

Final Disposal of Nuclear Waste

The Swedish National Council for Nuclear Waste's Review of the Swedish Nuclear Fuel and Waste Management Co's (SKB's) RD&D Programme 2007



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of the Swedish Nuclear Fuel and Waste Management Co's
(SKB's) RD&D Programme 2007*

*The Swedish National Council
for Nuclear Waste Report*

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To the minister and head of the Ministry of the Environment

The Swedish National Council for Nuclear Waste's Review of the Swedish Nuclear Fuel and Waste Management Co's (SKB's) RD&D Programme 2007 – Programme for research, development and demonstration of methods for the management and disposal of nuclear waste

One of the tasks assigned to the Swedish National Council for Nuclear Waste is (see Dir. 1992:72) to give the Government its independent assessment of the RD&D (research, development and demonstration) programme which the Swedish nuclear power companies are supposed to submit every three years via SKB (the Swedish Nuclear Fuel and Waste Management Co). According to the Act (1984:3) on Nuclear Activities, this programme shall describe the comprehensive research and other measures that are needed for safe management and disposal of the waste and for decommissioning and dismantling of the nuclear power plants.

RD&D Programme 2007 covers SKB's plans for the period 2008–2013, including more detailed account of the issues that will be addressed by 2010. In 2010, SKB intends to submit applications under the Environmental Code (1998:808) and the Nuclear Activities Act for a final repository for spent nuclear fuel.

This report is the Swedish National Council for Nuclear Waste's statement of opinion to the Government on RD&D Programme 2007. The Council's assessment is that the reactor owners have, via SKB's RD&D Programme 2007, fulfilled the

requirements in Section 12 of the Nuclear Activities Act. However, the Council has in its review identified a number of questions and deficiencies which we present in the report.

All members of the Council – Hannu Känninen (expert), Björn Hedberg (director) and Eva Simic (secretary) – stand behind the Council’s review. In addition, the following persons have contributed to the review work: Sören Mattsson (biosphere), Per Möller (climate evolution), Pekka Särkkä (rock engineering and geotechnology), Sören Norrby and Olof Söderberg.

Stockholm, June 2008

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1 Swedish National Council for Nuclear Waste's summary assessment

1.1 Overall assessment

The Swedish National Council for Nuclear Waste finds that RD&D Programme 2007 fulfils the requirements set forth in the Nuclear Activities Act. However, the Council has in its review identified a number of questions and deficiencies to which the Council wishes to draw attention and which are presented in sections 1.2 and 1.3.

SKB's applications under the Nuclear Activities Act and the Environmental Code for the final repository for spent nuclear fuel are planned for mid-2010, a few months before SKB submits RD&D Programme 2010. Based on their review of RD&D Programme 2007, it is the Council's opinion that a great deal of research and development remains to be done in order for SKB to be able to submit complete applications under the Nuclear Activities Act and the Environmental Code.

1.2 Questions of particular importance

Unclear points regarding buffer, backfill and closure

The Swedish National Council for Nuclear Waste finds that there are many unclear points regarding buffer, backfill and closure at this stage in SKB's programme.

- The most important properties of the buffer material should be specified and limit values should be determined with respect to swelling potential, retention capacity for radionuclides, chemical stability, hydraulic diffusion, resistance to erosion and level of impurities (inorganic as well as organic).
- Mechanical strength and chemical stability must be guaranteed for compacted components in the buffer.
- Models should be set up for transport of the most important radioactive isotopes (with positive and negative charge) through the bentonite.
- The final choice of materials and method for backfilling must be ready by the time the application to build a final repository is submitted. SKB must also be able to show that the buffer and backfill conform to the initial states assumed by the safety assessment.
- Special research is required on the interfaces between backfill and buffer and between backfill and rock.
- SKB needs to consider the problems that can arise during the expected climate change (due to the greenhouse effect), for example higher levels and flows of groundwater as well as altered water chemistry and higher sea levels, probably already during the construction period.
- The final design of the closure should be determined by the properties of the rock with respect to e.g. fractures at different depths and salinity. However, this presumes knowledge of what properties different materials – and mixtures of materials – have and how they can interact to best effect.

The Council wishes to emphasize the importance of clarifying these unclear points in time for the upcoming applications.

Site selection

The Swedish National Council for Nuclear Waste considers it imperative that SKB give a clear account of the judgements underlying site selection. Since long-term safety is the most important factor in site selection, the Council finds that the safety arguments underlying site selection must be based on two comprehensive safety assessments (i.e. two SR-Sites): one for Forsmark and one for Laxemar. The Council thereby wishes to

emphasize the importance of making a scientifically correct comparison between the sites prior to final site selection.

The Council is troubled by the fact that successful rock stress measurements performed so far in Forsmark are too few in number and uncertain at planned repository depth. The far-reaching conclusions drawn from the results can affect both site selection and the design and construction process, as well as in the longer term the durability of the repository. The Council therefore considers it imperative that existing knowledge of the rock stresses, particularly at repository depth in Forsmark, be considerably improved before a final choice of site is made. However, results that could clarify certain uncertainties have reportedly not yet been published.

A coherent programme for monitoring of the repository area and the surrounding environment must be presented – and promptly implemented – both for the period before and during the construction phase and for the post-closure period.

Safety assessment

SKB's safety assessments should show that the final repository system fulfils the regulatory requirements on long-term safety. The Swedish National Council for Nuclear Waste would also like to emphasize the internal role of safety assessment within SKB as a tool for both following up repository safety during construction and operation and providing guidelines for technology development and research.

SKB therefore needs to ensure and show that feedback and information sharing between different parts of SKB's organization works, for example feedback from safety assessment to research programmes, programmes for detailed investigations and technology development.

1.3 Other conclusions

Systems analysis

- An important purpose of a systems analysis is to describe and explain which parameters can or should be kept open for modification and improvement (i.e. how much flexibility should

exist and can be accepted in SKB's programme), and when decisions must be made to finalize these parameters. An example is to what degree the most important properties of the buffer material should be specified at the application occasion. Another example is how a possible switch from the KBS-3V concept to the KBS-3H concept might occur in the future.

- The Swedish National Council for Nuclear Waste finds that systems analysis methodology is valuable as part of a learning process that is controlled by the stakeholders and that involves analysis from new angles and adjustment of the system boundary in a dialogue with the central actors.

Account of alternative methods and designs

- The Swedish National Council for Nuclear Waste believes it to be of great importance for confidence in SKB's work that a coherent and clarifying account be given of alternative methods for the final disposal of spent nuclear fuel. SKB should present such an account not later than in conjunction with the company's permit applications under the Nuclear Activities Act and the Environmental Code. The Swedish National Council for Nuclear Waste believes that SKB should in this account clearly explain its positions on the deep borehole concept. In this context, SKB should also explain its plans for KBS-3 with horizontal deposition (KBS-3H).

Canister

- The material and casting process for the nodular iron insert must be optimized so that specified requirements can be met. Otherwise some other type of material must be used.
- In order to guarantee reliability during canister fabrication and final disposal, quality requirements must be developed with respect to fabrication defects in all parts of the canister, including welds. These criteria should take into account material structure, material properties and defects in both the copper shell and the cast iron insert. The quality requirements must be verified by methods for nondestructive testing (NDT).

- Continued corrosion studies are required in different areas: accelerated long-term stress corrosion cracking experiments, general corrosion in -chloride- and sulphide-containing water with bentonite, and microbial corrosion, as well as possible corrosion in oxygen-free water.

