have been documented in Scandinavian and Canadian bedrock. The study includes accounting for the possible coupling to older deformation zones, critically examining and compiling the magnitude calculations done previously, and if possible estimating how the parameters in the frequency/magnitude relationships should be modified so that effects in direct conjunction with the deglaciation are not neglected. Another independent study with the sole purpose of estimating these parameters will be conducted at Uppsala University.

The network of seismographs that now exists between Gävle and Örnsköldsvik will be extended further southward to Oskarshamn. The detection level will be quakes of magnitude 0.5. The network will be densified around Oskarshamn and northern Uppland County so that quakes with a magnitude of down around –0.5 can be detected. The purpose is to generally acquire a better understanding of large-scale movements in the shield, with a focus on the areas where site investigations will be done.

A network of seismographs is planned to be installed in the area around Lansjärv in northern Lapland. The purpose is to investigate what type of movement is now occurring in zones where large postglacial faulting is believed to have taken place earlier, and to acquire a better understanding of these movements.

Mechanisms behind earthquakes

A study of methods for dating of fracture and fracture zone materials has been commenced and will be concluded during 2001 /8-17/. The purpose is to acquire a better understanding of the deformation history of fracture zones in order to be able to judge whether parts of potentially active fracture zones may have been newly formed, e.g. in conjunction with the most recent glaciation, or whether postglacial fault movements are generally pure reactivation episodes.

Effects of faulting on a repository

A programme for calculating deformations in the fractures in the host rock with the aid of dynamic numerical models has been commenced with a pilot study. The objective is to determine relationships between the distance to the earthquake, the magnitude of the earthquake and the maximum shear deformation of a given fracture in the repository, so as to be able to determine seismic respect distances to potential earthquake zones. The programme has two main components:

- to derive boundary conditions that correspond to earthquakes of a given magnitude that take place at a given distance, and
- to assign boundary conditions to suitably designed models.

Standard methods and codes, e.g. WAWE, exist for numerically generating synthetic earthquakes of varying magnitude and character. Several established codes – e.g. UDEC, FLAC3D, 3DEC – may be considered for analysis of the effects in the host rock. In the recently completed pilot study, WAWE was used to determine boundary conditions and FLAC3D to analyze the effects. After evaluation of the pilot study, the application is intended to be developed during the coming years.

A programme has been initiated for compiling information on the documented impact of earthquakes on underground facilities. The purpose is to obtain empirical evidence pertaining to the concept of respect distance. The results will be integrated with the numerical analyses that have been initiated and planned.

A compilation of the effects of earthquakes on underground structures is under way. The project is being pursued in close contact with SKB's international sister organizations.

B. Hydromechanical effects

A general programme for review and evaluation of results generated within the field of rock-mechanical modelling during the past decade will be conducted. The purpose is also to identify knowledge gaps. The programme concerns not just the reactivation process, but all rock-mechanical problems that might be of importance for the design and long-term safety of the deep repository. An initial phase, consisting of an extensive inventory of papers published within the field, is finished. Questions having to do with hydromechanical effects will also be taken into consideration in this programme. Moreover, during the next few years programmes must be initiated to clarify what mechanically (or thermomechanically) induced changes in the permeability of the near-field rock and the far field can be permitted from a safety point of view. Within the framework of the international project DECOVALEX III, work is under way to clarify the need for conducting coupled analyses. SKB will continue to participate in this work.

8.2.8 Fracturing

Conclusions in SR 97 and its review

In SR 97, "fracturing" refers to both formation of new fractures and propagation of existing fractures. Two potential effects on safety are identified: direct mechanical impact on canisters, and effects in the form of changed flow conditions.

In general, SKB maintains in SR 97 that our understanding of how the process should be handled in calculations is inadequate. Developed theoretical models for fracturing and fracture propagation exist, but there is no good knowledge of how to translate these models into practical calculation models. There are, on the other hand, experience-based strength criteria.

The conclusion in SR 97 is that as far as changes in the deposition hole geometry and thereby the risk of mechanical damage to the canister are concerned, the process is of little importance compared with the reactivation process. The areas around the canister holes that are near a failure state, or in which a failure state can be induced by future loads, are small. These conclusions are based on the application of experience-based failure criteria, and on approximate specifications of typical values of strength parameters. This applies to the base scenario and the climate scenario. The importance of the process in the tectonics scenario has not been investigated, but is assumed to be less important than the reactivation process there as well.

The hydromechanical aspect, i.e. permeability changes due to fracturing, is not dealt with in SR 97.

The authorities believe that the scope of the testing of rock specimens that has been done to determine strength and deformation properties is too small. Otherwise, the authorities offer no viewpoints on the treatment of the process as such.

Conclusions in RD&D 98 and its review

The process is not commented on expressly in these documents.

Newfound knowledge since RD&D 98 and SR 97

A testing programme has been carried out for determination of the mechanical properties of the diorite that occurs widely in the Äspö HRL /8-18/. The testing programme has yielded parameters for two different strength criteria: Mohr-Coulomb and Hoek-Brown.

Research programme

Methods for developing descriptive rock-mechanical models for potential repository sites will be developed for the site investigations. In general, the need for further research initiatives when it comes to description and understanding of the fracturing process will be analyzed within the programme for this method development. Otherwise, the research initiatives described below are planned.

Development work is under way within the project Review and Development of Fracture Initiation Criteria. The objective is to formulate fracture propagation criteria that can be implemented in code for simulation of brittle fracturing in stressed rock around the cavities in the repository.

A research programme has been formulated aimed at investigating the role of the backfill/buffer in limiting the occurrence and development of progressive brittle failures in tunnel walls and deposition hole walls. The programme will take the form of a doctoral thesis at the University of Alberta in Canada.

8.2.9 Time-dependent deformations

Conclusions in SR 97 and its review

In SR 97, "time-dependent deformations" refers to both deformations that occur due to slow continuous load changes (caused by large-scale tectonic movements) and deformations (creep movements) due to the inherent time-dependent deformation properties of the rock mass.

The effect of load changes is bounded in SR 97 by using estimates of tectonically induced average strain rates in the Baltic Shield and translating them to stress growth. No credit is taken for the effects of absorption of the strain in deformation zones. The hypothesis is therefore generally deemed to be conservative. The conclusion is that the stress growth does not lead to deformations that could damage the canister. There is, however, uncertainty when it comes to the distribution of the strains, since the possibility cannot be excluded that there are regions with a greater strain rate than average.

Our conceptual understanding of creep movements in rock is poor, which means that the effects cannot be quantified or described in detail. The effects of creep movements are therefore approximately bounded in SR 97. If the rock behaves like a viscous fluid, the canister holes can be compressed until the bentonite's swelling pressure corresponds to the mean compressive stress in the rock. If the creep movement is instead limited to existing fractures, the movement can proceed until all shear stresses in all fractures have disappeared. The conclusion is that the canister can be damaged if the deposition hole is intersected by fractures several hundred metres in extent.

The process is not commented on expressly in these documents.

Conclusions in RD&D 98 and its review

The process is not dealt with expressly in these documents.

Newfound knowledge since RD&D 98 and SR 97

No results that expressly concern the process have been reported.

Research programme

A testing programme will be carried out aimed at computationally bounding the effects of creep-induced convergence of deposition tunnels. The purpose is above all to clarify what influence the mechanical properties of the backfill will have on convergence. The programme may lead to more fundamental analyses of creep movements in fractures. Time-dependent deformations in the intact, solid rock will continue to be regarded as negligible in comparison with the deformations that occur in existing fractures.

8.2.10 Erosion

Conclusions in SR 97 and its review

In SR 97, the process of erosion was not deemed to be of importance for the long-term safety of the repository.

The authorities observe that several potentially unfavourable FEPs have been excluded from the risk analysis in SR 97 on more or less good grounds, for example for the reason that they are improbable. One example given is long-term erosion of the geosphere.

Conclusions in RD&D 98 and its review

The process is not dealt with expressly in these documents.

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Newfound knowledge since RD&D 98 and SR 97

Erosion of crystalline rock has been little in most near-coast areas, while for example the Swedish Highland bears traces of more extensive erosion.

Research programme

SKB has made the judgement that long-term erosion of the geosphere is of subordinate importance for long-term performance and safety. There are, however, uncertainties regarding how deeply erosion can occur in deformation zones. SKB therefore intends to initiate an investigation aimed at answering this question.

8.2.11 Advection/mixing

Advection and dispersion in transport pathways is dealt with in the section on radionuclide transport. 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.

Conclusions in SR 97 and its review

Groundwater chemistry data from three different places were used in SR 97. They were evaluated and compared with each other based on the assumption that the water in the bedrock is mixed as a result of its advective transport and that this is the main reason why the water chemistry varies within and between the sites. With knowledge of what hydrogeological conditions currently prevail and prevailed earlier, a model was devised for the hydrogeochemical evolution on the three sites. Despite the fact that the quantity and quality of data varied from site to site, it was possible with this model to make a reasonable prediction of how the groundwater chemistry may evolve in the future on all three sites.

Mixing occurs in parallel with reactions. It is therefore difficult to discuss mixing as a isolated phenomenon, but this difficulty can be overcome with the methodology used in SR 97 /8-19/.

Conclusions in RD&D 98 and its review

> "SKI considers that SKB has made significant progress within the groundwater chemistry programme, with the aid of experience gained at the Äspö HRL. SKI welcomes continued efforts to refine the M3 method and believes that SKB has a highly useful tool for future site investigations. However, SKI wishes to point out that the method only partially covers the processes that are expected to be significant in the context of the repository, and that all interpretation models are dependent on the quality of the data on which they are based. SKI questions SKB's conclusion that the knowledge about the origin and evolution of different types of water acquired through the research at Äspö is directly useful in all conceivable site evaluation."

Newfound knowledge since RD&D 98 and SR 97

Mixing calculations that were originally performed with data from the Äspö area have been supplemented by calculations where data from other investigated sites in Sweden and Finland are included. It turns out that the mixing pattern is similar, but the proportions of the different "typical waters" varies from site to site /8-20/. 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.

Attempts have been made to include not only the chemical parameters but also hydrological data in the calculations of mixing proportions, so far without positive results. Results from the modelling task, Task 5, by the Äspö Task Force on Modelling of Groundwater Flow and Transport of Solutes have shown that it is possible to handle the advection/mixing process numerically on a large scale and thereby utilize both hydrological and chemical data.

Research programme

In future site investigations, site-specific mixing calculations will be one of the more important tools for understanding the evolution of the water on the site. It is possible but perhaps not probable that mixing calculations will show the presence of different types of water on the different sites.

See also section 8.2.21.

8.2.12 Diffusion

Molecular diffusion and matrix diffusion, and their importance for nuclide transport, are dealt with in the section on radionuclide transport. This section deals with the effects of molecular diffusion globally in a very long time perspective and how the process affects the hydrochemical conditions.

Conclusions in SR 97 and its review

No questions for further research were identified in SR 97 or its review.

Conclusions in RD&D 98 and its review

Calculations that were presented in RD&D-Programme 98 show that the salinity profile that was measured in the borehole KLX 02 largely agrees with a diffusive transport that has been in progress for on the order of one million years. Measurements of the residence time for the same water give 1.5 million years /8-21/.

SKI considers that SKB must more clearly justify its conclusions that the presence of so-called brines is a clear indicator that stagnant conditions prevail.

Newfound knowledge since RD&D 98 and SR 97

Site investigations in Finland have indicated very similar hydrogeochemical conditions in Olkiluoto and in Äspö. 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 ten thousand years /8-22/. This indicates that a dynamic process controlled by inflow of water from above in high-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. The fact that there appears to be a clear boundary between the dynamic regime and the deeper rock is interpreted as indicating that a water regime has existed for a long time that has developed a higher salinity than the overlying water. With the steadily increasing salinity of the water, as salt is dissolved from the rock matrix, the stagnant water has become even less mobile. It is not possible to say that the water is completely immobile, but in comparison with the overlying dynamic water its mobility is considerably lower, presumably in proportion to the measured residence time. If the dynamic water has a measured residence time of 1,000 to 10,000 years, the corresponding value for the stagnant water is a million to ten million years /8-21/. It can thereby be roughly assumed the flow is also a factor of 1,000 lower under otherwise identical conditions. The conclusion is that the water, which is mobile in a geological time perspective, can be considered to be stagnant in a 10,000–100,000-year perspective.

Research programme

Numerical modelling to exemplify the presence of brines under various boundary conditions is planned. The most important question to answer is: What is required for a brine to be formed, and what is required for it to be persistent? A related question is how to identify a stagnant or slowly moving water.

8.2.13 Reactions groundwater/rock matrix

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.

Conclusions in SR 97 and its review

The authorities stated that "to describe the importance of buffer erosion and colloid formation, SKB probably have to develop a more detailed model of the long-term evolution of the groundwater chemistry."

Conclusions in RD&D 98 and its review

SKI considers it urgent that SKB continue investing resources in models and experiments for studying chemical processes in deep groundwaters. These models and experiments should be able to show integrated effects of processes which are controlled by e.g. kinetics, microbial catalysis and chemical equilibrium.

What is essential is to assemble material as a basis for judging how the chemical conditions may be affected by the changes and disturbances that can occur (changed climate, changed groundwater flow, repository's impact on groundwater chemistry, etc.). SKB mentions a number of geochemical equilibrium codes each of which has its own thermodynamic database. SKI believes that a higher degree of consistency could be attained if SKB only uses one selected and verified database that can be adapted to all codes.

Newfound knowledge since RD&D 98 and SR 97

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 is under way at the Äspö HRL aimed at studying the matrix water composition.

The main goals of the experiment are to:

- Determine the age and origin of the matrix water.
- Ascertain whether ongoing or earlier diffusion processes have affected the composition of the matrix water by either dilution or increased concentration.
- Obtain a selection of groundwater compositions as suitable input data to near-field model calculations.
- Ascertain the influence of thin fractures and microfractures on the chemistry of the matrix water in the bedrock.

The experiment has been designed to sample matrix water from predetermined isolated borehole sections. The location of the borehole was chosen on the basis of e.g. rock type, minerals and geochemical homogeneity, depth, and presence or absence of fractures. Special equipment has been designed to sample matrix water.

An extensive investigation programme has been under way since the autumn of 1999 with activities involving mineralogical studies, porosity measurements, crushing/leaching experiments, permeability tests on Äspö diorite, studies of liquid inclusions and sampling of matrix water. Furthermore, groundwater and hydraulic data from TRUE, Prototype, Chemlab and Microbe experiments representing the bedrock environment in the vicinity of the borehole for the matrix experiment have been compiled and interpreted.

Crushing/leaching experiments and studies of liquid inclusions suggest that there is a strong source of salt in the rock, but it seems to mainly occur in the form of liquid inclusions. An experiment is being conducted to sample the actual matrix water (i.e. unbound water between the mineral grains) by using high-pressure equipment in the laboratory to expel unbound matrix water.

The sampled water from the borehole section in the Äspö diorite has an average salinity that reflects the ionic character of groundwater compositions in nearby fractures (with the exception of SO_4^{2-} and Mg^{2+}). The difference is chlorine and strontium isotope signatures and a higher concentration of most trace elements. Surrounding groundwater indicates that the more transmissive fractures are influenced by an influx of a contemporary groundwater component, such as the Baltic Sea and meteoric precipitation water, which is associated with the hydraulic drawdown caused by the tunnelling, at the expense of older saline water and glacial meltwater that has been diluted or carried away.

On the other hand, the matrix sample reflects groundwater that has penetrated down into the bedrock prior to the tunnelling and thus retained less diluted signatures of both glacial and older saline water. 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 and that most of it comes from fractures and microfractures that are in connection with larger structures. There is thereby at present no reason to suspect that a very saline water will seep into the deposition holes.

Research programme

A doctoral project has recently been started to study long-term effects on the groundwater chemistry in the deep repository. The work is focusing on redox reactions between groundwater and bentonite clay, since such reactions are considered to have a real potential to affect the natural water chemistry. Other weathering reactions between rock minerals and groundwater will be included to the extent they can also be considered to be of importance.

Chemical effects after repository closure up until original conditions are restored will be investigated as a separate project starting at the point when information is available from the selected candidate sites. These data, together with the design document, provide the necessary basis for scoping calculations.

See also section 8.2.21.

8.2.14 Dissolution/precipitation of fracture-filling minerals

Dissolution and precipitation of fracture-filling minerals is a constantly ongoing process. Even though the greater part has been formed under hydrothermal conditions, low-temperature minerals can be utilized to understand the evolution of the groundwater chemistry.

Conclusions in SR 97 and its review

The Process Report states that there is an uncertainty regarding the origin of certain iron oxides, and where it is of importance whether they have arisen under hydrothermal conditions or by oxidation of oxygenated groundwater.

The authorities were of the opinion that "a limited occurrence of oxygen in time and space at repository depth is less probable but cannot be excluded through the model studies, laboratory experiments or geochemical investigations that have so far been presented."

The international review team (IRT) said the following: "An important requirement for the long-term integrity of the EBS (engineered barrier system), in the KBS-3 concept, is the re-establishment and preservation of a reducing groundwater environment around the disposal galleries. Therefore, a clear identification and evaluation of all events, conditions and processes that could threaten the reducing state of the repository or its buffering capacity is required. The IRT identified the possible presence and effect of oxygenated glacial melt water penetrating to repository depth as a possible threat that deserved fuller consideration. Discussions revealed that SKB has confidence in reducing conditions at depth based on a range of arguments but these are not fully articulated in SR 97."

Conclusions in RD&D 98 and its review

SKI found that "it is important to produce material to be able to assess how the chemical conditions can be influenced by the changes and disturbances which may occur."

Newfound knowledge since RD&D 98 and SR 97

Oxidizing conditions at repository depth can mainly be broken down into two subproblems:

- The repository will be oxygenated during construction and operation. Some oxygen will thus probably remain in the repository and its vicinity until 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 /8-23/.

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 sources/8-24/. Data were also used to model the migration of a redox front /8-25/.

Evaluations of both water chemistry /8-19/ and fracture mineralogy /8-26/ show that there are clear indications that components of a glacial meltwater have reached great depths (>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 /8-26, 8-27/. It is therefore very misleading to automatically associate the presence of glacial meltwater with oxidizing conditions.

The importance of being able to substantiate reducing conditions backward in time (in order to be able to model forward) has underscored the importance of carefully mapping redox-sensitive fracture-filling minerals prior to future site investigations.

In the REX Project (Redox Experiment in Detailed Scale), studies were made of how oxygen that remains after closure of a repository can react with minerals and groundwater in the rock in the tunnel, the deposition holes or along the water-bearing fractures. The REX project consisted of:

- Field studies of microbial uptake of oxygen at several places along the Äspö tunnel.
- In-situ injection of oxygen and follow-up of oxygen uptake at an isolated fracture surface in the Äspö tunnel.
- A laboratory experiment with the other half of the fracture surface that was used in the in-situ experiment (so-called replica experiment).
- Laboratory experiments with groundwater, bacteria and mineral samples from Äspö aimed at supporting the interpretation of the field and replica experiments.

The results from the in-situ experiment were confirmed by the 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. For example, different microbial processes occurred in the two experiments.

Laboratory tests with rock fragments showed that microbial activity caused an increased formation of clay minerals. The rate of oxygen uptake on fracture-filling materials (mainly hydrothermally altered Äspö diorite with chlorite, calcite and clay minerals) was determined under laboratory conditions. These rates were higher than those reported for pure mineral systems and confirmed the rapid oxygen uptakes that were measured in both field and replica experiments.

The project has been concluded and reported /8-28/. The main conclusions are:

- 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 8.2.15.

EQUIP is a project in which the UK, France, Spain, Finland and Sweden have participated. The purpose of the project is to utilize fracture minerals as indicators of present-day and previous groundwater chemistry. Different methods have been applied to several types of fracture-filling minerals from one site in each country. The general usefulness of the methods has then been evaluated.

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.

Many laser ablation-based microanalytical techniques (analysis of a point of size 10–20 µm with regard to elemental or isotopic composition) shows very promising results. On the other hand, it is important to combine the microanalyses with a comprehensive picture in which thorough core mapping, textural studies based on microscoping of thin sections and general chemical and geological-isotopic information from bulk analyses comprise the backbone.

The work is reported in /8-26/. A continuation under the name PADAMONT is planned for 2001–2004.

Research programme

The results from the REX experiment will be utilized in repository optimization and design. New calculations are planned regarding how deep a glacial water can penetrate and how deep oxygenated glacial water can reach before its oxygen has been consumed, see further under hydrological processes. Beyond this, 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.

In nuclide transport models, retention is regarded as a reversible process and described with a distribution factor, K_d. This approach may be conservative from a safety assessment point of view, since it underestimates retention. On the other hand, processes such as co-precipitation and other immobilization cannot be described in an acceptable fashion.

Today there are analytical-chemical methods that can be used to study such processes and thereby provide data for quantitative calculations. Research efforts will therefore be devoted to such investigations during the coming six-year period. If the results prove to be useful, the co-precipitation reaction in calcite, and possibly iron hydroxide, will be able to be included in nuclide transport models in the future.

8.2.15 Microbial processes

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.

Conclusions in SR 97 and its review

SR 97: "Iron hydroxide and microbe precipitations that are formed when reducing groundwater seeps out and meets atmospheric oxygen in tunnels create large quantities of organic material. At closure of the repository, the organic carbon can be assimilated by other microbes, e.g. to reduce remaining oxygen."

Conclusions in RD&D 98 and its review

The following is noted from the review of RD&D-Programme 98:

> "Models and experiments should be able to show integrated effects of e.g. kinetics, microbial catalysis and chemical equilibrium."
>
> "In SKI's view, SKB, through its microbiology work, has contributed towards a decided improvement in the basic scientific understanding of microorganisms in deep groundwaters, which also provides a firm basis for being able to predict the effects on the long-term safety of a repository. As work continues, a clearer integration of microbial studies, principally with geochemistry but also with safety assessment and site characterization, is anticipated."

Newfound knowledge since RD&D 98 and SR 97

During the 1990s, 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 from the surface of the earth, while others can live on methane and hydrogen gas from the earth's mantle.

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 /8-29/. 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 /8-30/.

A specially-furnished room at a depth of 420 metres in the Äspö HRL permits continued studies of microbes and their importance in the deep repository in a project named MICROBE, see Figure 8-1 /8-31/. The MICROBE room has been instrumented and the chemistry and microbiology of the groundwater have been characterized and reported /8-32/. The composition and microbial content of the groundwater are fairly typical of groundwaters at this depth.

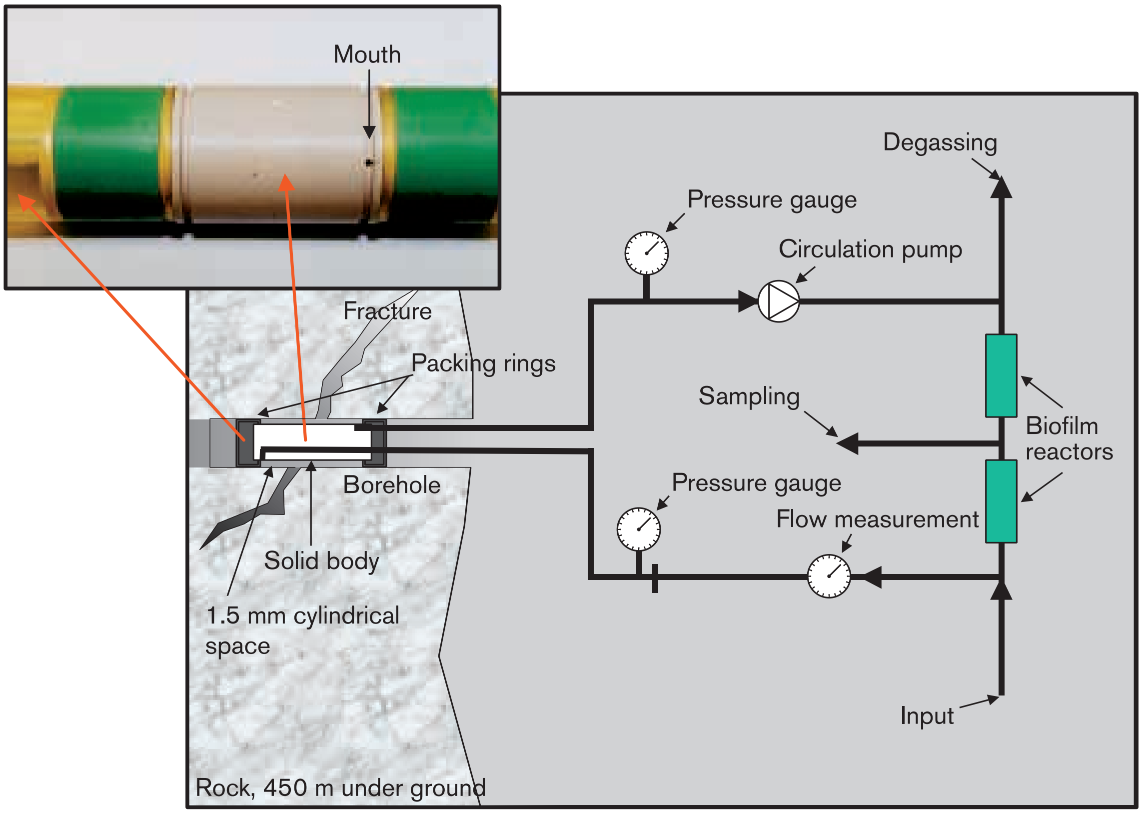

Figure 8-1. *Design of the experimental set-up of MICROBE. Water-bearing fractures are interconnected by separate circulation systems in the container outside the boreholes. Groundwater can circulate or be sampled from the system. In biofilm reactors it is possible to study how microbes on fracture surfaces can influence radionuclide transport. Inside the borehole is a solid body which, together with the small diameter of the pipes (about 2 mm), keeps the dead volume in the system very low.*

Research programme

The research efforts to date have largely been focused on processes that can be related to the near-surface hydrological turnover of groundwater that infiltrates up on the ground surface and is carried in the bedrock down to depths that are dependent on both historical and currently prevailing conditions.

Continued efforts will also extend to "deep microbiology" and processes that proceed without being affected by the near-surface water turnover. The influence of microbes on the redox stability of the rock will be studied in MICROBE at a depth of 420 metres in the Äspö HRL. MICROBE will also serve as a very well-characterized testing site for experiments requiring repository-like conditions. One important such research area concerns migration, survival and activity of sulphide-forming bacteria (sulphate-reducing bacteria) in buffer material, since sulphide is corrosive to the copper canisters. The influence of the microbes on radionuclide transport also requires an experimental area with repository-like conditions for when constants, processes and models developed in the laboratory need to be tested under realistic conditions.

8.2.16 Decomposition of inorganic engineering material

The process is of importance in an initial phase when the conditions are affected by the construction of the repository.

Conclusions in SR 97 and its review

The authorities say the following in their review: "The quantity of organic material that may be left behind after closure, or whether or not it is acceptable to leave large quantities of cement near to the deposition holes are not described in SR 97."

Conclusions in RD&D 98 and its review

No questions for further research were identified in RD&D-Programme 98 or its review.

Newfound knowledge since RD&D 98 and SR 97

No new knowledge has been forthcoming.

Research programme

A project is planned in cooperation with e.g. Posiva for the purpose of clarifying effects of concrete in the deposition holes and tunnels in order to determine which types and quantities of concrete can be used.

The other principal inorganic engineering material is steel. This field is judged today not to require any further research, development or demonstration.

For organic material, see section 8.2.15.

8.2.17 Colloid formation

Colloids are tiny particles that do not sediment. This means that they can accompany the groundwater and even act as carriers of radionuclides.

Conclusions in SR 97 and its review

The Process Report says the following: "Formation of colloids is dependent on several factors that are not fully understood today. In contrast to solutes, it is not possible to stipulate equilibrium conditions for colloids."

In their review, the authorities say: "The margins for buffer erosion and colloid formation not occurring are low. Shedding light on this would probably require that SKB develop a more detailed model of the long-term evolution of the groundwater chemistry."

Conclusions in RD&D 98 and its review

No questions for further research were identified in RD&D-Programme 98 or its review.

Newfound knowledge since RD&D 98 and SR 97

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 considered to be low /8-33/. The concentration is limited by the fact that the colloids adhere to the fracture surfaces, which reduces their stability and transport capacity.

In Nevada, 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 km from the detonation site /8-34/. This is an indication of rapid colloid transport.

Research programme

A project called Colloid was initiated in the autumn of 2000 and is expected to be concluded in December 2003. 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 results will be used in safety assessments for colloid transport modelling.

The role of bentonite clay as a colloid source is being investigated at varying groundwater salinities (NaCl/CaCl) in laboratory experiments, see Figure 8-2. The results of these measurements are decisive for how colloid transport is studied.

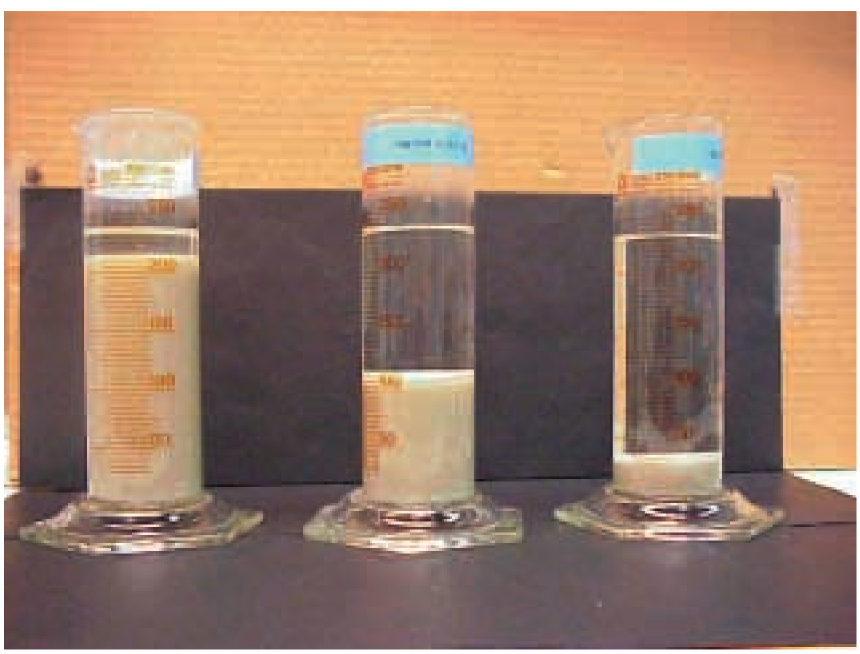

Figure 8-2. *The salinity of the water can influence the colloid concentration. The experiment shows different degrees of sedimentation of bentonite dissolved in water at different ionic strengths (NaCl) for the water. A high or low ionic strength can result in instability and colloid formation.*

The background colloid concentration in different water types and fracture zones along the Äspö tunnel will be measured with a high-resolution laser.

Studying transport of colloids between two nearby boreholes at the Äspö HRL has also been discussed. The boreholes penetrate the same fracture zone, the so-called TRUE feature A, which has a relatively homogeneous geology.

8.2.18 Gas formation/dissolution

Conclusions in SR 97 and its review

Gases that occur dissolved in the groundwater are of varying composition. The main components are often N_2, Ar, He, H_2 and CH_4. No questions for further research were identified in SR 97 or its review.

Conclusions in RD&D 98 and its review

Not dealt with.

Newfound knowledge since RD&D 98 and SR 97

It can now be regarded as established that the gas has several different origins. Some comes from the mantle, some with water from the ground surface, while other portions are formed biogenically or radiogenically in the rock. The proportions of the different types vary regionally, with rock type and with depth /8-35/. See also section 8.2.4.

The inflow of water to open boreholes and tunnels is lower than expected. One explanation for this that has been discussed is two-phase flow. Knowledge of how two-phase flow arises and manifests itself in the vicinity of boreholes and tunnels is necessary for being able to interpret the observations of hydraulic conditions that are made in the boreholes and tunnels. Furthermore, this knowledge is needed for interpretation of how buffer material and filling material behave, especially during the operating phase and during closure. The general conclusion drawn by SKB from the results of laboratory experiments and borehole experiments in Stripa and the Äspö HRL is that degassing of groundwater will not cause appreciable flow reductions in open boreholes under conditions that are normal for Swedish granitic bedrock /8-10/.

Research 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.

8.2.19 Methane ice formation

At low temperature and high pressure, water and methane form a solid phase called methane ice. Methane ice can form underneath permafrost.

Conclusions in SR 97 and its review

Methane ice formation was not dealt with in SR 97. The uncertainties around its formation, above all concerning how deep permafrost can reach and in what way methane can accumulate underneath permafrost, makes it impossible to calculate the effects with present-day knowledge.

Conclusions in RD&D 98 and its review

No questions for further research were identified in RD&D-Programme 98 or its review.

Newfound knowledge since RD&D 98 and SR 97

Climate change and its effects on a deep repository were analyzed in SR 97. The focus in this analysis was on conditions caused by the fact that an inland ice sheet with a thickness of up to three kilometres advances and retreats several times over during a glaciation cycle. Other climatic conditions were analyzed to a lesser extent because their influence on the host rock will be less dramatic, but also due to a lack of knowledge, e.g. concerning permafrost conditions. Now it is known that a relatively large portion of the most recent glaciation cycle was ice-free and may have caused a more extensive permafrost than previously believed.

Research programme

A project aimed at clarifying the hydrogeological and hydrochemical conditions associated with permafrost is planned in cooperation with e.g. Posiva. The project proposal includes studies of a site where permafrost occurs and which can thereby be considered to be an analogue for an equivalent situation in a future deep repository. One of the questions concerns the formation and occurrence of methane ice.

8.2.20 Salt exclusion

Conclusions in SR 97 and its review

When saline water freezes slowly, the solutes (salts) present in the water are forced out into solution. The process is of importance in conjunction with permafrost. No questions for further research were identified in SR 97 or its review.

Conclusions in RD&D 98 and its review

Not dealt with.

Newfound knowledge since RD&D 98 and SR 97

Since salt exclusion is dependent on permafrost, it can also be expected that a more extensive permafrost will also lead to more extensive salt exclusion.

Research programme

Included as one of the questions in the permafrost project, see section 8.2.19 above.

8.2.21 Integrated modelling – hydrogeochemical evolution

The composition of the groundwater is, in combination with the groundwater flow, 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 the 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 with environs from a safety assessment perspective and producing the body of chemical data required for design of the deep repository. In general, the chemistry 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 the 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 dissolved substances in the rock volume. The salinity distribution, the individual main components (Na, K, Ca, Mg, Cl, SO_4, HCO_3) and pH are the most common. It is also of great value to describe the stable and radioactive isotopes H-2, O-18, S-34, C-14, C-13, H-3 and Sr-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 in so-called 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 /8-19/. 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. This approach for hydrochemical modelling is called M3 (Mixing and Mass balance Modelling) and has been developed with MATLAB as a base.

Knowledge of the microbial processes has increased in recent years /8-30/. 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 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 /8-26/ has been to propose suitable methods for obtaining paleohydrological information, i.e. information from fracture-filling minerals on 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.

Carefully executed drilling and sampling is required to obtain relevant water chemistry data. A programme has been prepared for how water sampling is to be done during the site investigations /8-1/.

Conclusions in SR 97 and its review

The M3 code for hydrochemical modelling was used for the first time in a safety assessment in SR 97. The mixing conditions were related to earlier and currently prevailing hydrological conditions. Furthermore, equilibria were calculated for the mineral phases that quickly equilibrated with solutes in the aqueous phase.

The authorities judged that "The composition of the groundwater and its distribution in the bedrock at a candidate site should be analyzed and be included as an important part of the safety assessment, since it can provide many important clues on the evolution of chemical processes, climate and hydrology" and "to describe the importance of buffer erosion and colloid formation, SKB would probably have to develop a more detailed model of the long-term evolution of the groundwater chemistry."

Conclusions in RD&D 98 and its review

SKI's review report: SKI considers that, in addition to the above-mentioned aims, the modelling and description of groundwater chemistry must also contribute so that the understanding gained of the geochemical and hydrological evolution and history of the proposed repository site are able to create confidence in site selection and the formulation of scenarios within the safety assessment. Site characterization must provide a significantly more detailed understanding of the specific hydrochemical conditions than the understanding on which a safety assessment is based, otherwise it will be impossible to assess whether or not the simplifications and abstractions used are reasonable. However, SKI agrees with SKB that its top priority should be to investigate and create an understanding of the conditions which directly affect the performance of the engineered barriers, such as redox conditions, bentonite stability, the integrity of the copper canister, radionuclide solubility, sorption properties, etc.

Regarding models, in RD&D-Programme 98 SKB mainly emphasizes the M3 concept, which only indirectly takes into account specific geochemical processes as inputs or losses in mixing and mass balance calculations. For non-conservative components in the groundwater that may be affected by many processes, the M3 calculations may therefore need to be supplemented by other types of calculations. SKI considers that SKB should use both experimental studies and other models in parallel in order to clarify as much as possible the concentrations and distribution in the bedrock of the non-conservative components.

Newfound knowledge since RD&D 98 and SR 97

Task 5 by the joint international Äspö Task Force on Modelling of Groundwater Flow and Transport of Solutes aims at integrating hydro and chemistry data to describe the groundwater drawdown caused by the tunnel in the surrounding rock. The mixing concept has been used there to calculate proportions of waters of varying origin, which have then been included in the models for flow and transport calculations.

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 /8-20/. 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. The situation during a glaciation was analyzed thoroughly in the SR 97 safety assessment. Similar efforts are planned for permafrost conditions.

Research programme

The following describes how available methods will be used in the site investigations. There are no plans today for any extensive method development.

Hydrochemical modelling in future site investigations is planned to include quantitative calculations of mixing ratios as well as mass balance calculations of all data jointly. Hydrogeological calculations of current flow conditions are used as a basis for interpreting hydrochemical data. By looking at how the groundwater is flowing at the present time, it is possible to ascertain, for example, the variation of the water chemistry with depth (in recharge areas) and what importance the most conductive structures have for mixing of different water volumes that can differ in both origin and composition. Furthermore, quantitative calculations of equilibrium conditions are carried out for each individual mineral phase that is expected to be capable of achieving equilibrium.

The following processes are handled in an integrated model chain:

- Advection/mixing, M3 calculations.
- Diffusion, analytical solutions.
- Reactions between groundwater and rock matrix, mass balance calculations (M3).
- Dissolution/precipitation of fracture-filling minerals, equilibrium calculations (PHREEQE, EQ3 and others).

The quantitative calculation tools can be utilized to calculate what effects each individual process/reaction lead to. For example, calcite dissolution/precipitation influences pH, carbonate concentration and calcium concentration. Since several processes interact and the dominant processes have varied during different time periods, the models cannot fully clarify in what sequence and to what extent the different processes have occurred. Today's conditions are a result of various processes and reactions that have proceeded to a varying extent over a long period of time.

The following processes are handled individually, by means of simple scoping calculations, separate model studies or the like:

- Microbial processes.
- Decomposition of inorganic engineering material.
- Colloid formation.
- Gas formation/dissolution.
- Methane formation.
- Salt exclusion.

8.2.22 Radionuclide transport – advection and dispersion

Advection and dispersion for transport calculations are treated under this heading. Mixing of water in natural systems is handled under the heading "Advection/dispersion", see section 8.2.11.

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Conclusions in SR 97 and its review

It was observed in the Process Report that both the understanding and the description of advection are good, while the description of dispersion is highly model-dependent, since different model concepts describe the dispersion processes differently, see also section 8.2.28.

Conclusions in RD&D 98 and its review

No questions for further research were identified in RD&D-Programme 98 or its review.

Newfound knowledge since RD&D 98 and SR 97

No new knowledge has been forthcoming.

Research programme

See section 8.2.28.

8.2.23 Radionuclide transport – molecular diffusion and matrix diffusion

Conclusions in SR 97 and its review

It is observed in the Process Report that the concept of flow-wetted surface, which is of crucial importance for matrix diffusion, is associated with considerable conceptual uncertainties. Further development of the model concept and the very concept of flow-wetted surface is called for.

In SR 97, Main Report, it is stated that the methods for determination of the transport resistance (which is dependent on the flow-wetted surface) can be improved. Both field experiments, such as the TRUE projects on Äspö, and alternative model concepts are mentioned as possible ways to improve these estimations.

The main comment by the authorities is that the interpretation of flow-wetted surface, including methods that provide necessary field data to support its use, should be developed.

Conclusions in RD&D 98 and its review

In its review of RD&D-Programme 98, SKI observes that measurement methods for transport properties (specifically retention parameters) should be developed. This is particularly true of ground-based methods that may be utilized in conjunction with the planned site investigations. Much of the work that is being done to prepare and plan for the site investigation phase is taking place within the framework of specific projects. There is a special group for studies of transport parameters that is examining what available methods should be used and what new methods should be developed.

SKB says in RD&D-Programme 98 that the BIPS technique will be developed to permit estimation of the retention properties of fractures in the field. SKI supports this development in its assessment of RD&D-Programme 98.

Newfound knowledge since RD&D 98 and SR 97

Diffusion of radionuclides in the water-filled microfractures in the rock – matrix diffusion – has been studied by measuring electrical conductivity. The goals have been to develop a new measurement method and to study the mechanisms of diffusion. The results of the experiments are collected in a recently published doctoral thesis /8-37/. The method can be used in the laboratory and is much faster than conventional measurement methods. The well-known fact that alkali ions move relatively fast could be explained with a model where the ions are mobile in a diffuse sorption layer near the mineral surface. This is called surface diffusion and is a controversial phenomenon, but its influence on the total diffusion of e.g. cesium is quite substantial.

Laboratory experiments with both sorption and diffusion in crystalline rock have been conducted in connection with the TRUE experiments at the Äspö HRL. The laboratory experiments are reported in /8-38/and in a doctoral thesis /8-39/. Equivalent field results within TRUE and evaluation of the results are reported in /8-40/ and /8-41/. The results indicate an increased retention in the field relative to the results from the laboratory investigations. This is attributed to a zone nearest the fracture in the studied fracture system with elevated porosity and sorption /8-40/.

Based on the alternative model concepts for groundwater flow that were used in SR 97, additional simulations with discrete models have been done to understand how the flow-wetted surface and the transport resistance are dependent on input parameters that define the fracture network /8-42/. The results indicate that the linear relationship that is often assumed between transport resistance and flow-wetted surface in continuum conceptualizations does not exist. Further statistical analysis of the results indicates that the distribution of the local velocities in the fracture network and the distribution of a parameter related to the flow-wetted surface exhibit power-law features, despite the fact that input fracture data are described by traditional distributions /8-43/. These results clearly indicate the need for further research to correctly conceptualize and understand the implications of the concept "flow-wetted surface".

Use of the BIPS technique in the TRUE experiments on Äspö has shown that BIPS is above all useful together with flow logging to identify dominant conductive structures and set up structural models. The projects aimed at trying to estimate retention parameters from BIPS data will not continue during the ensuing three-year period.

Research programme

Simulations with discrete fracture network models will continue. The purpose of these simulations is to increase our understanding of flow-related transport parameters such as flow-wetted surface. Furthermore, the results will continue to be used as a basis for statistical analysis and simplified analytical calculations. Methods for how flow-wetted surface can be estimated in the field by means of individual methods or combinations of methods will also be investigated.

Based on the results /8-37/ a research project has been initiated aimed at being able to measure the diffusivity of the rock directly in the field. A better understanding of some of the fundamental processes that influence diffusion in situ may, however, be needed before the method can be considered ready for application in the site investigation phase.

For future safety assessments, a consensus should be reached among the parties concerned regarding how retention (specifically matrix diffusion) is handled in mathematical models and how and what data should be measured in the field. Moreover, the possibility can be explored of utilizing more easy-to-use concepts than "flow-wetted surface" and "transport resistance" for simply describing the retention capacity of the rock. SKB will pursue these questions either in international fora (e.g. the EU or OECD/NEA) or in bilateral contexts.

In the safety assessment, the process is modelled integrated with other transport processes, see section 8.2.28.

8.2.24 Radionuclide transport – sorption

Conclusions in SR 97 and its review

In the review of SR 97, the authorities observed that the K_d values used may have had too narrow uncertainty intervals, which in turn influences the choice of pessimistic value in the assessment. SKB believes that these uncertainty intervals can best be estimated when a better understanding of the fundamental mechanisms that control sorption is obtained.

Conclusions in RD&D 98 and its review

In its review of RD&D-Programme 98, SKI observed that both a good process understanding (via e.g. surface complexation models) and a relevant database of K_d values for the needs of the safety assessment are needed.

The review also points out that SKB should investigate sorption on mineral surfaces that is due to precipitation of secondary phases. It is further pointed out that SKB should study the importance of redox processes for sorption. However, this has been thoroughly investigated previously in the laboratory /8-44, 8-45/. SKB has also done tracer tests with redox-sensitive substances in the rock /8-44, 8-40/.

Newfound knowledge since RD&D 98 and SR 97

The mechanisms for sorption of radionuclides on mineral surfaces have been investigated in detail. The goal has not been to replace the use of K_d values but rather to show how the radionuclide ions are bound to the mineral's oxide surfaces. This should support the use of K_d.

Studies of sorption mechanisms are reported in a doctoral thesis /8-46/. The results show that the surface complex model can explain most of the radionuclide sorption that is measured.

Research programme

Studies of sorption mechanisms on mineral surfaces will continue to be supported, at least during the ensuing three-year period. Today, however, it is judged that no further research is required for sorption on mineral surfaces that is due to precipitation of secondary phases beyond studies of the phenomenon in nature, see section 8.2.14. The entire field is, however, being monitored and action will be taken when appropriate.

Further demonstration experiments to shed light on the importance of redox processes for sorption will be conducted on Äspö with the aid of the CHEMLAB probe. Beyond that, the field is judged today not to require any further research or development.

In the safety assessment, the process is modelled integrated with other transport processes, see section 8.2.28.

8.2.25 Radionuclide transport – speciation

The water's chemical environment (pH, redox conditions etc.) determines what speciation the radionuclides will have. This is of importance for sorption.