Geosphere

- Improved knowledge is needed of rock stresses at planned repository depth in Forsmark. General studies should be conducted regarding what effect existing and altered rock stresses may have on hydraulic conductivity in fractures in different directions and the consequences for the detailed design of the repository. Furthermore, measurements of possible rock movements in both Forsmark and Oskarshamn should continue for a period during the processing of the site application and then on the selected site for an extended period during construction and operation of the repository.
- Additional R&D on grouting for sealing of fractures is necessary. A timetable should be given for different steps in this R&D programme.
- A better account should be given of the extent and properties of the excavation-damaged zone in conjunction with controlled blasting, along with an explanation of why full-face boring has been abandoned.
- Additional aspects of changes associated with an open repository should be examined, such as changes in groundwater chemistry, "short-circuiting", i.e. interconnection of different groundwater-conducting zones, and altered rock stress conditions.
- The altered hydrological, hydrogeological and hydrochemical conditions associated with expected climate change should be modelled. Continued modelling should be done of transport and hydrochemistry in the near-surface groundwater and in the interface zone between geosphere and biosphere, taking into account different climate scenarios.

Biosphere

- SKB must show more clearly how the results of the biosphere work are integrated in the safety assessment and the EIA process and what importance the biosphere will have for siting.
- SKB should conduct sensitivity analyses of the modelling results regarding the biosphere.
- SKB should prepare a programme for modelling of conditions in connection with expected climate change.

Climate evolution

- SKB's climate research should be developed according to three time scales: the next 100 years, the subsequent 1,000 years and the 100,000 years following that.
- The results obtained must be taken into account in the planning, design and construction of the final repository. As pointed out at various places in the review report (see Chapters 9, 10 and 12), new knowledge concerning climate change has not always been taken into account.

Retrieval

- SKB's level of ambition in shedding light on possibilities and risks with retrieval is satisfactory.

Societal research

- The social science research programme should be supplemented by studies of future economic consequences of the handling of the nuclear waste issue, mainly cost-benefit analyses. This is needed in order to judge what societal resources are needed for alternative solutions.
- We consider research projects on global changes and safety culture (see point 2 in section 14.2 for details) to be a very urgent research field, since such research can shed light on the social barrier for safety in the final disposal solution.
- SKB's social science research programme should continue after an application has been submitted in 2010 and be developed in a

similar manner as the RD&D programme for natural science and technology.

LILW and decommissioning

- SKB should specify when different facilities can be decommissioned and give reasons for this. The desire for immediate dismantling can be evaluated in relation to the need to have final repositories ready to receive decommissioning waste before the dismantling work is begun. The Swedish National Council for Nuclear Waste therefore believes that there is a need for a systems analysis encompassing all the facilities and activities covered by SKB's account of LILW and decommissioning.
- Questions concerning the decision process for decommissioning and management of the waste need to be studied. The need for environmental impact assessments of decommissioning of nuclear power plants should be illuminated. The implications of current EU directives and provisions of the Environmental Code need to be clarified prior to decommissioning of nuclear power plants.
- The Swedish National Council for Nuclear Waste wishes to emphasize the importance of a transparent decision process with regard to decommissioning and dismantling where the municipalities are invited to participate in the dialogue.

2 Points of departure for the Swedish National Council for Nuclear Waste's review of RD&D Programme 2007

Society's requirements on the safe management and final disposal of spent nuclear fuel and the decommissioning of the nuclear facilities have found expression primarily in the Nuclear Activities Act from 1984, in SKI's and SSI's regulations, and in the Environmental Code. (A general description of the Swedish nuclear waste programme is provided in Appendix 1.)

The review of SKB's RD&D Programme 2007 which is now being presented by the Swedish National Council for Nuclear Waste involves a judgement of whether RD&D Programme 2007 fulfils the requirements set forth in the Nuclear Activities Act. The Council also passes judgement on whether SKB's description of completed, ongoing and planned work with research, development and demonstration appears convincing, as well as whether this work has good prospects of leading to the fulfilment of society's requirements on above all the safe final disposal of the high-level waste (the spent nuclear fuel) from the Swedish nuclear power programme.

SKB plans to apply in mid-2010 for permits under the Nuclear Activities Act and the Environmental Code for a system for final disposal of the spent nuclear fuel. These applications will pertain to a final repository according to the KBS-3 method that is assumed to be located at one of the two sites that have now been investigated: near the Forsmark nuclear power plant or at Laxemar, a couple of kilometres from the Oskarshamn nuclear power plant.

SKB further assumes that RD&D programmes will continue to be published every three years.

The Swedish National Council for Nuclear Waste thus notes that RD&D Programme 2007 is the last RD&D programme before SKB submits its applications. The Council has had this as a point of departure in its review and focuses its review on the issues deemed to be critical at this juncture.

An important step in the preparations is the scrutiny of different issues carried out by the Council in recent years. This scrutiny has mainly taken place at the following seminars and hearings:

- Nuclear waste – What alternatives for method and site should be presented? (February 2006, see Report 2006:1, in Swedish only).
- Final disposal of spent nuclear fuel – regulatory system and roles of different actors during the decision process (November 2006, see Report 2007:1e).
- Deep boreholes – An alternative for final disposal of spent nuclear fuel? (March 2007, see Report 2007:6e).
- Decommissioning of Nuclear Facilities in Sweden (December 2007, see Report 2007:7e).
- System analysis for final disposal of nuclear waste (April 2008, Report 2008:1, to be published later this year in Swedish only).
- Site selection for final disposal of nuclear waste – on what grounds? (June 2008, Report 2008:2e, to be published later this year).

3 System analysis

3.1 Background

Over the years, the Government, the regulatory authorities (SKI and SSI) and Oskarshamn Municipality have imposed requirements on SKB regarding system analysis. For their part, SKB has on a number of occasions presented system analyses, both on a general level regarding choice of strategy for management of the spent nuclear fuel (e.g. SKB Report R-00-32) and on a more detailed level regarding the KBS-3 method (e.g. SKB Report R-00-29 and R-06-117).

In its decision on RD&D Programme 1995, the Government formulated the requirement that SKB “shall, in its further research and development work, carry out a system analysis of the entire final repository system (encapsulation plant, transportation and final repository). This system analysis shall permit an overall safety evaluation of the entire final repository system, including how principles for safety and radiation protection should be applied in safety assessments.”

In connection with several RD&D reviews, the regulatory authorities have stated that SKB must give a systematic account of its choice of method, alternative solutions, different detailed designs of the applied-for alternative, and how the different parts of the system are interconnected. The regulatory authorities have also requested a connection between system analysis and assessment of long-term safety.

Prior to the start of the site investigations, Oskarshamn Municipality stipulated 13 conditions in a decision of the municipal assembly on 11 March 2002. One of these concerns system analysis and reads: “SKB’s system analysis has not yet lived up to the

regulatory authorities' requirements and the municipality's expectations, since it has been more of an account of the different parts of the system than a true analysis of the whole. For Oskarshamn, SKB's future accounts must cover an entire final repository system with Clab, encapsulation, transportation and final disposal, and how they are all connected."

In the current situation, however, the regulatory authorities and SKB agree that a separate system analysis is not necessary, since the regulatory requirements are now formulated in regulations and recommendations/guidelines (see notes from the regulatory authorities' consultations with SKB on system analysis and safety assessment, 11 May 2007).

The Swedish National Council for Nuclear Waste notes that SKB has chosen not to discuss system analysis in RD&D programme 2007. However, the Council believes it would have been appropriate for SKB to explain in the context of its RD&D programme why the system analysis is no longer needed so that the Government can decide whether the requirement they stipulated in the decision regarding RD&D Programme 1995 has been satisfied.

3.2 System analysis – process and product

In order to clarify the possible role of the system analysis in connection with SKB's future permit applications, the Swedish National Council for Nuclear Waste held a hearing this last spring on the role of the system analysis¹. The judgement of the Swedish National Council for Nuclear Waste is that a system analysis (regarding a final repository system for nuclear waste) should be regarded as a process as well as a product:

If any actor (the Government, a concerned authority or municipality, or SKB themselves) wants to get anything specific out of a systematic analysis of a final repository system, a dialogue needs to be held regarding *what system or subsystem* is to be analyzed, and for *what purpose or purposes* (e.g. cost analysis, material flows, municipal perspective, radiation protection requirements etc.). This naturally means that the actor in question must be able to clearly define his demands and expectations in this regard.