The speciation process is discussed in section 4.2.14. The same type of speciation calculations as in SR 97 are planned in future safety assessments.

8.2.26 Radionuclide transport – colloid transport

Conclusions in SR 97 and its review

It is observed in SR 97, Process Report, that colloid transport is not relevant when the concentrations of colloidal material required for the process to be important do not occur in the groundwaters in question. In the authorities' review, however, it is observed that colloid transport should be quantified and included in the consequence analysis especially for cases where the buffer does not perform as intended. In near-surface groundwaters, colloid transport can be assumed to provide the dominant transport pathway.

Conclusions in RD&D 98 and its review

SKI offered similar viewpoints in the review of RD&D-Programme 98 as in the review of SR 97. Furthermore, it was stated in the review of RD&D-Programme 98 that the importance of colloids and complexes needs to be clarified for extreme conditions, e.g. in the presence of cement and organic substances. Such investigations are restricted for the time being to the research being conducted in relation to the final disposal of long-lived low- and intermediate-level waste, see Chapter 18.

Newfound knowledge since RD&D 98 and SR 97

Relatively many studies have been reported in recent years within the field of colloidal transport. A much talked-about and debated study /8-47/shows that plutonium at the Nevada Test Site in the USA is transported a much longer distance from the source than the distance that is estimated based on laboratory results of sorption on the solid phase (the rock). This indicates that plutonium is transported sorbed on the colloids rather than dissolved in the aqueous phase. Even though conditions at the Nevada Test Site are not comparable to Swedish conditions, this study has created a general interest in colloids.

Like many earlier studies, laboratory experiments also show that colloids in a fracture can be transported faster than solutes /8-48/. Furthermore, it has been shown that colloids tend to be retained in the system, i.e. that the outflow shows lower concentrations than the inflow of colloids. The two reported processes have an apparently opposed effect in a consequence analysis. If colloidal transport is to be incorporated in the safety assessment model chain, further research is required to understand the most important processes that control colloid mobility. However, SKB believes that colloids can be handled separately, see below.

Research programme

An experimental demonstration project is planned where formation of colloids from bentonite buffer will be investigated. The purpose is to study under what conditions colloids are formed and are stable. Based on the laboratory experiment, field experiments may also be conducted in the Äspö Laboratory, see further sections 6.2.19 and 8.2.17.

Some model development is also planned for the purpose of being able to quantify the importance of colloidal transport for safety. These models will primarily be developed as analytical tools for scoping calculations. If it turns out there is a need to incorporate colloidal transport in SKB's calculation chain as well, this will be developed separately.

Otherwise 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.

8.2.27 Radionuclide transport – transport in gas phase

Conclusions in SR 97 and its review

No questions for further research were identified in SR 97 or its review.

Conclusions in RD&D 98 and its review

Not treated except for what is described in section 8.2.4 about gas flow/dissolution.

Newfound knowledge since RD&D 98 and SR 97

A knowledge compilation concerning two-phase flow and gas migration has recently been carried out as a joint project within the EU and the NEA /8-11/. The report identifies problems, conceptualization and still-open questions for storage of spent fuel in fractured rock.

Research programme

The need for the literature study mentioned in RD&D-Programme 98 can be regarded as having been met by the EU/NEA compilation /8-11/.

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.

8.2.28 Integrated modelling – radionuclide transport

Conclusions in SR 97 and its review

Radionuclide transport is modelled in SR 97 with the model FARF31 /8-49/, which handles the processes advection, dispersion, molecular/matrix diffusion, sorption and chain decay.

In their review of SR 97, the authorities observed that the model FARF31 should be compared with more detailed process models and a more detailed account of simplification errors should be given. Specifically, the importance of a variable porosity and varying Peclet number is asked about. In addition, the experts would like to see a better documentation of conceptual assumptions and mathematical formulations, along with a presentation of scientific support for the model.

Further, the authorities point out that FARF31 should perhaps be developed to incorporate variable penetration depth for matrix diffusion.

Conclusions in RD&D 98 and its review

The integrated modelling is not discussed specifically in RD&D-Programme 98.

Newfound knowledge since RD&D 98 and SR 97

Model studies

Since SR 97, an analytical approximation of FARF31 has been developed /8-50/, see section 2.4.1. The agreement with the numerical model for the calculation cases in SR 97 is generally good. Figure 8-3 shows a comparison of release curves from the geosphere for one of the calculation cases in SR 97 calculated with FARF31 and with the analytical model.

Figure 8-4 shows a comparison of maximum annual releases in the time interval up to a million years after closure for all uncertainty cases in SR 97 /8-51/, including cases where all parameters are simultaneously given either consistently reasonable or consistently pessimistic values. The figure includes the three sites that were analyzed in SR 97 and the 16 most important nuclides. Discrepancies greater than a factor of ten are due above all to the approximative treatment of dispersion in the analytical model.

The analytical model will be used as one of the tools in future safety assessments, among other things for preliminary probabilistic calculations, see further section 2.4.

Field studies

The overall goal of Tracer Retention Understanding Experiments (TRUE) is to increase our understanding of transport and retardation of radionuclides in fractured rock and show whether utilized model concepts are realistic descriptions of fractured rock. The experiments are also intended to show whether relevant input data for important model parameters can be determined from downhole investigations, evaluate whether different model concepts can be applied to modelling of radionuclide transport, and collect in-situ data on radionuclide migration.

A field experiment in an interpreted single fracture has been conducted on the detailed scale (TRUE-1) /8-40/. Another experiment, TRUE Block Scale, has been conducted in a network of structures on the block scale and is currently being evaluated and reported. A detailed-scale experiment (Long-Term Diffusion Experiment) aimed at describing diffusion and sorption in the rock mass in connection with a naturally water-conducting fracture under in-situ conditions is currently being prepared.

The results of completed in-situ experiments in an interpreted single structure (TRUE-1) show a relative retardation of used tracers as follows:

$^{22}Na^{+} < {}^{47}Ca^{2+} \approx {}^{85}Sr^{2+} << {}^{86}Rb^{+} \approx {}^{133}Ba^{2+} < {}^{137}Cs^{+}$,

which also agrees with what has been measured in the laboratory on material from rock cores.

The tracer tests have been predicted with different modelling tools within the framework of the work of the Äspö Task Force, see /8-52, 8-53/. The analysis, which has been performed by SKB's experiment group /8-40, 41/, includes development and

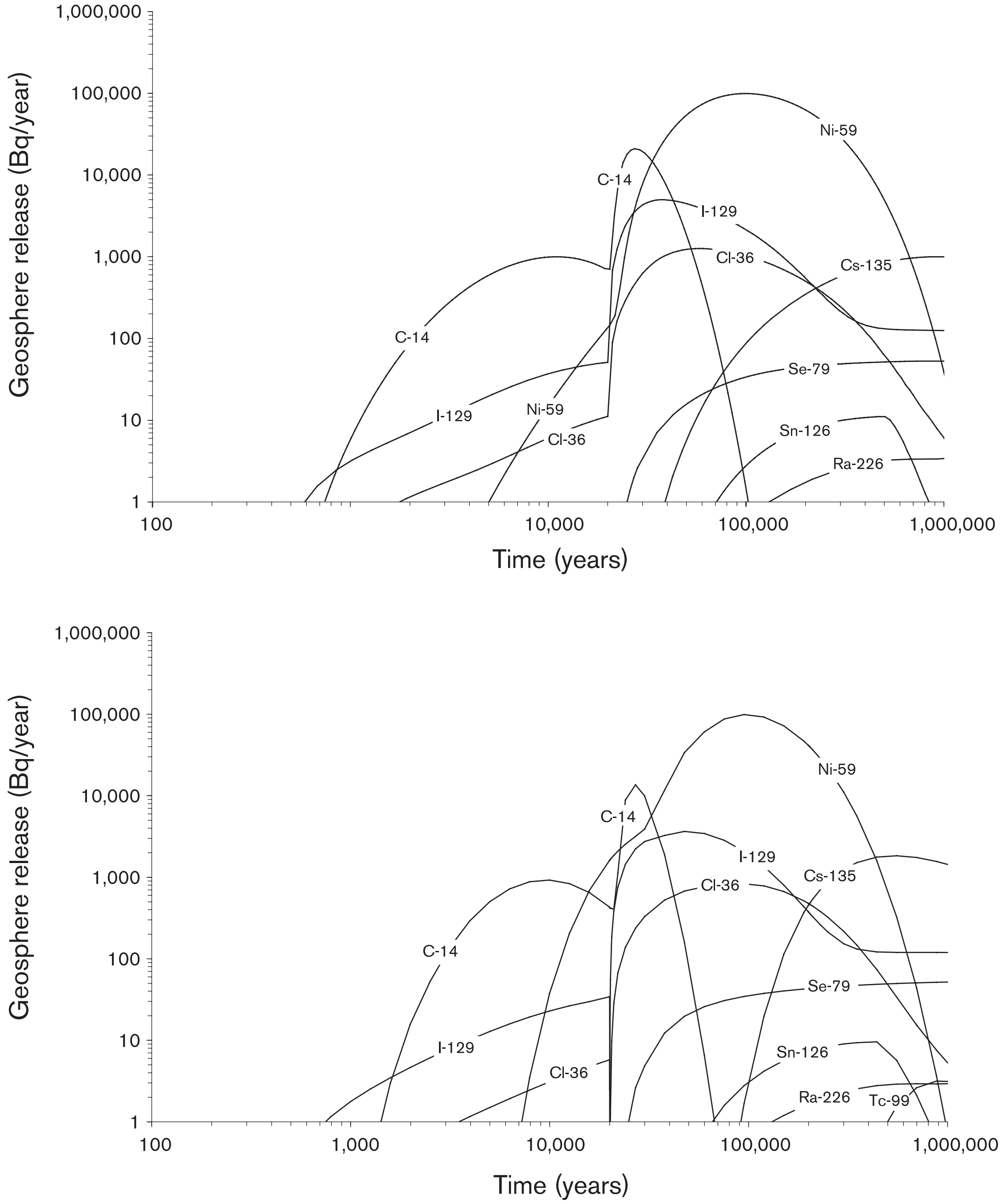

Figure 8-3. *Release curves from the geosphere for one of the calculation cases in SR 97, calculated with a numerical (upper) and an analytical (lower) model.*

testing of a new modelling tool (LaSAR) /8-54/. The model concept introduces a parameter β which is dependent on the groundwater flow in a single fracture and which controls matrix diffusion. The evaluation shows that the principal retention mechanism is unlimited diffusion/sorption in the matrix, see Figure 8-5, and that porosity, diffusivity and sorption in the altered rim zone of the studied structure is higher in situ, compared with equivalent parameter values from drill core samples of intact rock investigated in the laboratory.

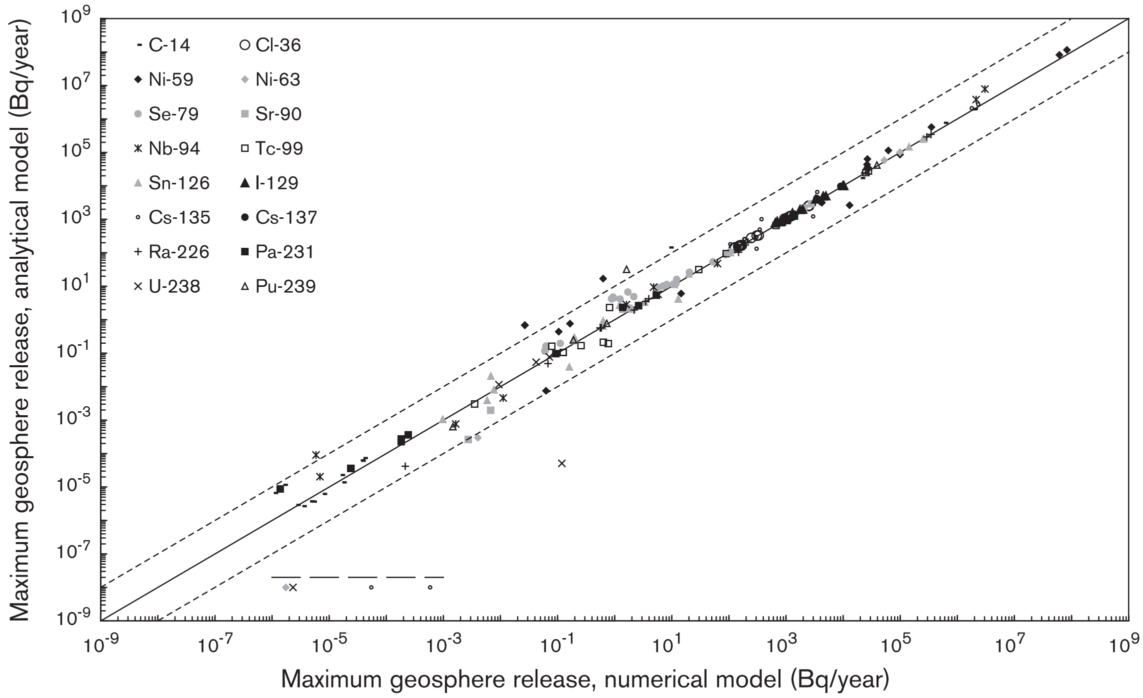

Figure 8-4. *Comparison of maximum annual releases for the three sites and the 16 most important nuclides in SR 97, calculated with numerical and analytical models. The figure shows the results of nine different calculation cases for each of the three sites in SR 97.*

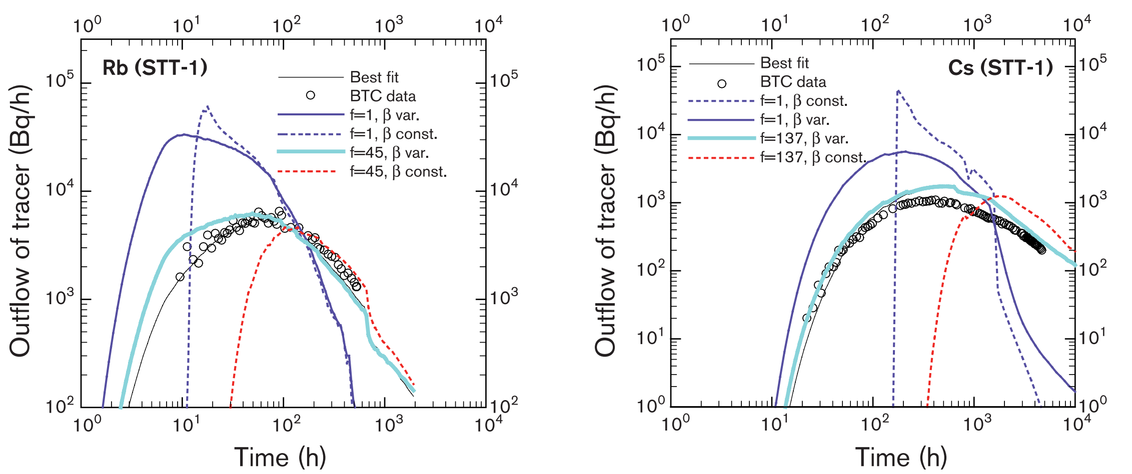

Figure 8-5. *TRUE-1. Predictive capacity of the LaSAR model for the studied structure. f=1 represents prediction based on laboratory data from intact matrix rock (only equilibrium sorption), f≠1 represents evaluated factor of elevated diffusion in situ in relation to laboratory parameters for matrix rock (equilibrium sorption and diffusion/sorption in the rock matrix), β=var. represents prediction with a distribution and β=const. with a constant effective value of β. Best fit means that f=1, β=var. and also includes sorption in fracture-filling material.*

In the ongoing TRUE Block Scale experiment, transport and retention are being studied in a network of fractures with lengths of 10–100 metres. A key question here is whether the longer time and length scale (greater degree of heterogeneity and exposed surfaces) will lead to greater retention. A total of four injections of radioactive sorbing tracers have been performed in flow paths involving one or more structures over distances of 15–100 metres. The results of experiments over distances of 15 metres in a single structure show retention of a similar character as that noted on the detailed scale (TRUE-1), while breakthroughs of more sorbing tracers over longer distances have not been noted. For example, after six months of sampling, no breakthrough has been observed noted for Cs (L~100 metres, > 3 structures) and for Rb (L~40 m, ≥ 1 structure). This preliminary indication of a greater degree of retention on the block scale will be followed up by careful comparison between model predictions and new field data from the ongoing experiment.

Research programme

Model studies

Both model studies and model development will take place during the coming three-year period. Specifically, the assumption that transport along streamtubes can be described with a dispersion term (Peclet number) will be evaluated with the aid of alternative conceptual models for radionuclide transport.

The transport model in SR 97, FARF31 /8-50/, should be updated so that flow-related transport data from discrete models (transport resistance and/or flow-wetted surface) can be directly utilized as input data in the model.

FARF31 should further be compared with models with a higher process complexity. Specific points that may need to be analyzed are the effect of a matrix with variable sorption and diffusion properties (e.g. variability in the penetration direction or variability along flow paths) and/or the effect of diffusion in the mobile aqueous phase. More complex models are available today that can be used for this purpose. During the ensuing three-year period, the Äspö Task Force will, in Task 6, describe transport of radionuclides with different model concepts in both a single fracture and in a fracture network.

The above questions can hopefully be partially answered by Task 6. Validity documents will be prepared for all important models. Conceptual assumptions and mathematical formulations will be discussed in this document, section 2.4.1. The scientific support that exists for the model will also be reported.

Field studies

TRUE

One remaining conceptual uncertainty is whether the retention noted in the TRUE-1 alternatively can be ascribed to diffusion/sorption in fracture-filling material in the studied structure, or whether the noted elevated retention can be attributed to transport in a three-dimensional network of fractures (larger flow-wetted surface) that could generate a retention effect corresponding to the interpreted elevated diffusion/sorption in the rim zone of the studied structure. An injection of epoxy, followed by breakout and analysis of the pore volume and the flow paths affected by the experiment, is expected to answer these questions.

An important part of the coming work is the integration of the understanding obtained from experiments on a detailed scale and a block scale, of which the planned work within Task 6 by the Äspö Task Force (see "Model studies" above) comprises a part. With the evaluation results from the TRUE Block Scale experiment as a base, it is expected that new hypotheses can be set up that can be addressed by new efforts in the laboratory and/or the field. Experiments are, for example, foreseen which, in combination with modelling, can be utilized to improve understanding and quantification of the flow-wetted surface.

Early during the TRUE project, a need was identified to conduct a diffusion experiment in situ in intact matrix rock. The main reason was to avoid the effects of the mechanical unloading phenomena that occur when a drill core is extracted at great depth, and to permit comparison with the diffusivity values that are determined on core specimens in the laboratory. The experimental concept in the planned Long-Term Diffusion Experiment (LTDE) includes study of diffusion and sorption in connection with a natural water-bearing fracture.

CHEMLAB

Transport of actinides and redox-sensitive nuclides in a fracture will be studied in the CHEMLAB probe at Äspö. The work is expected to proceed during all of 2001 and half of 2002. Cooperation with Institut für Nukleare Entsorgung provides access to know-how and experience concerning actinide chemistry.

9 Biosphere

SKB's biosphere programme for the coming six years was described in RD&D-Programme 98. After more than two years it can be noted that the programme has largely proceeded according to plan and that the research has had the desired results. More than 30 reports have been produced during the period. Furthermore, three safety assessments /9-1, 9-2, 9-3/ have been carried out in which the biosphere has had a more detailed role than before. A programme for site investigations of the biosphere has been prepared.

The ambition during the coming three-year period is to fortify and deepen this knowledge in ongoing projects which include increased publication in international journals, as well as to carry out the remaining parts of the research.

The knowledge and data that are expected from the site investigations should deepen our understanding of many biosphere processes and provide opportunities to develop modern models for the safety assessments that will be based on site-specific data.

New phenomena or problems may also emerge from the site investigations, requiring targeted research efforts. Furthermore, methods need to be developed and tested for analysis of collected data. The collection of data is also expected to arouse interest on the part of Swedish and international research groups working on radioecology and environmental problems.

9.1 Background

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 repository in the form of radiation dose to humans and other organisms occur in the biosphere. Calculations of the turnover 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 that are expressed in doses and risk are met, and as a yardstick for comparing different facilities, technical solutions or sitings. Credible calculations require a realistic description of events and processes in the biosphere with reasons why certain processes are important and why others can be ruled out. The states of the surface ecosystems also comprise chemical (salinity, oxygen content), hydrological (water balance) and geological (shoreline displacement) boundary conditions for processes in the geosphere. These conditions are climate-dependent.

In 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 surveillance of the repository area, and during the surveillance 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.

9.2 Reviews of RD&D 98, SR 97 and SFL 3-5

Following are the most important comments from various reviewers of the biosphere programme in RD&D 98, SR 97 and the preliminary safety assessment of SFL 3-5. The review of "Integrated account of method, site selection and programme prior to the site investigation phase" /9-4/ was recently concluded. The renewed safety assessment of SFR, Project SAFE, will be reviewed during the autumn of 2001. Viewpoints from these reviews will also be worked into the research programme for the upcoming six-year period, if possible. General comments are responded to below, while specific viewpoints are commented on in the following programme descriptions.

9.2.1 RD&D-Programme 98

In its statement of comment, SSI writes that SKB's biosphere studies have fallen far behind studies in other disciplines, but that SKB has satisfactory ambitions and that the systems ecology approach being taken is valuable. At the same time, SSI says that considerable work remains to be done before SKB reaches its goal of credible consequence calculations.

With its past and planned research efforts, SKB intends to increase the credibility of its biosphere analyses.

SSI says that SKB should prioritize the study of uncertainties in the description of today's biosphere and analyze how the biosphere will evolve in a distant future.

Conceptual uncertainties are handled in conjunction with process descriptions and alternative systems ecology models, see sections 9.3 and 9.4. Uncertainties are also included in the probabilistic calculations that are being done for the biosphere. The upcoming site investigations are expected to provide a good basis for uncertainties in data. The long-term evolution has been handled in SAFE by reconstructing the site-specific evolution in time (see section 9.9).

SKI, SSI and SGU believe that SKB should investigate and explain the importance of biosphere conditions as site selection criteria prior to selection of areas. SSI wants to have an account of the relevant ecosystems included in the screening material and a preliminary account of how SSI's regulations /9-5/ can be met.

SR 97 provides a preliminary account of how SSI's regulations can be met, and ongoing work in the planning of the site investigations provides an idea of the biosphere on the sites. Nothing has emerged that radically differs from the accounts in SR 97 and SAFE.

9.2.2 SR 97 and SFL 3-5

The results of the SR 97 safety assessment and the preliminary safety assessment of SFL 3-5 have been reviewed by international experts /9-6, 9-7/. SKI and SSI have reviewed SR 97 and summarized their viewpoints /9-8/.

In general the reviewers are positive towards SKB's handling of the biosphere in the safety assessments. They point out shortcomings in argumentation and documentation for chosen typical ecosystems, models and data and the lack of a structure in the process descriptions. The reviewers point out that a forest ecosystem model is lacking, and that the assumptions regarding the peat bog are incomplete, as is the description of the transition and interaction between geosphere and biosphere.

It is SKB's perception that the reviewers find the proposed methodology for handling the biosphere to be laudable, and SKB shares the opinion that improvements are needed in understanding and data. A large part of the following description of the research programme is intended to improve understanding, for example via the process descriptions. The forest model and the understanding of the most important processes comprise their own subarea of the development work, as do mires, sediments and transport processes in the biosphere, which are described below.

Several of the reviewers call for a clarification of how the risk criteria are to be handled and an explanation of SKB's reasoning in selecting these criteria. Moreover, the authorities would like SKB to clarify the role of the biosphere in the safety assessment.

As is evident from section 9.11, SKB intends to look into these matters, which will require discussions with SSI regarding how the Inspectorate's regulations are to be applied. Such discussions are under way.

Kasam and SSI believe that time-dependent biospheres are important and that the course of events during the first 1,000 years should be better described.

Time-dependent biospheres have been developed in SAFE, and an attempt has been made to describe the first 1,000 years.

The authorities find the account of environmental consequences given in SR 97 to be unsatisfactory and believe that this work must be prioritized. They remark that the ecosystem-based analysis which SKB is developing is a suitable tool for this assessment.

It is SKB's intention to develop the systems ecology models for this purpose, see section 9.4, and to define a framework for how the environmental consequences are to be handled, among other things in cooperation with SSI in the EU project FASSET, see sections 9.10 and 9.11.

The authorities also express reservations regarding the fact that the account of the biosphere in the main reports is inadequate and point out detailed deficiencies in the data.

SKB intends to remedy these deficiencies prior to the next safety assessment for the deep repository and upcoming site investigations.

9.3 Understanding and conceptual models

A summary of how SKB's understanding of the biosphere has developed over the years is provided in /9-9/.

The authorities' regulations require that future safety assessments provide a more realistic description of the biosphere and an estimation of the consequences for surrounding fauna and flora /9-5/. 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 9.4. An systems ecology approach is taken, where both biological and abiotic processes in the ecosystems are taken into account. Knowledge of the processes is found within many areas, e.g. in conceptual and numerical models for forestry, and in studies of the cycling of nutrients in lakes and seas or of the turn-over of toxic pollutants. On the other hand, this information has seldom been used for studies of radionuclide turnover. Generalizations are also required for the long time-spans and varying environments encountered in a safety assessment.

In order to get a credible description of the evolution of the biosphere, the conceptual models that are used must be in harmony with the scientific view within the fields of not only radioecology, but also ecology, ecotoxicology and environmental protection.

Newfound knowledge since RD&D 98

SKB has begun the work of compiling process descriptions in a similar manner as for other repository parts /9-10/. It is a large task due to the multitude of processes in the biosphere, requiring surveying of and focusing on the most essential processes /9-11/. Interaction matrices have been a useful tool for identifying important processes. In the SAFE project, a general biosphere interaction matrix has been developed that can be used for different repository types /9-12/, see Figure 9-1. The matrix will be revised during 2001 to serve as a basis for refining and updating knowledge in a systematic way. The matrix has already been used to define the parameters and variables that need to be determined in the site investigations /9-13/, see further section 9.12.

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
1	GEOSPHERE (B.C.)	Erosion/ weathering	NONE	NONE	NONE	NONE	NONE	NONE	a) Erosion/weath. b) Changes in rock surface location	Discharge/ recharge	Discharge/ recharge	Mass flux	Gas transport	Heat transport	Contaminant transport	NONE
2	a) Mech. load b) Consolidation (Water flow = 10.1)	Quaternary deposits	a)Settlement b)Deposition	a)Settlement b)Consumption	a)Settlement b)Consumption	a)Settlement b)Consumption	a)Settlement b)Consumption	a)Settlement b)Consumption c)Material supply	Relocation	a) Water transport b) Dehydration	NONE	a)Resuspension b)Leaching c)Sorpt./desorpt.	a)Resuspension b)Non-biological decomposition	a)Radiation b)Heat transport c)Heat storage	Sorption/desorpt.	Export
3	Root penetration a) Rock b) Tunnels c) Biological	Root growth	Primary producers (a)	a)Stimul./Inhib. b)Food supply	a)Stimul./Inhib. b)Food supply	a)Stimul./Inhib. b)Food supply	a)Stimul./Inhib.	a)Stimul./Inhib. b)Food supply d)Material supply		Root uptake	a)Interception b)Retard./Accel. c)Uptake/Excret. d)Covering	a)Uptake./Excret. b)Particle prod	a)Gas uptake/rel b)Part. trap/prod c)Wind retard.	a)Radiation b)Exo/Endo react. c)Heat transp.	a) Uptake/sorpt. b) Excretion c) Degradation d) Growth	Export detached outflow of plankton
4	Potential intrusion	a)Decomposition b)Bioturbation	a)Stimul./Inhib.	Decomposers (a,b,c)	a)Stimul./Inhib. b)Food supply	a)Stimul./Inhib. b)Food supply	a)Stimul./Inhib. b)Food supply	a)Stimul./Inhib. b)Food supply d)Material supply		Decomposition	a)Decomposition b)Retard./Accel. c)Uptake/Excret. d)Movement	a)Uptake./Excret. b)Particle prod	a)Gas uptake/rel b)Part. trap/prod	a)Radiation b)Exo/Endo react. c)Heat transp.	a) Uptake/sorpt. b) Excretion c) Degradation d) Growth	Export
5	Potential intrusion	Bioturbation	a)Stimul./Inhib. c)Feeding	a)Stimul./Inhib. b)Food supply c)Feeding	Filter feeders (a,b,c)	a)Stimul./Inhib. c)Feeding	a)Stimul./Inhib. b)Food supply c)Feeding	a)Stimul./Inhib. b)Food supply d)Material supply		NONE	a)Water-pumping b)Retard./Accel. c)Uptake/Excret.	a)Uptake./Excret. b)Particle prod	NONE	a)Radiation b)Exo/Endo react. c)Heat transp.	a) Uptake/sorpt. b) Excretion c) Degradation d) Growth	Export detachment spawn
6	Potential intrusion	Bioturbation	a)Stimul./Inhib. c)Feeding	a)Stimul./Inhib. b)Food supply c)Eating mushrooms	a)Stimul./Inhib. b)Food supply	Herbivores (a)	a)Stimul./Inhib. b)Food supply	a)Stimul./Inhib. b)Food supply d)Resource		NONE	a)Movement b)Retard./Accel. c)Uptake/Excret.	a)Uptake./Excret. b)Particle prod	a)Gas uptake/rel b)Part. trap/prod	a)Radiation b)Exo/Endo react. c)Heat transp.	a) Uptake/sorpt. b) Excretion c) Degradation d) Growth	Export
7	Potential intrusion	Bioturbation	a)Stimul./Inhib.	a)Stimul./Inhib. b)Food supply c)Feeding	a)Stimul./Inhib. b)Food supply c)Feeding	a)Stimul./Inhib. c)Feeding	Carnivores (a,b,c)	a)Stimul./Inhib. b)Food supply c)Feeding d)Resource		NONE	a)Movement b)Retard./Accel. c)Uptake/Excret.	a)Uptake./Excret. b)Particle prod	a)Gas uptake/rel b)Part. trap/prod	a)Radiation b)Exo/Endo react. c)Heat transp.	a) Uptake/sorpt. b) Excretion c) Degradation d) Growth	Export swimming running
8	NONE	Disturbance (dredging, digging)	a)Stimul./Inhib. c)Feeding d)Dispersal/ Extermination	a)Stimul./Inhib. b)Food supply c)Feeding d)Dispersal/ Extermination	a)Stimul./Inhib. c)Feeding d)Dispersal/ Extermination	a)Stimul./Inhib. c)Feeding d)Dispersal/ Extermination	a)Stimul./Inhib. b)Food supply c)Feeding d)Dispersal/ Extermination e)Material use	Humans (a)	digging dumping	a)Water extraction b)Artific.infiltr.	a)Movement b)Retard./Accel. c)Uptake/Excret. d)Covering	a)Excretion b)Filtering c)Pollution	a)Gas uptake/rel b)Part. trap/prod c)Pollution d)Wind retard/acc.	a)Radiation b)Exo/Endo react. c)Heat transp. d)Antropogen eff	a) Uptake/sorpt. b) Excretion c) Degradation d) Growth	a)Export of energy b)Emigration?
9	NONE	Relocation	shelter insolation						Topography	Water transport	a)Water transport b)Wave formation	NONE	a)Windfield changes b)Air pressure	a)Radiation b)Adiabatic temp. change	NONE	NONE
10	a) Rech./disch. b) Press. change c) Mass flux d) Erosion/weath.	a)Erosion b)Water content change	a) Settlement b) Water uptake	a) Settlement b) Water uptake	NONE	a) Settlement b) Water uptake	a) Settlement b) Water uptake	a) Settlement b) Water use	Pingo formation	Water in quarternary deposits	Discharge (recharge)	a) Erosion b) Mixing c) Dens. effects	a)Evapo./Cond. b)Sublimation	a)Heat transp. b)Heat storage	Mixing	Export
11	a) Rech./disch. b) Press. change c) Mass flux d) Erosion/weath. e) Ice-load	Erosion (icescoring)	a)Settlement b)Relocation c)Water uptake	a)Settlement b)Relocation c)Water uptake	a)Settlement b)Relocation c)Water uptake	a)Settlement b)Relocation c)Water uptake	a)Settlement b)Relocation c)Water uptake	a)Settlement b)Relocation c)Water use	a)Water level? b)Ice onsurface?	Recharge (discharge)	Surface water	a) Mixing b)Dens. effects	a)Evapo./Cond. b)Sublimation c)Erosion (seaspray/snowdrift	a)Radiation b)Exo/Endo react. c)Heat transp. d)Heat storage e)Light reflection	Mixing	Export/import
12	a) Mass flux b)Erosion/weath.	a) Sedimentation b) Precip./dissol. c) Erosion/weath	a)Settlement b)Stimul./Inhib. c)Light attenu.	a)Settlement b)Stimul./Inhib.	a)Settlement b)Stimul./Inhib.	a)Settlement b)Stimul./Inhib.	a)Settlement b)Stimul./Inhib.	a)Settlement b)Stimul./Inhib.	NONE	Water transport	Water transport	Water composition	a)Spray/Snowdrift b)Dissol./Degas.	a)Exo/Endo react. b)Light absorb. c)Light reflect./scatt. d)Adiab. compr.	a) Sorpt./desorpt. b) Dissol./precip.	Export
13	Gas transport	a)Erosion b)Deposition c)Oxidation	a)Settlement b)Stimul./Inhib. c)Relocation d)Depos./Remov.	a)Settlement b)Stimul./Inhib. c)Relocation d)Depos./Remov.	NONE	a)Settlement b)Stimul./Inhib. c)Relocation d)Depos./Remov.	a)Settlement b)Stimul./Inhib. c)Relocation d)Depos./Remov.	a)Settlement b)Stimul./Inhib. c)Relocation d)Depos./Remov.	NONE	a)Water transport b)Evapo./cond. c)Sublimation	a)Water transport b)Evapo./Cond. c)Precipitation d)Wind stress e)Sublimation	a)Precipitation b)Deposition c)Evapo./Cond. d)Dissol./Degas.	Gas ------------ Atmosphere	a)Radiation b)Exo/Endo react. c)Heat transp. d)Heat storage e)Adiab.temp.change f)Phase changes	a)Mixing b)Sorpt./desorpt. c)Photochem. reactions??	Export
14	a)Heat transport b)Erosion/weath.	Weathering	a)Settlement b)Stimul./Inhib.	a)Settlement b)Stimul./Inhib.	a)Settlement b)Stimul./Inhib.	a)Settlement b)Stimul./Inhib.	a)Settlement b)Stimul./Inhib.	a)Settlement b)Stimul./Inhib.	Volume expansion/ contraction	Phase transitions	a)Phase transitions b)Convection	a)Kinetics & chem. equil. b)Property changes c)Mixing	a)Pressure change b)Phase transitions	Temperature	a)Kinetics & chem equil. b)Phase transitions	Export of heat
15	Contaminant transport	a) Surface dep./uptake b) Irradiation	a) Int. exposure b) Ext. exposure	a) Int. exposure b) Ext. exposure	a) Int. exposure b) Ext. exposure	a) Int. exposure b) Ext. exposure	a) Int. exposure b) Ext. exposure	a) Int. exposure b) Ext. exposure	NONE	NONE	NONE	a) Radiolysis b) Stab. isotopes c) Chem. react.	Phase transition	Heat from decay	Radionuclides and toxicants	Export
16		Import	a) Import b) Insolation	Import	Import	Import	Import	a)Import of energy b)Immigration	Land rise	Import	a) Sea level changes b) Sea currents	Import	a)Import b)Photochem-reactions	a) Import of heat b) Insolation	External load	External conditions

Figure 9-1. *Example of general interaction matrix that is under development and used for the safety assessment of SFR.*

SKB has continued to adapt the systems ecology approach to describe the turnover 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 efforts have been made to compile current radioecological knowledge. A review of bioaccumulation factors in aquatic ecosystems and a statistical analysis of relationships between various environmental factors have been done /9-14, 9-15/. A literature study has been done of how different iodine isotopes occur and how they move in soil /9-16/. A knowledge compilation of biosphere parameters for the radionuclides in the most recent safety assessments is under way and will comprise the basis for a radionuclide catalogue. Knowledge in the field of radioecology and the environmental impact of radiation is being compiled in BIOMASS and the EU project FASSET, see section 9.10.

In this context it can also be noted that institutional support for the discipline of radioecology has diminished sharply in recent years in Sweden.

Development programme

The long-term support for competence development continues as per the 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 will continue. Moreover, newfound knowledge in the follow subprogrammes (e.g. model development, transport processes, forest ecosystems, mireland, sediments) will be captured.

9.4 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 EcoSafe 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 progressively refined by SKB's efforts, summarized in a review by Edlund et al. /9-9/ and in the most recent safety assessments /9-17, 9-18/. 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 /9-19 to 9-22/. The concept is based to a large extent on the use of generic transfer factors to different compartments, which presumes that the system being modelled is in equilibrium. Furthermore, the transfer factors are based in many cases on empirical data without a mechanical explanation. 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 /9-23/.

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It is stated in RD&D-Programme 98 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 on processes and states in the ecosystems. Furthermore, a more realistic description of the biosphere is needed to satisfy the requirements made by the authorities on an analysis of the future consequences of the deep repository. To estimate the consequences for surrounding fauna and flora in accordance with the regulations in /9-5/, 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.

It is further claimed in RD&D-Programme 98 that 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 non-nuclide-specific, e.g. geometry of the drainage basin, insolation, water balance, and composition of the ecosystem.

Newfound knowledge since RD&D 98

The typical ecosystems lake, running water, sea (archipelago and coast), mire, agricultural land and well were analyzed in SR 97. BIOPATH models that described the different typical ecosystems were developed /9-17/. The three sites in the safety assessment provided an opportunity to make use of site-specific data for the biosphere models. The above biosphere for the three repository sites was divided into squares sized 250 x 250 metres which were associated with one of the above typical ecosystems based on available map information /9-24/. Site-specific data based on a literature compilation were utilized where possible /9-25/.

The advantage of this approach is that the causes of the variation in estimated dose can be separated. The uncertainty in the data used for the models accounted for a variation of roughly one order of magnitude in dose, while the choice of the typical ecosystem accounted for variations of up to seven orders of magnitude.

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 /9-17, 9-26/. The site-specific information was limited in SR 97, however, since few biosphere investigations have been conducted on the old study sites. This made it difficult to subdivide the areas into typical biospheres and resulted in uncertainties in parameter values.

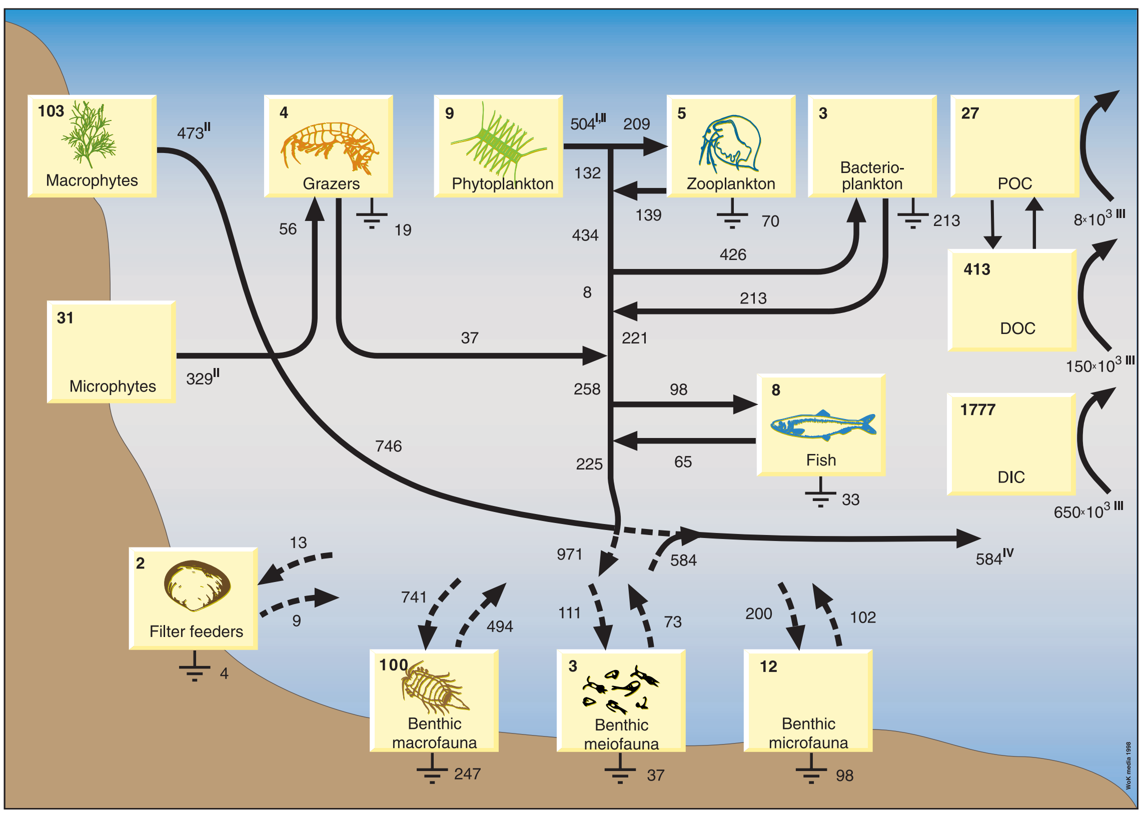
In the SAFE project, the safety assessment for SFR, the BIOPATH models were further refined for different types of ecosystems and a time-dependent evolution was introduced /9-18/. In addition, site-specific biosphere data were gathered and investigations were conducted to obtain a better body of data /9-27/.

New models for the coastal area were developed for SAFE based on the principles of systems ecology /9-28, 9-29/. They describe the flow of C-14 through the food web and the concentration of C-14 is calculated in different compartments without using concentration factors, see Figure 9-2. The transfer of radionuclides is based solely on mechanisms such as food ingestion, photosynthesis and degradation. This model is currently being tested for cesium. The results are promising and are being evaluated during 2001.

A review of calculation 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 programs and specific programs for safety assessments.

Development programme

The systems ecology models will be further refined and validated against field observations (e.g. Chernobyl releases and the environmental monitoring at the Swedish nuclear power plants). A continued review and evaluation of the calculation tools BIOPATH and PRISM will be done so that they can be adapted to a modern calculation environment and site-specific data can be used. This also requires integration with GIS databases and other numerical tools.



I Includes all planktonic primary production. (Bacterioplankton 33 percent and Phytoplankton 67 percent).
II Net production (gross production less respiration).
III Annual turnover of POC and DOC.
IV Amount of carbon exported from the area.

Figure 9-2. *Example of carbon flow model from coastal area at SFR. The rectangles represent different compartments with quantities in tonnes, the arrows indicate the flow of organic carbon in tonnes per year, /9-28, 9-29/.*

9.5 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, provided the radionuclides are dissolved in water.

It was shown in RD&D-Programme 98 that a large 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.

Newfound knowledge since RD&D 98

It was noted in RD&D 98 that the new models for the turnover time of the coastal waters around Äspö /9-30/ should be further refined. The water turnover models for coastal waters were improved in the SAFE project /9-31, 9-32/. Now there is a model that covers the entire Baltic Sea and provides boundary conditions for the local coastal models /9-31/. The model's sensitivity to different climatic changes (temperature and ice formation), salinity changes and a change in land uplift was evaluated for Öre-

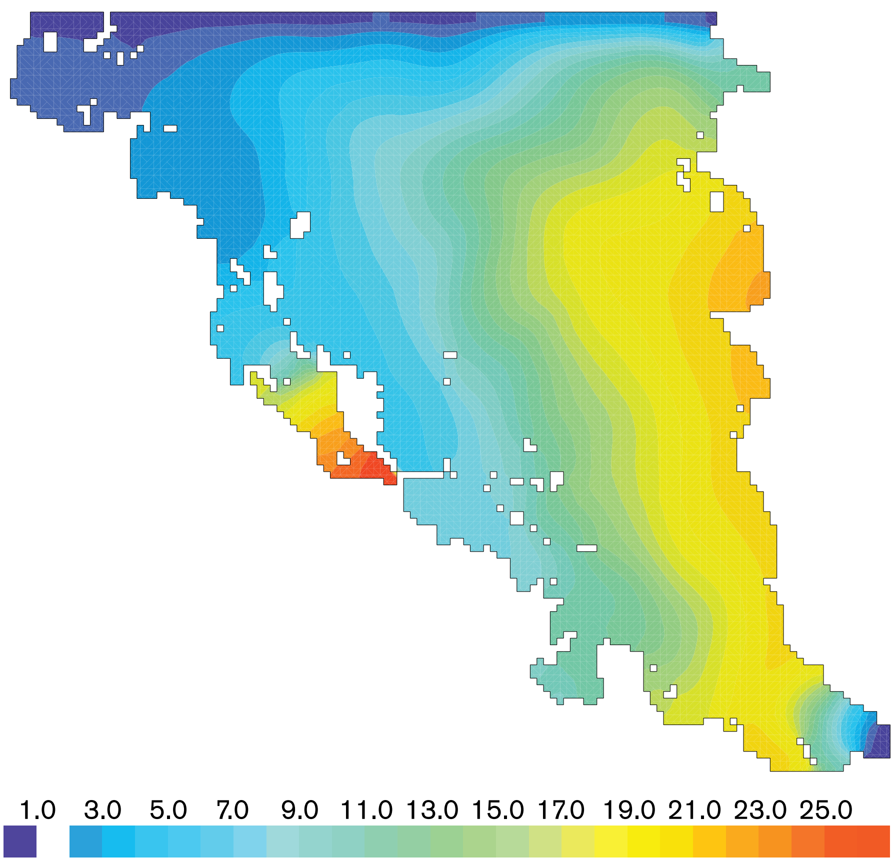


Figure 9-3. *Example of results from water exchange model in Öregrundsgrepen at SFR /9-31/. Modelled retention time in days in Öregrundsgrepen. The area is bounded by the coast of Gräsö on the eastern side and the mainland at Forsmark in the west (area with long retention times).*

grundsgrepen /9-32/, see Figure 9-3. The model has also been used by the Swedish Environmental Protection Agency and the Finnish Meteorological Institute to study water exchange in coastal waters.

In RD&D-Programme 98 it is pointed out that the near-surface hydrology is important for understanding what transport pathways and dispersal and dilution processes affect contaminated water after it has left the rock. Certain interactions in the boundary layer between rock and surface water were studied in the SAFE project /9-33/. This has shown, for example, that water in the layers above the rock is diluted by water from the surrounding rock. Furthermore, this water is diluted approximately 100 times by groundwater from the surface. The study showed that it is possible that the water may follow conductive layers in Quaternary deposits and discharge near the shoreline. This will be followed up in the upcoming period and be studied in the field as well.

Surface hydrology studies have been done at KTH for two lakes in northern Uppland /9-34/ in a project funded by the Swedish Environmental Protection Agency. The continuation of the project is being supported by SKB and may yield results that validate the model studies /9-33/. The site investigation programme has identified several important hydrological studies and measurements that should be conducted to facilitate the biosphere modelling /9-13/. These data will also be used to develop the models. The studies are being coordinated with the programmes for hydromodelling and hydrogeochemistry, see sections 8.2.3 and 8.2.21, respectively.

Model studies have been initiated to identify discharge areas from existing map material with the aid of GIS. The systems ecology models that are being developed describe the flow of particles (as organic material) in a coastal area /9-28, 9-29/, see Figure 9-2. These modellings need to be supplemented with field studies and a systematic literature review to estimate the movement and flows of particles in aquatic environments.

The transfer of radionuclides between plants and zooplankton has been studied experimentally at the University of Kalmar /9-35/. The results of this work will be compiled during the year.

Furthermore, field measurements in the Simpevarp area have detected chemical signals from the transport of deep groundwater and mixing conditions between deep and superficial water /9-36/. The work shows that it may be possible to trace certain substances from great depth, which will be evaluated in the upcoming programme in cooperation with the geochemistry programme.

A literature study is being compiled of transport processes in soil in particular. Sedimentation and similar transport processes are described in greater detail under the heading "Sediments" below.

Development programme

The projects described above will continue and can be summarized in the following main topics:

- In-depth surface hydrology with model development, mapping of recharge and discharge areas, and GIS analysis, plus hydrological and geochemical field studies. This work will be pursued in cooperation with the programmes for geochemistry and hydrology. This will be supplemented with field data from the site investigations.
- 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 /9-5/.

9.6 Forest ecosystem

The forest is the dominant ecosystem for the hypothetical sitings /9-25/. It is likely that the forest will be a recipient. The forest has been the focus of several projects that have studied the fallout from Chernobyl /9-37, 9-38, 9-39/. 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 in BIOMASS, see section 9.10. 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 lysimeter experiments performed in BIOMOVS II /9-40/ suggest that the biological processes (root transport, bioturbation by worms) in the soil are important transport mechanisms from groundwater to the topsoil.

Newfound knowledge since RD&D 98

SKB has participated in the Forest Working Group in BIOMASS Theme 3 /9-41/. Several interesting models have been compared in this working group. The dominant knowledge was obtained from atmospheric deposition of cesium, but attempts were also made to study a groundwater source. SSI has conducted research on radionuclide transport in the forest which should be taken into account in future safety assessments /9-39, 9-39/. Forest models will also be evaluated in the EU project FASSET.

SKB has initiated a project at FOI Umeå involving modelling of radionuclide transport from groundwater /9-42/. The factors that drive this transport are photosynthesis and water uptake. The work will be reported during 2001.

In the SAFE project, SKB intended to study the forest more thoroughly, but it has been difficult to find research teams in Sweden able to carry out these studies. However, the forests of interest, wetland forests and near-shore deciduous and mixed forests, are seldom represented among the models developed to calculate the yield of forest in Sweden. An attempt was also made to start an EU project for the purpose of studying forest models and processes together with SSI. Contacts have also been made with SLU and the Department of Systems Ecology at Stockholm University to further develop an existing forest model /9-43/.

In discussions with various experts, it has emerged that the forest as an ecosystem must be differentiated. The forest question is closely linked to near-surface hydrology and the evolution of wetlands. It is above all forests in depressions that will be of interest with respect to the effects of a deep repository, i.e. wetland forests and not, for example, flat-rock pine forests. The evolution of the forest will therefore be closely linked to the mire, see section 9.2.

A compilation is currently being made at the Department of Botany at Stockholm University of how different substances get into plants via root transport. 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.

Development programme

Extensive work remains to be done for the forest ecosystem before satisfactory process knowledge exists and models have been developed. It should be possible to make use of current work internationally and at SSI as a basis for further development. Data on the forest are obtained at an early stage from the site investigations, which can be used to identify the types of forest that may be of interest. Furthermore, the surface hydrology studies and the work with mireland will further supplement the body of knowledge on the forest and limit potential forest types. The following is planned:

- Continued process and model studies and collection of information available in the literature and through FASSET.
- Experiments and field measurements of uptake in vegetation in cooperation with the geochemistry programme.
- GIS analysis of the correlation between potential discharge areas and type of vegetation, supplemented with data from site investigations.

9.7 Mires

Mires and wetlands are important and probably the most likely recipients for the hypothetical sitings, especially in the future. 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 is 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 /9-44/ 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.

Newfound knowledge since RD&D 98

The ontogeny (evolution) of a marine area to a lake and then a mire has been described in connection with the SAFE project /9-27, 9-45 to 9-47/, see Figure 9-4. In addition, corings with datings have been done in northern Uppland /9-48/ and in Värmland /9-49/ to determine isolation times and growth rates, for the purpose of reconstructing climatic changes, see section 9.9. Additional information is currently being compiled from the more than 400 corings in northern Uppland by the Department of Limnology, Uppsala University and Umeå University.

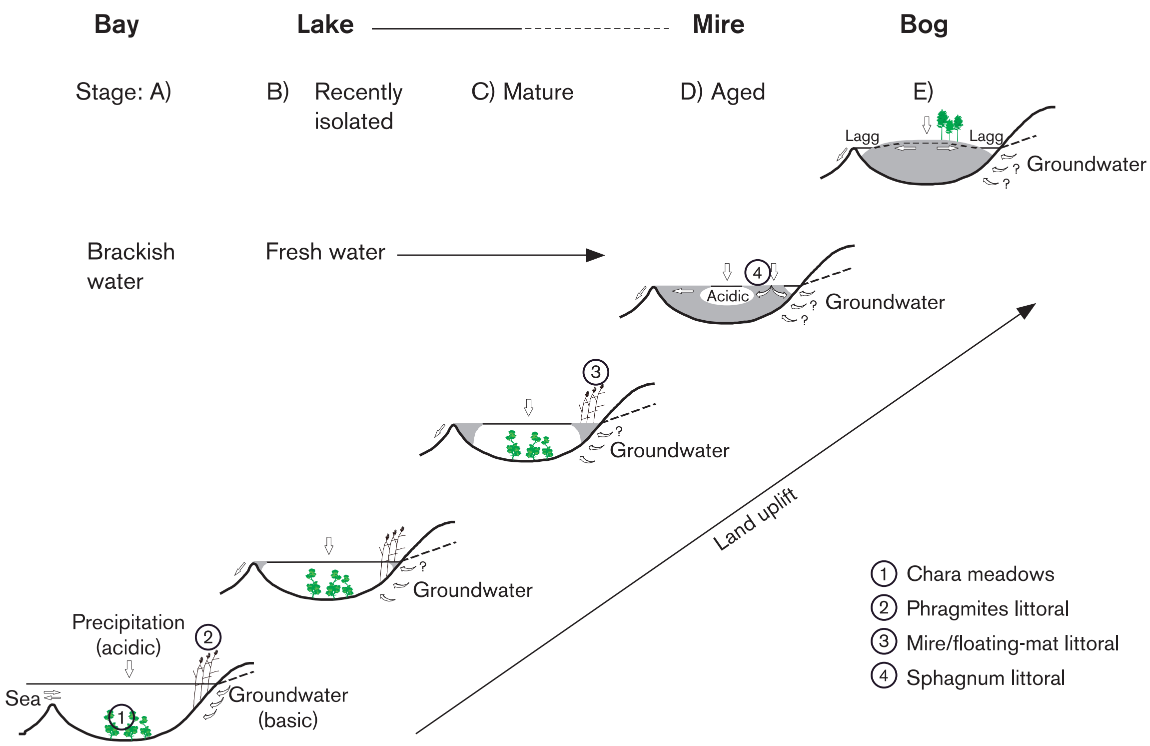


Figure 9-4. *Schematic description of ontogeny of a closed-off bay of the sea to a mire /9-46/. The figures represent different important components of the ecosystems.*

FOI's work with the forest model /9-42/ also includes an explanation and model of the transport of carbon through a mire before the forest forms.

Development programme

The most important work involves obtaining greater in-depth knowledge of mirelands with a process description, and refining today's models. Further knowledge is needed concerning growth rates, the formation process and man's exploitation of wetlands. A large portion of this information can be obtained from the literature, ongoing studies and the data that are collected during site investigations. Efforts are being coordinated with the studies of forestland, sediment and transport processes. Further, FASSET will compile important fauna and flora that can be affected in mires. The main points in the upcoming work are:

- Description of important processes in the form of a literature compilation.
- Further refining of today's models.
- Studies of the hydrology of mires and wetlands.
- Field studies in mires that exist in regions for siting in order to determine growth rates, isolation time and other parameters, but also to provide information on the long-term evolution of the area. Data will primarily be generated by the site investigations.

9.8 Sediments

The sediments in seas, rivers and lakes comprise important areas that influence radionuclide transport to biota. In many potential discharge areas, the radionuclides will pass a sediment layer. 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 /9-50/, which can greatly influence the radionuclide flow. In the short term, these processes will probably reduce radionuclide efflux and result in lower doses. In the long term, however, large quantities of 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.

Newfound knowledge since RD&D 98

In connection with the SAFE project, the sedimentation environment in northern Uppland has been modelled from approximately 10,000 years ago to 5,000 years in the future /9-51/. The controlling parameters were wave fetch, which has determined the force of wave erosion, and the process of land uplift, which has determined the depth and creation of protective islands and archipelagos. The study has shown unexpectedly good agreement with the Quaternary geological map of the area. At present, attempts are being made to predict the thickness of the sediment layers by developing this model. To calibrate the model, new field data have been collected /9-48/ and older, unpublished data have been compiled /9-52/, see section 9.7.

Existing knowledge concerning the processes in and on the sediments has been compiled in two literature studies /9-50, 9-53/. They describe processes in above all marine and brackish water environments and methods on sunlit freshwater sediments. The material provides input data for an experimental project concerning radionuclide transport through a sediment profile.

The ontogeny of closed-off marine bays, lakes and mirelands as it influences sediment formation has been described /9-45, 9-46/. Some of the biological processes that influence sediment formation have been described and modelled for coastal areas /9-28, 9-29/ and lakes /9-54/. The hydrological processes have been modelled in the SAFE project /9-33/ and measured for two lakes in northern Uppland by KTH /9-34/.

A project has been started at the Department of Geology at Stockholm University to study the extent and causes of indications of heavy erosion incidents approximately 8,000 years ago on the bottom of the Baltic Sea. The efforts are being coordinated with the geology programme. The cycling, transport and sedimentation of Cs-137 after Chernobyl have been followed along the Baltic Sea coast /9-55) and are expected to be reported in 2001. The study shows that the near-coast sedimentation in the deep holes can be considerably higher than previous estimates. Furthermore, Cs-137 is transported from the sea and enriched in areas that were not originally contaminated, such as the Stockholm archipelago.

Development programme

The project described above will continue. A major effort will be initiated to study experimentally chemical, physical and biological processes that affect radionuclides in sediments from the coast and possibly lakes. This will be supplemented by hydrological models to describe the pathway taken by the groundwater through the sediments and field measurements of substances that may have been transported by deep groundwater. Some of the work is planned to be done in cooperation with Posiva. 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 mires and transport processes. Some important work that will be done is:

- Experimental work to study chemical, physical and biological processes in the boundary layer formed by sediments.
- Continued modelling of migration processes beneath and through sediments.
- Modelling of reworking and accumulation of sediments, supplemented with field data.

9.9 Long-term variations in climate, land uplift and salinity

The factors determining the biosphere are largely controlled by the climate and the distribution between land and water. The salinity affects 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 conditions since the most recent ice age.

Shoreline displacement in Scandinavia since the ice age is described in /9-56, 9-57/and a forecast is given for the next 5,000 years. Shoreline displacement was studied during several glaciations for SR 97 /9-58/. Shoreline displacement can be influenced by global warming, which is expected to result in sea level rise. The sea level may rise approximately 0.4 metre over the next 100 years, according to one compilation /9-59/. This means that shoreline displacement will cease during one period, which has also been measured /9-60/. 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 /9-58, 9-61, 9-62/. This influences discharge areas on the coast, which has repercussions on the environment around the deep repository. It also influences the salinity of the Baltic Sea and the composition of the biosphere.

Newfound knowledge since RD&D 98

SKB has initiated a joint project between the Department of Quaternary Research at Stockholm University, the Department of Oceanography at Göteborg University, and SMHI, where knowledge of the salinity of the Baltic Sea since the last ice age has been compared with an oceanographic model describing the water exchange /9-63/. The study shows that the highest salinity in the Baltic Sea during the Littorina Sea stage was more like 10–15‰ rather than over 20‰ as had previously been assumed, see Figure 9-5. The study also shows that changes in the sill depths in the sounds between the Danish mainland and Sweden are not enough to explain the different salinity stages of the Baltic Sea; changes in freshwater input to the Baltic Sea are also

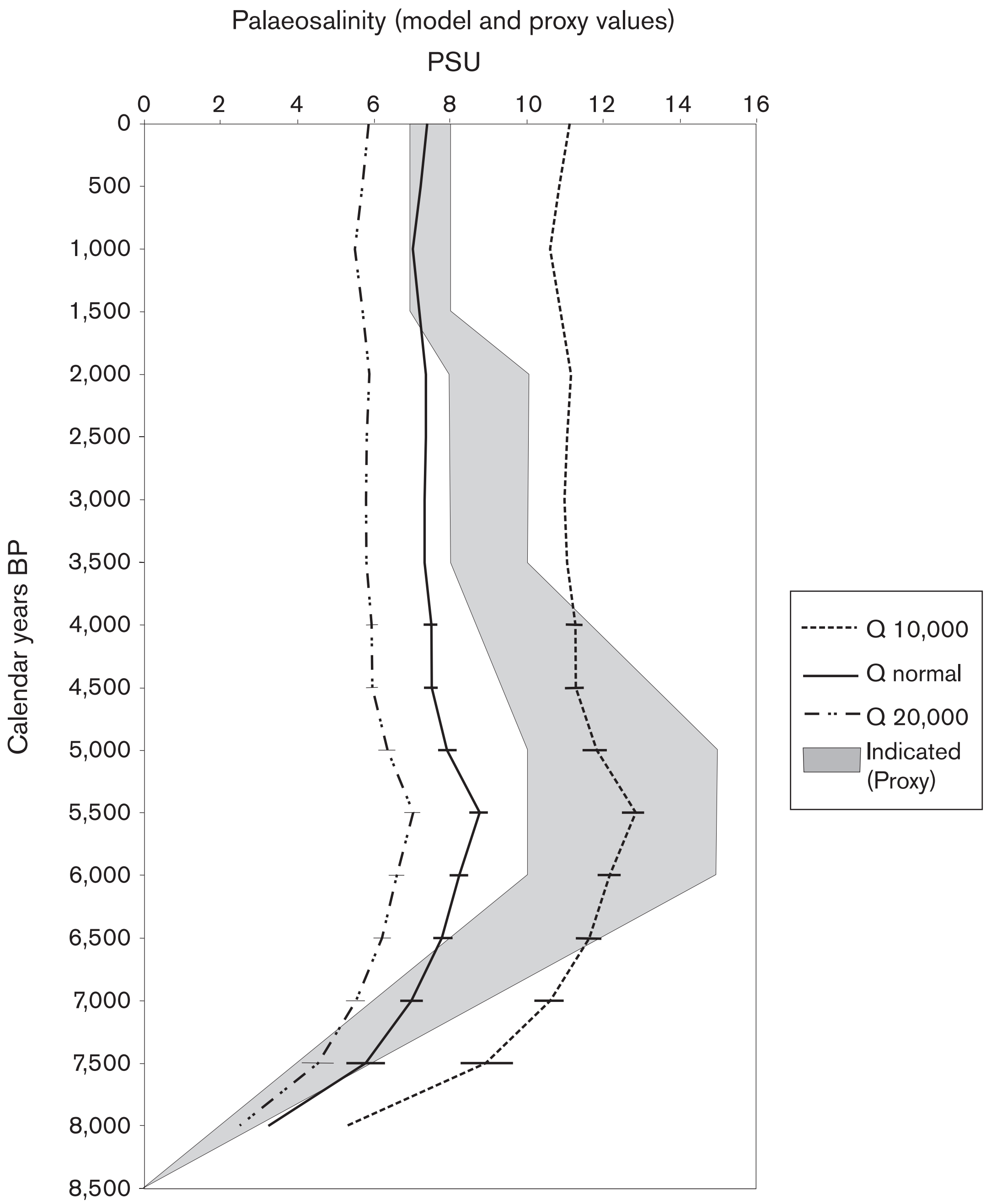


Figure 9-5. *Estimated salinity in the Baltic Sea after the ice age compared with model predictions /9-63/. The shaded area represents estimates of salinity from fossil finds, lines represent modelled salinities dependent on the freshwater input to the Baltic Sea (Q m³/year), bars on lines represent uncertainties due to assumptions concerning the sill depth at the different sounds between Sweden and Denmark.*

required. Periods of higher salinity coincide with periods that may have been drier. This model has also been used to predict future salinities in the Baltic Sea depending on different climatic evolutions and shoreline displacements /9-64/.

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. An estimate of possible variations in groundwater recharge in the Äspö area has been done by SMHI /9-65/. These results can then be coupled to the climatic evolution which took place during the Holocene to reconstruct groundwater recharge and predict its possible future evolution. A compilation has been made of the climate changes that have taken place over the past 200,000 years /9-66/. 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 that is considered to be due to dry periods /9-49, 9-63/. Further, a feasibility study was made of the possibility of using dripstones from Scandinavian limestone caves to trace temperature and precipitation changes with a method previously used in tropical areas /9-67/. The preliminary results and results from other Swedish caves show that it may be possible to trace changes over the past 100,000 years or more.

Additional information on the course of land uplift in Uppland has been obtained from field studies /9-48/, compilation of unpublished data (see sections 9.7 and 9.8) and modellings /9-47/.

A compilation of expected changes in the biosphere during the climate cycle was made for SR 97 /9-68/.

Development programme

The above-mentioned initiated projects will continue. 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 /9-69/, and most of the work entails keeping track of the results obtained from these projects. 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 variation in 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.
- Field measurements that furnish information on long-term changes in runoff.
- Knowledge compilation regarding permafrost and the importance of the tundra for radionuclide transport in the biosphere.
- Follow the global warming discussion.

9.10 International work

Standards, methodology and legislation are being discussed in the international work within e.g. IAEA, EU, IRPA 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.

Newfound knowledge since RD&D 98

The international BIOMASS project under the auspices of the IAEA was concluded in the autumn of 2000 and will produce several reports. SKB has participated actively in the work in Theme 1 (Radioactive Waste Disposal) and Theme 3 (Forest and Fruit Group).

SKB is participating in a three-year project within the EU's Fifth Framework Programme, FASSET, which started in November 2000. The purpose of FASSET is to compile knowledge concerning the radiological impact of ionizing radiation on the environment, i.e. flora and fauna. The purpose is to propose a framework for how such matters can be handled by industry and regulatory authorities. 14 organizations are participating in the work with representatives from radiation protection authorities and national radiation protection bodies from several countries. SSI is the coordinator of the project. SKB is participating, 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. This work is expected to result in better means for handling effects on the environment, which SSI's regulations require.

SKB is supporting a project together with KSU aimed at shedding light on a proposal for a changed view of ICRP recommendations /9-70/. In cooperation with Nagra and Enresa, a compilation of the view of the biosphere in these organizations is being discussed. Cooperation is being discussed with Posiva within certain biosphere areas, see section 9.8.

In addition to the above, SKB has presented material on the biosphere work at several symposia.

Development 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. SKB's involvement in FASSET will also be an important activity.

The following main activities are planned:

- Active work within the EU project FASSET.
- Following the work within the EU, NKS, ICRP and IRPA.
- Following and presenting the work at important meetings on radiation biology, environmental protection and systems ecology.
- Following the work at SKI and SSI and keeping track of legislation.
- Presenting the work within the biosphere to interested researchers and students.

9.11 Safety assessment

The account of the biosphere in SKB's safety assessments has evolved from a pessimistic dose conversion factor for a well to increased realism. The authorities' requirements have also increased for the biosphere.

Newfound knowledge since RD&D 98

SKB has performed three safety assessments during the past period where the biosphere has been treated more thoroughly than in previous assessments. Site-specific biospheres were used for the first time in SR 97 and SFL 3-5. One of the greatest uncertainties in the dose calculations stemmed from biosphere parameters /9-17, 9-24, 9-26, 9-71/. A time-dependent biosphere was used in the safety assessment for SFR reported in July 2001. Alternative tools are being tested and site-specific data are being used to a much greater extent than in previous assessments /9-18, 9-27/.

It has not been possible to utilize all the knowledge presented above for the SR 97 and SFL 3-5 safety assessments, since the work with safety assessment and development of understanding has proceeded in parallel. This means, for instance, that new insights concerning terrestrial ecosystems have not been fully utlized. There have been greater opportunities to utilize improved understanding and site-specific data in SAFE, but it has not been possible to fully take into account the viewpoints from the review of the preceding assessments, since most of SAFE had already been completed before the review results became available. 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 work of dealing with effects on the environment has been commenced by participation in the EU project FASSET, see section 9.10, and by the start of a project at the Department of Systems Ecology at Stockholm University aimed at compiling experience from ecotoxicology and protection of the environment from toxic substances.

The factual basis needed for the safety assessment is presented above under the different subprogrammes and is compiled in the reports for the dose models /9-17, 9-18, 9-24/ and in the summarizing report for the biosphere part in SAFE /9-27/. These reports also describe the status of the calculation tools.

SSI has also issued new regulations during this period /9-5/. SKI has published a statement of comment on regulations for final disposal of radioactive waste. SKB and SSI have initiated discussions to clarify how the risk measure in SSI's regulations is to be applied.

Finland /9-72/, Japan /9-73/ and the USA /9-19, 9-74/ have also published safety assessments during the period in which the role of the biosphere is examined.

Development programme

Experience from safety assessments performed by SKB will be evaluated to be used to develop modern tools for the next safety assessment. 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. 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 9.4.

Methods and knowledge concerning the consequences of radionuclides for the environment will be developed in close connection with the results produced by FASSET.

9.12 Site investigation programme

Some of the uncertainties in the biosphere are caused by inadequate availability and quality of data. To support the development of models and furnish site-specific data for the safety assessments, data need to be gathered during site investigations. In contrast to the situation in other disciplines, SKB has relatively little experience gathering biosphere data. Methods must therefore be developed at the same time as available knowledge and resources are compiled. RD&D 98 specified important areas in which more in-depth information was needed for the site investigations in the biosphere, but no special programme was specified for this.

Newfound knowledge since RD&D 98

The site investigation programme that will start during 2002 will be one of the most extensive data collections ever conducted in Sweden. An overview of the scope of the programme is provided in the background material for "Integrated account of method, site selection and programme prior to the site investigation phase" /9-75, 9-76/. In order to satisfy the need for data and understanding for the safety assessments and the biosphere models, data must be collected from the surface ecosystems. Variables and parameters judged to be important are given in /9-13/. Efforts have been coordinated with the geosphere programme to find common needs of data for boundary conditions, input data for the environmental impact assessment and background material for future monitoring programmes. Moreover, variables have been identified which are of value for the planning of the site investigation programme in order, for example, to reduce environment disturbances. Various compilations have since been made of existing data and methods within various fields, e.g. meteorology, oceanography, hydrology /9-77/, existing information on agriculture, forestry, population etc. /9-78/, methods for studying lakes and rivers /9-79, 9-80/ and other biological methods /9-81/.

A first attempt has been made to compile and evaluate existing data for the Forsmark and Simpevarp areas /9-82, 9-83/ and will be used as a basis for the site-specific programmes. The development of a GIS application for Uppland has been used in this work /9-84/.

For the SAFE project, biosphere data have been supplemented with field surveys /9-85/ and literature compilations of existing data /9-27, 9-28, 9-31, 9-47, 9-51, 9-84, 9-86, 9-87/ as a basis for the site investigation programme.

Development programme

During the upcoming period, method descriptions and detailing of the programme will be done in the new site organization /9-76/. Since the models and the knowledge of the biosphere will be further refined, close cooperation between research, safety assessment and the site investigations will be necessary. New methods for the site investigations will need to be developed and evaluated, e.g. production measurements. The results from the site investigation are moreover expected to give rise to questions that may require research. Furthermore, methods for analysis of collected data need to be developed and tested, e.g. analytical GIS applications, statistical evaluation and dynamic modelling.

10 Climatic evolution

Climate changes of such scope that they affect above all the biosphere, but also the bedrock all the way down to repository depth, will occur with great certainty in the future. Such changes must thereby be included in an assessment of the long-term safety of the repository. This was done in SR 97 in a special climate scenario.

Conclusions in SR 97 and its review

The climate scenario in SR 97 was based on three expected climate driven process domains: Temperate/boreal domain, permafrost domain and glacial domain, see Figure 10. Within each domain, changes in the repository's surroundings and how they can influence the evolution of the repository were described and evaluated. It is currently not possible to predict climate changes. However, we know that they follow cyclical progressions. Descriptions of conditions within each process driven climate domain is the basis of the analysis of the climate change impact on the deep repository. SKB's conclusion from SR 97 was that climate-related changes should not affect the safety of the repository. At the same time, a number of areas for further study were identified:

- Possible variations of the Scandinavian climate – for the purpose of improving the biosphere descriptions, and as a basis for studies of permafrost and ice development.

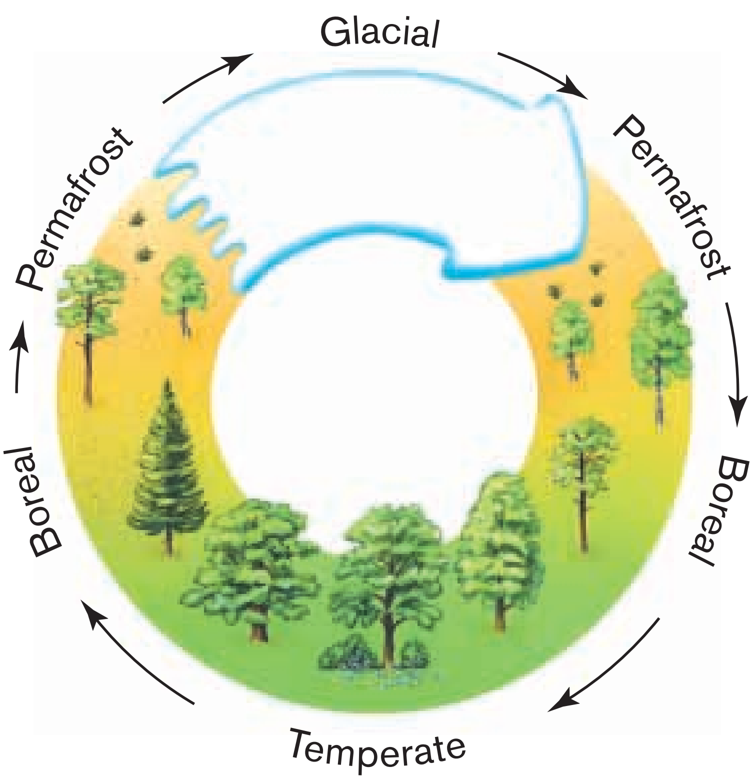


Figure 10-1. *Climate-related changes can be viewed as a cyclical progression with successive transitions between different climatic domains.*

- Development of permafrost in Scandinavia, and the hydrological conditions associated with permafrost.
- The relationship between ice load and stresses/movements in the bedrock; both the coupling between hydraulic and mechanical evolution, and the large-scale tectonic changes.
- Mixing of waters of different origins in the rock's system of fractures and pores.
- Canister strength, where calculations need to be refined by the use of more realistic material data.
- Buffer erosion with extremely ion-poor groundwater compositions.
- Evolution and performance of the backfill in conjunction with climate change.

Several of these questions are dealt with in the process descriptions in Chapters 5 to 8. The question regarding the impact of the future climate on the biosphere is dealt with in Chapter 9. Questions not fully covered in these chapters are dealt with below.

The reviewers of SR 97 considered that other climatic evolution alternatives should have been analyzed in greater detail in SR 97.

Evolution of the climate on a 100,000-year timescale

The downwarping (depression) of the earth's crust, as well as the process of postglacial land uplift following the most recent glacial maximum, are relatively well-known phenomena. Knowledge of the process during an entire glacial cycle is limited, however. This includes both the size of the ice load and the properties of the lithosphere and the viscous medium on which the lithosphere is assumed to rest, which influence the amount and rate of the downwarping. The position of the coastline is important for biosphere description, geohydrology and groundwater composition. The land uplift process should therefore be further investigated.

Temperate/boreal domain

The position of the coastline is an important parameter for estimating the hydrological boundary conditions for the deep repository and estimating the salinity of the groundwater. There is therefore also a need for research around land uplift in order to obtain a good understanding of the conditions during the temperate/boreal domain. This applies not least to a description of ecosystems and biosphere, see further Chapter 9.

Climatic variations due to the greenhouse effect are judged to be covered by the variations included in the temperate/boreal domain.

Permafrost domain

Better knowledge of climatic conditions during a glacial cycle is needed to assess the occurrence of permafrost in Sweden. The position of the coastline is important in this context as well.

Glacial domain

A conceptual model describing the hydraulic conditions under a continental ice sheet was presented in SR 97. There are several uncertainties in the model which should be further investigated, for example:

- Basal thermal regime and occurrence of melt water at the ice-bed interface.
- Influx and importance of meltwater from the surface of the ice.
- Variations of flows and pressures in time and space.

The coupling between hydraulic and mechanical processes beneath, and in the vicinity of an ice sheet, also needs to be further studied. The large scale state of stress underneath an advancing and retreating ice sheet and its importance for the occurrence of earthquakes is an other topic that should be further investigated.

Conclusions in RD&D 98 and its review

The palaeohydrological programme that was started in 1994 is described in RD&D 98 /10-1/. The purpose of the programme was to:

- Identify and improve the understanding of the principal climate-driven processes that can influence the performance of a deep repository.
- Compile material for long-term performance and safety assessments of the repository.

The programme contained modelling of glaciations, mechanical, hydrogeological and hydrochemical aspects, and coupled effects. It was concluded and reported in conjunction with the execution of the SR 97 safety assessment /10-2/.

The largest and most important changes for the performance and safety of the repository that can be expected over a timescale of 100,000 years are most probably associated with climate changes and the formation of continental ice sheets. The questions that were particularly highlighted in RD&D 98 were permafrost, the impact on groundwater chemistry, transport and coupled effects. In its evaluation of RD&D 98, SKI points out that all of the issues dealt with by SKB in the paleohydrogeological programme are relevant and should be included in SKB's continued work and that SKB needs to describe how they intend to integrate the questions in their activities. Further, SKI observes that much of the knowledge accumulation is achieved within international projects and that this is good, but that it is important that questions that are relevant to Swedish conditions should be taken care of within the framework of SKB's own projects.

Newfound knowledge since RD&D 98 and SR 97

In conjunction with the execution of SR 97, knowledge within the field was compiled and integrated with other knowledge. Most of the results of the projects mentioned in RD&D 98 are included in SR 97. Since SR 97 the work has mainly consisted of planning of continued work taking into account the viewpoints offered on the safety assessment and on RD&D 98. Research has been conducted on land uplift and on large-scale tectonic movements and earthquakes, see further section 8.2.7.

The two EU projects mentioned in RD&D 98 – EQUIP (Evidence from QUaternary Infills for Palaeohydrology) and PAGEPA (PAleohydrogeology and GEoforecasting for Performance Assessment) – have been concluded. The goal of EQUIP was to test different methods for investigating fracture-filling minerals and their usefulness for tracing earlier hydrochemical and hydrological conditions. The result was improved measurement and analysis methods, an awareness of what can be achieved, and a realization that there are salient uncertainties in the interpretations of past conditions /10-3/.

A glaciation model, different hydrological models and a geochemical computer model were used in PAGEPA to simulate how the composition of the groundwater may have varied during the Weichsel glaciation. By using a chain of computer models, it is possible to create scenarios that describe the evolution of the groundwater composition over time. Modelling results in combination with field data provide input data for bounding the variations that can be expected during a glacial cycle /10-4/.

Research programme

Evolution of the climate on a 100,000-year timescale

The empirical studies of the land uplift process that served as a basis for the scenario description in SR 97 will be concluded during 2001. Continued studies are currently planned. The work is integrated with studies of the large-scale tectonic evolution in the Scandinavian Shield, see section 8.2.7.

An inventory is planned of the different geological and biological archives on the past climate that are available in Scandinavia, see section 9.9.

Temperate/boreal domain

All planned research that solely deals with this climatic domain relates to the biosphere, see Chapter 9.

Permafrost domain

The development of permafrost and its importance for the safety of the deep repository will, according to plans, be studied in cooperation with Finland, Canada and the UK. The project is planned to include a survey of present-day areas with permafrost, model calculations and field studies on a site in Canada.

Glacial domain

The coupling between hydraulic and mechanical processes and their influence on the conditions in the near field of a deposited canister is being studied in the EU project BENCHPAR, in which SKB is participating. Different models are being used to build up an understanding of the processes and to quantify their effects. Development of the aforementioned conceptual model, which describes the hydraulic conditions beneath a continental ice sheet, is currently planned.

11 Natural analogues

The assessment of the long-term safety of a final repository mainly relies on the results of laboratory experiments and measurements in the field. The measurement results are used for model calculations of e.g. how radionuclides dissolve in the groundwater. Models and assumptions are then underpinned with further experiments in the laboratory or in situ. The research in the Äspö HRL provides many examples of the latter. As a complement to experiments in the laboratory and in the field, natural analogues are also studied, see Figure 11-1. The advantages of natural analogues is that they provide an opportunity to study processes that have been going on for much longer times than can normally be followed in an experiment in the laboratory or in the field. The importance of kinetic limitations becomes clearer and the effects of complex and coupled processes can be studied. The analogues generally cover times that are comparable to the expected life of the repository, but a disadvantage is the lack of control. The "experiment" cannot be arranged. It is always difficult to find a good enough analogue, and there are seldom clear boundary conditions. It is therefore unusual that measurement data from natural analogues can be used directly in assessments of long-term safety. In cases where this has been done, it has often been in lieu of other measurements. On the other hand, it is not unusual that models in the safety assessment are tested on natural analogues to see if they work as intended, see Table 11-1. SKB has participated in half of the tabulated studies.

SKB has participated in an overview of all the natural analogues that have been studied at various places in the world, as well as how they have been used in various contexts /11-1/.

Natural analogues were utilized very sparingly in the SR 97 safety assessment. The plans for natural analogues in future assessments will be presented in the Method Report written beforehand, see further section 2.1.1.

__Figure 11-1.__ Natural analogues of the fuel, the canister and the buffer exist all over the world.

Table 11-1. Examples of natural analogues that have been used to study processes of importance for safety assessments of final repositories.

Analogue, country	Processes and scenarios	Data have been used in safety assessments	Models have been used in safety assessments
Uranium			
Alligator Rivers, Australia	Radionuclide transport and retardation (especially for uranium). Groundwater flow and transport of solutes. Transport with colloids.		
Poços de Caldas, Brazil	Development of a redox front. Transport with colloids. Solubility and coprecipitation of radionuclides.	Field data have been used to show that colloids are only of limited importance (SKB 91) /11-2/. Field data have been used to set bounds on the development of a redox front (KRISTALLIN-I) /11-3/.	Test of models needed to calculate solubilities of radionuclides (KRISTALLIN-I) /11-3/.
Cigar Lake, Canada	Fuel dissolution. Radiolysis in groundwater with uranium dioxide. Processes in a clay buffer. Radionuclide retention. Influence of colloids and organic substances on transport of radionuclides.	The observations have been used to show that the calculations of radiolytic oxidation are conservative (SKB 91, SR 97) /11-2, 11-4/. Have also been used to show that assumptions regarding the rate of fuel dissolution have been conservative (TILA 99) /11-5/. Solubility of uranium in deep groundwaters /11-6/.	Test of models needed to calculate solubilities of radionuclides (SKB 91) /11-2/.
Palmottu, Finland	Geochemical control of redox conditions with uranium mineral. Geochemical traces of glacial meltwater and permafrost. Influence of colloids on transport of radionuclides. Influence of microbes on geochemistry. Matrix diffusion.	Profiles from matrix diffusion.	Have been used as example of the fact that matrix diffusion is a process in nature (SR 97) /11-4/.
Oklo, Gabon	Formation of uranium silicate. Influence of radiolysis on spent fuel. Release of radionuclides. Solubility of radionuclides. Geochemical redox reactions. Influence of microbes.		Test of models needed to calculate solubilities of radionuclides (SR 97, KRISTALLIN-I) /11-2, 11-4, 11-7/. Test of model M3 which is used to analyze mixing of groundwater (SR 97) /11-4, 11-8/.

Analogue, country	Processes and scenarios	Data have been used in safety assessments	Models have been used in safety assessments
Peña Blanca, Mexico	Release and transport of uranium under unsaturated conditions. The relative importance of transport in the rock matrix.	Identified secondary phases of importance for release of uranium.	Calculations of radionuclide release (WIPP at Yucca Mountain) /11-9/. Transport of dissolved elements under unsaturated conditions (WIPP at Yucca Mountain) /11-9/.
Shinkolobwe, Zaire	Oxidation of uranium. Formation of secondary uranium phases.	Long list of uranyl minerals.	
El Berrocal, Spain	Transport and retention of radionuclides (especially uranium). Matrix diffusion. Solubilities of radionuclides. Groundwater flow and transport.		Test of models needed to calculate solubilities of radionuclides /11-10/.
Tono, Japan	Transport and retention of radionuclides (especially uranium). Influence of tectonic activity (earthquake) on uranium ore.		
Marysvale, Utah, USA	Transport and retention of radionuclides.		
Copper			
Warship Kronan, Sweden	Copper corrosion /11-11/. Diffusion of copper ions in clay /11-11/.	Limit value of corrosion rate.	Copper corrosion (TVO 92) /11-12/.
Lightning conductor plates, Sweden	Pitting in copper /11-13/.	Limit value of pitting factor (KBS-3) /11-14/.	
Keweenaw, Michigan, USA	Life of copper /11-15/.		
Hyrkkölä, Finland	Copper stability /11-16/.	Life of copper canister based on occurrence of native copper (TILA 99) /11-5/.	
Littleham Cove, UK	Copper corrosion /11-17/.		
Iron			
Bühl, Germany	Iron corrosion /11-18/.	Limit value of corrosion rate.	
Disko Island, Greenland	Iron corrosion /11-18/.	Limit value of corrosion rate.	
Archaeological finds and meteorites	Iron corrosion /11-19/.	Limit value of corrosion rate (0.1–10 μm/y).	

Analogue, country	Processes and scenarios	Data have been used in safety assessments	Models have been used in safety assessments
Roman nails in Inchtutil, Scotland	Iron corrosion /11-20/.	Limit value of corrosion rate (KRISTALLIN I) /11-3/.	
Clay			
Dunarobba, Italy	Isolating properties of clay /11-21/.	Clay as a barrier to microbes (SR 97) /11-4/.	
Gotland, Sweden	Bentonite stability /11-22/.	Limit for illitization of bentonite /11-2/.	
Sardinia, Italy	Bentonite stability /11-22/.	Limit for illitization of bentonite /11-2/.	
Almeria, Spain	Bentonite stability /11-23/.		
Cement			
Maqarin, Jordan	See Chapter 18.	See Chapter 18.	See Chapter 18.
Oman	Influence of high pH.	Colloids and microbes in water with high pH.	Test of models needed to calculate solubilities of radionuclides /11-24/.
Old concrete, Sweden	See Chapter 18.	See Chapter 18.	See Chapter 18.

As is evident from the table, analogues have often been used to test models, which in turn have been used to calculate solubilities of radionuclides in the groundwater. The studies are often carried out in such a manner that several groups have, independently of each other, calculated what concentrations of the elements of interest should be encountered, so-called Blind Predictive Modelling (BPM). This has in several cases led to improvements of databases and a better insight into how poorly soluble elements occur in the groundwater. Such exercises can also be of great pedagogical value.

The material analogues are prominent. Deposits of native copper and iron are studied as analogues of canisters; clays are studied as analogues of buffer and backfill. Both copper and bentonite exist in pure form in nature, which is a great advantage.

Colloids have been investigated thoroughly in several studies. The analogues show that colloids occur, and there are observations that indicate that poorly soluble substances can be transported far by colloids /11-25, 11-26/. At least as important are all the measurements showing that the concentration of colloids in deep groundwaters is always low – too low for colloids to be a serious problem for the rock as a barrier /11-27/.

Perhaps the greatest deficiency of the analogues is the inexact physical and chemical boundary conditions. To rectify this, attempts have been made recently to try to integrate the analogue investigations with experiments both in the laboratory and in situ. The laboratory experiments use samples from the analogue and the field tests are done in or adjacent to the analogue /11-28/.

The investigations of the analogues have also offered an opportunity to test and develop methods that should be useful for the site investigations as well. Sampling of colloids is an example of this, as well as models that can distinguish the effect of mixing and reaction in the chemical composition of the groundwater. Equipment for water sampling, borehole imaging, radar and flow logging have also been tested on natural analogues, e.g. in Palmottu /11-29/.

Conclusions in RD&D 98 and its review

The importance of studying natural analogues, and that SKB should be prepared to devote itself to such studies in the future as well, was stressed in the review of RD&D-Programme 98.

Newfound knowledge since RD&D 98 and SR 97

Two international EU projects about natural analogues (the Oklo project /11-30/ and the Palmottu project /11-29/) were recently concluded. SKB participated in both. The only major analogue project still in progress is an investigation of the cement analogue in Jordan. The results of Phase II of Project Maqarin in Jordan have been reported and are summarized in Chapter 18. Phase IV is still in progress. Studies of material analogues to the copper canister and the bentonite buffer are in progress, and SKB is prepared to undertake new initiatives if interesting projects are presented.

Research programme

Phase IV of the Jordan project will be concluded during the period. The results of the Jordan project and other analogue projects are being processed. Investigations of material analogues continue, mainly copper (see section 5.2.12) and bentonite (see section 6.2.17), but also concrete (see section 18.4.2).

12 Äspö Hard Rock Laboratory

12.1 Purpose of the Äspö HRL

One of the fundamental reasons behind SKB's decision to construct the Äspö HRL (Hard Rock Laboratory) was to create an opportunity for research, development and demonstration in a realistic and undisturbed rock environment down to repository depth, see Figure 12-1. A dress rehearsal for the commissioning of the deep repository is under way at the Äspö HRL.

Important tasks for the Äspö HRL are to:

- Develop, test, evaluate and demonstrate methods for site characterization, detailed characterization, repository design and construction, and deposition of spent nuclear fuel and other long-lived waste.
- Develop and test alternative technology with the potential to reduce costs and simplify the deep repository concept without sacrificing quality and safety.
- Increase the scientific understanding of the deep repository's safety margins and provide data for safety assessments of the long-term safety of the repository.
- Provide experience and train personnel for various tasks in the deep repository.
- Provide information to outsiders on technology and methods that are being developed for the deep repository.

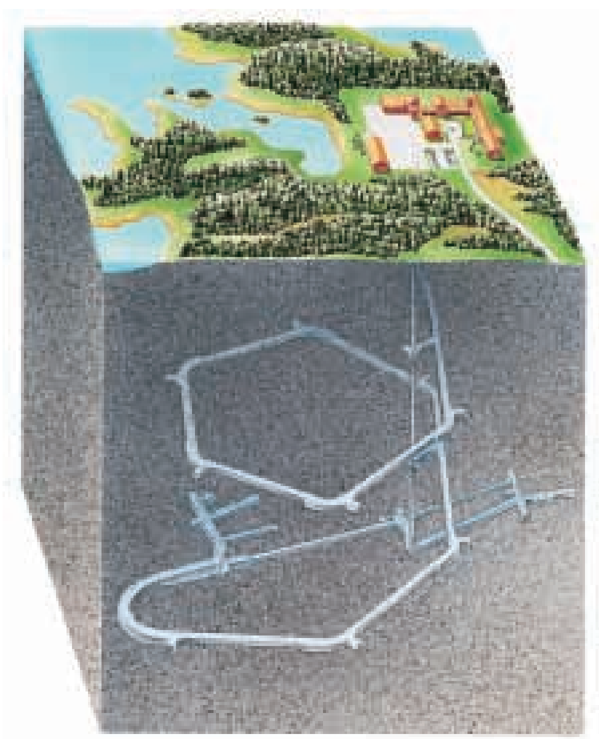


Figure 12-1. *The underground portion of the Äspö HRL reaches a depth of 460 metres. The total length of the tunnel is 3,600 metres. The underground portion is connected to the surface facilities by hoist and ventilation shafts.*

As new research and demonstration projects have been added, new experimental sites have been established. The Äspö HRL is now fully utilized and new rooms are needed if additional major experiments are to be initiated. SKB has no plans to expand the underground portion during the ensuing six-year period. New conditions or needs may change this, however.

When the site investigations in Forsmark, Tierp and Oskarshamn are commenced, activities in the Äspö HRL will fall off slightly. This is particularly true of the investigations aimed at developing methods and training personnel for upcoming duties in the site investigations.