¹ Hearing on 24 April 2008 on system analysis for final disposal of nuclear waste, Näringslivets Hus, Stockholm

Accordingly, system analysis can be regarded as a process that proceeds continuously throughout the final repository programme. The work may sometimes be put on hold, but it must always be possible to reactivate the process if one or more actors bring up new, relevant questions. At such a time, the goal of the system analysis is to deliver a product that proposes solutions to the new questions. It would be naive to believe that a system boundary and purpose could be defined once and for all. Instead, the system analysis should be regarded as a valuable part of a learning process that is controlled by the stakeholders and that involves analysis from new angles and adjustment of the system boundary in a dialogue with the central actors.

System analysis as a process² can be described as a “Stakeholder model” or “Flower model”. The system’s stakeholders are grouped like the petals of a flower around the analysis of the system in question. A large part of the stakeholders’ system lies outside the current system boundary. New stakeholders/actors and activities outside the system bring up new questions that require revision of the system boundary and analysis from new angles. In this view, the System Analysis is a learning process that is controlled by the stakeholders and driven forward by what lies outside the system.

Figure 3.1 provides a general and simplified description of a process for selection of strategy (with alternatives), and selected method, with variants, that has led to the selected method, KBS-3.

² The CATWOE model described in Appendix 4 develops the “flower model” with identification of different types of stakeholders and their purposes and world views

Figure 3.1. Process for selection of method for final repository system

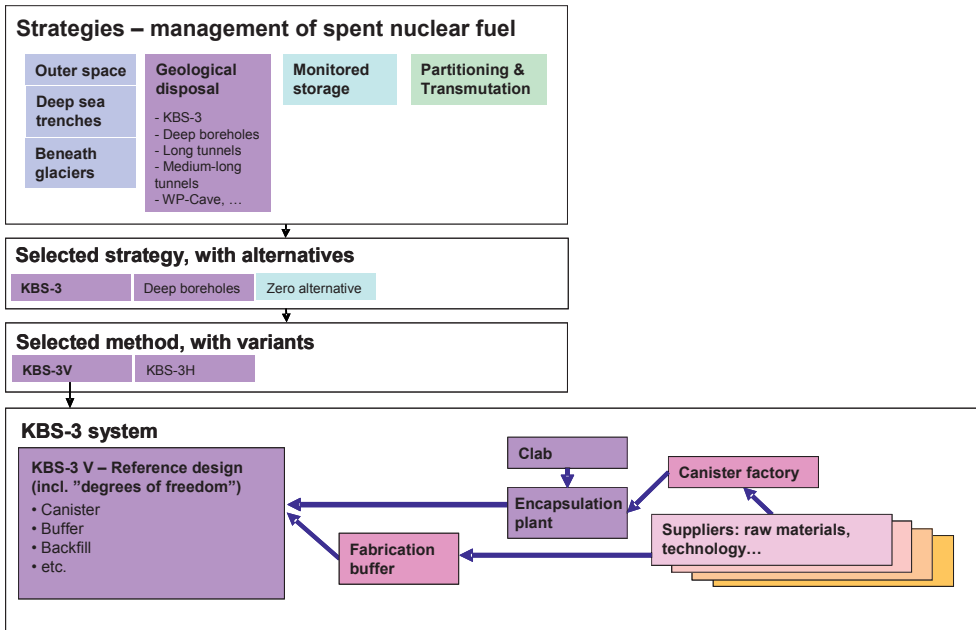
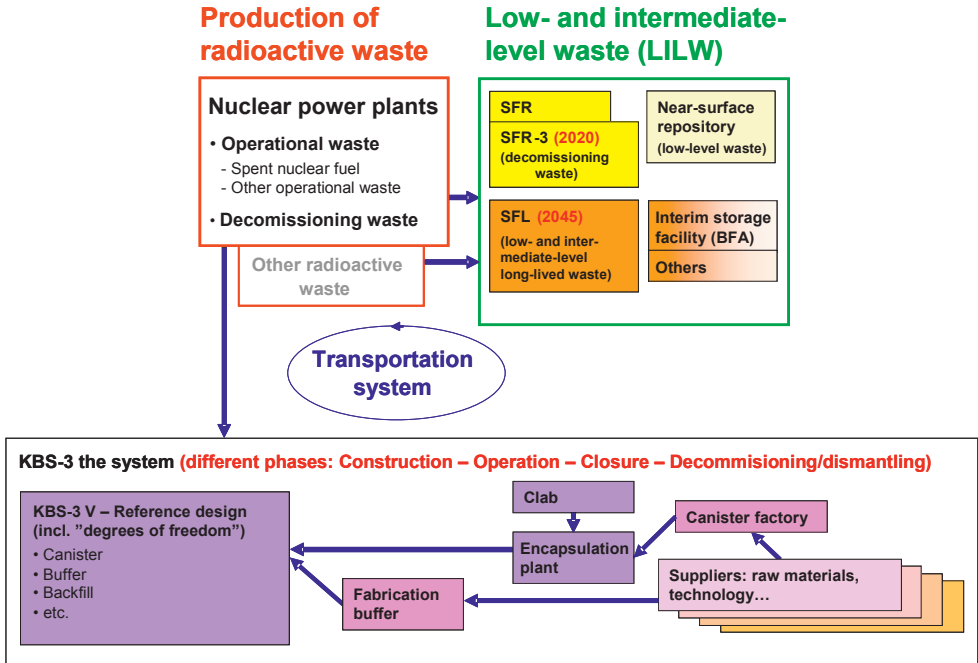


Figure 3.2 provides a general and simplified description of the system for production of radioactive waste connected to a final repository system according to the KBS-3 concept.

Figure 3.2 System for management of radioactive waste



Another purpose of a system analysis can be to describe and explain the system's *degrees of freedom*, i.e. what parameters could or should be kept open for modification and improvement, and when a decision should be made to finalize them. Examples of such degrees of freedom in SKB's final repository programme are:

- The canister; grade of iron used in the canister insert
- Reference material for buffer
- Reference material for backfill
- Reference material for closure
- Variants of KBS-3 such as KBS-3H (horizontal deposition of canister)
- Possible interim storage facility for the LILW system

With regard to KBS-3H, SKB has announced that they plan to develop this alternative design of the KBS-3 system to a level equivalent to that of KBS-3V (vertical deposition) by around 2012, i.e. about 2 years after SKB plans to submit applications for a final repository system.

3.3 Swedish National Council for Nuclear Waste's conclusions

- An important purpose of a system analysis is to describe and explain which parameters can or should be kept open for modification and improvement (i.e. how much flexibility should exist and can be accepted in SKB's programme), and when decisions must be made to finalize these parameters. An example is to what degree the most important properties of the buffer material should be specified at the application occasion. Another example is how a possible switch from the KBS-3V concept to the KBS-3H concept might occur in the future.
- The Swedish National Council for Nuclear Waste finds that system analysis methodology is valuable as part of a learning process that is controlled by the stakeholders and that involves analysis from new angles and adjustment of the system boundary in a dialogue with the central actors.

4 Account of alternative methods

In this chapter the Swedish National Council for Nuclear Waste gives its viewpoints on SKB's work regarding both alternative *methods* to the KBS-3 concept and the alternative *design* (variant) of KBS-3 with horizontal deposition (KBS-3H).

4.1 Strategic choices of method

In 2001 the Government decided that SKB “should use the KBS-3 method as a planning premise for the site investigations carried out in Forsmark and Laxemar. In that context the Government emphasized “that final approval of a specific method for final disposal cannot be given until a decision is made on applications under the Environmental Code and the Nuclear Activities Act for permits to build a final repository for spent nuclear fuel.” The Government has also recommended, in various contexts and most recently in its decision in 2005 regarding SKB's RD&D Programme 2004, that SKB should continue to keep track of technology development regarding different alternatives for managing and disposing of spent nuclear fuel.

The review of SKB's RD&D Programme 2004 led the Swedish National Council for Nuclear Waste to the following conclusions in the matter of alternative methods for final disposal of spent nuclear fuel (SOU 2005:47, p. 144):

- With present-day knowledge of possible alternatives to the KBS-3 method, there are strong reasons to continue current research and development work focusing on direct disposal in accordance with the KBS-3 method. In KASAM's view, it is not acceptable to postpone the Swedish final repository programme with reference to alternative methods as possible technologies.

- It is urgent that SKB study alternative methods that can be expected to be technically feasible and that this can be shown in connection with the environmental review.

The Swedish National Council for Nuclear Waste notes that SKB has chosen in RD&D Programme 2007 not to discuss in any coherent fashion the possible merits of other alternatives than the KBS-3 method. SKB gives an account of its work on the alternatives issue on pages 395–406, and it is evident from the programme (p. 406) that SKB intends to give an account of its reasons for its assessment of the deep borehole alternative not later than in conjunction with future applications for permits for a final repository according to the KBS-3 method.

The Swedish National Council for Nuclear Waste assumes that SKB will, in such an account, give a thorough and clear explanation of the considerations that have led to the selection of the method and the pros and cons of the alternative methods that have been considered. The Council considers such an account to be of great importance for instilling confidence in SKB's work in the various authorities and others who participate in the examination of the applications in question as well as in the general public.

4.1.1 Partitioning and transmutation (P&T)

The Swedish National Council for Nuclear Waste finds that adequate resources are being devoted to work in the field of partitioning and transmutation. The Council concurs with SKB's assessment that transmutation presumes that Sweden makes a much more long-term commitment to nuclear energy than is currently the case. However, the Council also notes that even this technology leads to long-lived waste, although in smaller volumes.

4.1.2 Deep boreholes

SKB has made the judgement in RD&D Programme 2007 that there is no reason to conduct a research programme for deep boreholes. The judgement is based partly on SKB's own studies from the early 1990s, and partly on studies SKB commissioned during the period 2000–2006.

In the middle of 2006, the Swedish NGO Office for Nuclear Waste Review published a study about final disposal of high-level nuclear waste in deep boreholes (MKG-Rapport 1, in Swedish only). The study asserts that “new knowledge and findings within hydrology and drilling technology have increased the opportunities for using deep boreholes for final disposal of the Swedish nuclear waste” (p. 24). The author’s main thesis is that a more thorough analysis is required before the deep borehole concept can be dismissed from further discussion. Among other things, it must be clarified whether the hydrogeological prerequisite for the concept exists, namely that there is groundwater at a depth of 3–5 km in Swedish bedrock that is sufficiently stably density-stratified.

The discussion in the mass media and elsewhere of the possible need for further research and development on the deep borehole alternative led to a decision by the Swedish National Council for Nuclear Waste to arrange a special hearing on the topic in March 2007. Experts not affiliated with SKB in areas such as drilling technology and hydrogeology were engaged for presentations and were questioned along with representatives of SKB, the Swedish Nuclear Power Inspectorate, the Swedish Radiation Protection Authority and environmental organizations. The purpose was to shed further light on the feasibility and pros and cons of this alternative.

It emerged that the prospects of overcoming the drilling-related difficulties are now better than previously judged. However, extensive and costly development work is required. SKB’s view at this time was that even if the drilling-related technical problems can be solved, this does not alter the weaknesses of the concept when it comes to long-term safety.

In the Swedish National Council for Nuclear Waste’s report from the hearing (Report 2007:6e), the Council presents a number of reflections on the arguments that were offered by various parties, above all by SKB and the environmental organizations. The Council finds that the following quote from the report (p. 92 ff.) is also valid in the context of this review:

If, as SKB claims, deep borehole disposal has serious inherent fundamental disadvantages that cannot be altered by more research, it is only logical to minimize such unnecessary costs. The question is, however, whether these disadvantages (e.g. reduced reparability during the operating period, reduced adaptability to geological conditions on the site, deviation from the multiple barrier principle) are actual

disadvantages for all actors or for society as a whole, or whether they serve as arguments for SKB's intentions. It is also, as SKB's representatives expressed it, a question of how far SKB can be expected to pursue an alternative method that they don't believe in. Those who, on the other hand, advocate more research, including drilling of one or more deep holes, need to define what the purpose would be. Is it just to find out what the groundwater conditions are at great depths, or to find out if it is technically possible to drill holes of the size required? What do we do if we get positive answers to these questions? Arguments are offered in this question as well that appear to rest on different judgements of what is possible to do. SKB does not believe drilling a few test holes will permit a better assessment of safety, while Åhäll¹ and MKG are more optimistic about the possibilities of obtaining the relevant information.

Gunnar Nord² says that it is the nuclear power industry itself that has to pursue and pay for the technology development that is required. Questions that were discussed during the question-and-answer session and that need to be answered if society wants to go further with deep boreholes are therefore who should conduct further R&D, and how this research and technology development is to be financed.

As noted in the report on the state-of-the-art in the field of nuclear waste submitted by the Council to the Government in June 2007 (SOU 2007:38), the Council's conclusion after the hearing on deep boreholes (p. 46–47) is “that there does not appear to be any available technology (in the sense of the Environmental Code) for disposal in deep boreholes, and that such technology cannot be expected to become available within the timespan of the planned decision process.” However, both drilling technology and sensor technology have been developed during the past 10–15 years. The Council therefore believed “that very good reasons exist for SKB to clearly present and explain its standpoints regarding the deep borehole concept” both in RD&D Programme 2007 and in the upcoming applications for permits under the Environmental Code and the Nuclear Activities Act to build a final repository for spent nuclear fuel.

The Swedish National Council for Nuclear Waste now notes that SKB has chosen in RD&D Programme 2007 not to reproduce or comment on the discussions that were held at the aforementioned hearing and has not in any other way to date presented a thorough comparison of the KBS-3 method and deep boreholes. However, it is evident from the programme (p. 406)

¹ Karl Inge Åhäll is the author of MKG-rapport 1, mentioned in the text.

² Gunnar Nord is a drilling expert associated with Atlas Copco.

that SKB intends to report the reasons for its assessments “prior to the submission of an application for the final repository system” at which time they will present a general comparison between the KBS-3 method and deep boreholes. According to SKB, such a comparison will concern six aspects, namely (1) premises for siting as well as characterization and selection of repository site, (2) current drilling technology and its potential for development, (3) premises for construction, operation and closure, (4) nuclear safety in connection with the handling of encapsulated spent nuclear fuel, (5) physical protection and safeguards, and (6) long-term safety of a closed repository.

It is further evident from RD&D Programme 2007 that SKB intends to continue to follow the development work in the field of deep boreholes, even though it does not consider it justified to carry out a research programme.

The Swedish National Council for Nuclear Waste stands firm in its judgement that there still does not appear to be any available technology (in the sense of the Environmental Code) for disposal in deep boreholes. However, the Council would like to reiterate that it is urgent that SKB clearly state and justify its positions on the deep borehole concept not later than in conjunction with applications for permits under the Environmental Code and the Nuclear Activities Act. The Council would naturally like to see research conducted in the field, but it does not necessarily have to be SKB who conducts the research.

4.2 KBS-3H

The KBS-3 concept has been studied by SKB primarily with vertical deposition holes for the canisters. SKB has also studied an alternative design with horizontal deposition, KBS-3H. Posiva is collaborating with SKB in this matter. Experiments are being conducted in the Äspö HRL for evaluation of this concept.