According to plans, the activities at the Äspö HRL will continue until the initial operating stage of the deep repository is finished. An integrated evaluation of experience from this initial operation and the results from the Äspö HRL will thus provide supporting material for an application for a licence for regular operation of the repository. An important role for the Äspö HRL in this perspective is to conduct long-term experiments where different aspects of importance for the performance of the deep repository are tested over a long time, in some cases up to 15–20 years.

This chapter describes the experiments that will be conducted to increase knowledge of the natural barriers, see section 12.2, and the experiments concerned with disposal technology, see section 12.3. The location of the different experiments is shown in Figure 12-2. The base activities at the Äspö HRL are described in section 12.4. An

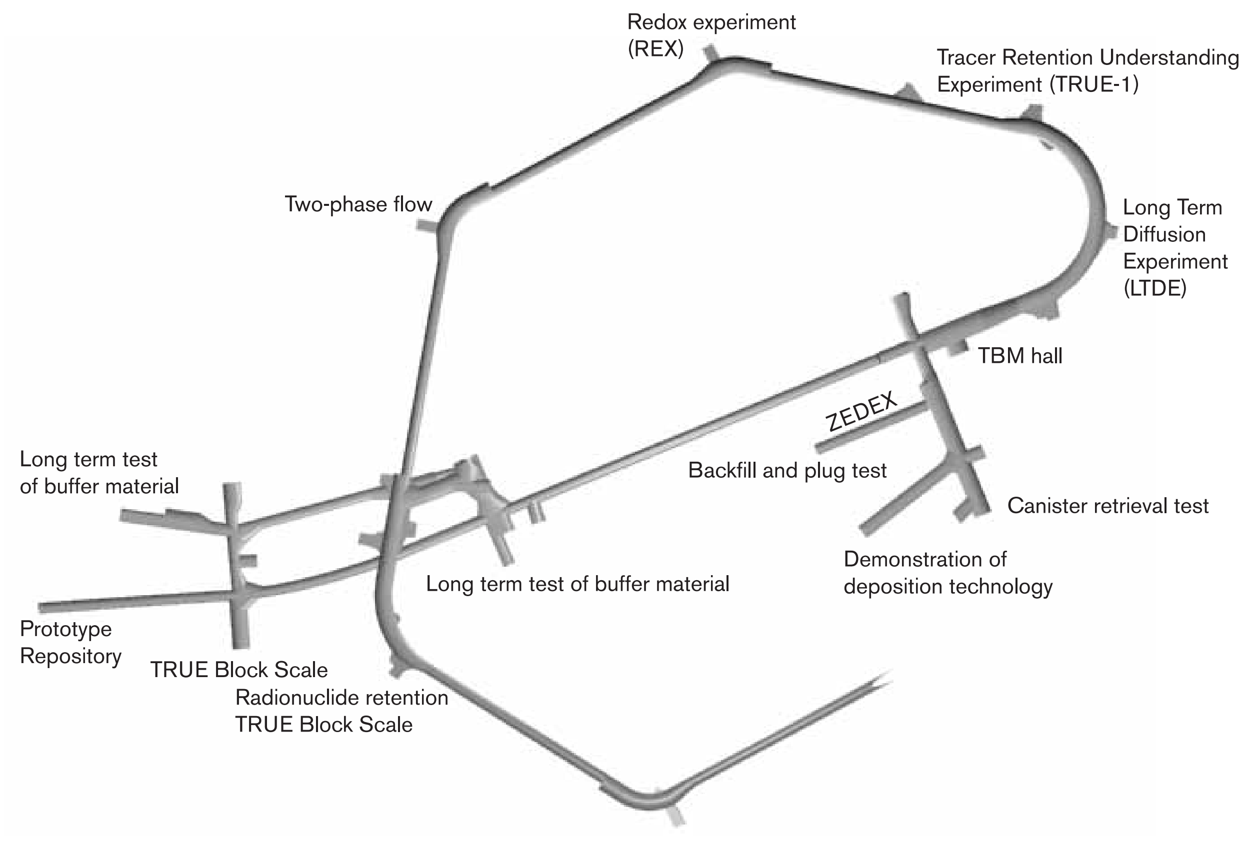


Figure 12-2. *The tunnel system between –300 and –450 metres and the location of the different experiments.*

account of the handling of the investigation data and the development of site-descriptive models is provided in section 12.5. The chapter is concluded with a review of international activities, see section 12.6.

Several of the processes that are studied in experiments at the Äspö HRL have been described in preceding chapters (Chapters 4, 5, 6, 7 and 8). Some aspects of the technical development work are dealt with in Chapter 14. But since the Äspö HRL is such an important facility for conducting full-scale experiments and developing deep disposal technology, we have chosen to provide a general account of all its activities in this chapter.

12.2 Natural barriers

KBS-3 is based on a system of natural and engineered barriers. In order to improve our understanding of the long-term performance of the barriers, it is possible to conduct experiments in the Äspö HRL under conditions that resemble those that will prevail in the deep repository, at a depth of about 500 metres.

The bedrock, its properties, and the physical and chemical processes that occur in it comprise the natural barriers. The experiments and studies that have been or are being conducted are aimed at testing models that describe the functions of the natural barriers: isolation, retardation and dilution. Experiments and projects with natural barriers cover isolation and retardation. Dilution is currently only being used in the biosphere modelling connected with assessment of the long-term safety of the repository.

The following has been studied in the experiments completed so far:

- Structure and hydraulic properties of the fracture system in the rock (FCC /12-1, 12-2/ and HPF /12-3/).
- The capacity of the rock to retain radionuclides in the flow paths (TRUE-1 /12-4/, TRUE Block Scale).
- Damage caused by blasting and boring of tunnels (ZEDEX /12-5/).
- Influx of oxygenated surface water (REDOX /12-6/) and in-situ consumption of oxygen (REX /12-7/).
- Degassing of groundwater and investigation of matrix water chemistry (DEGASSING /12-8/).

In addition, Äspö data have been used for modelling in several international projects, for example the Äspö Task Force and the EU project EQUIP (Evidence from Quaternary Infills for Palaeohydrology) /12-9/.

Newfound knowledge since RD&D 98

A summary of experimental activities during the period 1995–2000 /12-10/ provides an overview of purpose, essential results and possible remaining questions in the completed projects.

Research programme

The overall purposes of testing models of the barrier function of the rock are to:

- Improve the scientific understanding of the deep repository's safety margins and provide input data for assessments of the repository's long-term safety.
- Obtain the special material needed to supplement data from the site investigations in support of an application for a siting permit for the deep repository.
- Clearly present the role of the geosphere for the barrier functions: isolation, retardation and dilution.

The superordinate goals towards which the work is aimed are:

- Background material for future safety assessment of candidate sites.
- Background material for preparation of programme for detailed site characterization.

Ongoing or planned experiments are:

- Tracer Retention Understanding Experiments (TRUE).
- Long Term Diffusion Experiment (LTDE).
- Radionuclide retention experiment (CHEMLAB).
- Microbial experiments (MICROBE).
- Experiments with colloids (COLLOID).
- Matrix water chemistry (MATRIX).

Results and knowledge gained from experiments, as far as they have come or are planned, are described in brief in Chapters 4, 6 and 8 in connection with the respective process, see Table 12-1. The research and development that is planned during the coming six-year period is also described in brief there. Sections 12.2.1–12.2.6 provide a general description of ongoing or planned experiments.

Table 12-1. References to sections in this report where the experiments are described.

Experiment	Section	Process
MATRIX	8.2.13	Reactions groundwater/rock matrix
MICROBE	8.2.15	Microbial processes
COLLOID	8.2.17	Colloid turnover
	6.2.19	Colloid – release/erosion
TRUE	8.2.28	Integrated modelling: radionuclide transport
	8.2.23	Radionuclide transport: molecular diffusion and matrix diffusion
CHEMLAB	4.2.12	Fuel dissolution
	4.2.14	Speciation, colloid formation
	6.2.25	Radionuclide transport: diffusion
	6.2.26	Radionuclide transport: sorption
	8.2.24	Radionuclide transport: sorption
	8.2.28	Integrated modelling: radionuclide transport

12.2.1 TRUE

Tracer Retention Understanding Experiments (TRUE) are carried out in order to increase our understanding of transport and retardation of radionuclides in fractured rock. Of particular importance are tracer tests, which are carried out on different scales, see Figure 12-3. The TRUE programme was initiated in 1994 and is expected to continue until 2005.

A field experiment (TRUE-1) in a single fracture has been carried out on the detailed scale (< 10 metres) /12-4/. Another experiment, TRUE Block Scale, has been carried out in a network of structures on the block scale (10–100 metres), and evaluation and reporting are currently under way. The international group that has participated in TRUE Block Scale is planning further tracer tests.

12.2.2 Long Term Diffusion Experiment

A new experiment has been initiated called Long Term Diffusion Experiment, LTDE. The purpose of the experiment is to describe diffusion and sorption in the rock mass in connection with a natural water-bearing fracture plane under in-situ conditions. In a borehole with a large diameter, a "core stub" is left which is shielded off from the surroundings. By means of an automatic control system, a tracer is circulated in such a way that only diffusion and sorption can take place in the core stub and the rock volume behind it.

The experiment is expected to go on for between three and four years. During this time an inward diffusion of weakly sorbing tracers is expected to occur over a distance of several decimetres. Then the core stub and the rock volume behind it will be overcored and analyzed with respect to concentration of the relevant tracers and radionuclides.

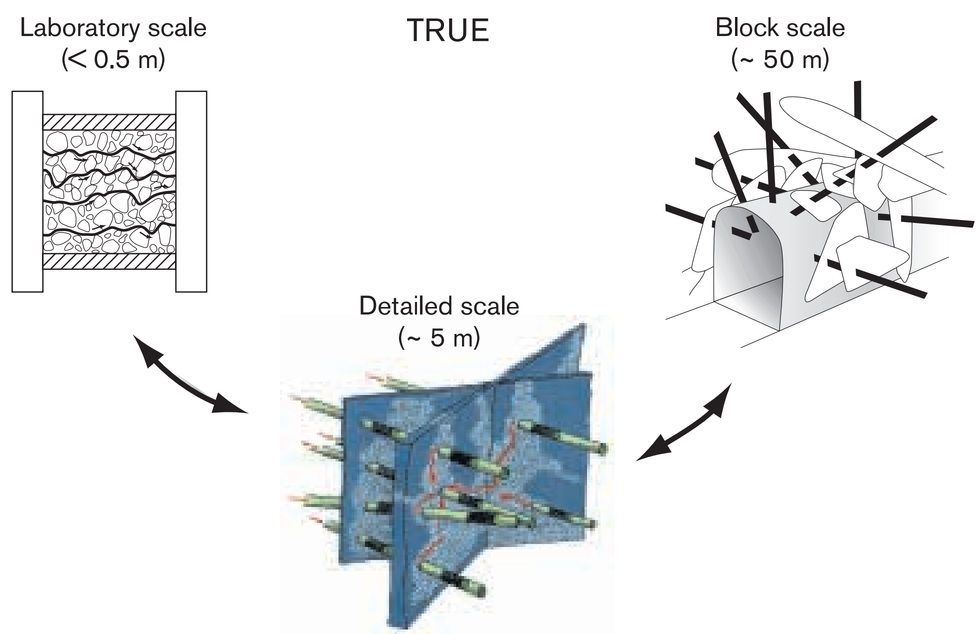


Figure 12-3. *Schematic description of the transport scales in the TRUE project.*

12.2.3 CHEMLAB

The CHEMLAB probe /12-11/ is a chemical laboratory built into a borehole probe. The experiment can be carried out under natural groundwater conditions (temperature, pressure and composition). The probe is used to study radionuclide retention. Experiments can be conducted with radionuclides without risk of contamination of surrounding rock and groundwater. The planned experiments are expected to last more than five years and include:

- Radiolysis experiments with technetium.
- Transport of strontium, cesium and iodine from the bentonite barrier out to a water-bearing fracture.
- Additional demonstration experiments to show the influence of redox processes on sorption.
- Transport of actinides and redox-sensitive nuclides in a fracture.
- Fuel dissolution under repository conditions.

12.2.4 MICROBE

The influence of microbes on the redox stability of the rock will be studied in the MICROBE project /12-12/. The experimental area for MICROBE will also serve as a very well characterized area for experiments in which repository-like conditions are required, e.g. to study the influence of the microbes on radionuclide transport. An important research field is the migration, survival and activity of sulphide-forming (sulphate-reducing) bacteria in buffer material.

The field experiments are conducted in a specially equipped niche at the 450-metre level in the Äspö HRL. Three horizontal boreholes have been drilled in a fan pattern. Each borehole has hit at least one groundwater-bearing fracture. These fractures have been fitted with a non-metallic packer system. Groundwater can be tapped for different experiments, or recirculated to the borehole section.

The microbe investigations will be coupled to other ongoing experiments with bentonite and copper. The project is planned to proceed during the entire period 2002–2007.

12.2.5 COLLOID

The COLLOID project /12-13/ is aimed at studying the role of bentonite as a source of colloid formation, verifying previously measured colloid concentrations at Äspö, and investigating the potential for colloid transport in natural flow paths in the bedrock.

The role of bentonite clay as a colloid source at varying groundwater salinities is being investigated in laboratory experiments. The colloid concentration in different fracture zones along the Äspö tunnel will be measured with a laser instrument that has a higher resolution than previously used equipment. Two nearby boreholes that penetrate the same fracture zone will be used for the transport-related measurements.

SKB initiated the project in 2000 and it is scheduled to continue through 2003.

12.2.6 MATRIX

Groundwater is normally sampled in the fractures in the rock. The composition of this water is not necessarily representative of the matrix fluid, i.e. the water in the pores and microfractures in the rock. The MATRIX project /12-14/ aims at conducting field studies of the chemical composition of matrix fluids.

The goals of the experiment are to:

- Determine the origin and age of the matrix fluids.
- Establish whether present or past diffusion processes have influenced the composition of the matrix fluids, by either dilution or increased concentration.
- Derive a range of groundwater compositions as suitable input data for near-field model calculations.
- Establish the influence of fissures and microfractures on the chemistry of the matrix fluids in the bedrock.

The experiment has been designed to sample matrix fluids from predetermined isolated borehole sections. The location of the boreholes was chosen on the basis of rock type, mineral and geochemical homogeneity, depth, and presence and absence of fractures. Special equipment has been designed to sample the matrix fluids.

An extensive investigation programme has been under way from September 1999 up to the present, and the project will be concluded during 2002.

12.3 Disposal technology

The Äspö HRL provides valuable experience when it comes to refining and testing technology for building a repository and investigating the rock during construction. Tunnelling has been carried out by means of both conventional drill and blast and a tunnel boring machine (TBM) as a basis for the selection of excavation methodology in the deep repository.

The Äspö HRL is used for testing, investigating and demonstrating various components in the deep repository system on a full scale and under realistic conditions. It is also important to show that high quality can be achieved in the design, construction and operation of a deep repository. A full-scale prototype of the repository is being built to simulate repository function and interaction between its parts during the initial postclosure stage. Development of quality systems is included in the work.

Newfound knowledge since RD&D 98

At the Äspö HRL, the technology for handling and depositing canisters and backfilling deposition tunnels has been developed and demonstrated, and preparations have been made for retrieving deposited canisters, largely according to the plan described in RD&D-Programme 98 /12-15/.

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Development programme

The overall purposes of the experiments are to:

- Develop technology and demonstrate the entire handling chain prior to the initial operation of the deep repository.
- Demonstrate retrieval of a deposited canister.
- Investigate the function of buffer and backfill both during the resaturation process and in the water-saturated state in the repository environment.

The experiments that are under way or planned are:

- Demonstration of deposition technology.
- Prototype Repository.
- Backfill and Plug Test.
- Canister Retrieval Test.
- Long Term Test of Buffer Material.

Results and knowledge gained from experiments, as far as they have come or are planned, are described in brief in Chapters 6, 7 and 14, see Table 12-2. The research and development that is planned during the coming six-year period is also described in brief there. Sections 12.3.1–12.3.5 provide a general description of ongoing or planned experiments.

A number of projects with international participation are also under way. They include modelling of the engineered barriers by a Task Force and an EU project in connection with the Prototype Repository, see section 12.6.2.

Table 12-2. References to sections in this report where the experiments are described.

Experiment	Section	
Demonstration of deposition technology	14.5.3	Emplacement of bentonite and deposition of canisters
Prototype Repository	14.5.3	Emplacement of bentonite and deposition of canisters
Backfill and Plug Test	14.5.4 7.2.2	Backfilling Integrated studies: composition and function of backfill
Canister Retrieval Test	14.5.3 14.5.6	Emplacement of bentonite and deposition of canisters Retrieval
Long Term Test of Buffer Material (LOT)	6.2.17 6.2.18 6.2.23 6.2.24 6.2.25	Montmorillonite transformation Dissolution/precipitation of impurities Integrated studies: evolution of buffer under saturated conditions Radionuclide transport: advection Radionuclide transport: diffusion

12.3.1 Demonstration of deposition technology

The goals of the project "Demonstration of deposition technology" are to:

- Develop and test methodology and equipment for deposition of spent nuclear fuel.
- Demonstrate in an instructive manner the different steps in the deposition and retrieval of canisters for specialists and the general public.
- Develop and test appropriate criteria and quality systems for the deposition process.

To enable the project to be carried out, SKB has developed a full-scale prototype of a deposition machine.

Demonstration of deposition technology has been carried out in the Canister Retrieval Test, where bentonite and a canister of natural size with a heater have been deposited. In the Prototype Repository experiment, six more canisters will be deposited. These experiments are described below.

12.3.2 Prototype Repository

The experiments in the Prototype Repository focus on monitoring of the function of the repository system and the interaction of the parts of the repository. Certain activities aimed at development and testing of practical solutions for carrying out deposition have also been included.

Altogether, six deposition holes will be made in a TBM-bored tunnel, two in an inner section and four in an outer, see Figure 12-4. The tunnels will be backfilled with a

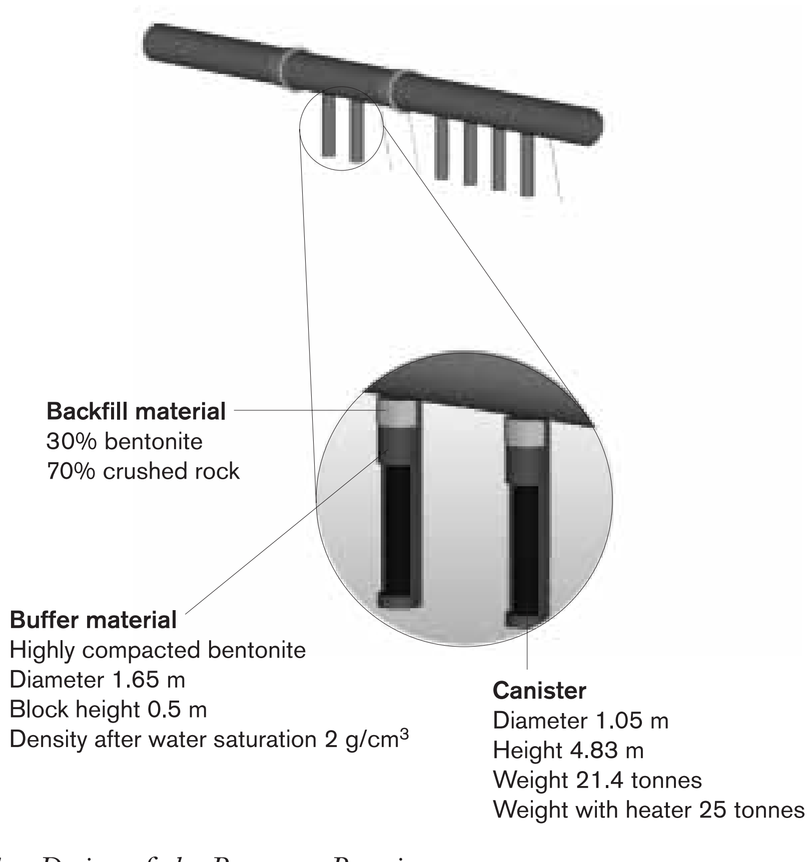


Figure 12-4. *Design of the Prototype Repository.*

mixture of bentonite and crushed rock, and the two sections will be separated by a plug. The Prototype Repository differs from a real repository in that the heat output is generated by heaters instead of spent nuclear fuel.

The experiments in the Prototype Repository will start during 2001 and 2002, after which they will continue for about 20 years.

12.3.3 Backfill and Plug Test

Research on backfilling with mixtures of bentonite and crushed rock is currently being done to a large extent at the Äspö HRL within the framework of the Backfill and Plug Test there. The objectives of the test are:

- To develop and test different materials and compaction techniques for backfilling of drill-and-blast tunnels.
- To test the function of the backfill and its interaction with the surrounding rock on a full scale in drill-and-blast tunnels.
- To develop technology for building plugs and testing their function.

In the experiment, a tunnel has been backfilled with crushed rock and with a mixture of 70 percent bentonite and 30 percent crushed rock. The tunnel has been sealed with a plug designed to resist full water pressure and the bentonite's swelling pressure. Drainage mats are used to hasten the wetting of the backfill. During the test, the water flow in the backfill is measured. This is done in the unsaturated state (during the water saturation process) and in the water-saturated state.

The experiment was started in 1999. To start with the backfill will be water-saturated, which is estimated to take a few years. Then flow tests will be conducted for about one year. The experiment will be concluded by excavation and analysis of the backfill material.

12.3.4 Canister Retrieval Test

In the Canister Retrieval Test, methodology and equipment are being developed and tested to retrieve the canister from a water-saturated and swelled bentonite buffer and it is being demonstrated how a freed canister can be retrieved under realistic conditions. The project was started in 2000 when bentonite and a canister of natural size with a heater were deposited in a full-sized deposition hole, see Figure 12-5.

During the water saturation period, data are collected on water saturation, temperature, swelling pressure and movements in the buffer. The rock is instrumented for monitoring of temperature, rock stresses and rock movements. Furthermore, the deformation of the copper shell and the temperature of the canister are measured.

After the bentonite has been water-saturated, which is expected to take between three and five years, SKB will demonstrate how a canister can be freed and retrieved. The bentonite will be removed by flushing with saline water. When the canister has been dislodged from the bentonite, it will be lifted by its lid and placed in a radiation shield.

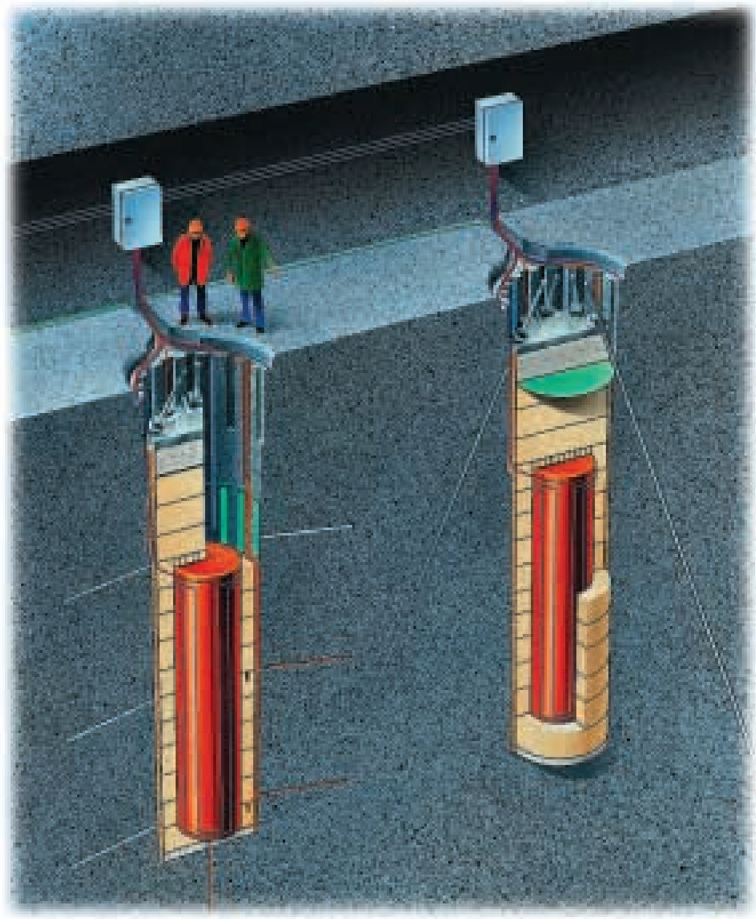


Figure 12-5. *Sketch of experimental set-up in Canister Retrieval Test. The two pictures show different parts of design and installation in the same hole.*

12.3.5 Long Term Test of Buffer Material

The Long Term Test of Buffer Material (LOT) is being carried out at the 450 metre level in Äspö. The test series comprises a total of seven test parcels with test times of one, five or 20 years. In each test, a parcel containing heater, copper tube, precompacted bentonite blocks and instruments is emplaced in a vertical borehole. The heaters are used to simulate the decay heat from spent nuclear fuel and are controlled to provide both KBS-3 conditions (maximum 90ºC) and more adverse conditions (approx. 130ºC).

Heat output, temperature, pressure and moisture content in the bentonite are recorded during the tests. Reference and exposed bentonite material is analyzed with respect to physical properties (swelling pressure, hydraulic conductivity, rheology etc.) and mineralogical properties (cation exchange capacity, ion content, mineral distribution etc.).

Bentonite doped with radioactive tracers has been placed in the bentonite to study diffusion. A large number of microorganisms have been placed in the bentonite at selected places. Moreover, small, well-characterized copper coupons have been placed in the bentonite at selected locations.

Two pilot tests (one-year tests) have been concluded and reported with respect to design, field data and laboratory results /12-16/. An ongoing one-year test with elevated temperature will be concluded and analyzed during 2001 in accordance with the testing programme. The three ongoing five-year tests will be concluded and analyzed during 2004 /12-16/.

12.4 Base activities at the Äspö HRL

Base activities at the Äspö HRL are conducted to support the research, development and demonstration projects. The base activities include carrying out measurements of common interest to all projects, supplying results and compiling models from different scientific disciplines, as well as development and administration of SKB's geodatabase.

12.4.1 Monitoring of groundwater head

The work of building a system for monitoring of the groundwater heads in boreholes on Äspö and nearby areas, known as the Hydro Monitoring System (HMS), was begun during the pre-investigation phase. The system has gradually been built out and now also includes a large number of boreholes underground. The groundwater pressure head is normally measured every other hour and the results are stored in a database. The system makes it possible to measure disturbances of groundwater levels caused by various events in the laboratory and elsewhere. These measurement values can then be used to refine and evaluate various hydraulic models of Äspö and to check the boundary conditions for different experiments conducted at the laboratory. HMS will be built out to meet the needs created by the various projects.

The number of both boreholes and borehole sections was increased during the preceding period, mainly due to the needs of the TRUE Block Scale and Prototype Repository projects.

Monitoring of the groundwater heads on Äspö is also required by a water court ruling.

Newfound knowledge since RD&D 98

An overall evaluation of the monitoring system was carried for the purpose of proposing improvements and to serve as a basis for the design of a groundwater monitoring system for the site investigations.

The monitoring system has been utilized in a pilot project to calculate the dip and strike of fracture zones from pressure variations caused by tidal effects. Besides the groundwater heads, the water level in the Baltic Sea and air pressure data are used for this. The reliability of the method has not yet been established.

Development programme

For the upcoming period, SKB intends to maintain the operation of the system and support ongoing and future experiments as needed.

12.4.2 Monitoring of the chemical composition of the groundwater

A comprehensive programme for hydrogeochemical characterization was carried out during the pre-investigation phase prior to the construction of the Äspö HRL /12-17/. The samplings continued during the construction phase in observation boreholes drilled from the ground surface on Äspö and from probe holes in the tunnel. Many of these holes were part of a monitoring programme and were sampled several times /12-18/. The results were used to cross-check and refine the hydrochemical models that had been set up on the basis of the pre-investigations /12-19/.

Newfound knowledge since RD&D 98

The samplings have continued as planned during the operating phase in order to follow the changes induced by the facility. Samples are taken regularly once a year from selected boreholes above and below ground.

Analysis data have shown that the chemical composition in the entire Äspö HRL is very stable and that a sampling frequency of once a year is sufficient.

Obtained data are used in models of groundwater flow and groundwater chemistry to interpret the long-term impact of the facility on groundwater flux in the area and on geochemical conditions. These data have been used by the international Äspö Task Force on Modelling of Groundwater Flow and Transport of Solutes for a modelling exercise, Task 5, aimed at integrating hydraulic and chemical data, see sections 8.2.3, 8.2.21 and 12.6.1.

Development programme

The current scope and frequency of the samplings is planned to continue for the time being.

12.5 Investigation data and site-descriptive models

SKB has been developing methods for administering and archiving investigation data for a long time. Investigation data collected recently are managed centrally in a database called SICADA, which is described in section 12.5.1.

A geographic information system, GIS, was utilized during the feasibility studies to compile and present collected information.

SKB uses CAD methods to set up a three-dimensional site-descriptive model. The model is created in a format that can be directly used for design and documentation of the deep repository. Several systems for simulation of the processes (process models) are also integrated with different types of CAD systems. This makes it possible to transfer information about the site-descriptive model directly to the process models, although this will require special interfaces in many cases. SKB plans to use an own-developed system for creating the site-descriptive models. The system is called the Rock Visualization System (RVS) and is described in section 12.5.3.

Continued efforts during the upcoming three-year period are first and foremost aimed at further streamlining and broadening the flow of data between the different subsystems. The most important milestone is finishing the methodology to such an extent that the site investigation phase can be commenced with tools that enable quality-assured data to be administered in an efficient and traceable manner.

12.5.1 Geoscientific database – SICADA

Data from SKB's investigations, including the measurements performed in connection with experiments at the Äspö HRL, are stored in SKB's geoscientific database SICADA. The database is a tool for long-term storage of data in a reliable and traceable manner and comprises a source of consistent data for field work, interpretations, evaluations and models. Ultimately, this means that safety assessments are based on correct data.

Newfound knowledge since RD&D 98

The work has continued according to plan towards the goal of keeping SICADA up-to-date and making it an effective tool for use in ongoing experiments at the Äspö HRL and in future site investigations.

Development of the database during the most recent period has led to a customized and stable system. A number of modifications have been made to improve user-friendliness and to interconnect the database with surrounding systems for pre- and post-treatment of data. An example of such a system is the modelling tool RVS developed by SKB.

Development programme

The ongoing development work will be intensified so that all major development work can be finished before the site investigations are begun. Continuous maintenance and development will then be undertaken to satisfy requirements on the system that arise in the course of the investigations.

The information administration organization will be strengthened and the procedures for data management will be refined so that the collected data can be efficiently processed and forwarded to the beneficiaries, see also section 13.3.

During the same period, the system will be modified for the benefit of the Äspö HRL so that it can handle activities and information from deposition of buffer and canisters, backfilling of tunnels, and plugging of tunnels and boreholes.

12.5.2 Geographic Information System – GIS

GIS was used during the completed feasibility studies as a powerful tool to compile and present information. During the site investigations, GIS will be one of SKB's tools for information processing. Its role will be broadened so that, in addition to compilations and presentations, it will also be used for more comprehensive analyses of data and as a tool for informing the public.

Newfound knowledge since RD&D 98

Roles and responsibilities have been defined and processes for operation, development and information administration have been introduced.

Development programme

Operation of the system will be organized and operating procedures developed to ensure high availability and reliable handling of the information in the system. Components will therefore be added that permit structured internal and external access to data.

In the same way as SICADA, the GIS system shall be able to preserve data in the long term in a reliable and traceable manner and comprise a source of consistent data for field work, interpretations, evaluations and models.

Development will also be pursued to permit a structured exchange of information between GIS and SICADA. Moreover, a methodology is needed for transferring GIS data to RVS. Applications for SKB's vital analysis needs will be designed in-house when not available on the market.

12.5.3 Visualization of investigation data – RVS

As mentioned at the beginning of this section, SKB is developing a system for three-dimensional visualization of investigation data and modelling of the interfaces. The system is called the Rock Visualization System (RVS) and is based on the commercial CAD program MicroStation/J. It is also included as a basic tool for design of underground facilities.

Newfound knowledge since RD&D 98

A decision has been made to augment and modify the system so that it meets the specified needs /12-20/. This work is very concretely focused on preparing the system for the site investigation phase. At the same time the system will be based on the new version of MicroStation called MicroStation V8, which is expected to entail considerable operational advantages.

Development programme

An administration organization for the system will be staffed and operating and monitoring procedures will be developed and established during the initial phase of the site investigations, after which they will be augmented and modified as needed.

An intensive development effort is planned to provide the system with capabilities that support the modelling technique presented in /12-20/. This work also includes establishing a central database for administration of site-descriptive models. In addition, tools are needed for transferring the information on the site-descriptive model to the process models. It may also be necessary to support feedback of results to the site-descriptive model in order to facilitate its interpretation.

Planning and implementation of user training are also needed, as well as development of procedures for how the system is to be used.

12.5.4 Geoscientific models of the Äspö area

Geoscientific information was systematically collected during the pre-investigation, construction and operating phases on Äspö. Data continue to be collected from the various tests and projects that are being conducted. The information that has been gathered by the completion of the main tunnel down to the 450-metre level has been used to devise site-specific models of conditions on Äspö. The purpose of devising these models has been to verify the ability to predict the properties of a rock mass based on information obtained from completed investigations.

The plan in 1998 was to update the geological, geohydrological and geochemical models of Äspö by detailing of the rock block within the spiral ramp based on data obtained during the excavation of the ramp. Plans were also made to devise a rock-mechanical model and a heat transport model of the same rock volume. None of this has been realized in its entirety during the period, and updating of the geological, geohydrological and geochemical models has been postponed in favour of preparation for site investigations. Work on the geomechanical model was begun during the period, but will presumably not be completed during 2001. Work on the heat transport model has also been commenced, but will probably not be completed during 2001 either.

Newfound knowledge since RD&D 98

The geological, geohydrological and geochemical models of the Äspö volume are described in /12-21/ and have proved to be adequate for planning of the site investigations. Nor has further detailing been necessary for the experiments that are conducted. Suitable boundary conditions for the modelling needs have been able to be calculated with existing information.

Rock-mechanical questions are of particular interest in the Prototype Repository, where heating with the simulated canisters will induce such great stresses in the rock that the changes can be followed via e.g. acoustic emission. Mathematical models are thereby also of interest, since predictions can be compared with actual outcomes.

The same applies to heat transport; it should, however, be noted that in the large-scale experiments that have been conducted in granitic bedrock (BMT in Stripa, FEBEX in Grimsel and the Buffer Container Experiment in the URL in Pinawa), mathematical codes for heat transport have proved to be reliable and the most accurate of all model codes. This is assumed to be the case in the Prototype Repository at the Äspö HRL as well.

Development programme

The development of a geomechanical and a heat transport model will be completed. Data will be gathered for updating of the radionuclide transport model that has been used in SKB's safety assessments of a deep repository.

12.6 International cooperation

The activities at the Äspö HRL have attracted great international interest. Agreements on participation exist with: the Japan Nuclear Cycle Development Institute (JNC), Japan; the Central Research Institute of Electric Power Industry (Criepi), Japan; Agence National Pour la Gestion des Dechets Radioactifs (ANDRA), France; Posiva Oy, Finland; UK Nirex, UK; Nationale Genossenschaft für die Lagerung von Radioaktiver Abfälle (Nagra), Switzerland; Bundesministerium für Wirtschaft und Technologie (BMWi), Germany; Empresa Nacional de Residuos Radiactivos (Enresa), Spain; and the United States Department of Energy, Carlsbad Area Office (USDOE/CBFO), USA.

The international cooperation 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. Besides the IJC members, technical experts from each organization that participates in the activities of the Äspö HRL participate in the TEFs.

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 planned further investigations and experiments, which are specified in the agreements concluded with the respective organizations. These experiments are being conducted above and beyond the programme described here and provide considerable added value to SKB's activites.

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. Examples of this are the cooperation that takes place in a Task Force consisting of members from the participating organizations. Such Task Forces exist for modelling of groundwater flow and transport of solutes (see section 12.6.1) and for modelling of engineered barriers (see 12.6.2). Another important part of this cooperation is the peer review of the Äspö HRL's plans for design of different experiments as well as obtained results performed by SKB's international partners and their experts.

The results of the international cooperation are published in a separate report series: Äspö International Cooperation Reports.

12.6.1 Task Force for modelling of hydraulic transport

A Task Force on Modelling of Groundwater Flow and Transport of Solutes has been created at the Äspö HRL. The Task Force was started by SKB at the end of 1992 for the purpose of evaluating the suitability of different models.

The Task Force is supposed to serve as a forum for consultation and discussion of conceptual and numerical modelling of groundwater flow and radionuclide transport for the cooperating organizations.

The tasks have so far included:

Task 1 Modelling of LPT-2, a large-scale long-term pumping test and associated tracer test /12-22/.

Task 2 Scoping calculations for planned detailed-scale tracer tests /12-23 to 12-27/.

Task 3 Modelling of the hydraulic impact of the Äspö tunnel /12-28/.

Task 4 Predictive modelling of tracer tests with sorbing and non-sorbing tracers carried out within the TRUE-1 project /12-29, 12-30/.

Task 5 Coupling between hydrogeological and hydrochemical models /12-31/.

Task 6 Safety assessment modelling based on data from site characterization.

The Task Force is currently working on Task 6, which aims at increasing the realism of models utilized for safety assessment by making use of results and methodology used for site investigation evaluation. This is done by applying both modelling methods to the same data and setting boundary conditions which are usually utilized in safety assessment modelling. The hope is to be able to identify conceptualizations (in processes and geologies) that are relevant in the long time perspective of the safety assessment. Conversely, this can provide information on which data from a site investigation are needed for the safety assessment. The modelling is projected to start during 2001 and to continue for three to four years.

Work on Tasks 4 and 5 has been pursued in accordance with the plan, and both will be concluded during 2001. A new task – Task 6 – has been defined and initiated.

Newfound knowledge since RD&D 98

The modelling that was carried out within the framework of the Task Force has been able to relate the knowledge and the tools for modelling which SKB uses to international standard and practice.

Development programme

The goal is to carry out Task 6. Further modelling exercises may be defined in cooperation with the international organizations that are participating in the Task Force.

12.6.2 Task Force for modelling of engineered barriers

Background

A Task Force on Engineered Barrier Systems has also been initiated. During the three-year period, it will concentrate on the water saturation process in buffer, backfill and rock. Since the water saturation process is also a part of the modelling work in the Prototype Repository, the work of the Task Force has also been linked together with modelling work in an EU project. The difference is that GRS (Germany) and ANDRA (France), which are not participating in the EU project, are participating in the modelling work being undertaken by the Task Force. They are being given access to the same data as the participants in the EU project. The relevant task is:

Task 1 Thermo-hydro-mechanical modelling of processes during water transport in buffer, backfill and near-field rock.

Development programme

The goal is to carry out Task 1. New tasks will gradually be defined in cooperation with the international organizations that are participating in the Äspö project.

13 Instruments and methods for site investigations

SKB has today a comprehensive programme for planning and preparations for upcoming site investigations. Investigation methods and measurement instruments are being developed and tested. The preparations also include devising a policy for long-term observations and drawing up preliminary programmes for them. The supplement to RD&D-Programme 98 /13-1/ provided an integrated account of SKB's programme prior to the site investigation phase, and no further details are given here. Site-specific programmes will be presented during the autumn of 2001. Instead, the chapter focuses on the ongoing development of important investigation methods and measurement systems. Data management, building of site-descriptive models and transfer of information between investigations, design and safety assessment are also elucidated.

13.1 Background

The geoscientific conditions are fundamental for determining whether a site is suitable for a deep repository. Development of the site investigation programme has been under way for the past decade. The information requested by the regulatory authorities in conjunction with the review of RD&D-Programme 98 has been furnished via the account in the supplement and its background reports /13-1/. A scientific programme for investigation and evaluation of sites is presented there /13-2/. This latter document explains what type of information is intended to be collected from a site and how it is to be used in evaluation of a site's suitability for a deep repository. A more extensive and detailed description of how the investigations of the geosphere and biosphere on the sites can be carried out has also been provided /13-3/. This report specifies what will or can be measured, what methods will be used, and how site-descriptive models will be set up. Both reports describe in general terms how the activities in the site investigation phase can be carried out, without direct adaptation to the sites to be investigated. When the contents and scope of the sub-steps of the various stages are tailored to the different sites, however, it may be found that certain investigation steps must be added, while others are unnecessary and can therefore be omitted. The sequence of the different investigation steps may also need to be modified. What is essential is that the site-specific information is collected when it is needed and that it is ultimately sufficient for the site-descriptive account and the safety assessment.

The work of preparing programmes for executing the site investigations is now under way for the selected areas. These programmes will be adapted to the areas' specific conditions and special questions. These site-specific programmes, which will mainly deal with the initial investigations, will be presented during the autumn of 2001. The aim is to be able to commence the site investigations at the beginning of 2002. During the course of designing the site-specific programmes, viewpoints will be solicited from e.g. concerned landowners, regulatory authorities and municipalities. SKB will strive to conduct the investigations in such a way that incursions and disturbances for nearby residents and for the natural and cultural environment are limited without any adverse impact on the investigation results as a whole. The site-specific investigations will initially be aimed at answering the site-specific questions regarding the bedrock that are presented in SKB's integrated account of method, site selection and programme prior to the site investigation phase /13-1/.

SKB assumes in its planning that the site-specific programmes presented during the autumn of 2001 can be executed more or less as foreseen. SKB will attempt to maintain a running dialogue with SKI and SSI during the site investigation phase as regards the execution and results of the investigations.

13.2 Investigations, design and safety assessment

The work during the site investigation phase will revolve around three technical main activities: investigations, design and safety assessment, see Figure 13-1. The investigations yield results which must be analyzed and interpreted in order to provide a useful description of the site. The design activity needs the site-descriptive model to produce a facility description with repository design. Design must also judge the consequences of the construction work. The safety assessment activity evaluates long-term safety based on the site-descriptive model and the repository design. A detailed account is given in /13-2/.

Major safety judgements are delivered on at least two occasions during the site investigation phase: Firstly in the form of a preliminary safety judgement based on data from the initial site investigation, and secondly in the form of a safety report based on data from the complete site investigation. In addition, the preliminary judgements and assessments made within the framework of the safety assessment work in conjunction with the planning of the continued investigations and the site-descriptive modelling are also used. Safety-related aspects of layout proposals or more detailed questions regarding the design of the repository are analyzed and judged and serve as a basis for the continued design work. See also Chapter 2 for safety assessment and Chapter 14 for design of the deep repository and preparation of the facility description.

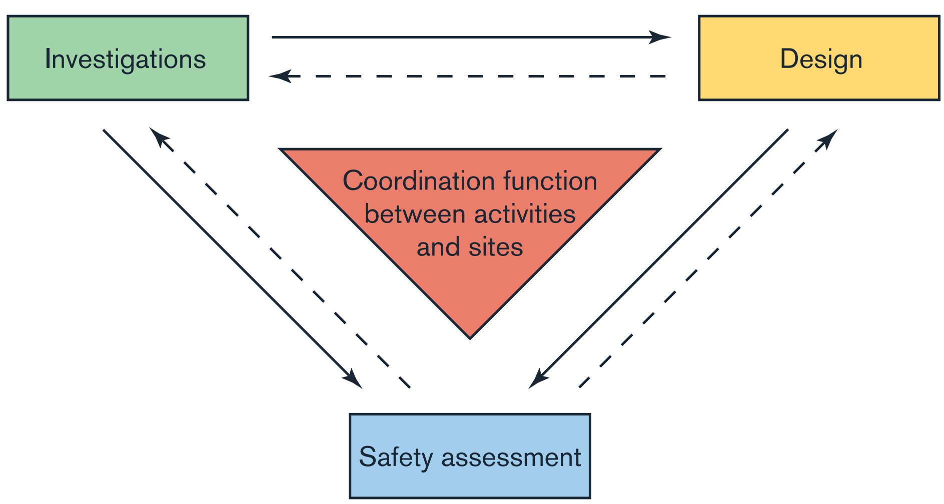


Figure 13-1. *The three main activities investigations, design and safety assessment, their main products and information flows. The information exchange makes heavy demands on coordination between the different main activities and different sites.*

13.3 Data management and site-descriptive models

A very important part of the work of quality-assuring the investigations and ensuring traceability in data management is the preparation of method descriptions. A method description describes the method to be used in SKB's work with respect to requirements on function and accuracy, what information quantities are to be produced, and how the results are to be documented.

Primary investigation data are stored in site-specific databases in SICADA. The database's primary data mainly represent parameter values for single measurement points or limited measurement objects. For this, SKB has developed a special computer system for visualizing the bedrock called RVS (Rock Visualization System), which is a central tool in site-descriptive modelling. The site-specific model is furthermore represented by means of the geographic information (GIS). The SICADA database and RVS have been developed and used in conjunction with investigations in the Äspö HRL. The geographic information system GIS has been used both in the feasibility study work and at the Äspö HRL.

The site-descriptive model, as a part of the evaluation of a site, consists of a description of the site's geometry and properties and comprises, together with databases, the backbone of the site description /13-3/. During the site investigation, collected primary data are analyzed and interpreted both discipline-specifically and integrated over the disciplines. This is done to be able to divide the site into suitable geometric units and to assign discipline-specific properties to these units. In this way a three-dimensional site-descriptive model of rock and soil is built. The relationship between database and model is illustrated in Figure 13-2.

The purpose of dividing the site-descriptive model into different geometric units is to be able to describe spatial variation in a manageable way. The geometric units are chosen so that the spatial variation within the unit is limited, or can be described with relatively simple statistical measures. The extent of the units is essentially based on the interpreted geometry of fracture zones and soil and rock type distribution, but e.g. hydrogeological information can also be used to achieve an appropriate geometric subdivision. For each geometric unit, the model describes geological conditions, mechanical, thermal, hydraulic and hydrogeochemical properties, and properties of importance for transport of solutes in the groundwater in the rock. In addition, it describes the surface ecosystems. What needs to be included in the site-descriptive model and how detailed the description needs to be is mainly determined by the need of the design activity's need to produce a facility description, the safety assessment activity's need to study the long-term evolution of the site, and the need to achieve and demonstrate geoscientific understanding.