SKB states in RD&D Programme 2007 that work to date has shown that the concept has a number of uncertainties and problems, such as channelling in the buffer material, strict requirements on the water inflow to the deposition drift, heterogeneous water saturation and cracking in the blocks between the waste packages.

SKB intends to carry out a site-specific safety assessment for the KBS-3H concept for the site selected by SKB as the site of the final repository. The purpose is to be able to compare safety for the two alternatives vertical deposition and horizontal deposition.

SKB also states in RD&D Programme 2007 that a decision to switch to horizontal deposition can be made when enough background data exists for comparison with KBS-3V, and that this will be possible in around 2012/2013. The Swedish National Council for Nuclear Waste notes that the Swedish Radiation Safety Authority and the Environmental Court will at this time probably have begun their review of SKB's application for a final repository according to the KBS-3V method and that a Government decision can be expected within a relatively near future. The Council therefore considers it urgent that SKB explain how a possible switch to KBS-3H can take place.

4.3 Swedish National Council for Nuclear Waste's conclusions

- The Swedish National Council for Nuclear Waste believes it to be of great importance for confidence in SKB's work that a coherent and clarifying account be given of alternative methods for the final disposal of spent nuclear fuel. SKB should present such an account not later than in conjunction with the company's permit applications under the Nuclear Activities Act and the Environmental Code. The Swedish National Council for Nuclear Waste believes that SKB should in this account clearly explain its positions on the deep borehole concept. In this context, SKB should also explain its plans for KBS-3 with horizontal deposition (KBS-3H).

5 Site selection

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

The Swedish National Council for Nuclear Waste has previously (SOU 2005:47) stressed the importance of conducting the investigations in a similar manner so that a scientifically correct comparison can be made between the sites. It is also important that the description of the sites will be similar and the presentation will be easy to understand so that even laymen can judge what the most suitable site is. The brief descriptive sections in RD&D 2007 leave something to be desired in this respect. Regarding Forsmark, there is no legend on the geological map, and there is no information on existing rock types in the text (“had bedrock that warranted further investigations”). Regarding Laxemar, no tectonic zones are marked on the geological map, but there is a clear legend. The explanation for choice of subarea for further investigations in Forsmark states mainly practical reasons, but only a few geoscientific ones. As far as Simpevarp and Laxemar are concerned, there are both geoscientific and practical reasons for the choice of subarea.

Models for site description have been developed step-by-step and adapted to site-specific conditions. Greater weight has been placed on conceptual descriptions, which is conducive to a better understanding of complicated phenomena. There are some good examples in the Biosphere chapter, but more examples should be given in other appropriate sections, such as the Geosphere chapter. It is also valuable that stress has been placed on a harmonious

geological, rock mechanical and hydrogeological description of different parameters and a final integrated site descriptive model.

Monitoring is said to be necessary at a number of places in the text. In order to obtain a coherent picture of where, when and how this monitoring will be done, the Council considers it necessary that a programme will be presented that includes methods for evaluation of measurement data. Since development of both measurement and evaluation technology is rapid and since new measurement needs may arise, for example due to disturbances during the construction phase, it should also be stated that the programme will be revised as needed. The reference area should be established as soon as possible after site selection in order to obtain comparable time series. Methods should also eventually be developed for post-closure monitoring of the biosphere, the geosphere and the hydrosphere.

5.2 Integrated evaluation and site selection

The presentation on pp. 75–78 has shortcomings in terms of cogency and clarity. In several cases the text expresses self-evident truths, mixed with formulations with imprecise content. An example can be taken from the concluding paragraph of section 4.3.1 (p. 78) which reads:

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

Another example is that it is said under the heading "Site-by-site evaluation" (p. 77) that a facility should be able to be built and operated with "reasonable consideration for the environment and a reasonable input of resources". An attempt is made in the following text to further define the meaning of the concept "reasonable" in these contexts. A more exhaustive treatment of these matters is needed.

A third example is provided under the heading "Comparative evaluation" (p. 78). In the summary, SKB states that provided that

site selection can be carried out in the manner recommended by SKB, the selected site will be able to be “justified in relation to every other site that can be considered suitable in the sense of being a potential siting alternative.” The Swedish National Council for Nuclear Waste cannot conclude from RD&D Programme 2007 that this is the case.

5.3 Swedish National Council for Nuclear Waste’s conclusions

- The Swedish National Council for Nuclear Waste considers it imperative that SKB give a clear account of the judgements underlying site selection. Since long-term safety is the most important factor in site selection, the Council finds that the safety arguments underlying site selection must be based on two comprehensive safety assessments (i.e. two SR-Sites): one for Forsmark and one for Laxemar. The Council thereby wishes to emphasize the importance of making a scientifically correct comparison between the sites prior to final site selection.
- The Council is troubled by the fact that successful rock stress measurements performed so far in Forsmark are too few in number and uncertain at planned repository depth (see section 10.1). The far-reaching conclusions drawn from the results can affect both site selection and the design and construction process, as well as in the longer term the durability of the repository. The Council therefore considers it imperative that existing knowledge of the rock stresses, particularly at repository depth in Forsmark, will be considerably improved before a final choice of site is made. However, results that could clarify certain uncertainties have reportedly not yet been published.
- A coherent programme for monitoring of the repository area and the surrounding environment must be presented – and promptly implemented – both for the period before and during the construction phase and for the post-closure period.

6 The safety assessment

6.1 Background

In November 2006, SKB submitted a preliminary safety assessment, SR-Can (SKB Technical Report TR-06-09), of the two candidate areas for a final repository in Oskarshamn and Forsmark. A new safety assessment, SR-Site, is planned prior to the permit application for the final repository. SKB believes that the safety assessment methodology is now mature and intends to make only updates and minor modifications of the SR-Can methodology in preparation for the work with SR-Site. SR-Can has been subject to separate review by SKI and SSI (SKI report 2008:23, SSI report 2008:04 E). The regulatory authorities conclude that SKB's safety assessment methodology essentially complies with the regulatory requirements, but that parts of the methodology need to be further developed prior to a permit application. The authorities also find that SKB's quality assurance of the safety assessment is insufficient in SR-Can, that a better knowledge base is needed concerning certain critical processes, that SKB needs to confirm the fact that the assumed initial state of the final repository is realistic, and that the account of the risk of early releases needs to be strengthened. The site investigation municipalities of Östhammar and Oskarshamn, as well as the Swedish NGO Office for Nuclear Waste Review (MKG) and the Swedish Environmental Movement's Nuclear Waste Secretariat (Milkas), have also submitted viewpoints on SR-Can.

The Swedish National Council for Nuclear Waste has not conducted its own review of the safety assessment methodology presented in SR-Can or the need for further development of this methodology. Based on the Council's transparency programme,

section 6.2 instead addresses a special method issue, namely the transparency of the safety assessment and its ability to convey the complexity of the background material. The connection between the safety assessment and scientific/technical research is discussed in section 6.3. As an introduction to these two sections, we discuss in section 6.1 the safety assessment's role in the work of developing a system for final disposal of spent nuclear fuel as well as its role as a part of the supporting material for SKB's upcoming permit application for a final repository.

6.2 The different roles of the safety assessment

SKB gives the safety assessment a double role in the nuclear waste system: an *internal* role as a management tool within SKB and an *external* role in society's licensing process. By "management tool" we mean the role assigned by SKB to the safety assessment in the planning of different research initiatives, technology development and further site investigations.

It is in its external role that an outside observer meets the safety assessment. In this role, the safety assessment is supposed to provide a basis for *society's* assessment of the repository's long-term safety based on science and proven experience. The external role is well documented in a development process that spans over three decades and where SR-Can (SKB Report TR-06-09) is the latest link in a long chain of safety assessments.

Already at an early stage, the safety assessment was also given a role as a management tool for managing the relevance of research and development activities (R&D). However, the Council notes that this role for the safety assessment is less well documented. The question is what role the safety assessment has *de facto* played and could play in the prioritization of research. This question is addressed in connection with the scientific/technical research programme in section 6.3. Here we start by examining the question in relation to how SKB organizes its work.

According to the RD&D report, the activities for planning of the construction and operation of the final repository have been divided at an overall level into two main processes: (i) Construction and operation, and (ii) Safety assessment and site modelling (see p. 93 in RD&D Programme 2007). The main process "Construction and operation" is in turn divided into eight

sub-processes, two of which are “Investigations” (not included in Figure 6-1) and “Evaluation of safety of facility and activity”. “Investigations” produces data as a basis for updating the site description. According to SKB, “Evaluation of safety of facility and activity” is only activated when conditions deviate from given assumptions.

The main process “Safety assessment and site modelling” consists of two sub-processes: “Site modelling and safety evaluation” (not included in Figure 6-1) and “Safety assessment”. According to SKB, the result of the sub-process “Safety assessment” is an updated safety analysis report prior to an application for trial operation, but if the repository deviates from what is established in SR-Site, a new assessment of safety is first made within the main process “Construction and operation”. The background material for the sub-process “Safety assessment” is a built and designed facility, an up-to-date site description and RD&D results.

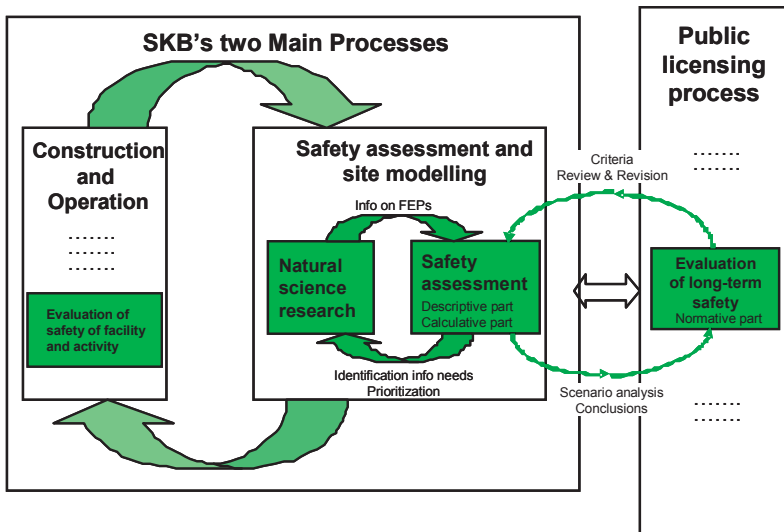
As far as the safety assessment is concerned, the Swedish National Council for Nuclear Waste interprets the RD&D report’s description as saying that it has, or should have, two functions in SKB that are depicted in Figure 6-1:

- *Management tool for construction and operation.* Here the safety assessment and safety evaluations are used almost routinely to “regularly” cross-check the site description against premises and assumptions in SR-Site and to “continuously” cross-check assumptions in the “preliminary safety analysis report operation” against the actual designed and built plant. In the event of deviations, a special sub-process within the main process “Construction and operation” is activated: “Evaluation of safety of facility and activity”. This sub-process either handles the deviation within “Construction and operation” or refers the deviation to the main process “Safety assessment and site modelling” for further study.
- *Management tool for natural science research and technology development.* SKB’s RD&D Programme 2007 states with regard to natural science research that the safety assessment in “SR-Can has provided guidance in the planning of the research programme”. The research programme is in turn “directly aimed at furnishing background data for SKB’s safety assessments of the final repository for spent fuel.” (SKB 2007 p. 219). The role

of the safety assessment when it comes to planning of technology development is not as clear, but Figure 11.1 (p. 125) shows a similar connection as that between safety assessment and the RD&D programme.

The RD&D report thus also divides the internal role into a number of different functions. Within the main process “Construction and operation”, “Safety assessment and site modelling” is supposed to contribute to coordinating ongoing activities and serve as a conversation partner in a dialogue about measures within “Construction and operation” in order to handle deviations from premises and assumptions in the safety assessment.

Figure 6-1. The Swedish National Council for Nuclear Waste’s interpretation of the roles of the safety assessment, both internally within SKB (the left-hand loop) and externally for society’s decision process (the right-hand loop)



The safety assessment is also assumed to help in the identification and prioritization of research activities. This function is of current relevance, but will also be required when construction of the final repository begins. It is unclear within which main process responsibility for identification and execution of research activities lies. In Figure 6-1 we have assumed that natural science research

lies within “Safety assessment and site modelling” and technology development for the different production lines within “Construction and operation”.

The distinction between the internal and external roles for the safety assessment is important from the perspective of the licensing process. These two roles are discussed with the aid of a systems analysis tool called CATWOE in Appendix 4. The purpose is to analyze whether the safety assessment is used appropriately with respect to both its internal and external roles. The analysis further supports our conclusion that the two roles of the safety assessment need to be clarified and developed, especially since the balance between SKB and the regulatory authorities has changed over the past ten years. Today only SKB has the competence to carry out a complete safety assessment. A prerequisite for the external role to be fulfilled is that the internal role works. In unfortunate cases, however, the two roles may conflict from an SKB perspective. For example, safety assessment for research planning is aimed at finding relevant weak points in the system, while safety assessment in its external role is aimed at showing that the proposed repository meets all stipulated safety requirements.

The Swedish National Council for Nuclear Waste would therefore like to stress the necessity of handling the safety assessment in a transparent and quality-assured manner within SKB’s entire *organization*. The safety assessment is a prerequisite for the licensing process according to the Nuclear Activities Act and the Environmental Code. It is naturally both desirable and efficient that SKB can use the assessment for internal processes. But it is extremely important that the safety assessment within SKB’s organization has *one* clear owner who carries out the assessment, takes responsibility for the identity and quality of the assessment process, and maintains a clear division of roles. The Swedish National Council for Nuclear Waste stresses the importance of regular audits by the Swedish Radiation Safety Authority to follow how the different roles of the safety assessment are reflected in SKB’s organization and processes. The audits may require the support of outside organizational expertise.

The Council would like to stress the importance of giving the new Swedish Radiation Safety Authority sufficient competence in safety assessment to enable it to scrutinize both SKB’s technical execution of the safety assessment and its use in different roles. In

the judgement of the Council, this will require additional resources beyond what SKI and SSI together have today.

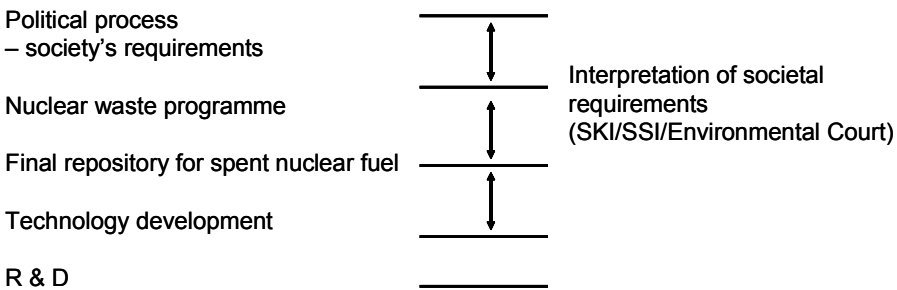
Our discussion of the different roles of the safety assessment brings up a number of questions that will be discussed in the following sections:

- *SKB's capacity.* How far does SKB follow through with its alleged methodology, i.e. to what extent are the priorities in the research programme guided by the safety assessment and to what extent does each production line and scientific and technical field generate its own priorities? How is the information from the safety assessment applied within the different sub-programmes within the research programme? How can the dialogue between safety assessment and research programme be followed in the RD&D report and the quality assurance programme?
- *Consensus can lead to lock-in.* Well functioning feedbacks as shown in Figure 1 result in an effective system for agreeing on where R&D is needed and for guiding resources and generating new knowledge within the areas where the R&D need has been identified. But the management literature also contains cautionary examples of lock-ins, where the system receiving feedback is transformed into a resource-demanding system for effectively learning more about what is already known. The system discourages innovation and meets new threats with more of the same measures. What mechanisms exist to terminate SKB-funded R&D when sufficient knowledge is deemed to have been obtained, but strong intradisciplinary reasons exist for continued research? What processes exist in the system in Figure 1 to identify and allocate resources to radically new R&D needs?
- *Complexity – the whole and the details.* The safety assessment is supposed to promote an exchange between R&D and decision processes at all levels. How are the different roles of the safety assessment clarified? How is all this made transparent? These questions are addressed in the next section.