The uncertainties in the geological models are handled within the framework of the site-descriptive models as described above. In view of the spatial variation and the difficulty of determining in detail a reasonable geometric subdivision of the rock, it is essential not to commit to a single model alternative, especially at an early phase of characterization. Alternative geometric subdivisions or alternative values of the models' parameters are postulated and the consequences analyzed. The uncertainties described in the site-descriptive models then serve as a basis for the safety assessment.

The work with the site-descriptive models also includes management and administration of the models, creating traceability to data, handling variability in parameters used, reporting uncertainties, and management of alternative models. A well-functioning methodology should facilitate external review of the models and the constituent param-

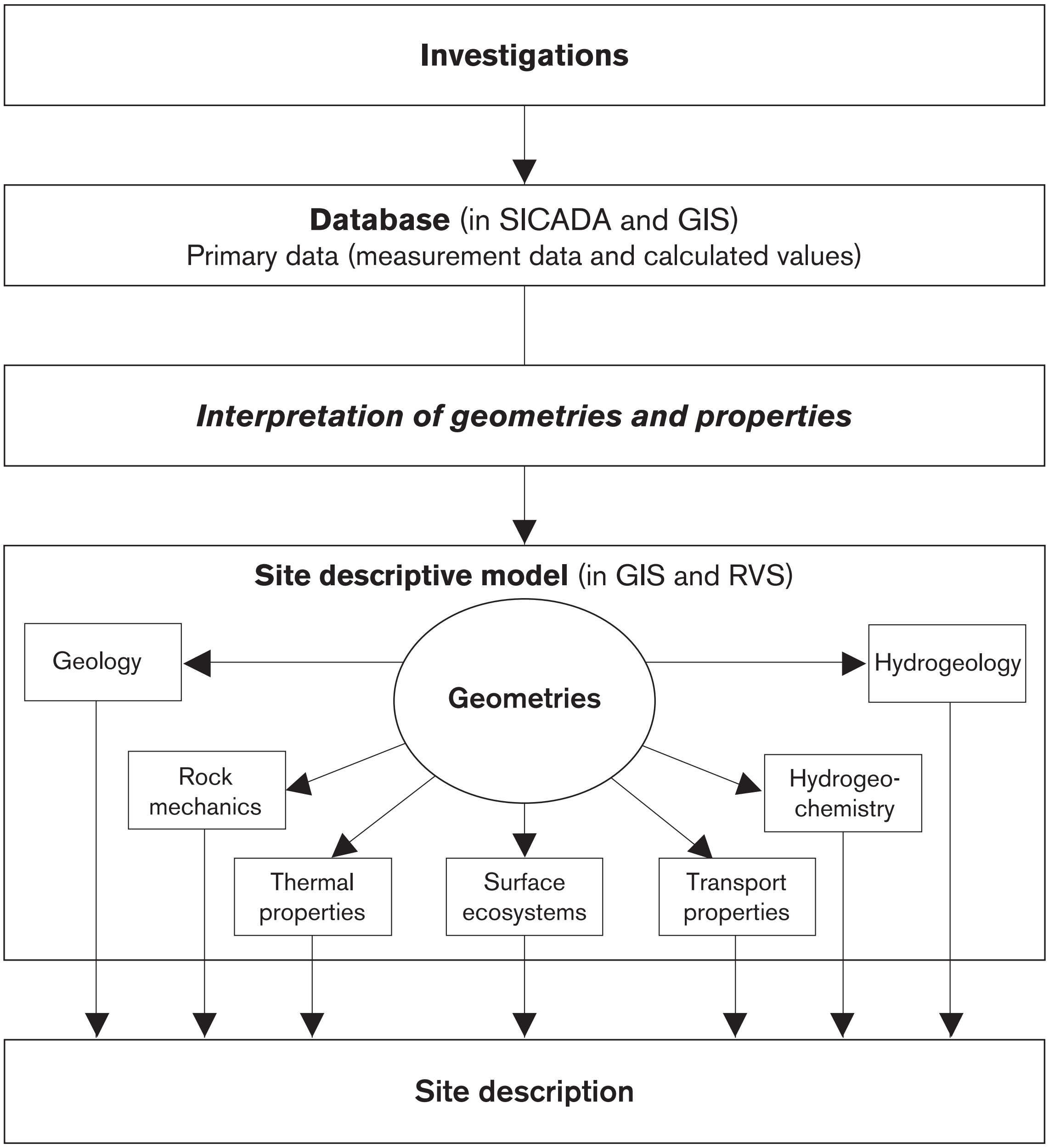


Figure 13-2. The primary data from the investigations are collected in a database. Data are interpreted and presented in a site-descriptive model, which consists of a description of the geometry and different properties of the site.

eters while offering much better opportunities for including the calculated or judged variability of the parameters in various types of analyses.

A project was initiated in 1999 to develop geometric modelling /13-4, 13-5/. An essential part of this work is the management of model versions and documentation of how interpretations have been made /13-5/. This will be supplemented with a method for interpretation of the geological structures and surrounding rock.

The site-descriptive model is built step by step. Already available geological, hydrogeological and hydrogeochemical information is compiled in an initial version. This version is then used as a basis for planning of continued investigations.

The methodology for site-descriptive modelling will be further refined and adapted to the needs of future safety assessments. As a first step, the procedures described in the general execution programme for interpreting data and representing uncertainties in the site-descriptive models will be further refined /R-01-10/. Special projects are under way to improve the site-descriptive modelling within the disciplines of geology, rock mechanics, hydrogeology, hydrogeochemistry and the transport properties of the rock. In addition, special efforts will be made to clearly define how data from site-descriptive models are to be used to obtain input data for the models in the safety assessment.

13.4 Investigation methods and measurement systems

Investigation methods and a general execution programme have been presented in a report /13-3/. It contains a comprehensive survey of all available investigation methods plus detailed plans for which investigations SKB intends to conduct.

A basic principle for SKB when it comes to investigation methods and measurement instruments has always been to make use of existing and commercially available technology wherever possible. The often very special need for information from great depth has, however, also made it necessary for SKB to pursue its own method and instrument development. SKB's international network, involving both the exchange of information and knowledge and joint development projects, is another source of knowledge.

The preparations include documentation of all investigation methods. The preparation of method descriptions is an important part of the work of quality assurance of the investigations and ensures traceability in data management. A method description describes the execution of the method in SKB work and what information quantities are to be produced by the method.

The bedrock should be characterized down to about 1.5 times the envisioned repository depth, which means down to about 1,000 metres. The borehole investigations, see Figure 13-3, must be able to be executed in a rational manner down to this depth. If

Figure 13-3.
Core drilling on a prepared drilling site.

deeper boreholes are needed, technology is available for conducting investigations to depths of about 1,500 metres, which SKB has demonstrated with the 1,700-metre deep borehole in Laxemar west of Simpevarp /13-6/.

Methods to be used in the site investigations must be tested and documented, which is not to say that new methods cannot be developed and old ones improved. Many of the methods that will be used are well-proven and documented. Other methods still require some development. The continued development of methods and instruments is described before. The survey is by no means complete, but provides a picture of the most important ongoing and planned work.

Seismic reflection and VSP

Seismic measurement methods are used to investigate structures in the bedrock. Seismic reflection has been developed for practical use in site investigations. Both measurement methods and analysis methodology have been improved, the latter by utilizing the modelling tool RVS (Rock Visualization System) for interpreting the three-dimensional orientation of structures. Investigations conducted at Laxemar in the vicinity of the Äspö HRL have shown that the method works very well for investigating the rock down to a depth of around three to four kilometres /13-7/.

The previously conducted method tests have now been supplemented with VSP (Vertical Seismic Profiling). The application of VSP will be optimized, and co-interpretation of VSP and seismic reflection will be further refined, prior to the initial site investigations.

Rock stress measurements

A thorough review of rock stress methods is currently under way to find out more about the measurement accuracy of the different methods and their applicability for site investigations. The methods used to measure rock stresses are based on overcoring or hydraulic fracturing. Both methods have advantages and disadvantages, and measurement results may be associated with great uncertainty. SKB regards it as important that both methods be used in parallel wherever possible and the results compared. This has been done in Posiva's programme for rock stress measurements in Finland. SKB is supporting research for integrated analysis of stress results from different methods as a means of increasing confidence in measurement results /13-8/.

An important measure to limit the uncertainty in measurement results is to develop quality assurance methods for the purpose of checking whether the theoretical prerequisites for the method (for example homogeneous, elastic material) are fulfilled. This may put a limit on confidence in measurement results, e.g. in rock stress measurement with the overcoring method to great depths (greater than approx. 500–600 metres), where high stresses can cause damage to the core sample obtained from overcoring /13-9/. Such a programme has been initiated, partly in cooperation with Posiva.

Experiments are being conducted at Äspö during 2001 with a two-dimensional overcoring method (measures stresses perpendicular to the borehole). This method was developed by AECL at URL, Canada, and is considered to be a possibly more robust measurement method than the three-dimensional methods usually used by SKB, since it is judged to be less sensitive to core discing. Comparative measurement is done with the three-dimensional method.

An inventory is currently being conducted of the best technology for hydraulic fracturing in boreholes (76 mm). Relatively new results verify /13-10/ the previous judgement that it is difficult to measure the maximum horizontal stress by means of hydraulic fracturing. Despite the method's limitations, it is judged to be the most reliable option for characterizing the stress field at great depths (greater than approx. 600 metres).

Establishment of GPS networks for slow rock movements

GPS (Global Positioning System) is a satellite-based navigation and positioning system. Slow rock movements can be studied with the aid of GPS.

A local GPS network has been established in the Laxemar area. Four measurements have been carried out, and recurrent measurements will be performed. Prior to the start of the site investigations, additional GPS networks will be built up in the municipalities of Östhammar and Tierp. The networks will be established within an area of approx. 15 x 15 km and will primarily be used to study movements in regional fracture zones. The networks will enable movements on the order of 1 mm per year to be estimated with sufficient accuracy after two to three years' measurements.

Establishment of seismological network

Seismological measurements are made to monitor quakes in the bedrock. Uppsala University is currently operating 18 seismological stations in Sweden, twelve of which are situated along the coast of Norrland (the northern half of the country), from Gävle in the south to Luleå in the north, see also section 8.2.7. Prior to the start of the site investigations, an additional 20 seismological stations will be built along the Baltic Sea coast from Östhammar in the north to Oskarshamn in the south. A couple of stations will be placed closer together in the three municipalities of Östhammar, Tierp and Oskarshamn for the purpose of detecting small quakes.

The build-out of the seismological network will be carried out during 2001 to be completed at the time of the start of the site investigations. After field checks, an agreement will be reached with landowners concerning deployment of the seismic stations.

Drilling technique and measurements while drilling

A 1,000-metre deep cored borehole has been drilled in SKB's instrument store adjacent to the Canister Laboratory in Oskarshamn. The hole is intended for testing of equipment. The drilling technique itself, handling of drill cores, and measurement methods that can be used in conjunction with drilling were tested during the drilling of the hole. A new water sampling method and hydraulic tests were tested and modified during drilling, for example.

The borehole will be used for method tests and training purposes in the future.

Methodology for calibration of length in boreholes

Uncertainty in length measurement in boreholes is relatively great in relation to the requirements for co-evaluation of different types of measurement data. To resolve this, a methodology has been tested and developed for calibration of length in boreholes for correct positioning of measurement points. The methodology entails making marks at known borehole lengths, which are then detected during borehole investigations. The methodology will be implemented for relevant borehole methods prior to the site investigations.

Hydrogeological methods

Together with Posiva, SKB is carrying out a measurement programme for testing and possible further development of their flow logging method (Posiva Flow Log), by means of which the water flow at different levels in a borehole is measured. The method Posiva has developed measures the inflow to the borehole in one section, in contrast to traditional systems which measure without sections and thus obtain an aggregate flow in the borehole.

The purpose of the measurement programme is to investigate the ability of the instrument to determine transmissivity and natural pressure in the flowing fractures that have been identified, and furthermore to test the measurement technique for the purpose of formulating a suitable testing programme for the site investigations. Another ambition is to be able to measure electrical conductivity in single fractures.

The measurements are being done in the deep borehole at Laxemar, where particular interest is attached to the method's ability to handle the high salinities that occur at great depth.

The joint work with Posiva also includes testing of water samplers in the same borehole. The results of this test have been useful for the new water sampling system that is being developed.

Borehole radar

SKB has identified a need to replace the old borehole radar system RAMAC with a new equivalent system prior to the planned site investigations. A new borehole radar system with 20, 100 and 250 MHz dipole antennas was finished by the summer of 2000. During the subsequent autumn and winter, a theoretical study and verifying field tests were conducted regarding the function of the directional antenna. In summary, these analyses have confirmed that the directional antenna works in its current form, but that its function under certain circumstances can be improved. The existing system will be augmented with a directional antenna function with associated software by the beginning of 2002.

Mobile chemistry unit

SKB's mobile system for hydrochemical investigations includes umbilical hose carts and mobile chemistry laboratories. The umbilical hose carts contain the equipment needed to pump up sample water from bordering sections in a borehole and to carry out measurements of chemical parameters in the borehole section and in the flow cell on the ground surface. The chemistry laboratories contain instruments for sampling and analysis of the pumped-up section water.

Two mobile systems will be needed for future site investigations. A new umbilical hose cart with associated downhole equipment will be developed during 2001. The work includes developing a new chemistry probe for in-situ measurement of chemical parameters in packered-off sections in boreholes and a new sampler for sampling of pressurized section water.

Measurement of the transport properties of the rock

The majority of the transport parameters that are used in the site investigation phase are generic and determined by earlier experiments on various rock materials, in the field and in the laboratory. In order to site-adapt generic data, a judgement is made whether the site's lithological composition and hydrogeochemical state match the conditions that apply for generic data. Furthermore, certain supplementary, site-specific investigations are carried out. The discipline's characterization methods are described in their entirety in /13-3/.

One method currently being studied is the use of resistivity loggings in boreholes to determine matrix diffusivity in a similar manner as has been done in laboratory tests. The method is under development. The advantage is that data collection goes quickly and a spatial distribution of diffusivity data is obtained.

Groundwater flow measurements are carried out in a number of borehole sections during different stages of the site investigation. There are at present two different concepts for measurements of groundwater flow. SKB and Posiva have each developed their own method for logging of the groundwater flow in deep boreholes. SKB's method is based on the dilution of an injected tracer, while Posiva's method measures the flow with a thermal method. A comparison study is under way. Experience from experiments in the Äspö HRL (TRUE Block Scale) show that flow measurements provide valuable information on the connectivity and geometry of hydraulic structures by creating controlled pressure disturbances and measuring changes in groundwater flow.

Tracer tests in a single borehole are performed by injecting a tracer pulse under pressure, allowing it to remain in contact with the fracture surfaces for a brief time, and finally pumping the tracer solution back again. An advantage of this method is that it is not dependent on several boreholes intersecting the same geological structure, which can be crucial since the boreholes are generally situated relatively far from each other. The method provides in-situ values of dispersivity and flow porosity. Data from such push-pull tests can potentially also be used for estimations of the flow wetted surface and sorption parameters for a selection of weak-to-medium-sorbing substances. An evaluation of the potential of the method is under way within the TRUE project at the Äspö HRL. Good results have been obtained with this method for determining dispersivity, flow porosity, matrix diffusivity and sorption coefficients within other site investigation programmes as well, such as WIPP in the USA /13-11/ and Leuggern in Switzerland /13-12/.

13.5 Long-term observations

Continuous or periodically recurrent observations and measurements – long-term observations (monitoring) – are a natural activity in the implementation of a deep repository.

Long-term observations have a number of purposes, sometimes overlapping:

- Obtain knowledge of undisturbed conditions in nature and their seasonal variations in order to identify and evaluate the impact 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 deep repository and ensure there is no radiological impact.

- Ensure that the working environment is safe with regard to radiological and non-radiological effects.
- Show that requirements on radioactive waste verification (safeguards) are fulfilled.

The stepwise execution of a deep repository leads to a gradually improved understanding of the site and its properties. Scientific and technical data on the site and its historical evolution are compiled in general siting studies, feasibility studies and site investigations. Measurements during the site investigation phase provide undisturbed, local data with their seasonal variations.

A disturbance occurs in the detailed characterization phase due to groundwater lowering, and this is used to refine the scientific models of biosphere and bedrock. Monitoring programmes are also carried out during the detailed characterization phase to show that the environmental impact of the facility remains within the bounds laid down in the siting permit.

During initial operation, monitoring programmes are run to gain a better understanding of the site and its properties, and to monitor the working environment and external environment as before. Furthermore, radiological checks are performed to make sure the systems satisfy requirements on verification of nuclear materials (safeguards).

After completion and closure of the repository, environmental monitoring programmes will undoubtedly continue for several decades. In addition, many measurements and observations can be made if future generations deem them desirable. It is important that all information on the deep repository be preserved.

Methods and technologies are available for long-term observations. AECL has performed an overview of these monitoring methods /13-13/ and draws the conclusion that today's technical methods are good enough for their purposes, but that further development could improve their sensitivity, lower costs and speed up analysis and dissemination of data.

SKB carries out observations at the Äspö HRL as a base activity in support of the experimental projects being conducted there. Observations of groundwater (pressure and hydrogeochemical characterization) have been made during the pre-investigation, construction and operating phases, see section 12.4.

SKB plans to carry out the following activities with regard to long-term observations during the upcoming six-year period:

- Formulate an SKB policy for long-term observations.
- Within the framework of site investigations, commence observations and measurements in the municipalities of Oskarshamn, Tierp and Östhammar for the purpose of determining the initial state and seasonal variations.
- Draw up preliminary programmes for periodical observations and measurements during the detailed characterization phase and initial operation.
- Follow international developments regarding the need for institutional controls and long-term post-closure observations.

Table 13-1 provides an overview of possible needs for continuous and periodical observations and measurements of SKB's deep repository for different phases.

Table 13-1. Possible need for continuous and periodical observations and measurements in different phases.

Site investigation phase	Detailed characterization phase	Initial operation, regular operation, closure	Post-closure
Environmental monitoring programme – disturbance of ground surveys	**Environmental monitoring programme** – disturbance of supplementary ground surveys – impact of facility construction (soil, groundwater, gas, noise)	**Environmental monitoring programme** – disturbance of supplementary ground surveys – impact of facility construction (soil, groundwater, gas, noise)	**Environmental monitoring programme** – impact of rise in groundwater level **Documentation is preserved**
Climate – temperature, atmospheric pressure, precipitation, evaporation, runoff, sea level changes	**Climate** – temperature, atmospheric pressure, precipitation, evaporation, runoff, sea level changes	**Climate** – temperature, atmospheric pressure, precipitation, evaporation, runoff, sea level changes	**Climate** – temperature, atmospheric pressure, precipitation, evaporation, runoff, sea level changes
Biosphere – flora, fauna, soil layer, land use etc.	**Biosphere** – flora, fauna, soil layer, land use etc.	**Biosphere** – flora, fauna, soil layer, land use etc.	**Biosphere** – flora, fauna, soil layer, land use etc. for a decade or so **Documentation is preserved**
Borehole from ground surface – groundwater chemistry, pressure, temperature	**Borehole from ground surface** – groundwater chemistry, pressure, temperature	**Borehole from ground surface** – groundwater chemistry, pressure, temperature	**Documentation is preserved**
		Borehole from underground – groundwater chemistry, pressure, temperature – deformations in the rock	**Documentation is preserved**
Seismic and aseismic events – time, location and type of local quakes – slow deformations	**Seismic and aseismic events** – time, location and type of local quakes – slow deformations	**Seismic and aseismic events** – time, location and type of local quakes – slow deformations	**Documentation is preserved**
	Surveillance of facility – fire – floods – seeping water per facility section – pumped-out water (quantity, quality) – ventilation (temperature, quantity, quality) – noise – monitoring of conditions for preventive maintenance	**Surveillance of facility** – fire – floods – seeping water per facility section – pumped-out water (quantity, quality) – ventilation (temperature, quantity, quality) – noise – monitoring of conditions for preventive maintenance – radiation monitoring – safeguards	**Surveillance of facility** – safeguards **Documentation is preserved**

14 Deep repository

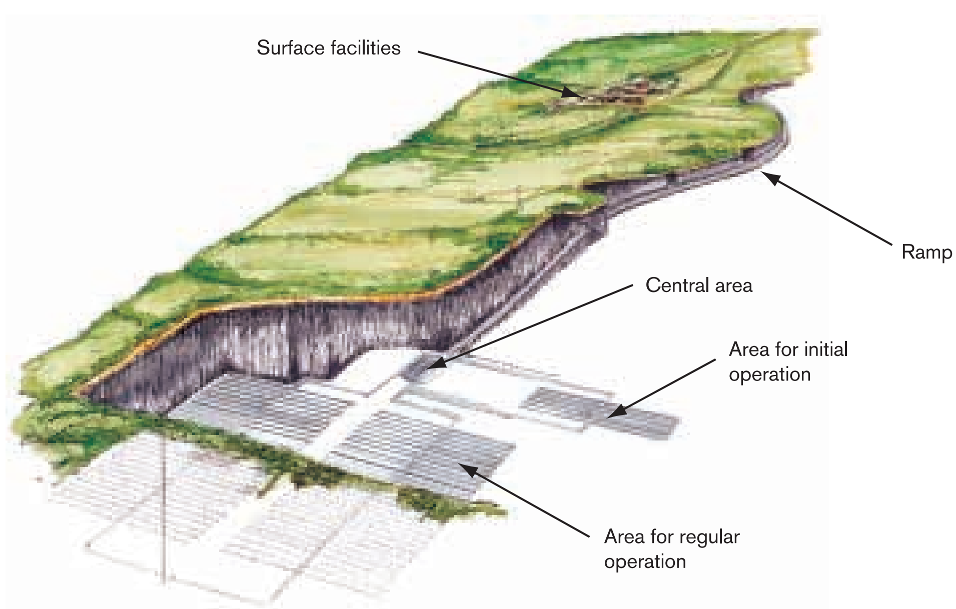
The facility for deep disposal of spent fuel consists of above- and blow-ground parts, which are connected to each other via a ramp and/or a shaft, see Figure 14-1.

The below-ground part is situated at a depth of 400–700 metres, where the mechanical and chemical conditions are stable. Under ground there is a central area, areas for deposition of fuel for initial operation, and deposition areas for regular operation.

Design and construction of the deep repository proceed stepwise. Feasibility studies for siting have been concluded, and SKB plans to initiate site investigations as the next step. This will be followed by detailed characterization with initial construction of the deep repository, initial operation, regular operation and closure.

The environmental impact of the deep repository was preliminarily studied in conjunction with the feasibility studies /14-1 to 14-8/. A non-specific preliminary description of land needs, design of buildings, transportation system etc. is provided in SKB's system analysis /14-9/. The scope of the environment impact depends on the quantity of extracted rock and the scope of new infrastructure, among other things.

The choice of various solutions, such as type of descent (shaft and/or ramp) and the location of the repository's rock caverns and tunnels in relation to each other and to the surface facilities, is dependent on e.g. the conditions on the selected site. The choice of descent and its location are determined in the site investigation phase, while the detailed layout of deposition areas will not be determined until the results of detailed characterization are available. A detailed environmental impact assessment will be presented when SKB applies for a siting permit.



Figur 14-1. *Schematic layout of the deep repository with a straight ramp from the above-ground part to the below-ground part.*

The detailed characterization phase extends in time from approval of the siting permit up until a licence has been obtained for initial operation. During the detailed characterization phase, the deep repository is built to full depth and rock chambers are excavated in parallell with detailed characterization of the rock. The site description that is prepared during the site investigation phase is refined and further detailed. The investigations during the detailed characterization phase provide a necessary and sufficient basis for adapting the deep repository to the conditions on the site and preparing a final safety report for initial operation. Besides work on the underground portion, SKB will also build surface facilities during the detailed characterization phase. A surface transportation system will be established.

The deposition of 200–400 canisters containing spent nuclear fuel is planned during initial operation. According to SKB's long-term plans, this work will begin around 2015. Before a decision is made on continued build-out and deposition, experience from the first stage and other newfound knowledge will be evaluated. If the evaluation lends support to continued build-out of the deep repository, construction and deposition will continue for about 40 years. Then the deep repository will be closed and sealed. After closure and sealing, it is possible to restore the site to a near-original state.

14.1 Viewpoints of the authorities on RD&D 98

SKI submitted its viewpoints on RD&D-Programme 98 in 1999 /14-10, 14-11/. Following is a summary of some important viewpoints and SKB's comments on them.

SKI wishes that SKB would, no later than when it submits a licence application, show that the performance requirements on the deep repository can be fulfilled. SKB should think through the structure of this account and how the requirements can be gradually developed towards increasingly detailed requirements and goals for the development work as the decision-making process and construction of the facilities progress. SKI also would like SKB to address more clearly the question of range of variation or freedom of choice in the deep repository design, and says that it is not only appropriate but also necessary that some range of variation is included in the licence.

SKB has commenced work on design premises and methods for acceptance testing. This work has high priority in SKB's planning and is presented in greater detail in sections 14.2 and 14.3. Like SKI, SKB is of the opinion that increasingly detailed requirements as well as methods, and criteria for acceptance testing, should be arrived at in a stepwise process. SKB agrees with SKI's viewpoints as regards freedom of choice and range of variation as well. SKB wishes to have a dialogue with the authorities regarding what can be considered to be sufficient as a basis for the various decisions that will be made in the future. This also includes clarifying how the stepwise repository design process is carried out and how range of variation and freedom of choice are progressively narrowed down.

SSI stipulates in its regulations that the best available technique shall be applied to limit the release of radioactive substances and their harmful effects, and that optimization shall be done for the purpose of keeping radiation doses to humans as low as reasonably achievable, economic and social factors being taken into account. SKB presumes there will be a dialogue with the authorities on how the principles of best available technique and optimization are to be applied in design. More detailed plans are given in section 14.3.

14.2 Design premises, acceptance testing and optimization

14.2.1 Design premises

In order to be able to design the repository, the various requirements made on the repository and its parts are compiled and prioritized. Current design premises are contained in numerous documents produced by various specialists and work groups in various contexts. The intention is that existing design premises should now be compiled in one document. By "design premises" is meant the requirements and other conditions that determine how the different parts of the deep repository are to be designed.

The design premises pertain to a deep repository for the spent nuclear fuel from the Swedish nuclear power programme. They pertain to a repository designed according to the KBS-3 method and assume that this strategy and method fulfil in general terms the requirements of Swedish law on a deep repository. The design premises shall taken into account construction and operation as well as long-term post-closure safety and preliminary embrace:

- Canister.
- Buffer.
- Deposition holes.
- Deposition tunnels.
- Other rock caverns (ramp, transport tunnels, hoist and ventilation shafts).
- Seals and reinforcements of fractures and zones of weakness.
- Plugging of deposition tunnels.
- Backfill.

The basis for the design premises is society's requirements on safety and protection of man and the environment as they are expressed in Swedish legislation and international agreements. The properties of the spent fuel, technical feasibility, and the owners' preferences are other factors that influence the design premises. The compilation of design premises now being done is predicated on the functional requirements on the deep repository and its parts presented in RD&D-Programme 98 /14-12, 14-13/. Based on these requirements and a review of the stresses to which the deep repository and its parts are subjected in various contexts, detailed design premises can be formulated.

The design premises are a point of departure for the engineering work and express e.g. what static loads, deformations or concentrations of corrosive substances the various parts of the deep repository should be designed to withstand. The design premises are based on the aggregate knowledge and information available on the deep repository and its safety. Results from research, development, demonstration and investigations of the bedrock contribute towards increasing this knowledge and thereby improving the prospects of formulating relevant design premises, which will progressively be modified.

The work of performing an initial compilation of design premises is under way. The compilation is based on the knowledge and information that is available today. As far as long-term safety is concerned, it is based on SR 97 /14-14/ and the compilation of the state of knowledge that is included as a background report to the safety assessment /14-15/. SKB has furthermore arrived at and presented requirements on the host rock /14-16/, as well as a programme for geoscientific investigation and evaluation of sites for the deep repository /14-17/. In addition, design premises for the canister have been compiled /14-18/. These documents are also included in the body of material on which the design premises are based.

Separate design premises are also being formulated for service and peripheral facilities on the surface, as well as equipment required for construction and operation under ground.

14.2.2 Acceptance testing

In the work with the design premises, the requirements made on the different parts of the repository are established. Acceptance testing aims at determining whether the requirements in the design premises can be considered to be fulfilled. The acceptance criteria that are formulated are connected to the chosen method for acceptance testing. With design premises, acceptance criteria and methods for acceptance testing, SKB intends to explain how functional and other requirements can be met. SKB presumes there will be a dialogue with the authorities regarding what can be considered to be sufficient and necessary as a basis for upcoming decisions.

An example is design premises for deposition holes. A detail is describing a methodology for acceptance or rejection of a deposition position. In order that experience gained from the Äspö HRL and the site investigations can be exploited, SKB presumes that formulation of acceptance criteria and methods for acceptance testing can proceed in parallel with design, optimization and data acquisition on the site in question.

14.2.3 Optimization and reasons for chosen design

In the present situation, SKB believes that a range of variation and freedom of choice in the repository design are necessary. As is evident from section 14.1, the authorities share this view. Within the six-year period, SKB intends to give a more detailed account of a methodology for repository optimization and also how we will systematically and progressively narrow down the alternatives. This systematic and progressive narrowing of alternatives is a natural ingredient in SKB's design model, but SKB is aware of the need for increased transparency in this respect.

By "optimization" is meant analysis of clearly defined problems for the purpose of finding the optimal solution. Aspects that should be analyzed and evaluated are:

- Long-term post-closure safety.
- Safety during operation.
- Safety during construction.
- Environment.
- Technology and feasibility.
- Economics.

In some cases, the possibility of retrieval may also be an optimization parameter. Examples of questions where optimization studies may be needed are: access to repository depth via shaft or ramp; repository in one or two levels; method and material for backfilling; method for blast and drill; and alternative deposition methods.

The design premises stipulate which requirements are made on the deep repository and its different parts. In most cases the requirements can be met by various technical solutions. SKB intends to successively publish the reasons for its choices of designs, materials and execution methods. The results from the optimization studies serve as a basis for justification of the choice of design. The chosen technical solution can both influence and be influenced by the work of formulating acceptance criteria and methods for acceptance testing.

14.2.4 Development programme

An initial version of the design premises is planned to be published in 2002. Design premises will then be progressively refined and detailed. The design premises that are required for the detailed characterization must have been produced by the end of the upcoming six-year period.

Design premises, acceptance criteria and methods for acceptance testing, as well as optimization and reasons for the chosen design, are interconnected. A progressive detailing of the background material will take place in all cases. It should be pointed out that site-specific factors can affect both analysis and evaluation.

SKB intends – in dialogue with the authorities – to develop methodology for site adaptation and optimization of the deep repository. Reasons for the design, choice of materials and choice of execution methods will progressively be presented.

14.3 Design

Design is a comprehensive term for the activity where technical material is gathered, processed and analyzed so that it can eventually be translated into a facility description, function descriptions, construction documents and engineering drawings. The design work includes producing criteria and methods for acceptance testing, optimization with regard to safety, environment, technology and economics, and reasons for the choice of design and/or technology. Design cannot be conducted as a separate activity, but must be coordinated with site investigations and with system analysis and safety assessment, as is pointed out by SKI in the review of RD&D-Programme 98 /14-11/.

The planned design of the deep repository is described below. The work with canister and encapsulation plant, as well as transport to the deep repository, is reported separately.

The design of the deep repository is based on the design premises as well as available information on the repository site. Design premises are presented for the deep repository, service and peripheral facilities, utility systems, machines and vehicles. The layout of the deep repository is determined partly by conditions on the repository site, and partly by non-site-specific factors such as space requirements for equipment and installations.

14.3.1 SKB's design model

SKB uses a stepwise design model for the deep repository. The layout is refined and documented as increased knowledge is obtained and the system is gradually built out. The stepwise detailing and build-out progressively narrows down the freedom of action for changes, as is illustrated in Figure 14-2. The parts that are built early should be designed to preserve reasonable freedom of action for the parts that are designed and built at later stages.

Design is divided into phases /14-9/ and follows the plan drawn up for a previous RD&D-programme /14-19/. During the two initial phases – named E and D – an overall design of the entire deep repository takes place. During the subsequent design and engineering phases – named C, B/A and DUL – the surface facilities, parts of the deep repository, and utility systems, machines and vehicles are designed in the order in which they are built and commissioned. For natural reasons, earthmoving work for industrial and operations areas is done and accesses to the deep repository (shaft and/ or ramp) are built in an initial phase. Detailed design of buildings on the surface, construction of other rock caverns, and design of utility systems and systems and equipment for handling of the radioactive waste can be done later, drawing on knowledge and experience available at that time.

Facility design of the deep repository, i.e. layout of the underground facility and surface facilities, is given the same designations as the different design phases. Design of utility systems, machines and vehicles takes place in parallel with facility design. The layout of the deep repository's rock caverns can be adapted to the equipment they are supposed to accommodate, and vice versa. Each finalized facility design therefore limits the possible design of utility systems, machines and vehicles, and vice versa.

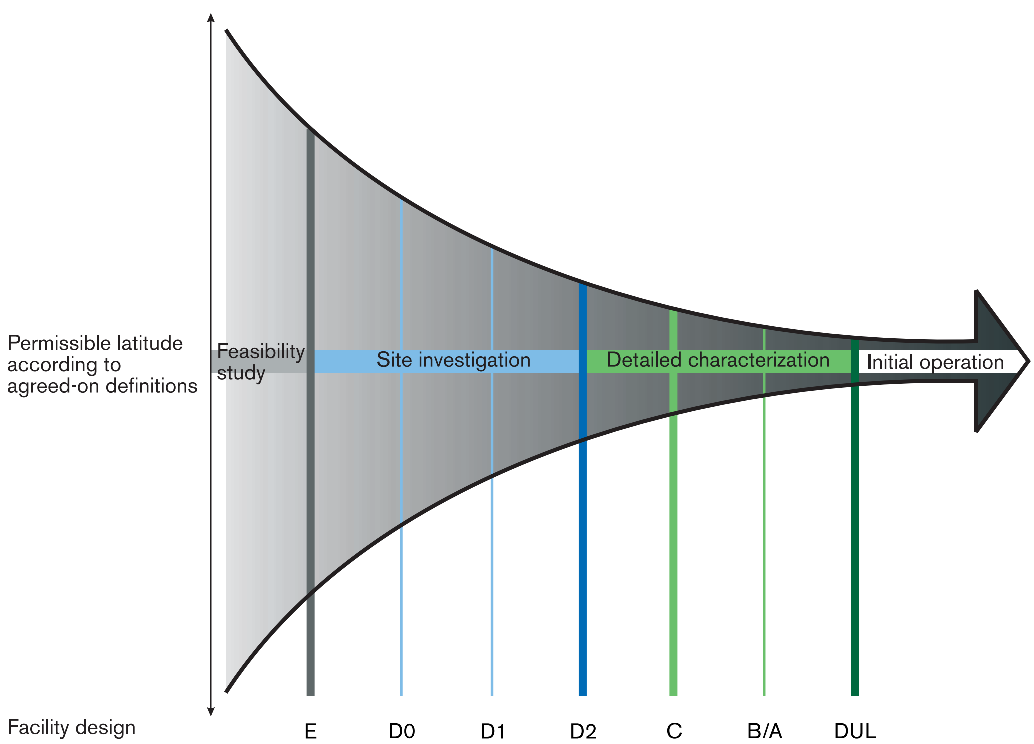


Figure 14-2. *SKB's design model entails a gradual narrowing-down of the freedom of action.*

Even though detailed design is planned to proceed step-by-step, part-by-part of the deep repository, it is necessary that each facility design encompass the entire deep repository. The layout of each individual part is dependent on and must be adapted to the layout of other components in the deep repository. When accesses to the deep repository are configured, for example, possible alternative designs of remaining parts of the deep repository, utility systems, machines and vehicles must be taken into consideration. This means that the parts that are planned to be built late must be preliminarily designed at an early stage to provide a basis for the detailed design of parts built early on.

14.3.2 Facility design

Design phase E

Phase E was concluded during 2001. A facility description with drawings showing the function, size and extent of the facility has been prepared. The description is general and not adapted to a specific site. Its purpose is to provide a clear picture of what establishment of a deep repository entails and comprise a basis for producing site-adapted facility descriptions in phase D.

Design phase D

Phase D begins when the site investigations are initiated and aims at providing sufficient material for the selection of a site for detailed characterization. Phase D is divided into the stages D0, D1 and D2. Each stage of more detailed layout in phase D is a part of the basis for the investigation programme in the site investigation phase. D0 and D1 also comprise a basis for early consultations, while D2 provides a basis for EIA, system analysis and safety assessment.

The activities investigations, design and optimization are coupled throughout phase D. When new data are obtained and interpreted, the description of the repository site is revised. The layout of the deep repository is adapted to the site model, whereupon it is evaluated with respect to safety, environment and other optimization parameters. The results of the evaluation comprise a basis for the continued site investigations.

Layout D0 is based on the first site-specific geoscientific descriptions. D0 takes into account early identified fracture zones as well as the thermal and mechanical properties of the rock. Layout D0 aims at determining whether sufficient rock volume is available on the site and whether the site is otherwise suitable from an environmental standpoint.

Layout D1 is prepared on the basis of a preliminary site model based on borehole information obtained in the initial site investigation. It contains an initial site-adapted facility description. Layout D1 is planned to be used to make a preliminary safety judgement.

In parallel with the site-specific design process, non-site-specific studies of e.g. equipment and technology for handling of bentonite, deposition of canisters and backfilling of deposition tunnels and rock caverns are planned. In-depth studies are carried out of driving methods for excavation of ramps, shafts, and transport and deposition tunnels, as well as of whether the repository should be built in one level, according to the main alternative, or whether it should be split into two levels. Further, the consequences of extended operating time and extended opening time of the repository will be analyzed. Site-specific data are factored into layouts D0 and D1 and the results of the general studies are augmented with site-specific information.

Layout D2 is a basis for the documents that are required in support of applications for permits for siting and construction of the deep repository. D2 contains an in-depth site adaptation and elaboration of the facility's layout on results from the general studies and experience from the Äspö HRL. Layout D2 sets bounds on the positioning of the facility horizontally and vertically. Locations of accesses (ramp and/or shaft) to the deep repository are fixed.

Design phase C

Layout C is the basis for detailed design and preparation of material for an application for a building permit for the parts of the deep repository that are built first, i.e. earth-moving work for the surface facility and the descent to the deep repository. Layout C is based on layout D2 and available design premises as regards design of utility systems, machines and vehicles.

An updating of background material and detailed planning of facility construction for initial operation are planned to be done during this phase. The results of the special studies that have been conducted – for example for deposition equipment, backfilling, plugging, driving and passage of water-bearing zones – are integrated in the layout. The industrial area above ground is fine-adapted to the terrain and the infrastructure on the site. The facility is laid out in consultation with the municipality and concerned parties and is approved by concerned authorities.

Design phase B/A

Layout B is a final plan solution for facility parts both above and below ground. In this phase, definitive target specifications are drawn up for the handling systems for the radioactive waste. The facility and function description is detailed and safety-related operating premises are described. Further, methods and technology for possible retrieval of the deposited fuel are described. Consequences of simultaneous deposition and build-out of the deep repository are analyzed. An in-depth study of the consequences of extended opening time may be conducted.

For parts of the facility that contain structures where complexity is great – involving for example coordination and adaptation of ventilation, utility systems and deposition equipment – a further adaptation of the layout named A may be needed.

Definitive documentation (DUL)

The design process is concluded by the preparation of definitive documentation (DUL). During this phase, final detailed data are delivered to enable working documents and installation and general arrangement drawings to be finalized. Definitive system descriptions for utility systems, handling equipment, vehicles, etc. are prepared. DUL comprises the supporting material for an application for a licence for initial operation.

14.3.3 Programme

In a six-year perspective the initial and complete site investigations have come so far that design can make use of data from the sites in question. Design phase D has been completed and site-adapted layouts of the deep repository's facilities are finished. The layout of the surface facilities has been presented. Facility parts under ground are positioned and delimited with respect to the site's geology, particularly the distance to major deformation zones.

Besides the site-specific design work, SKB plans during the six-year period to publish a report summarizing experience from the Äspö HRL pertaining to the practical feasibility of the deep disposal technology so that this experience can be drawn on in the detailed design work.

14.4 Variants of KBS-3

SKB has over the years developed and evaluated alternatives to KBS-3 /14-20, 14-21, 14-22/. All of these earlier evaluations clearly point to the fact that the KBS-3 method is preferable. Several variants of KBS-3 were compared in the recently concluded JADE project /14-23/, see Figure 14-3. The variants that were studied are:

- Vertical emplacement with one or more canisters in each deposition hole (KBS-3 V).
- Horizontal emplacement with one canister in each deposition hole (KBS-3 H).
- Horizontal emplacement with several canisters after one other in medium-long deposition holes (KBS-3 MLH).

The different variants mean that the same design can be used for the surface facility, the connecting ramp, the shaft and the central area under ground, regardless of what the deposition area looks like.

The result of the JADE study is that KBS-3 V, with one canister in each deposition hole, is still the reference design. Two canisters in each deposition hole may possibly give lower construction costs. KBS-3 H is dismissed, since horizontal emplacement is not judged to have any advantages over vertical emplacement. KBS-3 MLH, on the other hand, is preliminarily judged to be superior to the reference design in terms of environmental impact and economics.

Medium Long Holes

KBS-3 MLH entails that the canisters are emplaced horizontally, one after the other, in 200–250 metre long deposition holes. The canisters and the surrounding bentonite blocks are the same as in a KBS-3 repository. Figure 14-4 shows a schematic drawing of a KBS-3 V and a KBS-3 MLH repository.

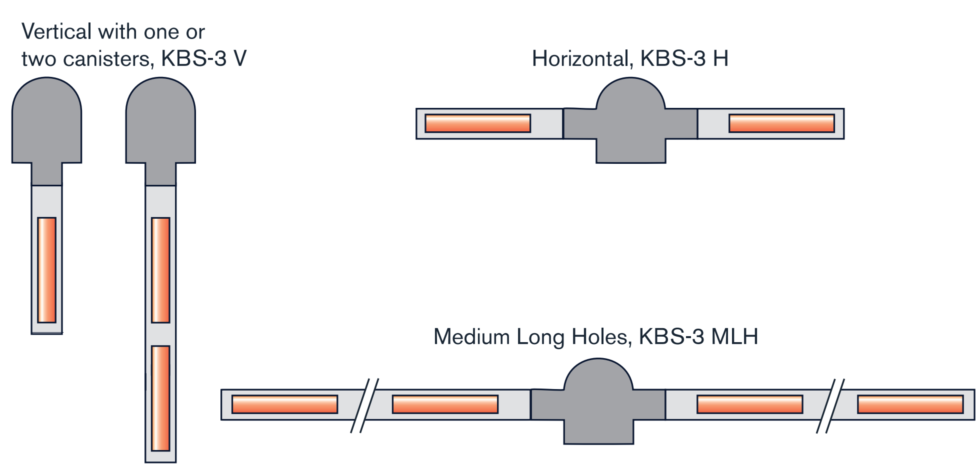


Figure 14-3. *Different variants of the KBS-3 method.*

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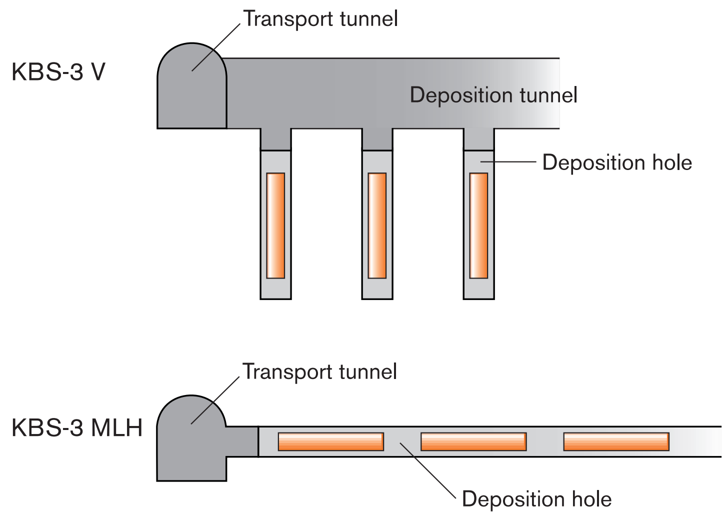

Figure 14-4. *Difference in principle between the reference method KBS-3 V and a KBS-3 MLH repository.*

As is evident from the schematic drawings, there are no deposition tunnels in a KBS-3 MLH repository. Instead, the deposition holes are bored directly from the transport tunnels. This means that the total quantity of rock extracted is much less than for the reference design KBS-3 V. This means lower costs for building the repository. The environmental impact is also less, since much less rock volume is extracted. On the other hand, no significant difference has been found in terms of long-term safety /14-24/.

The gains in terms of environmental impact in particular, but also costs, makes KBS-3 MLH an interesting variant of the reference design. However, this variant has not achieved the same maturity as KBS-3 V. Great efforts are required to develop deposition technology as well as machines and other equipment.

To further explore what resources would be needed in the form of time and money, SKB has begun the work of developing a research, development and demonstration programme for the Medium Long Holes concept. Besides clarifying the resource need, the programme could serve as a basis for a possible decision on continued research and development efforts.

During the ensuing six-year period, SKB does not plan to carry out any work for demonstration. The reason is that SKB prioritizes the ongoing experiments in the Äspö HRL. Expanding activities there by boring horizontal deposition holes for demonstration trial runs may change the boundary conditions for the other experiments.

Two canisters in each hole

During the coming RD&D period, SKB plans to study vertical deposition in accordance with KBS-3 V with two canisters in the same deposition hole.

14.5 Technology – development and demonstration

The deep repository is designed so that canisters can be handled and emplaced without jeopardizing the safety of the personnel or the environment. This applies to both radiation protection and other aspects of the external and internal environment.

SKB's work aims at ensuring that the methods and materials, as well as the technology, needed to build, operate and seal a deep repository in accordance with stipulated requirements are available. SKB is conducting experiments at the Äspö HRL to investigate the conditions that prevail at the projected repository depth and to develop and demonstrate the technology and methods to be used in the disposal construction and operation, see sections 12.2 and 12.3. Certain simplifications of the handling steps have been made in the experiments, since the canisters that are handled have not contained spent nuclear fuel and do not emit any radiation. Besides the fact that the experiments provide valuable experience, they are, as SKI has pointed out in its review of RD&D-Programme 98, absolutely necessary in order for SKB to achieve credibility and acceptance for the deep repository concept.

SKB has in essence followed the development programme presented in RD&D-Programme 98 when it comes to technology development and demonstration. The ongoing experiments in the Äspö HRL are providing additional experience of boring of deposition holes, emplacement of bentonite and canisters, backfilling and sealing of deposition tunnels, etc. This will mean that experience exists of the work procedures involved in the construction, operation and sealing/closure of the deep repository. In order to carry out detailed characterization and initial operation, technology and methods may have to be adapted to the conditions on the selected site, and requirements may arise from e.g. assessments of operation and long-term safety.

14.5.1 Construction methods

The construction of underground facilities has a mechanical impact on the rock mass. Stress redistributions and deformations occur around the cavities that are created. This impact is local and is determined by the initial rock stresses, the properties of the rock mass, and the geometry of the cavities.

Tunnelling can be done by conventional drill-and-blast or by mechanical excavation, usually full-face boring with a tunnel boring machine (TBM). Both methods have been used with good results in tunnelling at the Äspö HRL, providing valuable experience for the choice of excavation method in the deep repository. Experiments at the Äspö HRL, ZEDEX /14-25/, have shown that tunnelling by drill-and-blast causes much greater damage to the zone adjacent to the tunnel than tunnel boring. Possible methods for excavation of deposition holes are: full-face boring, core drilling and percussion drilling. At the Äspö HRL, full-scale boring of deposition holes has been done with a rebuilt tunnel boring machine and with good results. A total of 13 deposition holes have been bored, which complies with the plan presented in RD&D-Programme 98.

A final selection and further development of excavation methods, machines and equipment can take place based mainly on currently available knowledge. This will be done in parallel with the preparation of design documentation for detailed characterization and excavation for initial operation, i.e. when geological information from the site investigations is at hand. Freedom of choice as regards methods for excavation of deposition tunnels and holes will remain even after the commencement of deposition.

The quantity of groundwater that leaks into the repository during construction and operation must not be too great. An excessive influx of groundwater would adversely affect working conditions and handling of e.g. buffer material. Such seepage can be limited by sealing of fractures and transmissive zones. The experiments described in RD&D-Programme 98 concerning the flow properties, sealing capacity and durability of various grouting materials have been concluded during 2001. The experimental studies were carried out in the laboratory and in verifying field tests at the Äspö HRL. In connection with this work, an overview of results will be published. SKB will also continue to keep abreast of technical developments in this field.

14.5.2 Fabrication of bentonite blocks and rings

The choice of buffer material and design of the buffer around the canister are based on the fundamental requirements for its isolating and retarding functions. The buffer material being considered is swelling bentonite clay.

There are primarily two methods available for fabrication of bentonite blocks and rings: uniaxial pressing and isostatic pressing. Both methods have been studied by SKB and the goal is to develop methods and equipment that are capable of producing the blocks and rings needed in the deep repository on an industrial scale.

The development work so far shows that both isostatic and uniaxial pressing can be used for the production of the bentonite buffer around the canisters. Blocks with a height of 50 cm and a diameter of 165 cm for placement beneath and on top of the canister and rings with the same height and outside diameter and with an inside diameter of 107 cm have been pressed to both a natural water ratio (10 percent) and an elevated water ratio (17 percent), see section 6.1.7. Since RD&D-Programme 98, a total of about 100 bentonite blocks and rings have been produced for experiments in the Äspö HRL. They have been fabricated 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 handling and emplacement in the deposition holes. Consequently, studies of technology for production of blocks with a greater thickness are being conducted, aimed at fabrication by isostatic pressing. There is no isostatic press in Sweden today that is big enough to press full-diameter (165 cm) blocks. SKB plans to carry out isostatic pressing of blocks and rings with a diameter of about 100 cm with existing equipment.

So far, fabrication and trials have been conducted with bentonite with a high smectite content (MX-80). SKB intends to continue the evaluation, already mentioned in RD&D-Programme 98, of what importance bentonite quality and pretreatment methods have for the quality and function of the blocks.

14.5.3 Emplacement of bentonite and canisters

According to SKB's reference design, the canisters are deposited (emplaced) one at a time in vertical deposition holes in deposition tunnels.

SKB has manufactured a full-scale prototype of a deposition machine in order to be able to test and demonstrate the technology for deposition of canisters in the deep repository. The prototype was delivered to Äspö in 1999. The purpose is to acquire experience from the design, manufacture and operation of such a machine. The deposition machine is specially built to work in confined spaces, since this is very important in the deep repository, see Figure 14-5. It is also necessary that the machine can be moved reasonably easily between the deposition tunnels.

The arrangements at Äspö are limited to the deposition machine. 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.

The bentonite in the form of blocks and rings is emplaced in the deposition hole. When the bentonite is in place, the canister is driven up to the deposition hole by the deposition machine and lowered into the inner space in the bentonite. When the canister has been lowered, bentonite blocks are placed over the canister and the rest of the hole is filled up with backfill. All handling takes place behind radiation shields and personnel will supervise deposition.

Bottom levelling in the deposition hole is sensitive, since any slope will cause the stack of bentonite blocks to lean.

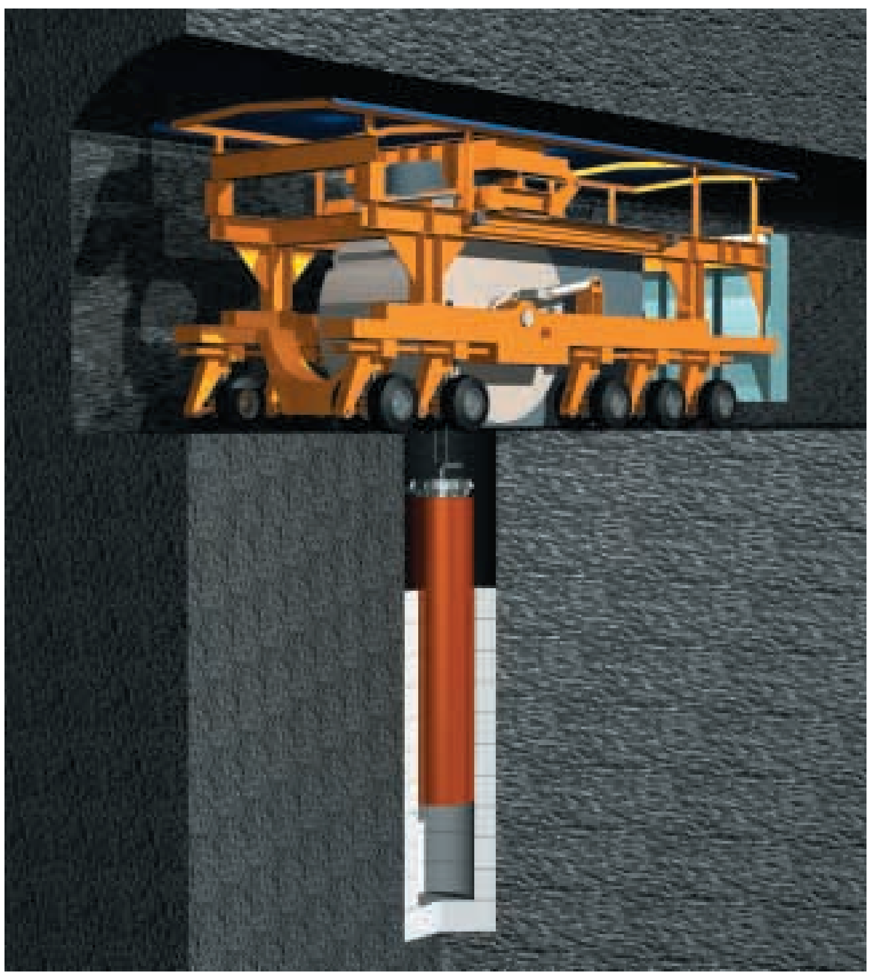

Figure 14-5. *SKB has had a prototype deposition machine manufactured.*

According to what was planned in RD&D-Programme 98, SKB has demonstrated the various steps in the deposition of canisters. This has been done in the Äspö HRL in the project Canister Retrieval Test, where a canister has been deposited in a full-size deposition hole. In a full-scale trial runs at the Äspö HRL of the KBS-3 method in its entirety, the Prototype Repository Test, additional canisters will be deposited during the period 2001–2002 in four full-size deposition holes in an inner section and two in an outer section. The Prototype Repository will simulate as closely as possible a KBS-3 repository under what can be described as normal conditions with respect to geometry, materials and rock conditions. The Prototype Repository differs from an actual repository in that the heat output will be generated by electric heaters instead of spent nuclear fuel. At the Äspö HRL, drainage of the deposition holes from seepage water has been solved by pumping. After installation of the bentonite blocks, a controlled humidity needs to be maintained in the gap between block and rock in order that the bentonite will not absorb water and swell or exude water and shrink.

Activities during the period 2002–2007 are mainly aimed at developing programmes for continued development of special machines for heavy transport and deposition of buffer and canisters.

SKB also plans to study how the requisite density can be achieved with respect to the dimensions of deposition holes and bentonite blocks (tolerances), deposition tools, moisture content in bentonite blocks and air, press pressure in block fabrication, etc. Different ways to increase the density of the bentonite buffer are to reduce the gap between buffer and rock or to fill it with bentonite pellets.

14.5.4 Backfilling

The material that is used as backfill will contribute to keeping the tunnels stable and keeping the bentonite around the canisters in place. The backfill will also limit the water flow. The backfill must not lead to any deterioration in the quality of the groundwater and must remain chemically stable for a long time.

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. Examples of materials are bentonite and crushed rock, bentonite and quartz sand or only crushed rock.

At the Äspö HRL, SKB is developing and testing compaction techniques and materials for backfilling on a full scale in the Backfill and Plug Test and the Prototype Repository Test. In the Backfill and Plug Test, which was completed according to the plan outlined in RD&D-Programme 98, a blasted tunnel was backfilled. The inner part of the tunnel was backfilled with a mixture of bentonite and crushed rock and the outer part with crushed rock alone. The backfill was applied in layers and compacted in situ with vibratory plates developed and built specially for this purpose. The layers were applied at an angle of 35 degrees to the horizontal plane, which has proved to be optimal. In the part of the tunnel that was backfilled with crushed rock alone, the space between the backfill and the tunnel roof was filled with blocks of compacted bentonite. This was done to obtain good contact between the backfill and the rock, since crushed rock does not have any swelling capacity.

Measurements of the sealing capacity of the backfill and the concrete plug are being made during the experiment, see section 7.2.2. When the measurements have been completed, the backfill material will be excavated and the excavated backfill will be investigated and analyzed. Another tunnel, the Prototype Repository, will be backfilled during 2001–2002 with a mixture of bentonite and crushed rock. Water leaking into deposition tunnels hinders the practical execution of the experiments, and SKB intends to try different technical solutions depending on e.g. the varying quantity of water leaking into a deposition tunnel.

14.5.5 Sealing

After a tunnel has been backfilled, the ends of the tunnel need to be sealed pending closure of the entire deep repository. Operating seals are sized so that rapid water transport in the backfill leading to material movement is avoided. The seal must also be strong enough to withstand the swelling pressure from the backfill and fully developed water pressure against the structure. Operating seals are not credited with any function with regard to long-term safety.

Tunnel seals in the form of plugs of the type planned for temporarily sealing deposition tunnels are included in the full-scale experiments Backfill and Plug Test and Prototype Repository Test in the Äspö HRL. The blast-and-drilled test tunnel in the Backfill and Plug Test was sealed with a concrete plug in 1999. The plug is cast into a 1.5 metre deep triangular slot in the rock in the periphery of the plug to resist the water pressure and swelling pressure from the backfill and cut off the disturbed zone.

SKB's judgement is that sufficient knowledge exists regarding the design and construction of operating seals.

When it comes to final sealing and closure of the repository, SKB plans to define in greater detail the function of the sealing during the upcoming three year period. Then technical solutions will be worked out. SKB is clear about the fact that the location of plugs in the deep repository is determined for the most part by site-specific conditions, and this is one of the design questions that is dealt with in the permit application for the deep repository.

14.5.6 Canister Retrieval

200–400 canisters will be deposited to begin with during the initial operating stage of the deep repository. Long-term safety is indirectly provided for by checking that the requirements on the deposition process are met.

If it is found necessary at the time of this evaluation or on later occasions to retrieve deposited canisters with spent nuclear fuel from the deep repository, technology and methods for this, as well as a facility for interim storage of the fuel, must be available. These aspects are noted by SKI in its review of RD&D-Programme 98 /14-11/.

No measures are adopted in the handling of the fuel and no arrangements are built into the deep repository that unnecessarily impair canister retrieval. In the same way, allowance for retrieval must not compromise the deep repository's ability to meet requirements on safety and radiation protection. There are no formal requirements in Sweden that retrieval must be possible. A permit is required for canister retrieval, so this is not something which SKB can decide on alone.

The manner in which deposited fuel canisters are handled during retrieval depends on when retrieval takes place. Canister retrieval immediately after deposition, before the bentonite blocks have swelled, is relatively simple. The process is more difficult when the buffer material has begun to swell. Then the canister must be freed, i.e. the buffer material must be removed, before it can be lifted out of the deposition hole. If the entire deposition tunnel has been backfilled and sealed, the retrieval process is more laborious. If the entire repository has been sealed after concluded deposition, the work and costs involved increase considerably.

After the canisters have been retrieved from the deep repository, they are taken to some kind of interim storage facility. If the system for management of spent nuclear fuel is still in operation at this time, it is reasonable that such an interim storage facility be co-sited with CLAB and the encapsulation plant. Otherwise a nuclear installation must be built on a suitable site.

A number of methods for removing bentonite have been studied in recent years /14-26/. The methods that have been studied can be divided into four main categories: mechanical, hydrodynamic, thermal and electrotechnical. Of these, the hydrodynamic method has shown the best results. It entails flushing the bentonite repeatedly with saline (4–6 percent salt) water. The bentonite forms a slurry and can be pumped out of the hole. The bentonite slurry can then be dewatered in a filter press or a centrifuge.

The hydrodynamic method will be demonstrated at the Äspö HRL in an ongoing experiment entitled "Canister Retrieval" where SKB is developing and testing the technology for retrieving a canister from water-saturated and swollen bentonite under realistic conditions.

14.5.7 Engineering and stray materials

Engineering and stray materials will be brought down into the deep repository during construction and operation. Examples of engineering materials are cement, concrete and steel used for rock sealing, rock reinforcement and floors. Before the canisters are deposited, engineered structures that are not necessary from the viewpoint of stability or safety will be removed. Besides engineering materials, stray materials will be present in the deep repository in the form of spillage and waste products from machine use, contaminants from blasting, human refuse and materials introduced via the ventilation air.

The quantity of material that is left in the deep repository after construction and operation has been estimated /14-27/. Based on this analysis and information concerning the chemical composition of the materials, the quantities of specific chemical substances introduced into the deep repository have been estimated /14-28/ and compared with the quantities introduced via the natural materials in the deep repository, i.e. canister materials, bentonite buffer, backfill and substances in the groundwater. The quantities of chemical substances introduced via engineering and stray materials are relatively small in comparison with the materials present naturally in the deep repository. An exception is the presence of calcium if cement is used for levelling the bottoms of the deposition holes. The processes that are of importance for the long-term performance and safety of the deep repository and that may be affected by the presence of the introduced chemical substances have been identified /14-28/.

SKB and Posiva are cooperating in a study aimed at testing whether low-alkalinity cement-based materials can be used as structural concrete, shotcrete and for grouting. This cement has the advantage of giving pH values less than 11.

SKB is also participating in an EU project (ECOCLAY II) aimed at obtaining a better understanding of, among other things, how the presence of cement affects bentonite.

During the upcoming period, SKB will conduct a critical review of the engineering and stray materials that might conceivably occur in a repository and shed light on their importance for long-term safety, see section 7.2.16.

14.5.8 Sealing of investigation boreholes

A number of investigation boreholes are drilled during site investigations and detailed characterization in order to obtain data on the properties of the rock. These boreholes must be sealed, no later than at the closure of the deep repository, so that they do not constitute flow paths from repository depth to the biosphere. This is done by filling the holes with bentonite or cement. Since most of the boreholes are instrumented for the investigations, reliable technology is also needed to clean boreholes so that they can later be sealed.

Technology for sealing of boreholes has previously been developed and tested within the framework of the Stripa Project /14-29/. Two different techniques were used to insert highly compacted bentonite blocks into boreholes up to 200 metres long. Very good sealing was obtained. A further development of this technique is required to show that boreholes with lengths of up to 1,000 metres can be sealed. Another sealing technique, which involves bentonite pellets being blown in through a hose, has been tested by Nagra. This technique has also been evaluated for possible testing under Swedish conditions.

Field tests at the Äspö HRL are planned during the coming six-year period. These tests include further refinement of existing technology for shorter boreholes (a few hundred metres) and development of technology for deep boreholes (up to about 1,000 metres). The work is being commenced with an analysis of what sealing requirements should be made. This will be followed by a survey of available techniques and their potential for satisfying the requirements. The most promising techniques will be chosen for continued development and testing.

The plan is to begin the work during 2002 and finish it during a three-year period. There are already a large number of investigation boreholes on Äspö. Equipment has become stuck in some of these holes and they no longer serve any function. One or two of these holes will be used in the development work.

14.5.9 Development programme

Planned technology development and demonstration activities have been discussed above. These accounts are summarized below.

The programme for technology development and demonstration covers construction, operation and sealing of the deep repository. The purpose is to provide support for the choice of equipment, materials and working methods at the deep repository. Ongoing and planned demonstration projects at the Äspö HRL, as well as site-specific information from the planned site investigations, will provide new and valuable experience and insight which will be able to be integrated into the design of the facility.

The main activities that are planned are:

- Compile practical experience from the Äspö HRL as regards feasibility of deposition etc. and practical operation of the facility.
- Further develop methods, machines and equipment for excavation of tunnels, shafts, ramps and deposition holes according to the needs that emerge in the designing of the facility.
- Further develop equipment for fabrication of nearly full-size bentonite blocks by isostatic pressing.
- Prepare a programme for continued development of special machines for heavy transport, deposition of buffer and canisters, and emplacement of backfill.
- Clarify the function of the seals in the deep repository during the coming three-year period and then arrive at technical solutions for them, if needed.
- Demonstrate how a canister can be retrieved from a water-saturated bentonite buffer.
- In cooperation with Posiva, explore and test whether low-alkalinity cement-based materials (pH<11) can be used as structural concrete, shotcrete and for grouting.
- Further develop methods and technology for cleaning and sealing investigation boreholes.

14.6 Transportation

Handling and transport of nuclear waste and spent nuclear fuel involves tried and tested technology. Both Sweden and other countries have several decades of experience in this area. Transport of radioactive waste, including encapsulated spent nuclear fuel, takes place within the framework of national and international laws and regulations. Such regulations have been issued by the International Atomic Energy Agency, IAEA, and by the Swedish nuclear regulatory authorities SSI and SKI.

Rock spoils, excavation spoils, building materials, machines, supplies and personnel have to be transported during the construction phase. Two types of goods transport will occur during the operating phase: heavy units with encapsulated spent nuclear fuel from the encapsulation plant to the deep repository, and bulk goods in the form of bentonite clay and possibly sand for the backfill. In addition, goods and personnel required for operation of the facility have to be transported.

Prior to establishment of the deep repository, the transportation system needs to be expanded to include transport of encapsulated spent nuclear fuel from the encapsulation plant to the deep repository. Encapsulated spent nuclear fuel is better protected than the fuel that is transported today, since the fuel assemblies are then enclosed in completely leaktight canisters. A canister with fuel assemblies weighs approximately 25 tonnes and is transported in special transport casks.

The transport casks, see Figure 14-6, which protect the canisters from the time they leave the encapsulation plant until they have been taken down to a transloading hall in the deep repository's central area under ground, are designed in accordance with the requirements issued by the IAEA. The casks shield off the radiation from the fuel so that they can be handled without additional shielding during transport. The casks also

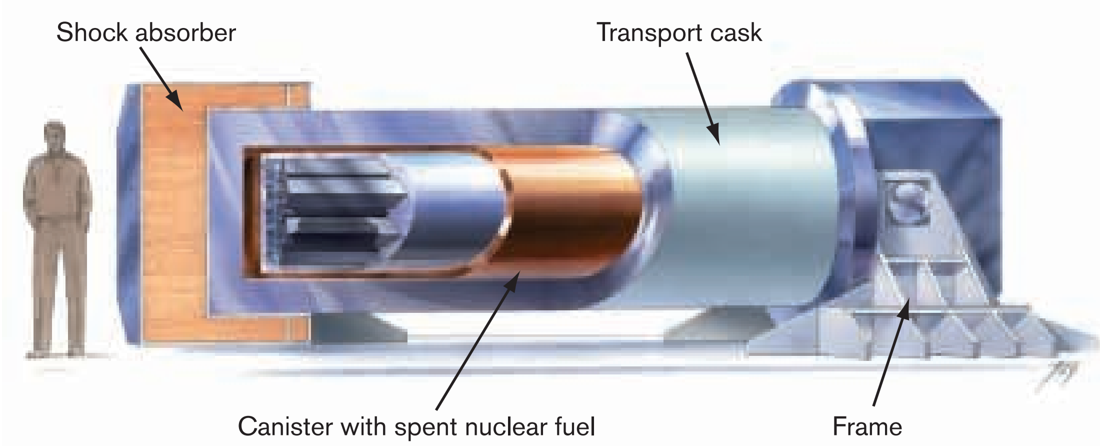

Figure 14-6. *Transport cask for canisters.*

protect the canister against damage. They satisfy requirements on strength and heat resistance and are able to dissipate the decay heat emitted by the spent fuel so that neither canister nor casks become too hot. The strength of the casks must be able to withstand the stresses that can arise in connection with possible accidents. The requirements on mechanical strength make the casks heavy. A transport cask containing a canister, see Figure 14-6, weighs around 65 tonnes without and 75 tonnes with frame. SKB has, in a joint project with Germany, conducted a feasibility study of transport casks for canisters.

The transport casks can be transported by sea, by road or by rail, depending on local conditions on the site. The siting of the deep repository is thus of importance for the choice of transport mode.

In both Forsmark in Östhammar Municipality and Simpevarp in Oskarshamn Municipality, the repository's surface facility can be situated in an industrial area with nuclear activities /14-3, 14-5/. The surface facility is connected to the underground facility via a tunnel. There is a harbour that can be used for sea transport, so no overland transport is necessary outside the industrial area. In Simpevarp, the underground portion of the repository may be sited separately from the nuclear power plant's industrial area. In this case it may be suitable to establish an operations area above the underground facility's central area, which means that a system for overland transport between the harbour and the operations area must be established.

The candidate geological area in Tierp Municipality is large. Its nearness to the East Coast Railway and E4 provides good possibilities for connections to road and rail. A new rail connection may be needed, since encapsulated fuel must be transported from a harbour (Skutskär is the likely candidate) to the operations area /14-6/.

Transport between the encapsulation plant and the deep repository take place using tried and tested technology. The choice of transport mode, the design of the transportation system, as well as the choice of equipment, are practical questions linked to local conditions on the site. The possible variants are dependent on, for example, whether the transport casks must be adapted to only transport by terminal vehicle or a combination of both terminal vehicle and sea, rail or overland transport. Local transport at the deep repository may also impose design-basis requirements on the transportation system. Routes and a transport description will be provided when siting of the deep repository is finished.

If the encapsulation plant is not situated, as in the main alternative, adjacent to the encapsulation plant, spent nuclear fuel will have to be transported from CLAB to the encapsulation plant. Spent fuel is transported today by sea between the nuclear power plants and CLAB, so there is already a transportation system for such shipments. If the encapsulation plant is sited inland, spent nuclear fuel will have to be transported by rail or road. If the encapsulation plant is not co-sited with CLAB, today's transport casks for spent nuclear fuel will probably be exchanged for a new type with greater payload capacity, since the spent fuel will then have much lower radioactivity. Such casks exist and are in use in other countries.

The system for surveillance, communication and accident preparedness that is used for present-day shipments of spent nuclear fuel serves as a model for shipments of encapsulated fuel. It fulfils both the requirements on physical protection and SKB's and the operating organizations' need for communication and follow-up during ongoing transport. The system consists of a combination of technical and administrative measures which protect the goods physically and permit rapid detection and alarm if abnormal conditions should arise.

Even in the event that a canister is damaged during transport or fails to obtain approval on inspection prior to deposition, procedures will be devised for transporting the defective canister to the encapsulation plant, where it must always be possible to take in a returned canister for checking and repair, regardless of the reason for its return.

Transport-related issues were recently examined and analyzed in conjunction with the feasibility studies. The development work that will be pursued with regard to transport over the next few years will be related to adapting the transportation system to the sites being considered for site investigations. General studies of the transportation system will be conducted in conjunction with the site investigations on the three sites. Alternatives and variants of the transportation system will be studied in conjunction with this work.

The transportation system and the transport need are presented in the environmental impact assessment which is prepared as a basis for an application for a permit for detailed characterization of a particular site.

14.7 Safeguards and physical protection

Through international treaties such as the Nuclear Non-Proliferation Treaty /14-30/, 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. The purpose of the safeguards is that the inspection bodies should discover if nuclear materials are diverted from the system in time.

The IAEA has issued a draft policy for safeguards for deep repositories /14-31/, where it is recommended that safeguards should also be maintained after the repository has been backfilled and sealed. 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 sealed repository. There may be a need to develop new technology in certain respects. 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.

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 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 15 where the safeguards system for the encapsulation plant is presented). Good control of the flow of fissionable material to and from the deep repository is therefore required during transport and operation of the deep repository. This imposes demands on the inspection function.

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. Arrangements are made to ensure that canisters are not taken out of the 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 inspections need to be conducted at regular intervals during the construction and operation of the deep repository.

A possible retrieval of deposited canisters after the initial demonstration stage or at any other time also imposes demands on the safeguards system. It is vital to be able to establish unambiguously the identity of the canisters retrieved. Otherwise, the same principles should be able to be applied to retrieval, transport and interim storage as to the various steps in deposition of the canisters.

During the period 2002–2007, SKB will keep track of international technology development in the field, but does not plan to conduct any development or demonstration of its own.

Physical protection includes guarding and other measures that are undertaken to protect the fuel from theft or sabotage. There is a well-functioning system for physical protection during handling and transport. At the deep repository, the operations area will be kept under control and surveillance in a similar manner as at the nuclear installations in operation today. No physical protection is needed in a sealed repository.

15 Encapsulation

There are several different methods for fabricating copper tubes, inserts, lids and bottoms. The final choice of fabrication method should be made as late as possible in order to maintain flexibility and take advantage of technical advances. The choice does not need to be made until the canister factory is designed, which is planned to begin in 2007.

Welding technology and methods for nondestructive testing (NDT) are mainly being developed at SKB's Canister Laboratory in Oskarshamn. The trials are being conducted on a full scale, and after initial problems with equipment and methods the development work picked up speed during 2000. A great deal of work remains, but the results so far look promising. The welding method being used today at the Canister Laboratory is electron beam welding, but alternative welding methods are also being studied.

One method which is under development and which has produced good results in practical trials for several years is friction stir welding. The technology is planned to be transferred to the Canister Laboratory to continue development there on a full scale during 2003. The choice of methods for welding and testing influences the design of the encapsulation plant and should therefore be completed by the time for application for a permit to erect the plant, which is planned for 2005. 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.

The design of the encapsulation plant has changed little from that described in RD&D-programme 98. The main alternative is that the plant will be sited at CLAB. An alternative siting at the site of the deep repository has been studied and the alternatives have been compared. The advantages of a location at CLAB outweigh the alternatives. The work of designing the plant will be resumed during 2001.

In the reference design of the canister, the copper thickness is 50 mm. Results from studies done to date /15-1/show that a copper thickness of 30 mm is adequate to meet requirements on durability and handleability. Fabrication trials of copper tubes and inserts for canisters with a copper thickness of 30 mm have been carried out and an expansion of the programme is planned. Tests of sealing technology and nondestructive testing are also planned to be carried out on canisters with a copper thickness of 30 mm. Even though the techniques which SKB is developing for welding in thick copper – electron beam welding (EBW) and friction stir welding (FSW) – work for 50 mm copper, the reliability and quality of the weld will probably be even higher with thinner material.

15.1 Canister design

The fundamental design premises for the canister have been thoroughly described and commented on in RD&D-Programme 98, in SR 97 and in /15-1, 15-2/. In the reference design, the canister consists of a pressure-bearing insert of spheroidal graphite iron (nodular iron) with a steel lid, see Figure 15-1. The insert is surrounded by an outer corrosion barrier of copper. In the reference canister, the thickness of the copper shell is set at 50 mm. In RD&D-Programme 98 and in /15-1/, SKB arrives at the conclusion that when the requirements on corrosion resistance and other design premises are weighed together, a 30 mm thickness of the copper shell is found to be sufficient. In /15-3/, a summary evaluation of existing knowledge concerning corrosion of copper under deep repository conditions has been made. Testing of fabrication methods and optimization of canister design have been focused on a 50 mm copper thickness. Canisters with a 30 mm wall thickness will also be trial-fabricated for the purpose of gaining experience and evaluating fabrication and inspection methods for such canisters. This knowledge will comprise a basis for a possible later decision to change the wall thickness.

After RD&D-Programme 98, SKI concurred with SKB that a smaller wall thickness of the copper canister has both advantages and disadvantages when it comes to fabrication, sealing and inspection methods. Fabrication of copper plates (for rolling), sealing and inspection methods are probably simplified by thinner material. Fabrication by means of extrusion or pierce and draw processing may, on the other hand, be more difficult if the wall thickness is reduced, and the canister may also be more sensitive in connection with e.g. machining and transport. The thicker insert that is needed for radiation protection reasons when the copper wall is thinner very likely has a positive effect on the canister's load-bearing capacity. A prerequisite for being able to reduce the copper thickness is naturally that SKB can demonstrate, by results obtained from fabrication and by consequence analyses in the safety assessment, that the canister satisfies the design requirements.

Figure 15-1. *Dimensions and weights of canister with 50 mm and 30 mm wall thickness.*

15.2 Canister fabrication

In recent years, continued fabrication trials with copper canisters and cast iron inserts have been conducted on a full scale in accordance with the programme described in RD&D-Programme 98. Results obtained up until August 1998 were reported in /15-4/, and the results from continued trial fabrication up until April 2001 are presented in a new report /15-5/.

All full-scale fabrication of copper tubes has been done with one of the following three methods: 1) roll forming of rolled copper plates to tube halves that are then welded together by electron beam welding, 2) extrusion, or 3) pierce and draw processing. The principle of pierce and draw processing is shown in Figure 15-2. Tubes fabricated by roll forming contain two longitudinal welds, which can be regarded as a disadvantage. Tubes fabricated by this means must be stress-relief-annealed to ensure shape stability.

In its assessment of RD&D-Programme 98, SKI was critical of fabrication of copper tubes by roll forming and longitudinal welding. SKI questions the method in terms of both the grain size obtained in the rolled copper plates and the quality of the longitudinal welds. SKB must show by means of further trial fabrication that much better and more uniform material can be obtained with roll forming if this method is to be used for fabricating copper canisters. SKI was, on the other hand, very positive to the results achieved in the trial fabrication of seamless tubes by means of extrusion and pierce and draw processing and encouraged SKB to continue developing these methods.

SKB has told SKI that they concur with this and development of tube fabrication has since 1998 been concentrated on fabrication of seamless tubes.

Extrusion and pierce and draw processing are two different methods for fabrication of solid-drawn or seamless tubes. All tubes fabricated after 1998 have been made using one of these two methods. Both methods appear at the present time to be fully applicable for SKB's canister fabrication. Tubes that meet the stipulated requirements have been fabricated with both 50 mm and 30 mm wall thickness. The results in terms of grain size have in particular been satisfactory. Altogether, 14 seamless tubes have been fabricated, 11 by extrusion and 3 by pierce and draw processing.

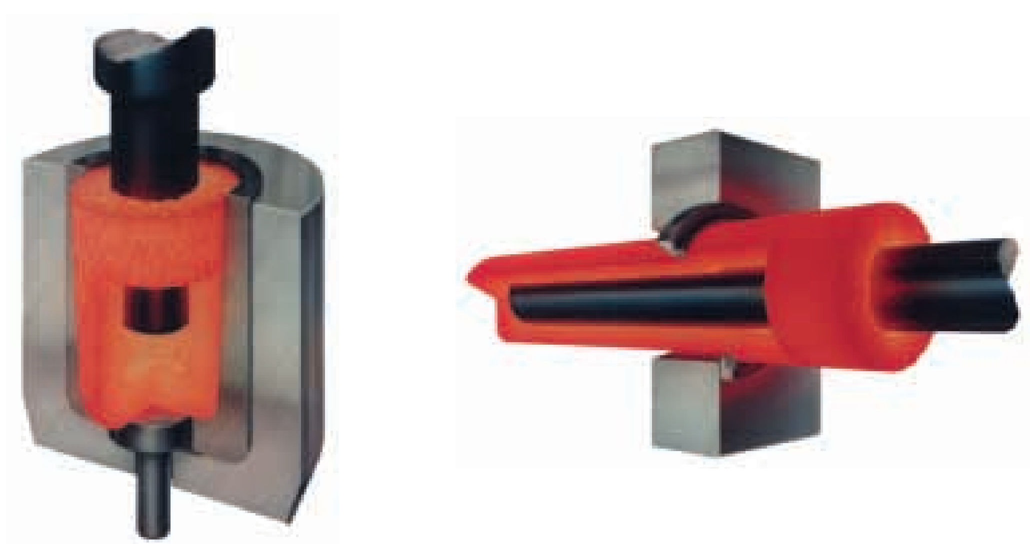

Figure 15-2. *The principle of pierce and draw processing. The first step, where the ingot is preformed into a blank with a centre hole and a retained bottom, is shown at left. The right figure shows step two, where the finished tube is produced by repeated drawing through a die.*

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When it comes to the question of continued development of the fabrication technique for roll formed and longitudinally welded tubes, SKB concludes that the method can nevertheless probably be developed into a practical alternative for tube fabrication. Altogether, twelve full-size copper tubes have been longitudinally welded. Eleven of them were made of 60 or 65 mm thick plates intended for 50 mm wall thickness in the finish-machined tubes. All tubes were welded in TWI's (a British institute for welding research) vacuum chamber. The number of weldings carried out has, however, been far from enough for the method to be considered fully tested. The presence of both porosities and superficial defects in the welded joint has been determined by means of nondestructive testing (NDT). At the same time, however, it can be concluded that the welding method has been progressively improved, and the most recent welds have been judged to be significantly better than the early ones. TWI also makes the judgement that welding at reduced pressure instead of high vacuum, which is the intended developed technique for welding of copper canisters, will make it easier to achieve a better quality of the welds.

It can also be concluded that longitudinal welding of a single tube with a thinner wall thickness (40 mm, intended for 30 mm finished thickness) was simpler and gave a better result than the more thick-walled tubes. A possible future focus on a wall thickness of 30 mm in finished canisters may be favourable for the application of roll forming and longitudinal welding in tube fabrication. The current development of friction stir welding may also lead to an alternative welding method for longitudinal welding of copper tubes.

A number of copper lids and bottoms have been fabricated since 1998 /15-5/. They are made by hot-forging of continuously-cast round bars, followed by machining to a blank that is so dimensioned that it can be finish-machined either to a lid or to a bottom. The fabrication trials have shown that a homogeneous and defect-free material is obtained in the finished components. The structure is coarser-grained than the material in extruded or pierced-and-drawn copper tubes, but satisfies the grain size requirement in SKB's specification. The continued development work should aim at optimizing the forging process in terms of both material structure and material yield.

Eight bottoms have been welded onto copper tubes at TWI by means of electron beam welding. In one case, a bottom was welded onto a copper tube with a 30 mm wall thickness. As in longitudinal welding of copper tubes, welding of bottoms was carried out in TWI's vacuum chamber. Some occurrence of pores and superficial defects was found in this case as well /15-5/. However, progressive development has led to considerably better results, and the method can probably be developed into a workable technique for welding of bottoms on copper tubes. As in the case of longitudinal welding, the judgement is that a 30 mm wall thickness entails a simplification. Friction stir welding is also an alternative of great interest for welding of bottoms. Further development will show which method is the most reliable.

After RD&D-Programme 98, SKI offered the viewpoint that the mechanical properties of spheroidal graphite iron are highly dependent on the dimensions of the cast body. Material testing must therefore be performed on the finished inserts. The results of such investigations can serve as a basis for changes in the casting process. The results will also serve as input data in the final strength calculations which SKI considers necessary. SKB concurs with this. The results of such investigations of inserts are reported in /15-5/. This is also work that will continue in conjunction with castings of new inserts. The results will also serve as a basis for optimization of both the casting process and the specified composition of the iron.

SKI has pointed out the importance of basing strength analyses, which are supposed to show that the canister satisfies the design requirements, on the actual material properties of fabricated canisters. When it comes to the copper shell, the testing should include tube, lid and bottom fabricated by different methods as well as welds done by both EBW and FSW. SKI has also pointed out the importance of SKB's producing a derivation of acceptance criteria for permissible defects in both the copper shell and the cast insert. The consequences if there are more or larger defects than stipulated by the acceptance criteria must be shown. SKB has concurred with this and extensive testing is under way and will continue for the next few years.

The development of a fabrication technique for detailed design of cast inserts of spheroidal graphite iron has continued. Altogether, 17 inserts have been fabricated of spheroidal graphite iron at four different foundries. It can be concluded that casting of inserts of spheroidal graphite iron with an integrated bottom can be developed into a workable method for SKB's needs /15-5/. Different foundries have tested different moulding and casting methods and the detailed design has been developed. The objective during the next few years is to optimize material specifications, the fabrication technology and quality control and to show that the method is sufficiently developed for serial production. Figure 15-3 shows examples of fabricated canister components and display objects.

Figure 15-3. *Examples of fabricated canister components and display objects.*

15.3 Development programme

The work with full-scale trial fabrication of all canister parts will continue for the next few years. SKI stated in its comments after RD&D-Programme 98 that SKB must show before the time for permit application that methods for fabrication and inspection are really available and are applicable for serial production. This means that a sufficiently large number of canisters must have been fabricated and inspected and shown to satisfy stipulated requirements. No specific number of approved canisters is stipulated however. With this as a background, the following systematization of the necessary continued development work can be done.

Fabrication of copper tubes with lids and bottoms

- Continued fabrication of seamless copper tubes for 50 mm wall thickness and to some extent for 30 mm wall thickness will primarily be done using the two methods extrusion and pierce and draw processing. The work will be focused on showing that full-scale copper tubes can be fabricated by means of these methods and satisfy applicable requirements. Important aspects are optimizing material yield, process parameters and inspection methods.
- Fabrication of copper tubes with 30 mm wall thickness by roll forming of rolled plate and longitudinal welding by electron beam welding (EBW) or friction stir welding (FSW) should be seen as a possible alternative, if the fabrication of seamless tubes results in unexpected problems.
- Fabrication of forged blanks for lids and bottoms will continue. Important aspects of the continued work are optimizing the grain size in the forged blanks and improving material yield and inspection methods. In order to improve material yield and grain size, different types of forging dies and different process parameters will be tried.
- 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 of the fabrication methods in question and by means of material testing, to obtain knowledge that can contribute to the desired optimization of material specifications and fabrication technology.
- Development of the technique for welding of bottoms on copper tubes will continue. Welding will be done by both EBW and FSW at TWI and at SKB's Canister Laboratory. Full-scale welding will be able to be performed using both methods at the Canister Laboratory during the next few years. Methods for NDT of bottom welds will be tested in parallel with the development of testing methods for sealing welds.

Fabrication of cast inserts with steel lids

- Continued fabrication of cast inserts of spheroidal graphite iron will be carried out in cooperation with various foundries. The focus in the coming work will be on optimizing the fabrication process, the material specifications and testing methods.
- Steel lids for inserts will be fabricated to meet the need in connection with the fabrication of complete canisters for e.g. projects at the Äspö HRL. The objective of the continued work is to further refine the design with associated material specifications and quality assurance criteria.

15.3.1 Assembly of complete canisters

A number of complete canisters will be assembled for the Prototype Repository in the Äspö HRL, but also as a demonstration of quality-assured canister fabrication. Canisters for the Äspö HRL will have screw-on lids of copper. In addition, canisters will be seal-welded at the Canister Laboratory. Important aspects are document control, handling technology, assessment and documentation of damages, cleaning technique and final quality inspection.

Quality assurance

- The canister fabrication work is being conducted in accordance with the requirements in ISO 9001. The activities are described in detail in the existing canister fabrication manual with appurtenant fabrication drawings, technical specifications and procedure descriptions. The quality system is being developed continuously and appurtenant documents are revised as needed.
- An important area is establishing acceptance criteria for all parts of the canister, including any welds. Such criteria are material requirements and acceptance limits for both superficial defects and defects inside the material. A consequence analysis should be carried out showing what happens if there are more or larger defects than stipulated by the acceptance criteria.
- Established acceptance criteria regarding defects must be able to be verified by NDT. The ongoing work of choosing suitable equipment and methodology will continue in cooperation with suppliers and experts at institutes of technology and universities.
- Relevant fabrication processes and inspection and testing procedures must be qualified. This work will be systematized and pursued during the next few years.

15.4 Canister factory

The empty canisters in which the fuel will be encapsulated will be fabricated in a special canister factory. A preliminary study of how such a factory could be designed is reported in /15-6/. This design is also discussed in RD&D-Programme 98. The study of the plant was based on the assumption that the copper tubes would be fabricated in the factory by roll forming of rolled copper plate into tube halves, which are subsequently welded together by longitudinal EBW.

After the first study /15-6/ and after RD&D-Programme 98, further analyses have been performed by SKB and an alternative design of the factory has been studied /15-5/, now focused on fabrication of copper tubes from seamless hollow cylinders.

The seamless hollow cylinders are delivered to the factory by subcontractors who produce hollow cylinders by methods such as pierce and draw processing or extrusion. In the factory, the hollow cylinders are machined to finished dimensions before welding of bottoms takes place. This means that the factory will be slightly smaller and not require as much equipment and personnel as the former one.

Otherwise the design of the factory is very similar to the previous one. The fundamental principle is still that handling of copper and spheroidal graphite iron are separated all the way up until the insert is lowered into the copper tube. Forged and possibly rough-machined blanks for copper lids and bottoms are machined to finished dimensions. Cast and rough-machined inserts of spheroidal graphite iron are delivered to the factory for finish machining. Blanks for insert lids cut from rolled steel plate are also finish-machined in the factory. After cleaning of all parts, the insert is lowered into the copper shell. Finally, the canister is finished for delivery to the encapsulation plant.

The entire canister factory, including maintenance shop, inspection laboratory and offices, is now projected to cover approximately 6,000 m^2, and the total investment cost for a new factory with machines and other equipment has been estimated at about SEK 180 million. The personnel requirement has been estimated at 21 persons.

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, as well as availability of labour and the 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.

Development programme

- The lessons learned from the trial fabrication of all canister parts will be applied to the further development of the factory. The work of researching 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 made 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 FSW shows that the technique may be suitable for canister fabrication, the consequences of this need to be examined and weighed into factory layout and investment costs.
- A part of the ongoing work with 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. The reliability of deliveries from various subcontractors is of fundamental importance for production in the canister factory. In conjunction with ongoing trial fabrication, continuous assessment of suppliers will be performed via regular quality audits and analysis of pricing, delivery reliability and probable future trends.
- To get a complete picture of potential uncertainties, a risk analysis will be conducted of the operation in the planned canister factory.

15.5 Welding technology

15.5.1 Electron beam welding

Development work on EBW at the Canister Laboratory is aimed at developing equipment and welding parameters to arrive at a stable process with high reliability where the sealing weld meets the durability and strength requirements.

EBW is a fusion welding method. It is based on the principle of bombarding the workpiece with a powerful stream of electrons with high kinetic energy. When the electrons hit the workpiece, local heating occurs and melts the material, see Figure 15-4.

Figure 15-4. *Cross-sectional photograph of sealing weld carried out at the Canister Laboratory. The surface has been etched to bring out the weld structure. Penetration depth 60 mm.*

The method has several advantages:

- Thick workpieces can be welded.
- The process takes place without contact with the workpiece.
- No filler metal is required, the weld has the same composition as the parent metal.
- The welding parameters are programmable and reproducible.

The method has been used for welding on an industrial scale since the 1930s. There are a number of EBW machines within Swedish industry.

Fusion welding of thick unalloyed copper entails certain difficulties due to the high thermal conductivity of the material and the low viscosity of the molten metal. To develop EBW in thick copper, SKB started a development project at TWI in 1982, and a machine designed for welding of copper canisters was developed for use in the Canister Laboratory.

Development programme

- Development of the welding process for sealing of copper canisters with a 50 mm wall thickness and a horizontal weld joint. The project is planned to be completed in early 2004. The goal is to develop the process and equipment for sealing of 50 mm thick copper canisters by electron beam welding in a way that provides the requisite material and strength properties in the weld while satisfying production requirements as regards production rate and reliability.
- Development of the welding process for sealing of copper canisters with a 30 mm wall thickness and a horizontal weld joint. Otherwise the same objective and timeframe as for 50 mm wall thickness.