6.3 The whole and the details

The safety assessment plays an important role in the entire Swedish organizational system relating to the final repository programme. It must meet regulatory requirements on safety, which in turn reflect the goals of society and national policy. At the same time it must, according to SKB, help guide technology development and research. Figure 6.2 provides a picture of different analysis levels needed to describe the role of the safety assessment.

Figure 6-2. Analysis levels for understanding the requirements and the roles of the safety assessment



At the top level, requirements on the nuclear waste programme are determined by the parliament and the Government, who pass laws and make decisions in connection with SKB's RD&D programmes. The regulatory authorities interpret society's requirements via their regulations and general recommendations/guidelines, which SKB in turn interprets and translates into practical requirements on its programme, not least regarding the choice of method for final disposal and sites for nuclear waste facilities. You could say that there is one level for the nuclear waste programme in its entirety, including decommissioning, and one level for the final repository, including the site selection programme. Within the framework of the "final repository project", SKB conducts the technology development and research that is needed to support the final repository programme.

A prerequisite in order for the safety assessment, which is a very complicated activity, to achieve all its purposes in an effective manner is that it be made transparent. This must be done at all levels, but the implications of this vary between the levels.

The external role of the safety assessment

The upper part of Figure 6.2 concerns the external role of the safety assessment according to section 6.1, i.e. to provide a basis for society's assessment of a proposal for a final repository.

The safety assessment is a part of the body of material which the politicians need to familiarize themselves with, instead of just accepting SKB's safety assessment and SKI's review of it as a set of factual data that cannot be questioned. It is therefore necessary to make the safety assessment transparent so it can be understood by laymen. The Swedish National Council for Nuclear Waste pointed out in its review of RD&D-Programme 2004 that "both SKB and the authorities must explain and publish pedagogical descriptions of the safety assessments that have been carried out and the models upon which the assessments are based"¹.

Against this background, the position of the safety assessment today, not least after the publication of SR-Can, is something of a paradox. On the one hand, SR-Can is a very heavy technical report (as it must be) with a large number of technical background reports comprehensible only to specialists. On the other hand, the safety assessment is the most important supporting document for the political decision whether or not to issue a permit for construction of the final repository. If awareness of the nuclear power issue is not raised among laymen, the political decision process will be susceptible to manoeuvring and fragmentation².

Naturally it is not reasonable to expect politicians in general or other laymen to fully comprehend FEP³ analysis, groundwater modelling or models for corrosion of the copper canister. But it should be possible to discuss certain fundamental assumptions, for example regarding the time aspect, what can (and cannot) be predicted over very long timespans, how to regard different scenarios for human intrusion, how to compare the risks from a final repository with other risks, what the safety assessment says about comparisons between sites, etc. A prerequisite for an effective decision process is that SKB and the regulatory authorities can communicate such matters in a way that inspires confidence. This has a lot to do with government regulations and general recommendations, how SKB chooses to interpret them and on

¹ Nuclear waste – Barriers, Biosphere and Society (p. 78, SOU 2005:47, English version).

² By "fragmentation" we mean that the focus is put on certain isolated parts of the whole issue at the cost of the whole picture.

³ FEP (Features, Events and Processes)

what grounds the regulatory authorities can accept SKB's interpretation.

It is important that this be communicated in the best possible way to decision-makers and the public. The goal of the dialogue is to make the safety evaluation transparent, which means making both technical issues and values visible and comprehensible. Good decisions require clarity in both parts, which makes special demands on the decision process. If the experts alone set the agenda, values can easily be overlooked. On the other hand, the technical issues can easily be brushed aside if the decision process is dominated by values. In both cases there is a risk that the background material will not cover all aspects of the question. Thus, the external role of the safety assessment is to systematically coordinate information from all relevant technical and scientific areas in order to show that the proposed final repository system meets all safety requirements imposed by the regulatory authorities (which must in turn reflect societal values).

The transparency requirement means that such an account from SKB is systematically challenged from different perspectives ("stretching" according to the RISCOM Model), which is a part of the Swedish National Council for Nuclear Waste's transparency programme.

The internal role of the safety assessment

In the same way as above for the external role, the internal role of the safety assessment can be summarized as follows:

clarify for everyone in the final repository programme (internally in SKB) the importance of information from all relevant technical and scientific areas for fulfilment of the safety requirements in a transparent and action-oriented way.

This, which involves the lower part of Figure 6.2, may appear to be a simpler task for SKB than the external task, since SKB's organization includes many scientists and experts. However, the safety assessment spans over many disciplines, and it is impossible for one person to know whether all parts are being carried out with the desired scientific and technical rigour. There is no "superexpert" for the entire field. Of central importance is the transfer of information to those who are in charge of the safety

assessment itself and how they appraise and handle this information. Completeness and certainty are unattainable goals in a safety assessment – it must be based on judgements.

Thus, the internal role of the safety assessment also requires an organized questioning of statements and requirements made by different parts of SKB's organization, both those who are responsible for the safety assessment and experts in the relevant knowledge areas. In this case, chief responsibility for stretching must be organized within SKB, while the regulatory authorities and the Swedish National Council for Nuclear Waste also play a role in this context, not least within the framework of the RD&D review. In the next section we examine the question of to what degree SKB has succeeded in clarifying the internal role of the safety assessment.

6.4 The connection between safety assessment and scientific/technical research

Quality assurance of information transfer

SKB writes in RD&D Programme 2007 (p. 9) that the safety assessment describes the repository's initial state, after which the changes that could occur in the long term and their consequences for man and the environment are analyzed. The changes are driven by processes (thermal, hydraulic, mechanical and chemical), which are described with models. The model calculations are based on data from research and SKB's site investigations in Forsmark and Oskarshamn. As this introductory paragraph suggests, it is necessary to have an exchange of information between safety assessment and a number of other activities within SKB's organization: technology development in order to verify the initial state, natural science research in order to chart the processes that drive the changes that occur in the final repository, and the site investigations that were recently concluded in Forsmark and Oskarshamn in order to obtain site-specific safety assessments. Moreover, there must be a connection between safety assessment and system design as well as between safety assessment and SKB's internal formulation of requirements. Finally, long-term safety must comply with government regulations, which represent society's requirements.

In order for this complex pattern of information transfer and feedbacks to work, the Swedish National Council for Nuclear Waste believes it is very important that SKB should have a well functioning quality plan that ensures that these feedbacks take place and that the measures entailed by the feedbacks also be implemented. SKB must, for example, be able to explain how they ensure that all research areas identified from safety assessment are dealt with in the RD&D programme and that critical research and technology development results will be available in time for SKB's next safety assessment, SR-Site. The Swedish National Council for Nuclear Waste is aware of the fact that the feedback between safety assessment and research takes place to a high degree on the individual level within SKB due to the fact that research administrators also participate in the safety assessment work. SKB says that this eliminates the need for a formal system for information transfer between safety assessment and research. The Council finds that this creates good conditions for direct feedback both with regard to how research results are handled in the safety assessment and with regard to knowledge gaps and thereby remaining research needs. However, the problem with this system in the Council's opinion is that the information transfer is untraceable and not transparent, which is negative from a review standpoint.