15.5.2 Friction Stir Welding

The alternative method of joining copper by FSW was not commented on in RD&D-Programme 98. The preliminary studies that had then been started by SKB were, however, described in brief /15-4/. Since then, continuous development efforts have been pursued in cooperation with TWI. A summary of results achieved thus far is presented in /15-5/. Certain results have also been published at three conferences during the period 1999–2001 /15-7, 15-8 and 15-9/. When the project was begun at TWI in 1996, the technology was tried and proven and used in production, particularly for welding of aluminium alloys. Copper of the thickness of SKB's copper canisters had, however, never been welded before using this technology. The fundamental difference from EBW is that the material does not melt when joined.

In FSW, a specially designed rotating tool is used. It is equipped with a central probe that is pressed down between the joint surfaces. When the tool rotates and moves along the joint, heat is generated, and under the right conditions the metal becomes soft and formable and the parts are joined together, see Figure 15-5. Because the metal doesn't melt and the temperature can be kept to a relatively low level by controlling the process parameters, a fine-grained, homogeneous structure is obtained in the weld, see Figure 15-6.

The development work in cooperation with TWI has shown that 50 mm thick copper can be joined by FSW and that the process can probably be developed into an alternative method for welding of copper canisters. During the first project stages, straight joining of copper plates was carried out in gradually increasing thicknesses, from 10

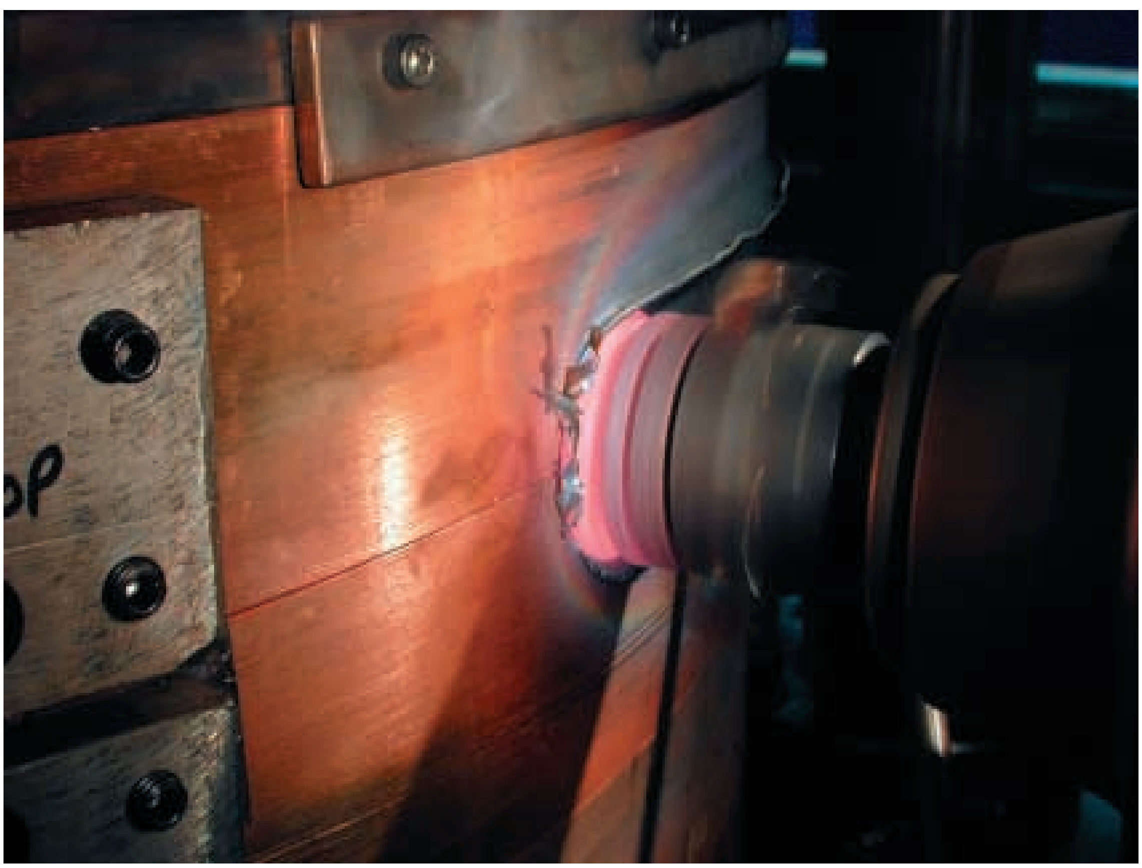

Figure 15-5. *Welding by FSW in the laboratory machine at TWI.*

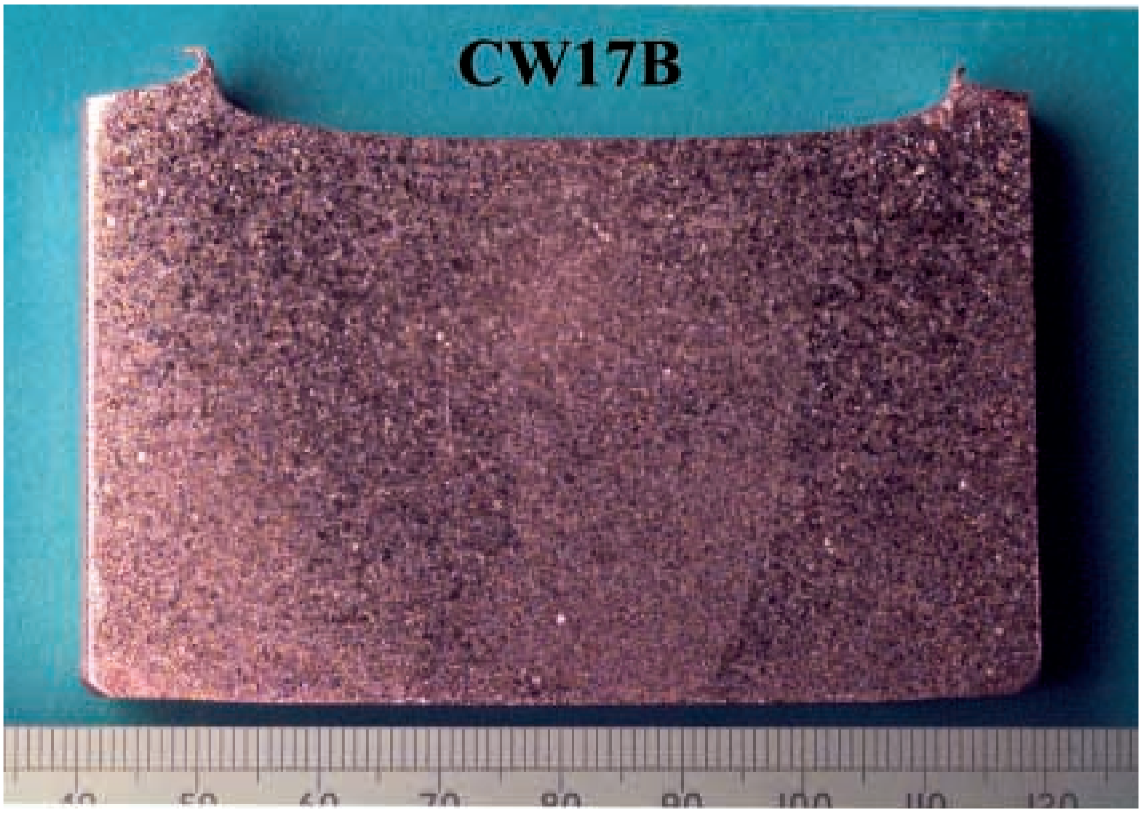

Figure 15-6. *Material structure in weld performed by FSW.*

to 50 mm, for the purpose of obtaining a preliminary test of tool design and process parameters. In the next development stage, a special machine was designed and built for welding of full-size lids or bottoms on copper tubes. The machine is full-scale when it comes to diameter and thickness of lids, bottoms and tubes, but cannot with its present design weld complete full-length canisters. The weldings are performed on copper tubes with a length of about two metres.

A number of complete welds around the entire canister circumference have been carried out on copper tubes with 50 mm wall thickness with good results. Experience to date has shown that tool material and tool design, plus a number of different process parameters, are crucial for the result. In this case as well, the judgement is that welding in 30 mm material will be easier.

After RD&D-Programme 98, and with knowledge of the ongoing development work at TWI, SKI said that they took a positive view of the exploration of alternative welding methods.

Development programme

The fundamental development work with the existing machine at TWI will continue during 2001 and, if necessary, 2002. The work is focused on further development of tool and process parameters. It is also important to develop technology for monitoring and control of certain process parameters. Welding will be carried out in both 50 and 30 mm thick copper tubes. Completed welds will be evaluated continuously by metallography and NDT.

- Thorough material investigations of welds are under way and will continue at the Swedish Institute for Metals Research in Stockholm. The strength of specimens extracted at different locations around the entire circumference of the welds will be tested in tensile tests and creep tests. Furthermore, the welds will be examined metallographically by microscope and, where necessary, microprobe analysis.
- Technology for NDT will be developed in cooperation with Uppsala University.
- One problem with friction stir welding is that after a completed revolution around the canister, the tool will leave an exit hole of the same size as the rotating central probe. There are alternative methods for solving this problem that will be tested and evaluated in cooperation with TWI.
- A project aimed at transferring the technology for FSW to the Canister Laboratory has been initiated. A completely new machine is planned to be built especially for welding of full-length canisters. The purpose is to be able to try out the technique for sealing welding of canisters in a similar manner as with EBW. The new machine is projected to be able to be put into use at the end of 2002.

15.5.3 Qualification of welding method

The welding method or methods that will be used in the final process of fabricating and sealing canisters will undergo qualification. SKB will produce supporting documentation regarding the reliability and performance of the method and the properties of the weld.

A programme for qualification will be drawn up by the time for application for a permit to erect the encapsulation plant, which is planned for 2005. Qualification of method(s) is done in conjunction with commissioning of the encapsulation plant.

15.6 Nondestructive testing (NDT)

Most of the practical work of developing methods for NDT is done at the Canister Laboratory. The weld is tested by several methods, see Figure 15-7. The whole weld is radiographed to detect volume discontinuities (pores). A linear accelerator with a maximum photon energy of 9 MeV and a dose rate of 1.8 kG/h is used as a radiation source. The system has sufficient basic performance to penetrate copper of the thickness in question and a sufficient dose rate to provide an acceptable examination time and negligible influence on the radiographing result by the radiation from a canister with fuel. The detector system is digital with a resolution of 0.4 x 0.4 mm.

The presence of discontinuities that lack volume, for example incomplete penetration, is investigated by ultrasonic inspection with phased array matrix scanning. The scanner head is applied to the top of the canister lid, which is rotated. The active part of the scanner head consists of 80 disc elements in a stack. With computer control it is possible to obtain electronic scanning, angling and focusing in the workpiece's radial direction. Focusing in the workpiece's tangential direction is fixed and determined by the geometry of the scanner head.

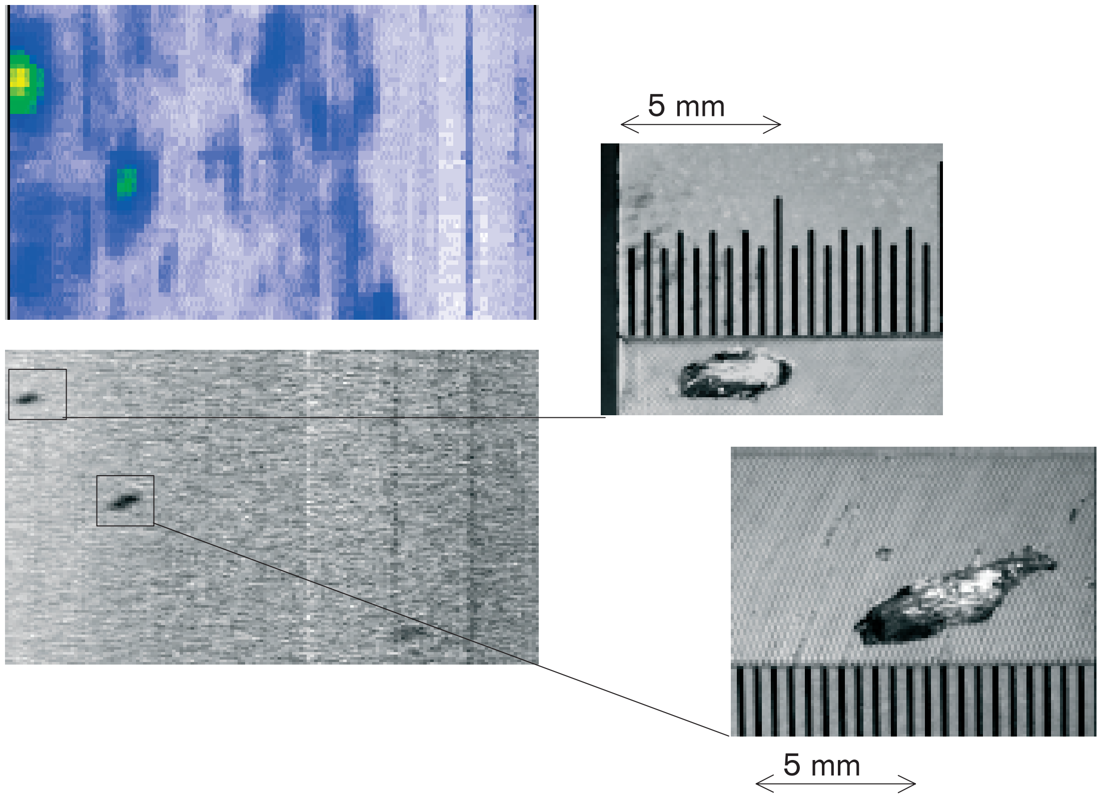

__Figure 15-7.__ Comparison of results obtained by ultrasonic testing (upper picture) with radiographing of the same area. The same discontinuities are shown at the right with a magnification of 5.3 x. The graduations are a superimposed millimetre scale.

Eddy-current testing is being developed to detect near-surface discontinuities. In eddy-current testing, a coil induces a weak eddy current in the weld. Discontinuities cause measurable changes in the secondary field created by the eddy current. In order for eddy-current testing to be performed, the weld reinforcement must first be machined off.

The results of NDT are evaluated by means of destructive tests where the actual size of the discontinuities is compared with the measured results.

Development programme

- A research project involving ultrasonic testing of EBW-welded copper canisters has been underway for five years at Uppsala University. The project, which involves several sub-projects, is aimed at improving the reliability of ultrasonic testing of welds in copper and the possibilities of characterizing defects in the weld, the heat-affected zone and the parent material. An important part is development of algorithms for reduction of noise from the grain boundaries in the copper. Other areas of research have been modelling of the propagation of the ultrasonic wave in copper and nondestructive characterization of copper material. The results obtained in the project will be implemented at the Canister Laboratory.

- A development project was initiated during 2000 where 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 results are being implemented at the Canister Laboratory.
- Development of methods and equipment for NDT of canisters sealed by EBW. The project is planned to be concluded in early 2004.
- Development of methods and equipment for NDT of canisters sealed by FSW. The project is planned to be commenced in 2003.
- Development of radiographic methods with improved performance for location and detection of discontinuities in the sealing weld.

15.6.1 Qualification of nondestructive testing methods

The NDT methods that will be used in the final process of fabricating and sealing canisters will undergo qualification.

Two milestones can be distinguished in qualification. The first will be reached in 2005 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 justifications entails is laid down in ENIQ (European Network for Inspection Qualification) Recommended Practice 2 /15-10/. SKB intends to apply this recommendation in the documentation of its NDT methods.

The second milestone is the commissioning of the encapsulation plant. Then SKB intends to qualify the NDT methods based on ENIQ Recommended Practice 4 /15-11/.

15.7 The Canister Laboratory

At the Canister Laboratory, SKB develops and demonstrates methods for sealing and NDT of copper canisters intended for deep disposal of spent nuclear fuel, see Figure 15-8. The activities at the Canister Laboratory are application-oriented and comprise the link between research/development and planned production in the encapsulation plant. The development work is conducted in project form. The Canister Laboratory has expertise in the fields of welding, NDT, electronics and mechanical systems. The laboratory is located in the shipyard area in Oskarshamn.

Design of the Canister Laboratory was begun in 1995 and operations started gradually during 1998. Start-up problems with several of the newly-developed systems led to delays in process development, however. Thus, despite intensive efforts, only four welds were done during 1999. Most of the problems were solved during 2000, and the development work got going in earnest. Twelve complete lids were welded onto copper tubes, and a number of welds were done in smaller test blocks.

15.7.1 Development programme

Development efforts in the laboratory are currently mainly focused on process and equipment for EBW and NDT. There are strong synergies in pursuing these efforts simultaneously within the same organization. Access to the NDT methods in the laboratory permits quick feedback of the results from the welding tests. Moreover, a very large body of investigation material is obtained, providing broad experience for

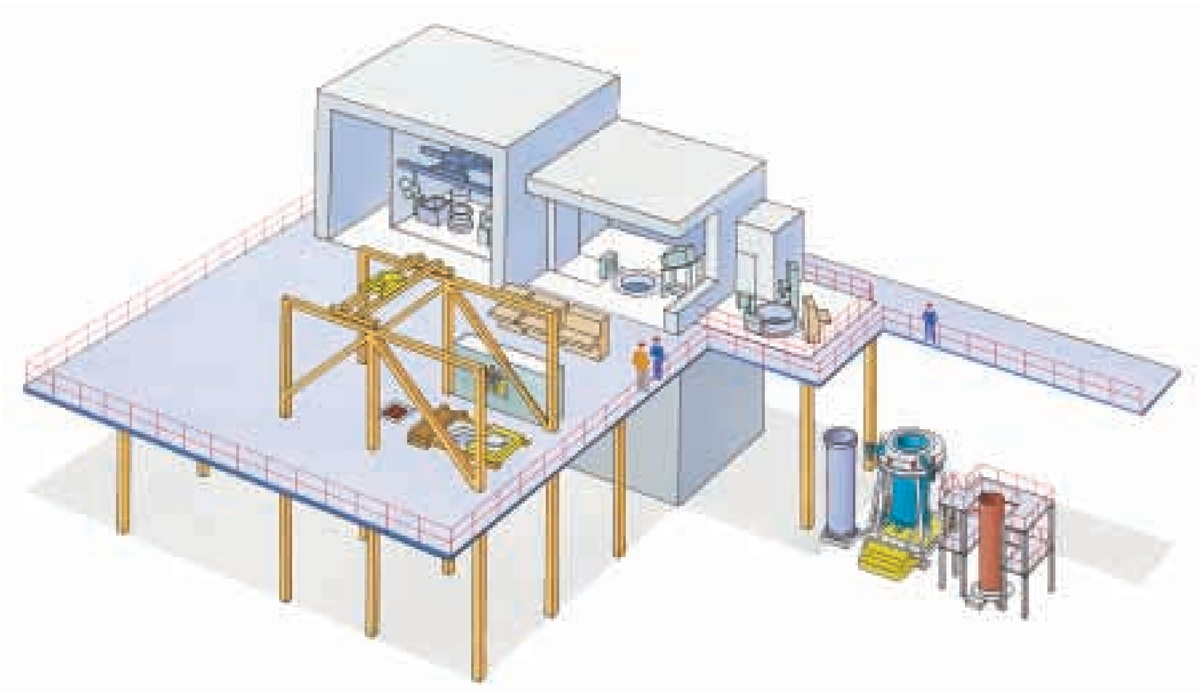

Figure 15-8. *The technology for sealing and NDT is being tested at SKB's Canister Laboratory in Oskarshamn.*

investigating the performance of NDT and developing these methods. Optimal use can be made of the investigation material by coordinating the projects when sectioning the weld for metallographic studies. Since the development work is done on a full scale, valuable experience is also gained in terms of plant design and mechanical auxiliary systems, which are continuously improved.

The programme for further work is naturally focused for the near future on development of methods for sealing and NDT described above. In addition, handling tests and improvement of capacity for NDT is planned as follows:

- Installation of equipment for drilling-out, preparation and examination of macro specimens from welds.
- Linked test series to verify the reliability of the equipment and the production capacity of the encapsulation plant.
- Testing of methods for repair of rejected welds.
- Testing of methods for removal of lids and unloading of fuel in the event of a rejected weld.
- Training of operating and maintenance personnel for the encapsulation plant.

15.7.2 Demonstration

The Canister Laboratory is largely designed in the same manner as the planned encapsulation plant and comprises a full-scale demonstration plant. One important difference is that radioactive material is not handled in the Canister Laboratory. The Canister Laboratory comprises an important resource for demonstrating the encapsulation technology for both regulatory authorities and the public. The plant was visited by approximately 3,000 persons during 2000.

15.8 Encapsulation plant

To encapsulate the spent nuclear fuel, SKB needs to build an encapsulation plant. In this plant it must be possible to encapsulate all fuel types from the Swedish nuclear power plants. The canisters will be sealed to exacting quality standards and inspected carefully before being transported to the deep repository. High demands will also be made on operational reliability so that canisters can be delivered at the pace required by the deep repository.

The encapsulation plant will be designed so that personnel and the surrounding environment are protected against radiation. The encapsulation process will therefore be carried out by remote control behind heavily radiation-shielded walls. Handling of canisters will also be done by remote control as much as possible. Experience from CLAB, SFR and the Canister Laboratory, as well as from various foreign facilities, will be applied in designing the encapsulation plant.

The work of planning and designing the encapsulation plant is proceeding in five stages (like the work for the deep repository). In the first stage (phase E), a conceptual design study of the plant is carried out. Then a basic design stage (phase D) is carried out as a basis for an application for a permit to build the encapsulation plant. While the permit application is being processed by the authorities, the general engineering documentation (phase C) needed to begin building the plant is produced. In the next stage (phase B), which proceeds during the time the plant is being built, detailed engineering is carried out. When the encapsulation plant is finished and commissioning is in progress, the design work is concluded by final documentation of the building layout and designs (phase A).

15.8.1 Siting of the encapsulation plant

The encapsulation plant can either be sited at CLAB, at the deep repository, at an existing nuclear installation, or at some other location. It is an advantage if the plant can be coordinated with an existing operation and if radiological competence and experience are available. Other factors that must be taken into account in the siting process are transportation of spent nuclear fuel, resource utilization, environmental impact and societal aspects.

The main alternative for siting of the encapsulation plant is adjacent to CLAB on the Simpevarp Peninsula in Oskarshamn Municipality, since this alternative offers a number of advantages /15-12, 15-13/. One of the advantages is that the experience of fuel handling possessed by the personnel at CLAB can best be exploited if the encapsulation plant is built on the same site. Furthermore, several of the existing systems and plant sections in CLAB can also be utilized for the encapsulation process. No new land needs to be developed, and no new roads are needed. Moreover, CLAB and the Oskarshamn Nuclear Power Station provide valuable access to other nuclear resources, such as expertise in radiation protection and handling of radioactive waste.

A co-siting with CLAB is also favourable in terms of transportation, since transferring fuel from interim storage to encapsulation does not require any off-site shipments. If the encapsulation plant is not co-sited with CLAB, the fuel first has to be transported in the same way as today from the NPPs to CLAB. The shipments to the deep repository will be simpler if the fuel is encapsulated. The number of shipments will, on the other hand, be greater compared with a siting at the deep repository, since a transport cask with a canister holds fewer fuel assemblies than today's transport casks for unencapsulated fuel. If the encapsulation plant is sited neither at CLAB nor at the deep repository, the transport requirement will be even greater.

The design process is based on co-siting with CLAB, but the design is arranged so that the plant can be adapted to other sitings as well. The alternative with siting at the deep repository has been studied /15-14/. The encapsulation plant is not dependent on the deep repository, so this alternative can also be regarded as covering other possible siting alternatives. The advantages and disadvantages of different sitings will also be explored in the Environmental Impact Statement (EIS) presented in support of the permit application.

15.8.2 Plant design

The work of designing an encapsulation plant co-sited with CLAB started in 1993 and the main features of this work were presented in RD&D-Programme 95. Since 1995 the encapsulation plant has been further developed and certain modifications have been made. The work being done in the Canister Laboratory will result in additional changes. A detailed description of the present-day design is given in /15-15/. The plant is designed with some flexibility for future changes and extensions. There is also some flexibility if the canister design should be modified in the future.

The encapsulation plant comprises an encapsulation building and a store for filled transport casks. The encapsulation building is planned to be built directly adjacent to CLAB's receiving building and to be connected to the fuel elevator that joins the receiving pools with the storage pools. Many of the existing systems in CLAB – such as cooling systems, water purification systems and electrical systems – will be expanded to cover the needs in the encapsulation plant.

In an initial phase, only spent fuel will be encapsulated, but the plant is prepared to be augmented at a later date with equipment for handling of long-lived LILW (low- and intermediate-level waste). Encapsulation of spent fuel and handling of other waste will take place in separate campaigns.

15.8.3 Safety in operation

To protect personnel and nearby residents, high standards of safety must be met in the operation of the encapsulation plant. The safety standards cover radiation protection and fire protection, among other things. The spent fuel must always be handled without risk of criticality. Requirements on safeguards issued by both Swedish and international competent bodies must be satisfied. The encapsulation plant must meet the safety requirements that apply to nuclear installations.

Possible accidents are analyzed during the design work. The encapsulation plant must be designed so that the damage caused by an accident is minimized and does not result in any serious releases of radioactive substances. All lifting devices for fuel and canisters must be designed so that handling can be concluded to a safe position even if a power failure occurs. Safety in the encapsulation plant is described in greater detail in /15-15/.

15.8.4 Safeguards

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 equipment that may be needed for verification. The plant must be designed so that opportunities to divert nuclear materials are prevented.

Each canister will have a unique identity that can be checked visually. The administrative safeguards system keeps track of which fuel assemblies are present in each canister, and visual verification of the identity of the fuel can be done before the canisters are sealed. 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 store that can be 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.

CLAB is an MBA (Material Balance Area) today. The intention is that the encapsulation plant should belong to the same MBA to facilitate administration.

15.8.5 Encapsulation process

Empty canisters are transported from the canister factory to the encapsulation plant in special transport cases which prevent corrosion during transport. When the canisters arrive at the encapsulation plant, they are checked thoroughly before being allowed to proceed into the encapsulation process.

The existing fuel elevator is used to transport fuel from the storage pools in CLAB to pools in the encapsulation plant. As in CLAB, the purpose of the water in the encapsulation plant is to cool the spent fuel and to shield off its radiation. In the encapsulation plant, the identity of the fuel is first checked by means of a camera. Then the assemblies are transloaded and placed in a transport canister with room for twelve BWR assemblies or four PWR assemblies, which is the same number of assemblies as fit in a disposal canister. During transloading the assemblies may pass a measuring station to verify, for example, burnup and decay heat.

When a transport canister is full, it is taken to a bogie situated in the lower position on a ramp in one of the pools. The bogie with the transport canister is moved up the ramp until the transport canister is above the surface of the water. To protect the personnel from radiation, all fuel handling from this point on takes place behind radiation-shielded walls or using radiation-shielded equipment.

At the ramp's upper position, the transport canister is lifted over to a handling cell. In the cell, the transport canister is placed in a drying position where the fuel is dried by hot air. When the fuel is dry, the assemblies are lifted out and placed in a disposal canister which is docked to another part of the cell. The disposal canister is mounted in a shielded transport frame that is used for moving canisters inside the plant. When the disposal canister is full, a steel lid is bolted onto the insert. The frame is then fetched by a remote-controlled air cushion transporter.

The canister is taken to a station where the leak-tightness of the steel lid is checked and the joint surface is inspected, see Figure 15-9.

At the next station the canister is docked to a vacuum chamber. The air in the chamber is evacuated so that a vacuum is also created in the gap between the copper canister and the cast insert. The copper lid, which has been transported to the station separately, is placed on the canister and sealed by electron beam welding, see Figure 15-9.

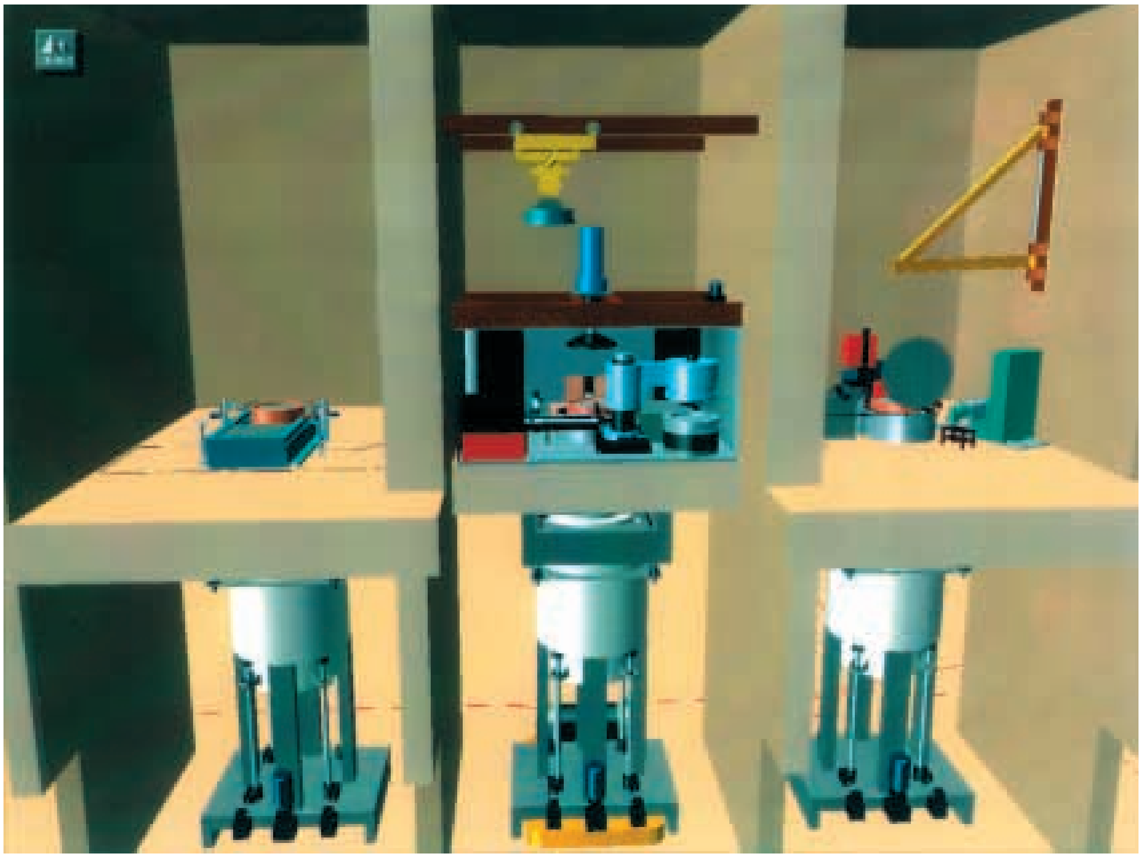

Figure 15-9. *Three stations in the encapsulation plant: testing of the leak-tightness of the insert, welding, nondestructive testing and machining of the weld.*

Machining and nondestructive testing of the weld take place in a separate station, see Figure 15-9. When a canister has been approved in NDT, the weld is finish-machined. Then the canister is transferred to a position where it is lifted up from the transport frame and transferred to the next station. This lift is done by a special canister handling machine, which is also used to place empty canisters in transport frames. The canister is checked in the station by means of smear tests to make sure it is not externally contaminated. The station is equipped with a high-pressure water spray system that is used if the canister needs to be decontaminated.

In the final operation in the encapsulation building, the canister is lifted over to a transport cask. The canister is lowered into the cask, which is then fitted with a lid. The filled transport cask is lifted by an overhead crane to a transport frame located in a transport air lock. The cask is taken out of the plant by a specially-built vehicle. Similar handling of transport casks is done routinely today in CLAB. From the encapsulation building, the canister is taken directly to the deep repository or to a store for full transport casks.

Handling of unapproved canisters

If the weld fails NDT but contains reparable defects, the canister is taken back to the welding station, where it is rewelded. Then the quality of the weld is checked once again. In cases where the weld cannot be repaired by rewelding, the transport frame with the rejected weld is put aside so that it does not obstruct normal production.

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At a suitable opportunity, the canister is transported back to the station for NDT and machining, where the copper lid is cut open by means of the cutting machine. The copper lid is then lifted of in the welding station, after which the canister is transported to the handling cell. There the fuel is transferred to an empty transport canister standing in one of the drying positions.

The canister is decontaminated 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.

Handling of damaged fuel

The cladding on a small number of fuel rods has suffered damage during power plant operation.

It is also possible for fuel to be damaged during transport from the NPPs to CLAB, although this has not happened yet. There are procedures at CLAB for how to deal with fuel damaged in transport.

The fuel assemblies that are damaged during operation at the NPPs and that contain rods damaged in such a way that fuel pellets can fall out of the rods are removed and the rods are subjected to special treatment before transport to CLAB. Fuel assemblies and rod canisters containing rods with less extensive damage are transported to CLAB in cans for leaking fuel. At CLAB the fuel assemblies can either be lifted out of the cans prior to storage or stored in the cans.

The damaged fuel assemblies that are not stored in cans for leaking fuel are handled in the encapsulation plant in the same way as intact fuel. Before being placed in the canister, fuel stored in a can must be lifted out of the can, which is done in the handling cell. A visual check can also be made in the cell to make sure the can is empty after the fuel has been lifted out. The empty can is taken back to CLAB.

15.8.6 Buffer storage of filled canisters

SKB plans to build a buffer store inside the fenced-in area for CLAB and the encapsulation plant where transport casks with finished canisters can be kept while awaiting delivery to the deep repository. The buffer store will be built in sections, where each section consists of a concrete slab in a building that holds about ten transport casks. Building in sections makes it possible to expand storage capacity as needed.

Buffer storage of canisters can also take place in a similar store at the deep repository. This provides greater flexibility and reduces the risk of disruptions if canister deliveries are delayed. The number of transport casks that need to be accommodated in the two stores depends on where the deep repository and the encapsulation plant are sited.

15.8.7 Encapsulation plant co-sited with deep repository

SKB has conducted a feasibility study of a standalone encapsulation plant, separate from CLAB /15-14/. The standalone encapsulation plant is assumed to be located next to the repository's surface facility.

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

The existing CLAB 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 additional equipment.

Technically speaking, good prospects exist for being able to erect an encapsulation plant located on the deep repository site.

Following is a short process description for an encapsulation plant co-sited with the deep repository.

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 transport 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 full the lid is fitted and it is transferred to a cooling cell. The water is drained out and a drying system is connected to the cask. Hot air is circulated through the fuel during the night. The next working day, 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. Only one cask at a time can be unloaded, which takes place in the transport air lock. The cask's shock absorbers are removed and a bottom adapted 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 passage sleeve is removed by the overhead crane in the handling cell. 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 fuel is to be moved to a canister, the canister insert's steel lid is first lifted up by magnets, permitting fuel assemblies to be placed in the canister.

When the canister is full, the steel lid is fitted on the insert. The subsequent operations – lid welding and NDT – are similar to those for the encapsulation plant at CLAB described above.

Development programme

In order to be able to optimize the deep repository, it is important to know with great accuracy what the decay heat from each fuel assembly is before it is placed in a canister for disposal. The total decay heat output in the canister may not exceed the capacity of the surrounding rock to remove it. The surface temperature on the copper canisters in the repository must be below 100ºC, which means that the canisters must be spaced at a certain distance in the repository. If the decay heat is high, or if there is great uncertainty concerning the heat output of the canisters, the canisters must be spaced at a greater distance, which means that the underground portion of the repository must be bigger and more expensive.

This means it is important to be able to determine the fuel's decay heat with high accuracy. The calorimetric decay heat measurements that have been carried out in the existing leak detection equipment at CLAB have proved to have poor reliability. New equipment will therefore be designed and installed in CLAB to obtain decay heat values with better accuracy. The new calorimeter, which will also be augmented by gamma probes for measuring heat losses in the calorimeter caused by unabsorbed gamma radiation, will be commissioned during 2001. A number of measurement series will then be performed on a selection of existing fuel assemblies in CLAB.

The encapsulation process will be further re-assessed, above and beyond the re-assessment of the pool parts that was concluded during 2000, to see whether further improvements can be made. Lessons learned from operation of the Canister Laboratory will also be applied.

Designing of SKB's encapsulation plant has been under way for around ten years now. A number of alternative proposals have been considered during the course of the work. Some have been dismissed, while others have been further developed. A number of important questions have emerged as a consequence of the design work. They will be dealt with in the interim up to the permit application.

In the encapsulation plant being designed by SKB, the welding chamber is designed for electron beam welding. A study will be conducted to evaluate the consequences for the layout of the encapsulation plant if friction stir welding is instead used as a sealing method for canisters.

With reference to SKB's siting work and overall timetable, an application for a permit to build the encapsulation plant should be able to be submitted in 2005. The application will include a preliminary safety report and an environmental impact statement. The plant design on which the application will be based is the result of the aforementioned work.

16 Alternative methods

In practice, we in Sweden have already chosen the strategy of geological disposal of our spent nuclear fuel. We are pursuing a main line with a system based on deep disposal according to the KBS-3 method. Various alternatives to this main line have been described and analyzed in depth /16-1/. 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 the two alternatives Partitioning and Transmutation (P&T) and Very Deep Holes (VDH).

16.1 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 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 e.g. electricity production.

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, i.e. the same way 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, followed by 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 98 and its review

In the review of RD&D-98, Kasam called for an overview of the work situation within partitioning and transmutation.

Newfound knowledge since RD&D 98

Development of P&T involves development of new nuclear technology and requires considerable resources and time.

According to a law from 1991, the French are aiming towards an interim goal in 2006. The costs of the programme are estimated at USD 600 million over 15 years /16-2/.

The Japanese have not released an exact timetable for their programme. The costs are on the order of tens of millions of US dollars per year /16-2/.

In the USA, the DOE presented a "roadmap for developing accelerator transmutation of waste (ATW)" in a report to the US congress /16-3/. This study estimated that the development of a system can be expected to take about 30 years before full-scale transmutation can be commenced in fully tested facilities. Transmutation of all nuclear fuel from existing light water reactors in the USA would in such a scenario then take approximately 90 years. The development costs are estimated at about USD 11,000 million, investments in transmutation facilities at about USD 50,000–60,000 million and annual operating costs at about USD 500 million.

Following the aforementioned study, the USDOE has initiated a programme for development of Advanced Accelerator Applications (AAA). This programme has three lines of development:

- Accelerator-driven transmutation, ATW.
- Continued development of a backup alternative for accelerator production of tritium.
- Scientific and technical development in the accelerator field.

The programme has a 2001 budget of USD 68 million, of which approximately 25 percent is reportedly going to ATW. An important goal is said to be to build an Accelerator-Driven Test Facility (ADTF) for the testing and demonstration of technology that is relevant to transmutation and other advanced nuclear systems. Such a facility may be finished in 2010. The programme does not adhere to the path staked out in the congressional report in terms of either cost, time or content. Instead it seems to take a broader approach and allow more time for the basic studies.

International development

A European working group chaired by Carlo Rubbia presented a report in April 2001 /16-4/ recommending that an experimental facility be built with start of operation in twelve years. The size of the facility is proposed to be 100 MW thermal power. Design studies of such a facility are included in the EU's fifth framework programme. Two variants of the subcritical reactor will be studied: cooling with helium and cooling with liquid lead-bismuth. Both variants are driven by fast neutrons from a spallation source with liquid lead-bismuth. The source is driven by a linear accelerator that produces more than 5 mA of protons with 600–1,000 MeV of energy. In the first phase, the fuel is MOX with approximately 20 percent plutonium. There is a possibility that existing unirradiated MOX from the decommissioned fast reactors SNR and Superphénix can be used. The cost of the experimental facility is estimated at USD 1,200 million up to the time of commissioning. This includes parallel development work in the fuel area, referring to the testing of fuel directly intended for transmutation of all transuranics.

Work on P&T within the EU's research programme has increased considerably in recent years. EUR 4.8 million was spent within this field during the third framework programme 1989–1994, and EUR 5.8 million during the fourth framework programme 1994–1998. Within the current fifth framework programme 1998–2002, EUR 26–27 million has been budgeted for P&T. Strong voices are recommending a further increase during the coming fifth framework programme 2002–2006. But there are also many scientists who are opposed to increased spending on transmutation. The reasons are high costs, limited availability due to the complexity of the process, and certain difficult problems with radiation protection.

The projects that are partially funded by the EU cover the most essential parts of a potential system for partitioning and transmutation, but without actually constituting a coherent programme for the EU. A number of the projects are dominated by national efforts, particularly on the part of the French. One of these projects is the above-mentioned experimental facility. This project is being coordinated by Framatome.

A couple of projects are also under way in Europe to build a spallation source, which is one of the vital components in an accelerator-driven system. There is such a source of solid material – tungsten, which is replaced every year – at PSI in Switzerland. The MEGAPIE project aims to build a source of liquid lead-bismuth with much greater power than now. This project will be a step along the road towards a source of the strength required for a transmutation system. Participants in the project are organizations from Switzerland, Germany, France, Italy and Belgium.

An accelerator-driven facility called MYRRHA is planned in Belgium for research and isotope production. The purpose is to replace the present-day research reactor in Mol. If this comes about, it will be yet another important step in the development of spallation sources.

There are also research programmes aimed at partitioning and transmutation in above all Russia, but also the Czech Republic, Korea and other countries.

Development in Sweden

The Department of Nuclear Chemistry at Chalmers University of Technology (CTH) is developing new water-based partitioning processes. To reduce the quantity of waste from future advanced partitioning processes, the extraction reagent contains only carbon, hydrogen, oxygen and nitrogen (the CHON principle). This makes the reagent completely combustible, which can contribute to reducing the secondary waste, which is a thorny problem in connection with partitioning. The results are published in two doctoral theses /16-5, 16-6/. Chalmers' research on partitioning is also reported in two annual reports for 1999 and 2000 /16-7, 16-8/. Recently a new strategy has been developed for systematically investigating the large quantity of possible reagents that can be synthesized nowadays. It is hoped that this will permit a screening of unsuitable reagents and a focusing on promising reagents, thereby avoiding expensive experiments on substances that later prove to be uninteresting. The results of these studies have been successful. The new strategy will be applied to studies of suitable reagents in the continued development work.

Since May 1996, the Department is also participating in the EU programme "Nuclear Energy – Fission" within the project NEWPART (1996–1999) and its successor PARTNEW (2000–2003). Besides the Department of Nuclear Chemistry at CTH in Sweden, research organizations from France, Italy, Spain, the UK and Germany are also participating in these EU projects. The Department is also cooperating more informally with LANL (USA) and JAERI (Japan).

The research in the field of 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, which is being supported by SKB (since 1993), is focused primarily on neutronics in accelerator-driven systems, burnup calculations, studies of spallation processes (of central importance in accelerator-driven systems), studies of radiotoxicity in substances formed during spallation, and fuel and material studies.

Sophisticated tools for ADS have been developed at KTH in the past few years. These include a new computer program for burnup calculations and a new nuclear database for temperature-dependent simulations of ADS. KTH has contributed to a new nuclear database for neutron energies up to 150 MeV /16-9/.

Important results of the most recent years' studies:

- Plutonium and americium are the substances that are most important to transmute in order to reduce long-lived radiotoxicity.
- Transmutation of plutonium in thermal neutron spectra does not lead to any significant decrease in radiotoxicity.
- Transmutation of plutonium in thermal neutron spectra leads to great problems with alpha and neutron activity from curium and Pu-238.
- Plutonium and americium should therefore be transmuted with fast neutron spectra.
- High concentrations of americium have adverse effects on void and temperature coefficients. Accelerator-driven subcritical systems are therefore more suitable for transmutation of americium.
- If it is possible to achieve a burnup of more than 10 percent and reduce the secondary losses to about 0.1 percent, it may be possible to reduce radiotoxicity in the long term by a factor of 100, which is usually given as a goal.
- The recycling of plutonium and americium from light water reactors in ADS gives rise to problems with reactivity losses, which leads to reduced output of the system and reduced efficiency of the transmutation. One proposal to compensate for this is the use of burnable absorbers /16-10/, another is more frequent refuelling /16-11, 16-12/.
- Sharp reactivity changes in ADS during burnup can lead to safety problems if the system is designed so that it is possible to vary the strength of the proton stream /16-13/.
- If lead-bismuth is used as a coolant, the void coefficient is better than with sodium /16-14/.

The international collaboration at KTH is mainly focused on participation in some EU projects. The institution is coordinator for the EU project CONFIRM, which aims at the design and fabrication of uranium-free nitride fuel and its irradiation in the R2 reactor in Studsvik. Besides KTH and Studsvik, participants in this project include CEA-Cadarache, France; BNFL and AEA, UK; the Paul Scherrer Institute, Switzerland; and the Joint Research Center ITU, EU.

The Department is also participating in the international projects MUSE and SPIRE. The first project involves subcritical measurements at the Masurca reactor in Cadarache, France. The SPIRE project is studying effects of radiation on martensitic steel using mixed neutron and proton irradiation.

KTH, in this case the Division of Nuclear Power Safety, together with the Department of Nuclear and Reactor Physics, is also participating in the EU project TECLA, which is studying technologies, materials, thermal-hydraulics and safety questions for lead alloys (liquid lead and lead-bismuth). This project is not partially funded by SKB, however.

Besides the EU projects, KTH is also involved in a number of projects being conducted within the framework of the ISTC (International Science and Technology Center). This Center is funded by the EU, Japan and the USA, and its mission is to enlist former nuclear weapons scientists in Eastern Europe in peaceful projects. A number of these projects fall within the field of accelerator-driven systems. One such project is manufacture of a spallation source of liquid lead-bismuth at Obninsk in Russia. The source is intended to be tested later by irradiation with protons at a linear accelerator in Los Alamos in the USA. Other ISTC projects of interest in this context are subcritical experiments with thermal neutrons in Minsk in Belarus and with fast neutrons in Dubna in Russia.

The activities at KTH are summarized in two annual reports to SKB /16-15, 16-16/.

A project for measurement of cross-sections for neutrons in the high-energy range 20 to 100 MeV is being conducted at The Svedberg Laboratory (TSL) and the Department of Neutron Research (INF) at the University of Uppsala. This is being used as a basis for designing accelerator-driven systems. SKB is supporting the project, along with SKI, Vattenfall AB and Barsebäck Kraft AB. Furthermore, the EU, the Swedish Defence Research Agency (FOI) and the Swedish Research Council are giving support to the same or similar activities.

The project started in 1998, and has since then grown greatly in scope, mainly because both the project support itself and the activities it funds have been used to attract additional resources. Today, five doctoral candidates and two doctorate-holding researchers are active in Uppsala within or near the project. Moreover, large research groups from Caen and Nantes (France) and Hanover (Germany) are conducting EU-funded experiments in Uppsala with the equipment developed in the project. The ISTC is funding experiments in Uppsala for a research group from St. Petersburg (Russia). Another group from Moscow is preparing experiments.

Nuclear data activities at high energies are being coordinated in Europe by the EU project HINDAS, which includes 16 institutes in seven countries. Uppsala occupies a central position, with a representative in the three-person steering group.

Since 1999, the work has resulted in 26 publications in international journals or proceedings from international conferences. In addition, the group has organized an international symposium and several international meetings. Furthermore, one of the doctoral candidates within the project has obtained his licentiate degree, and the ISTC collaboration has resulted in a doctoral thesis.

Through project, a small research group in basic nuclear physics has expanded to become the largest group in nuclear physics, with a clear focus on energy-related questions. This has led to spin-off effects. Recently a national research school in nuclear technology was formed with a researcher from INF as director of studies.

Physics in general and nuclear physics in particular has had difficulty recruiting doctoral candidates in recent years. This programme, however, has attracted many newcomers. At present, the focus in the project is planned to shift towards understanding the mechanisms behind radiation damage, an area which is of great relevance to all nuclear energy but where surprisingly little is known.

TSL's activities in 1999 and 2000 are summarized in an annual report to SKB /16-17/.

Research programme

The goal of SKB's research on partitioning and transmutation of long-lived radionuclides is to

- Examine how this technology is developing and how it will influence waste streams from nuclear installations and their nuclide content.
- Judge whether, and if so how, this can be utilized to simplify, improve or develop a system for disposal of the nuclear fuel waste from the Swedish nuclear power plants.

Research is 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 other countries. The development of such systems is very costly and highly dependent on international collaboration. SKB further observes that several fundamental technical questions must be further clarified via research before major projects can be defined regarding accelerator-driven systems. 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.

During the coming three-year period, SKB intends to conduct domestic research at universities and other institutions of higher learning 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 outlook 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 get under way.

There is considerable international agreement among responsible organizations and experts to the effect that even a successful development of P&T will not eliminate the need for a deep repository. It may, on the other hand, change the design premises for the deep repository and its barriers, and greatly reduce the quantities of long-lived radionuclides that have to be disposed of in the repository.

The national and international programmes are only in the beginning of their development, and the necessary verifying large-scale trials are still far in the future. A successful development and application of P&T will also require an adaptation of the whole nuclear fuel cycle with respect to recovered uranium. Success in this effort will require extensive international cooperation. For Sweden's part, such cooperation can mainly take place within the EU.

The prospects for an application of P&T differ from country to country. Those countries that reprocess their fuel today – e.g. Belgium, France, Japan, Switzerland, the UK and Germany – have already taken the first necessary step of separating remaining uranium and plutonium. Other countries that have opted for direct disposal – e.g. Finland, Spain, Sweden and the USA – have to abandon this line. In this context it is important to note that the trend today is rather the opposite, i.e. that countries are abandoning reprocessing and relying to an increasing extent on direct disposal. An example is Germany. In view of such factors as time and cost, development and application of P&T is much more likely in a scenario with continued use, renewal and possible expansion of nuclear energy than in the opposite case.

An important question that requires further data and study is how to balance the advantage of reducing a relatively small, perhaps only hypothetical risk far in the future against the disadvantage of greatly increasing the risk of exposure in the present or the near future due to the sharply increased handling of short-lived radionuclides. An optimization of radiation protection in this perspective and in the spirit of the ICRP will probably not be in favour of a far-reaching partitioning and transmutation of all long-lived nuclides.

16.2 Disposal in Very Deep Holes

The alternative of disposing of spent nuclear fuel in very deep boreholes was evaluated in the PASS project /16-18/. The study showed that knowledge of VDH was less than that of any of the other geological methods that were compared. The results of the PASS project and the compilation of geological conditions at great depth that was done later /16-19/ have served as a basis for a report on a research and development programme for the VDH disposal concept /16-20/.

Conclusions in RD&D 98 and its review

In conjunction with the review of RD&D-Programme 98, Kasam expressed wishes for a system analysis and a safety and performance assessment of VDH. Kasam also called for a presentation of the scope and contents of the RD&D programme that would be needed to judge the VDH concept on an equal basis with KBS-3. They wanted to get an idea of time and resources needed for this.

Newfound knowledge since RD&D 98

The Very Deep Holes concept is included in the system analysis that was presented in October 2000 /16-1/.

The study we have conducted /16-20/ shows that it would take about 30 years and cost over SEK 4 billion to raise knowledge of the concept to the level we have today for the KBS-3 method. The geoscientific studies are the time-determining factor for the programme. Development of drilling technology contains great uncertainties and could prolong the total time and further increase the cost.

The areas where the need for research and technology development is greatest are characterization of the bedrock, groundwater flow and chemistry, drilling technology, canister design, deposition technology, buffer design and retrievability.

The study contains five main parts:

- State of knowledge and research programme for geoscience.
- State of knowledge and research, development and demonstration programme for technical questions.
- State of knowledge and research programme for engineered barriers.
- State of knowledge and development programme for safety assessment.
- Timetables and costs.

The geoscientific questions would require drilling of pilot holes to a depth of at least four kilometres on three selected sites. Equipment and methods for measurement and investigation would be developed in these boreholes and on these sites. An active participation in international deep drilling projects would also be necessary.

For technology development and demonstration, one of the sites would have to be selected and an additional two very deep holes at least be drilled. These holes would accommodate up to full emplacement diameter (800 mm) and be used for development of deposition and retrieval technology and equipment.

The engineered barriers and their performance are closely associated with the assessment of long-term safety. High hydraulic pressures, mechanical loads, temperature and salinity make different demands on the engineered barriers than those that apply to a KBS-3 repository. Research and development would be required for design of canister and choice of encapsulation material as well as choice of buffer around the canister. Fuel dissolution at high temperatures and salinities would require work aimed at improving analysis technique and knowledge of how radionuclides occur in such an environment.

All factors considered, there is no evidence today that disposal in very deep holes would increase safety or reduce the cost of disposing of the spent nuclear fuel. SKB does therefore not plan to carry out the RD&D programme for VDH, but instead to concentrate its resources on realizing a repository based on the KBS-3 method in a relatively near future.

SKB will continue to follow developments in the field, since the results and experience obtained can also be beneficial for understanding the conditions in a KBS-3 repository at a depth of about 500 metres.

17 Decommissioning

The owner of a nuclear installation is obliged to ensure that the installation is decontaminated and dismantled to a sufficient extent when it has 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 in 1999, however, planning for a future decommissioning has assumed more concrete forms.

The division of responsibility between SKB and the owner companies is such that SKB carries out general studies to ensure that the necessary technology and competence exists and that the costs are estimated correctly. The nuclear power plants take responsibility for the planning, licensing and execution of the decommissioning of their own facilities. Management of the waste is coordinated with SKB. SKB keeps track of developments in the decommissioning field internationally by participation 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 timetable for decommissioning of the nuclear power plants has not been finalized. SKB's planning is that the NPPs will be operated for 40 years, after which they will be decommissioned and dismantled as quickly as possible. Planning for construction, operation and finally decommissioning of SKB's facilities follows the planning at the NPPs. Other facilities are decommissioned so that they fit in chronologically with these plans. The decommissioning of other facilities is financed outside the Financing Act and not by the Nuclear Waste Fund.

The cost of decommissioning a nuclear power plant has been roughly estimated to be MSEK 1,000 per unit. The total decommissioning cost is estimated to be around MSEK 20,000, including management and disposal of the waste. The cost is updated annually based on accumulated knowledge and experience.

17.1 Decommissioning technology

Experience from decommissioning of nuclear installations has mainly been gained in other countries, but technology studies are also conducted under SKB's auspices. The power companies will also eventually conduct studies for the purpose of planning for the decommissioning of their own facilities. Through the decommissioning projects that have been and are being carried out in various countries it has been shown that technology exists for decommissioning and disposal of the waste from all types of nuclear installations. It remains for SKB to improve and adapt existing technology for decommissioning of the Swedish NPPs.

The technology studies that SKB conducts /17-1/ are aimed at presenting a possible scenario for decommissioning of the Swedish NPPs based on existing technology. 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 should be restored (remediated) so that it can be used without radiation protection for other industrial activities. 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 engineering 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. This provides advantages as regards, for example, availability of special equipment. Furthermore, such cooperation provides access to specially trained personnel and experience feedback. The point of departure for planning is that the power plants are operated for about 40 years and that no unit is decommissioned as long as a nearby unit is still operating. Before decommissioning begins, a final repository for disposal of the short-lived decommissioning waste should stand finished and capacity should exist for interim storage of the long-lived waste. Taken together, this means that the first decommissioning will be commenced some time after 2015. A proposal for the logistics of decommissioning is presented in /17-2/.

The power companies bear primary responsibility for the planning and execution of the physical dismantling work. Their responsibility also includes determining which strategy is to be applied regarding the time for decommissioning and the technology to be used. The power companies can use SKB as a resource in this work. The power companies bear primary responsibility for treatment of the radioactive waste, but management and disposal must 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 adapted and a final repository built. The short-lived decommissioning waste is planned to be deposited in an extension to SFR. The waste that has been close to the reactor hearth is highly neutron-irradiated and is regarded as long-lived. This waste is first placed in interim storage before being disposed of in a repository similar to SFR but at greater depth. This repository can be built adjacent to SFR or the deep repository for spent fuel. Figure 17–1 shows a general timetable for decommissioning and disposal of the radioactive low- and intermediate-level waste.

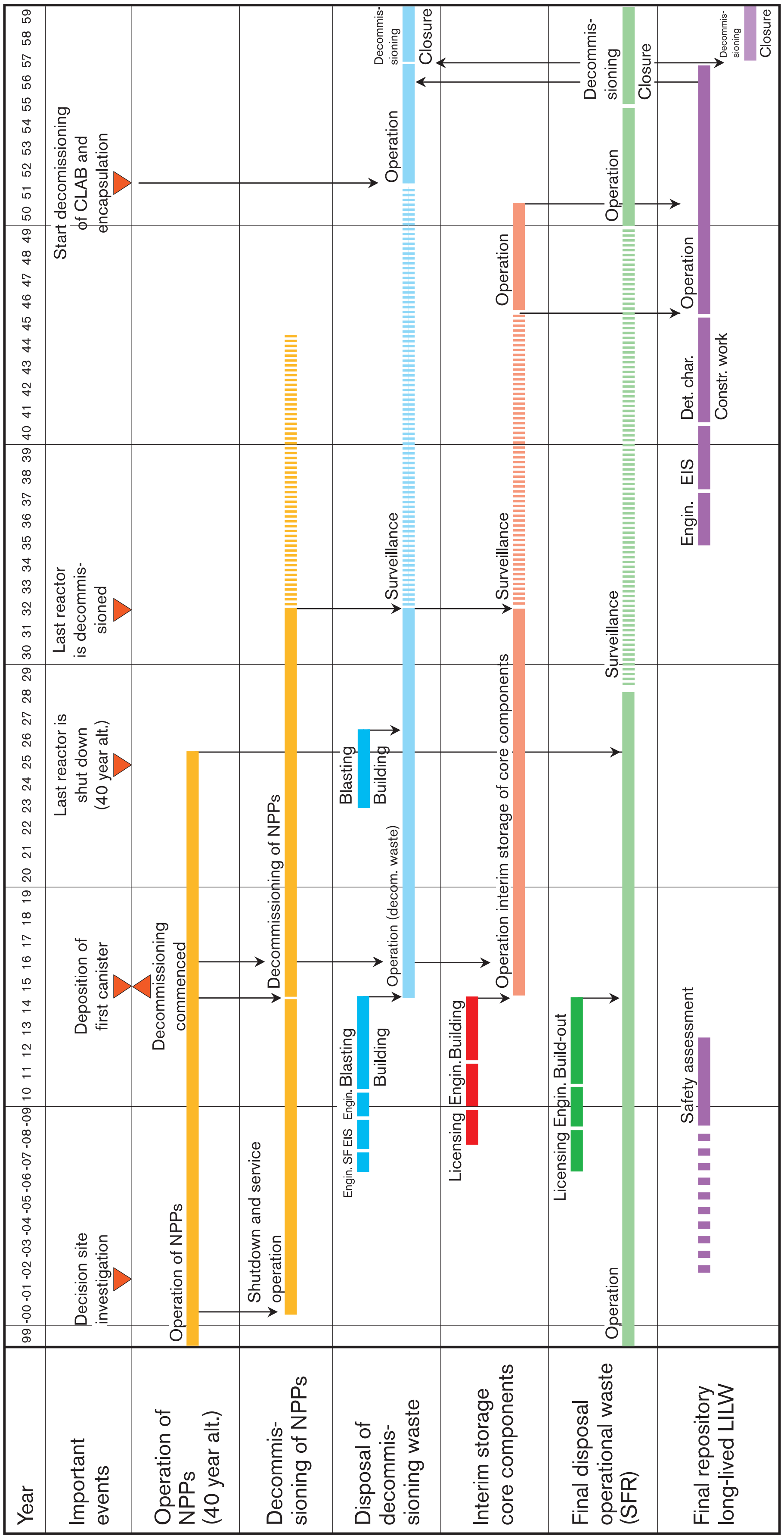

Figure 17-1. *Overall timetable for decommissioning of the NPPs and management and disposal of the low- and intermediate-level waste.*

17.2 Decommissioning logistics

The Swedish NPPs were commissioned during a relatively short span of time (1972–1985). Assuming that the service life of the different NPPs is equally long, they will also be taken out of service over a 13-year period. An exception is Barsebäck 1, which was deactivated (shut down) in 1999 despite the fact that a large portion of the technical life of the plant remained. The technical life of a nuclear power plant is generally put at 40 years. It should be possible to extend this life considerably by means of various measures, but a life of only 40 years is assumed in the logistics studies for decommissioning.

When should a deactivated nuclear power unit be decommissioned? International experience shows a multitude of variants, ranging from immediate dismantling 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, decommissioning is assumed to take place relatively soon after shutdown and removal of the spent fuel.

Dismantling is assumed to take place after a relatively thorough decontamination of the facility's process systems. This is done to reduce the radiation dose to the dismantling personnel. If the plant has low radiation levels from the start, this system decontamination can possibly be omitted. This is a judgement that has to be made for each nuclear power unit from an ALARA standpoint. When the plant is dismantled, it is assumed in SKB's studies that system dismantlement is done first and that it takes at least three years. Dismantlement of the conventional inactive systems and buildings then follows. This is estimated to take about two years. The plant site is then restored to an industrial site for other activities. A total dismantling time of about six years, plus one to two years for removal of the spent fuel, is judged to be the shortest possible decommissioning period.

17.3 Waste management and disposal

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 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 begun yet. For small quantities, rules exist for removal from the NPPs.

The waste that is not released for unrestricted use must be managed in SKB's facilities. 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 dismantlement of the NPPs begins. According to current plans, a final repository for the short-lived waste will be completed by about 2015.

The long-lived waste from decommissioning consists primarily of the reactor internals that were exposed to considerable neutron irradiation during operation. They comprise a small volume (less than 1,000 m^3 for a NPP when packaged), 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 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.

17.4 Current state of knowledge

Decommissioning of large and small nuclear installations is under way all over the world. Quite a few decommissioning projects have been completed and many are under way or planned. Sweden has experience of decommissioning of small research reactors, R1 in Stockholm and a few smaller plants at Studsvik. Decontamination for free release and dismantlement of the active central laboratory ACL is under way in Studsvik. Since experiments have been conducted with alpha-emitting materials in ACL, this will give us experience of decontamination and dismantlement of this type of facility. Major rebuilds and modifications of NPPs have been carried out and will be carried out, see Figure 17-2. These projects give us experience that will prove valuable in the future decommissioning work.

17.4.1 IAEA

Decommissioning has been an active issue with the IAEA since the early 1970s and became a separate programme in 1985. A number of documents of value for planning of decommissioning and disposal of decommissioning waste are available today. The IAEA's definitions of different stages of decommissioning are generally accepted:

Stage 1 Spent fuel removed, systems drained of liquids and operating systems disconnected. Access to the plant is limited and the plant is kept under surveillance and inspected periodically.

Stage 2 Most of the components containing radioactive materials have been collected in a contained space, for example the reactor building. The containment is sealed, reducing the need for surveillance. Areas and buildings outside this containment are released for unrestricted use. The site can be used for other activities with or without dismantlement of buildings.

Stage 3 All radioactive material has been removed and the site has been released for unrestricted use. Released buildings are dismantled or used for other activities. At this level it is also possible to arrange for limited storage of radioactive material within the area with surveillance for a few tens of years.

There are national variants of these definitions. The surveillance period in stages 1 and 2 varies from a few years in stage 1 to about 100 years in stage 2 before final dismantling takes place. The reasons for deferred dismantling/demolition are many: there may be limited capacity for disposal of decommissioning waste, a delay may be desirable to permit the radioactivity to decay, or there may be a lack of money or other resources for dismantlement.

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Figure 17-2. *Replacement of steam generator in Ringhals.*

17.4.2 OECD/NEA

A cooperative programme has existed for 15 years within the OECD/NEA for the exchange of scientific and technical information between ongoing decommissioning projects. Today the programme includes about 30 projects, including decommissioning of ACL in Studsvik. A number of groups have worked and are working with reuse of materials, decommissioning costs and decontamination technique. The purpose of the work of these groups is to gather experience and issue recommendations.

For the future, the work is being focused on achieving more standardized processes for decommissioning and on more general questions such as national and international rules, guidelines and standards.

17.4.3 EU

Historically there have been a number of research projects within the field of decommissioning in the EU. Today, the EU, like the IAEA and the OECD/NEA, deem that techniques for decommissioning and dismantling of nuclear installations are well-developed and that it is their application that can be refined and streamlined today. Research today is rather modest, but there are some decommissioning projects being conducted within the EU that can be of special interest to us in Sweden:

- KRB-A BWR (Boiling water reactor in Gundremmingen, Germany).
- BR-3 PWR (Pressurized water reactor in Mol, Belgium).

Within the fifth framework programme, the EU has decided to support a network of organizations involved in decommissioning of nuclear installations. The goal of the network is to exchange experience between participating organizations. It is furthermore envisioned that the network will disseminate experience and results from the research projects within the decommissioning field that are being conducted under the auspices of the EU.

17.4.4 Development 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 is to begin.
- Perform 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 developments and applying this experience to Swedish conditions, as well as by conducting independent studies and overseeing the rebuilding and repair work being done in the Swedish nuclear installations.

A final repository for the short-lived waste should be ready to receive waste when decommissioning is begun in earnest. The plan is to add an extension to SFR and in this connection license the entire facility for short-lived waste for 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 will therefore study alternative interim storage alternatives.

The main thrust of the work during the upcoming six-year period will be:

- Development of method for dry interim storage of core components and certain reactor internals as an alternative to storage in CLAB.
- Establishment of easily accessible decommissioning records.

- Introduction of system for registration of waste intended for disposal in future repositories (SFR 3, final repository for long-lived low- and intermediate-level waste).
- Estimation of individual doses in connection with decommissioning of NPPs.
- Management of inactive waste (quantities, disposal, reuse).
- Overview of decommissioning logistics.
- Preliminary safety assessments for final repository for short-lived waste (coordination of SFR 1 and SFR 3).

18 Other long-lived waste

Low- and intermediate-level waste (LILW) from research, industry and medicine is packaged at Studsvik and stored in a special rock cavern there. Most of the LILW goes to SFR for final disposal in the same way as operational waste from the NPPs. However, some of the waste at Studsvik contains too much long-lived radionuclides to be accepted at SFR, as the facility is designed today. Such waste is being stored for the time being at Studsvik.

LILW also comes from the NPPs in the form of discarded reactor internals, including core components. This waste is stored today at CLAB or at the NPPs. When the NPPs are decommissioned on a large scale, a common interim storage facility will be needed as an alternative to CLAB. If all long-lived decommissioning waste is to be taken to CLAB, an additional pool must be built. Conditioning and disposal of reactor internals does not have to be commenced until around 2045 at the earliest. If SKB builds the final repository earlier, it must be kept open for a longer time, making it more expensive than interim storage during this period.

Siting of a repository for LILW is thereby a question that does not need to be addressed until around 2035. A final repository for LILW can then be built adjacent to SFR or the deep repository.

A preliminary design of this repository has been studied and a safety assessment has been carried out /18-1/. The work of designing packages and developing methods for handling the waste will continue in the coming years, along with research and development work on the design of the repository and safety assessments.

18.1 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 kept in interim storage in Studsvik in moulds or drums for subsequent disposal. The material from the NPPs is stored today in so-called scrap canisters in CLAB or at the NPPs. The 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 (SFL 3-5) which was carried out the following year /18-1/. 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 m³ for BWRs and 1,800 m³ for PWRs (the volumes are calculated from the outside dimensions of the waste packages which already exist or will be produced).

A system for documentation of the long-lived waste is being developed by SKB. The system will resemble the one for SFR waste, but documentation will also take place progressively. This is occasioned by 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 98 and its review

In its review of RD&D-Programme 98, SKI considered it important that SKB should characterize the uncertainties in the radionuclide inventory in the waste.

Newfound knowledge since RD&D 98

The long-lived LILW will be followed up 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.

18.2 Repository

A new layout was arrived at in 1996 for the preliminary safety assessment of a repository for long-lived LILW that was reported in December 1999 /18-1/. The proposed layout was based in all essential respects on experience from the BMA rock vault, which is a part of the SFR-1 repository for the operational waste from nuclear power. BMA has been in operation since 1988, and was before that subjected to a thorough safety assessment. Two such rock vaults would be needed to accommodate the long-lived waste, which would then be placed in concrete enclosures in a similar manner as in BMA. An important difference, however, is that the rock vaults for long-lived waste would be located much deeper, at least 300 metres below the ground surface. In this way the rock would be utilized better as a barrier and protect the long-lived waste against external forces, while preventing the escape of radionuclides.

By placing the concrete enclosures on packed gravel and finally backfilling the rock vaults with crushed rock, a so-called hydraulic cage is eventually created. This happens when the repository has been sealed and groundwater has filled up all empty spaces. Water is then diverted past the waste enclosures instead of through them. This is because the concrete enclosures are much denser than the gravel backfill; the concrete has a lower hydraulic conductivity.

The enclosures will also be backfilled after completed deposition, but with concrete. This will better enable the enclosures to withstand external mechanical pressure. However, it is important that any gas that may have formed in parts of the waste can easily escape from the enclosures. For this reason the backfill concrete must be porous. This is a similar solution as for the silo in SFR 1, where a special porous concrete is regularly used for backfilling. We have proposed that the same porous concrete be used here as well. Any gas that is formed will then be able to rise through the porous concrete to reach fractures in the rock via the gravel backfill. This prevent gas from accumulating and forming gas pockets that could expel contaminated water.

The draft proposal for a deep repository for long-lived LILW also included utilizing some of the transport tunnels for deposition. Some low-level waste could be emplaced there – particularly waste that arises late, e.g. some decommissioning waste from CLAB.

Conclusions in RD&D 98 and its review

The new layout from 1996 was presented in RD&D-Programme 98. In its review, SKI expressed a wish for a clearer justification of the changes in layout that were made in 1996.

Newfound knowledge since RD&D 98

The changes in layout were mainly justified by purely practical considerations and not least the good experience from construction, operation and safety assessment of BMA in SFR 1. We also wanted to simplify the repository by having as few components as possible and thereby facilitating the assessment of long-term safety. Eliminating bentonite, which was included in the previous layout, was a step in this direction. A third reason was a desire to enable gas to escape more easily from the enclosures /18-2/. Metals in the waste and the steel reinforcing bar in the concrete can give rise to gas through corrosion.

18.3 Safety assessment

A preliminary safety assessment has been conducted of final disposal of long-lived LILW /18-1/. The goal was to evaluate the new design and see what importance the properties of the repository site have for long-term safety. "Preliminary" in this context means that all aspects were not analyzed. This includes, for example, the scenario with a new ice age. The preliminary safety assessment was an early step in the direction towards such a repository, and the results of the assessment will guide the continued development work.

Within the framework of the preliminary safety assessment, we calculated the potential dispersal and impact on the environment of the radionuclides in the waste. Environmentally hazardous substances in the waste such as lead, beryllium and cadmium were also included in the calculations.

The analyses were based on the same hypothetical repository sites as in SR 97, i.e. Aberg (Äspö), Beberg (Finnsjön) and Ceberg (Gideå) /18-3/. In this way we were able to make use of some of the large body of data produced for SR 97. The three sites had different hydraulic properties, which made it possible to see the importance of site selection for this type of repository. For example, the (representative) water flow at Beberg could be assumed to be 1 litre/m^2/year, at Aberg a factor of ten higher and at Ceberg a factor of ten lower. This gave for Beberg a (specific) water flux of 0.01 l/m^2/year in the concrete enclosures and about 30 l/m^2/year in the gravel fill. For a repository at Aberg, the corresponding fluxes were ten times higher, and at Ceberg ten times lower.

By choosing Aberg, Beberg and Ceberg, we were also able to shed light on the importance of releases in different types of areas in the biosphere. The flow paths from the repository discharge into what is classified "archipelago" and "coast" at Aberg, "agricultural land" at Beberg and "peatland" at Ceberg.

A reference scenario was chosen where groundwater enters the repository after closure, but where other conditions remain unchanged. We also studied other scenarios. Climate change, seismic activity and human actions are examples of factors that could affect the future function of the repository. However, the impact on the environment has only been calculated for the reference scenario and for the scenario with a future drilled well in the vicinity of the repository.

Conclusions in the preliminary safety assessment and its review

The primary conclusions from the completed study are as follows:

- The radionuclides in the waste that are of the greatest importance for assessing safety are the ones that are highly mobile and long-lived. The long life means that the barriers and the ecosystems must be regarded on a very long timescale.
- To reduce the uncertainty in calculated environmental impact, we should concentrate on reducing uncertainties in the estimates of the dose-dominant radionuclides Cl-36 and Mo-93. Studies that lead to a greater understanding of their accessibility in the waste, migration in the barriers and dose impact are also of importance.
- The properties of the site are of importance for safety. Two parameters emerge as being particularly important: the water flow at repository depth and the ecosystem in the areas on the ground surface where releases may occur in the future.
- An unfavourably high water flow in the rock around the repository can be compensated for by better barriers in the near field. However, their function must be sustained for a very long time. This requires materials that are durable in the chemical and mechanical environment of the repository.

The preliminary safety assessment has been 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 /18-4, 18-5/. 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 with that associated with the final repository for spent fuel." It is not enough, say the authorities, to refer to the knowledge on SFR, since "the longer time scale imposes greater demands on our level of knowledge, if we are to arrive at reliable assessments of e.g. technical barriers and site-specific conditions (for the repository for LILW)."

SKI and SSI note that according to SKB's plans, the repository will not be sited and built for more than 30 years and that we wish to make use of this time to conduct the necessary research and development.

Regarding new safety assessments, the authorities observe that: "Once the site studies are completed, the time should be right to produce a more comprehensive safety assessment (of the repository for LILW)." SKB concurs. After the site investigations, time and data will be available for a safety assessment, and not least we will have knowledge of the rock as a barrier. The latter is of great importance for this type of deep repository. The fact that the investigations focus on the repository for spent fuel is of no great importance, since basically the same type of site data are needed. The exact point in time for the safety assessment is chosen with reference to other safety assessments and resources, see Figure 18-1.

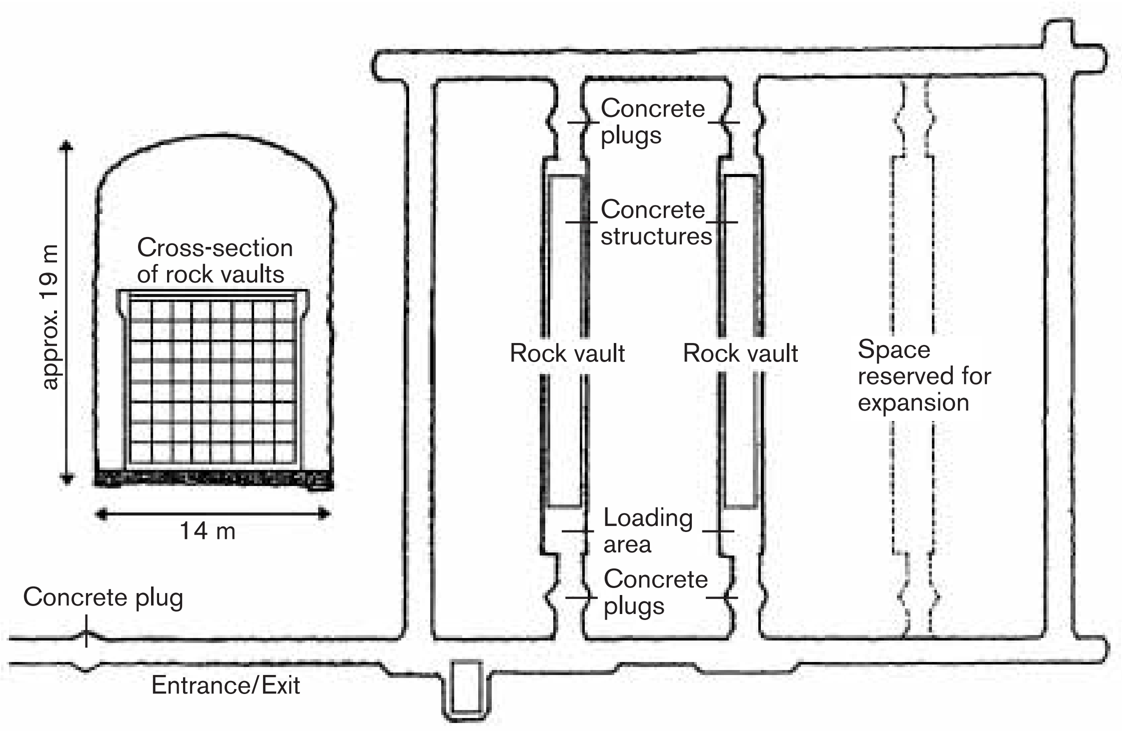

Figure 18-1. *Plan of deep repository for long-lived LILW /18-1/.*

18.4 Research

18.4.1 Focus on long-term safety

The investigations that are being done are mainly aimed at furnishing data and models for assessing long-term safety. The reference scenario in the preliminary safety assessment is essentially based on our sum total of knowledge in this field. This knowledge has been 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 long-term properties of the barriers are the following:

- Corrosion of steel and aluminium (formation of gas and corrosion products).
- Microbial degradation of organic material in the waste.
- Build-up of gas pressure in the waste packages and concrete enclosure.
- Leaching of cement and concrete (high pH).
- Reactions between leaching products from cement and surrounding gravel fill.
- Precipitation of calcite and brucite (i.e. calcium carbonate and magnesium hydroxide).
- Alkaline degradation of cellulose in the waste (formation of complexing agents).

Metal reactor internals form 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, and 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 environmentally 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 presence of organic complexing agents are important parameters.

18.4.2 Newfound knowledge since RD&D 98

Column experiments at BGS

In order to test how rock (including backfill gravel and aggregate) is affected by cement pore water, the British Geological Survey, BGS, in the UK has conducted laboratory experiments in which cement pore water was pumped through columns of crushed mineral. This international project is now concluded. The experiments showed that the rock's minerals react with cement pore water and form e.g. calcium silica hydrates. The secondary products tended to clog the columns. The tendency in water-bearing fractures in the rock is probably the same, i.e. eventual clogging.

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 has been investigated thoroughly in a doctoral thesis at the University of Linköping /18-6/. ISA is formed with high yield (70–85 percent), but the reaction ceases when approximately 20 percent of the cellulose has been broken down. The latter needs to be studied further.

Diffusion of radionuclides and ISA 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 that are sorbed on the concrete are retained. Sorption and diffusion of radionuclides in concrete has been studied in a doctoral thesis at Chalmers University of Technology /18-7/. SKB has also had researchers at the Chalmers University of Technology and the University of Linköping investigate the influence of ISA on diffusion of radionuclides in concrete. An important observation is that ISA itself is strongly sorbed in concrete, which mitigates the effect which complexation with ISA can have on the mobility of the radionuclides. The results also suggest that the complexes are sorbed.

Old concrete

Much of the waste will be enclosed in containers of concrete, and 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 the ingress of groundwater after repository closure, it will retain radionuclides, partly by virtue of its low hydraulic conductivity and partly by sorbing dissolved radionuclides. It is therefore important that the concrete is not altered too much as time passes. It is not so critical if some new cracks should form. 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 not collapse entirely and that its chemical properties are not completely altered.

Water in contact with concrete can 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. An urgent task has been to test these models. Specimens of old concrete that has been in a water-saturated environment have been collected and investigated for this purpose /18-8/. Although none of the specimens is older than 90 years, it is nevertheless possible to follow the changes by means of microscopic examination. The results have been used in the preliminary safety assessment.

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, see Figure 18-2. 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 /18-9/. The results of the project have been used in the preliminary safety assessment, for example the following conclusions:

- 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.

Figure 18-2. *Sampling of colloids under ground in Maqarin, Jordan.*

- The surfaces on water-bearing fractures react with hyperalkaline water, but the porosity of adjacent rock is still available for matrix diffusion of solutes.
- The colloid concentrations are low (as 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.

Experiments in situ

The column experiments conducted by the BGS 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 this will work in an actual repository environment and how it will 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 will be injected in 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 2002. The experiment is being prepared by laboratory experiments and calculations. 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.

18.4.3 Development programme

The overall goals for the period 2002–2007 are to:

- Prepare for future safety assessments.
- Develop handling and storage of the waste.

The experience gained from the preliminary safety assessment has given us valuable guidance for this. We 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 accounts 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, 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 repository is also 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. These include the following:

- Properties of groundwater and concrete in the repository.
- Diffusion and sorption of radionuclides in concrete and rock at high pHs.

- Influence of organic materials (particularly cellulose).
- Corrosion of metals in concrete.

The importance of concrete is emphasized in the team of expert's comments on the preliminary safety assessment /18-4/. One of their viewpoints is that we should particularly examine the influence of saline groundwater on concrete.

In the preliminary safety assessment we used roughly the same model as in SR 97 to calculate transport of radionuclides in the near field. But a more adapted calculation model for LILW would probably have been better. We will investigate what models may be available.

Methods for handling and storage of the waste are being developed together with the NPPs.

The size and layout of the repository will be dependent to some extent on its siting. If it is co-sited with SFR, SFR can be expected to remain open until the final repository for long-lived waste is to be closed. In this situation, all short-lived waste that arises late will be emplaced in SFR. The repository for long-lived waste can then be made smaller.

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Abbreviations

3DEC	Computer code for earthquake-related calculations
AAA	Advanced Accelerator Application
ABACUS	Computer code for strength calculations
Aberg	Hypothetical repository site in SR 97, data from Äspö
ACL	Active Central Laboratory, Studsvik
ADS	Accelerator Driven System (transmutation)
ADTF	Accelerator Driven Test Facility
AEA	AEA Technology, UK
AECL	Atomic Energy of Canada Limited
ALARA	As Low As Reasonably Achievable
ANDRA	Agence National pour la Gestion des Déchets Radioactifs, France
ATW	Accelerator Transmutation of Waste
BARRA	ENRESA project
Beberg	Hypothetical repository site in SR 97, data from Finnsjön
BENCHPAR	Benchmark tests and guidance on coupled processes for performance assessment of nuclear waste repositories, EU project
BET	Method for measuring surfaces (Brown, Emmet, Teller)
BGS	British Geological Survey, UK
BIOMASS	IAEA project (Biosphere Modelling and Assessment)
BIOMOVS	Biospheric model validation study, IAEA project
BIOPATH	SKB's calculation tool for the biosphere
BIPS	Borehole Image Processing System
BMA	Rock vault for intermediate-level waste in SFR 1
BMT	Buffer Mass Test, Stripa
BMWi	Bundesministerium für Wirtschaft und Technologie, Germany
BNFL	British Nuclear Fuels Limited
BWR	Boiling Water Reactor
CAD	Computer Aided Design
CEA	Commissariat à l'Energie Atomique, France
Ceberg	Hypothetical repository site in SR 97, data from Gideå
CHEMLAB	Measurement probe for downhole investigations, Äspö HRL
CHON	Carbon-hydrogen-oxygen-nitrogen compounds
CLAB	Central interim storage facility for spent nuclear fuel
CODE-BRIGHT	Computer code for thermo-hydro-mechanical calculations
COLLOID	Colloid experiment, Äspö HRL
COMP23	SKB's computer code for calculation of radionuclide transport in the near field
COMPASS	Comparison of alternative waste management strategies for long-lived radioactive waste, EU project
CONFIRM	EU project
CRIEPI	Central Research Institute of Electric Power Industry, Japan
CRUD	Chalk River Unidentified Deposits, surface contamination
CTH	Chalmers University of Technology, Göteborg
DECOVALEX	Mathematical Models of Coupled THM Processes for Nuclear Waste Repositories
DUL	Definitive documentation (design)

EBS	Engineered Barrier System
EBW	Electron Beam Welding
ECOCLAY	Effect of cement water on clay barrier performance, EU project
EDF	Ecosystem Dose Factor
EIA	Environmental Impact Assessment
EIS	Environmental Impact Statement
ENIQ	European Network for Inspection Qualification
ENRESA	Empresa Nacional de Residuos Radiactivos, Spain
EQUIP	Evidence from quarternary infillings for palaeohydrology, EU project
EU	European Union
FA 17x17	Type of PWR fuel
FARF31	SKB's computer code for calculation of radionuclide transport in the far field
FASSET	Framework for Assessment of Environmental Impact, EU project
FCC	Fracture Classification and Characterization Project, Äspö HRL
FEBEX	Full-scale Engineered Barriers Experiment in Crystalline Host Rock, Grimsel, Switzerland
FEP	Feature, Events and Processes
FLAC3D	Computer code for earthquake-related calculations
FOI	Swedish Defence Research Agency, Umeå
FSW	Friction Stir Welding
FZK	Forschungszentrum Karlsruhe
GAMBIT	Gas Migration in Bentonite
GEHYC	Included in DarcyTools
GIS	Geographic Information System
GPS	Global Positioning System
GRS	Gesellschaft für Reaktorsicherheit, Germany
HINDAS	High and Intermediate Energy Nuclear Data for ADS Accelerators, EU project
HLW	High-level waste
HMC	Hydro-mechanical-chemical
HMS	Hydro Monitoring System
HPF	High Permeability Features, Äspö HRL
HPF	Hyperalkaline Plume in Fractured Rocks, Grimsel, Switzerland
HPLC	High Pressure Liquid Chromatography
HRL	Hard Rock Laboratory
HYDRASTAR	SKB's computer code for hydrology calculations
IAEA	International Atomic Energy Agency
ICP-MS	Inductively Coupled Plasma - Mass Spectrometer
ICRP	International Commission on Radiological Protection
IJC	International Joint Committee
ILW	Intermediate-level waste
IRPA	International Radiation Protection Association
IRT	International review team, SR 97
ISA	Isosaccharinic acid
ISI	Initial site investigation
ISO 9001	International quality standard
ISTC	International Science and Technology Center
ITU	Institute for Transuranium Elements, Karlsruhe
JADE	SKB project involving comparison of disposal methods
JNC	Japan Nuclear Cycle Development Institute, Japan

KASAM	Swedish National Council for Nuclear Waste
KBS	Kärnbränslesäkerhet = Nuclear Fuel Safety
KBS-3 H	Variant of KBS-3, horizontal emplacement with one canister in each deposition hole
KBS-3 MLH	Variant of KBS-3, horizontal emplacement with several canisters after one another in medium-long deposition holes
KBS-3 V	Reference variant of KBS-3, vertical emplacement with one or more canisters in each deposition hole
Kr-BET	Method for measuring surfaces by adsorption of krypton
KRISTALLIN-I	Swiss safety assessment, 1994
KSU	Kärnkraftens Säkerhet och Utbildning = Nuclear Power Safety and Training
KTH	Kungliga Tekniska Högskolan = Royal Institute of Technology, Stockholm
LANL	Los Alamos National Laboratory, USA
LILW	Low- and intermediate-level waste
LLW	Low-level waste
LOT	Long Term Test of Buffer Material, Äspö HRL
LPT-2	Long Term Pumping Test, Äspö HRL
LTDE	Long Term Diffusion Experiment, Äspö HRL
LWR	Light Water Reactor
M3	Mixing and Mass balance Modelling
MATLAB	Computer code for mathematical calculations
MATRIX	Matrix water experiment, Äspö HRL
MBA	Material Balance Area
MEGAPIE	Megawatt Pilot Experiment, EU project
MICROBE	Microbial experiment, Äspö HRL
MISTRA	Swedish Foundation for Strategic Environmental Research
MLH	Medium Long Holes
MONITOR 2000	SKB's user interface for hydrology calculations and calculations of radionuclide transport
MOX	Mixed oxide fuel
MUSE	EU project involving subscritical accelerator-driven systems
MX-80	Na bentonite of Wyoming type, reference material for the buffer
NAGRA	Nationalen Genossenschaft für die Lagerung Radioaktiver Abfälle, Switzerland
NAMMU	Numeric computer modelling, hydrology
NDT	Nondestructive testing
NEA	Nuclear Energy Agency, Paris
NEWPART	European research programme for minor actinide partitioning, EU project
NKS	Nordic nuclear safety collaboration
NPP	Nuclear power plant
NUCTRAN	SKB's computer code for calculation of radionuclide transport in the near field
OECD	Organisation for Economic Cooperation and Development, Paris
ORIGEN	Computer code for calculation of decay power, radionuclide content, alpha, beta, gamma and neutron source strengths in spent nuclear fuel
P&T	Partitioning and Transmutation
PAGEPA	Paleohydrogeology and Geoforecasting for Performance Assessment, EU project
PARTNEW	Partitioning: New solvent extraction process for minor actinides, EU project
PASS	SKB project, Project on Alternative Systems Study
PGF	Post-Glacial Faulting
PNC	Power Reactor and Nuclear Fuel Development Corporation, Japan
PRISM	Computer code for probabilistic calculations for the biosphere
PROPER	SKB's computer code package for handling of probabilistic hydrocalculations and calculations of radionuclide transport

PSI	Paul Scherrer Institute, Switzerland
P&T	Partitioning and transmutation
PWR	Pressurized Water Reactor
R1	Research reactor on Drottning Kristinas väg in Stockholm
R2	Research reactor in Studsvik, Sweden
RD&D	Research, Development and Demonstration
R&D	Research and Development
REDOX	Large scale redox experiment, Äspö HRL
REE	Rare Earth Element
REX	Redox experiment in detailed scale, Äspö HRL
RVS	Rock Visualization System
SAFE	SKB project, renewed safety account for final repository for operational waste in Forsmark
Sandia	Sandia National Laboratories, New Mexico, USA
SC	Stochastic Continuum
SCE	Standard Calomel Electrode
SEM-EDS	Scanning Electron Microscope – Energy Dispersive
SFL 3-5	Final repository for long-lived low- and intermediate-level waste
SFR	Final repository for radioactive operational waste at Forsmark
SGU	Geological Survey of Sweden
SI	Site investigation
SICADA	SKB's database program for investigation data
SIMFUEL	Synthetic uranium dioxide polycrystalline material
SKB	Svensk Kärnbränslehantering AB (Swedish Nuclear Fuel and Waste Management Co)
SKB91	SKB's safety assessment, 1992
SKI	Statens Kärnkraftinspektion (Swedish Nuclear Power Inspectorate)
SLU	Swedish University of Agricultural Sciences, Uppsala
SMHI	Swedish Meteorological and Hydrological Institute
SPIRE	Spallation and Irradiation Effects, EU project
SR 97	SKB project, safety after closure of deep repository
SSI	Statens Strålskyddsinstitut (Swedish Radiation Protection Institute)
SVEA 96	Type of BWR fuel
SVEA-64	Type of BWR fuel
SWECLIM	MISTRA project, Swedish regional climate modelling programme
TAG	Cooperative programme for exchange of scientific and technical information between ongoing decommissioning projects
TBM	Tunnel Boring Machine
TECLA	Technologies, materials and thermal-hydraulics for lead alloys, EU project
TEF	Technical Evaluation Forum
THM	Thermo-hydro-mechanical
THMC	Thermo-hydro-mechanical-chemical
TRUE	Tracer Retention Understanding Experiments, Äspö HRL
TSL	The Svedberg Laboratory, Uppsala
TWI	The Welding Institute, Cambridge, England
TVO-92	Finnish safety assessment, 1992
UDEC	Computer code for earthquake-related calculations
UPC	Universidad Politècnica de Catalunya, Spain
URL	Underground Rock Laboratory
USDOE	United States Department of Energy
USDOE/CBFO	United States Department of Energy, Carlsbad Field Office

VDH	Very Deep Holes
VLH	Very Long Holes
VSP	Vertical Seismic Profiling
WAWE	Computer code for earthquake-related calculations
WIPP	Waste Isolation Pilot Plant, New Mexico, USA
XPS	X-ray Photoelectron Spectroscopy
ZEDEX	Zone of excavation disturbance experiment, Äspö HRL
α	Alpha radiation
β	Beta radiation
γ	Gamma radiation