Connection to natural science research

SKB's natural science research programme spans two fields: Long-term safety and other final disposal methods than KBS-3 (see p. 219 in RD&D Programme 2007). Of these, the biggest field is research on long-term safety, and according to SKB it is directly aimed at furnishing background data for SKB's safety assessments of the final repository for spent fuel. SKB goes on to say that SR-Can, which is the most recent of SKB's safety assessments, has provided guidance in the planning of the research programme.

In the concluding chapter of SR-Can, a number of topics (9) have been identified which SKB believes require additional research to improve the safety assessment. But the Swedish National Council for Nuclear Waste Research finds it unclear how SKB will ensure that all identified research areas will be included in the RD&D programme. The Council has not, for example, managed to

trace all of these 9 areas in the overview covering 143 research activities provided in Table 19-1 (pp. 221–222 of the RD&D Programme 2007). This is a good example of when SKB's direct feedback methodology is not transparent and traceable.

Another example is the information transfer between safety assessment and the different special disciplines. It is, for example, still unclear how the results of the biosphere work will be integrated in the safety assessment and what importance the biosphere will have for siting (see Chap. 11). There are also issues in the geosphere programme that can affect the results of the safety assessment, for example the issue of supraregional groundwater flow and modelling of changed hydrological and hydrogeological conditions in conjunction with an expected climate change due to the greenhouse effect.

The Council also believes that SKB should clarify in what respect the safety assessment provides guidance for the natural science research programme and how the safety assessment fulfils the role of identifying research areas.

When it comes to the natural science research in the area of long-term safety, Table 19-1 is a good point of departure. The table provides a good overview of the research that is being conducted and will be conducted within the framework of SKB's research programme. For each research activity, the table also states whether large, moderate or small resources are required. But it is not evident how critical the different research activities are and what results need to be available when and why. The Council deems this to be a shortcoming. The Council also believes that SKB must describe more clearly what factors determine which issues are to be included in the research programme, i.e. how SKB identifies the research areas listed in Table 19.1. The Council believes that such information is necessary to be able to judge the appropriateness of SKB's research programme.

However, the Council does not find any evidence to indicate that the quality of the research conducted by SKB needs to be questioned. It is published internationally at conferences and in different scientific journals and thereby undergoes peer review and quality assurance.

Connection to technology development

The technology development that is taking place and is planned is discussed in Part III of RD&D Programme 2007 and is commented on by the Swedish National Council for Nuclear Waste in Chapter 4 of this report. The Council notes here that it is of great importance that SKB, within the framework of its technology development, be able to quality-assure e.g. fabrication and testing of technical components and thereby their initial state in the final repository. This is important because the credibility of the safety assessment is dependent on how realistic the assumptions that are made in the safety assessment regarding the initial state are. This has also been pointed out in the regulatory review of SR-Can (see SKI report 2008:23, SSI report 2008:04 E).

6.5 Swedish National Council for Nuclear Waste's conclusions

- SKB's safety assessments should show that the final repository system fulfils the regulatory requirements on long-term safety. The Swedish National Council for Nuclear Waste would also like to emphasize the internal role of safety assessment within SKB as a tool for both following up repository safety during construction and operation and providing guidelines for technology development and research.
- SKB therefore needs to ensure and show that feedback and information sharing between different parts of SKB's organization works, for example feedback from safety assessment to research programmes, programmes for detailed investigations and technology development.

7 Canister

7.1 Canister fabrication

Background

The function of the canister is to isolate the nuclear waste from the surrounding environment for a very long period of time (> 100,000 years). The canister must be resistant to various types of corrosion attack in the deep repository environment and withstand the mechanical stresses that can arise during a glacial cycle as well – both isostatic loads and shear loads. The canister must have negligible adverse thermal, chemical and mechanical effects on the other barriers and on the fuel. The canister must be able to be transported, deposited and handled in a safe manner. Canister fabrication must be based on proven technology. Canisters with specified properties must be able to be fabricated, sealed and inspected with high reliability at the desired production rate. It must be possible to verify the properties of the canister against specified acceptance criteria. The detailed design requirements for the canister and the requirements on long-term safety must be logically related.

SKB's reference canister consists of an inner container of nodular cast iron and an outer shell of copper. The fabrication of the reference canister's copper shell comprises the following reference processes: casting of copper ingot, extrusion of copper tube, forging of copper lid and bottom, welding of bottom by friction stir welding (FSW) and quality inspection of components and bottom weld by nondestructive testing (NDT). In addition, finish machining of components and the bottom weld are needed. Besides extrusion and FSW, SKB also has alternative methods for both fabrication of copper tubes and welding: pierce and draw

processing and forging for fabrication of copper tubes and electron beam welding (EBW) for welding of the bottom. Copper lids and bottoms are fabricated by forging. Fabrication of the insert comprises fabrication of a steel cassette and casting of the insert, plus machining of the insert and nondestructive testing. In 2005 SKB chose friction stir welding as the reference method for sealing the canister, and optimization of this process is under way.

The fabrication methods are being further developed for the different canister components and trial fabrication is under way. Different suppliers are developing their fabrication processes so that the components will meet stipulated specifications. Method development is also under way on nondestructive testing of both canister components and welds in order to determine material structure and the presence of discontinuities (defects and material flaws). Together with the canister welds, testing now also includes the canister components: copper tubes, nodular iron inserts, lids and bottoms. Optimization of the testing methods and evaluation of their reliability are under way, and the first results from testing of canister components will soon be available. Demonstrations of methods for nondestructive testing are linked to prequalification of fabrication processes.

Copper canister

SKB has chosen a pure oxygen-free copper that complies with the standard EN 1976 for Cu-OFE or Cu-OF1 with a number of additional requirements regarding the mean grain size ($< 360 \mu\text{m}$) in the material (the grain size affects the properties of the material and ultrasonic testing) and the quantity of certain substances (maximum oxygen ($< 5 \text{ ppm}$) and hydrogen content ($< 0.6 \text{ ppm}$) for optimal electron beam welding and hot forming, plus maximum sulphur content ($< 8 \text{ ppm}$) and a certain phosphorus content (30–70 ppm) to reduce sulphide segregation and improve the creep properties of the material).

A number of copper ingots have been fabricated, extruded, pierced and drawn (including with integral bottom) and forged in recent years. At the same time, a large number of lids and bottoms have been fabricated by forging. Development of reference and alternative fabrication methods for copper tubes will continue during the years to come. Studies will particularly concentrate on

local variations in material structure along extruded tubes and in forged lids and bottom blanks. Material structure (microstructure) affects ultrasonic testing via grain size, but other properties such as texture, variations in degree of deformation, residual stresses, type of grain boundaries etc. are also important. More studies are needed in this area in order to be able to formulate requirements on material structure and how it affects material properties and ultrasonic testing in order to make testing more reliable.

SKB plans to use the same reference method, friction stir welding, for welding both bottom and lid (sealing). This method is expected to be a repeatable and reliable method that produces a good microstructure and good quality of the weld.

Cast iron insert

SKB has chosen nodular iron in accordance with the requirements in standard EN 1563 grade EN-GJS-400-15U as a material for the insert. The design premises stipulate certain detailed requirements on material structure and mechanical properties for the nodular iron insert (e.g. ultimate elongation min. 11% (cast-on test bars) or 7% (test bars from the insert)). Material testing of insert material has shown a relatively wide spread in the material properties of most inserts. This wide spread is due to the fact that the material's microstructure contains non-nodular graphite (chunky graphite) and discontinuities (casting defects) in the form of pores and other defects. The casting method has been developed during the trial castings by improvements of cassette attachment and increased cast length to permit impurities and discontinuities to be cut away. Analyses have been made of the statistical distribution of material parameters and discontinuities in order to calculate the probability of plastic collapse caused by high pressure or of failure caused by fracture growth in regions with tensile stresses. The probability of failure has been found to be very low in both cases. But residual stresses, creep and time-dependent material embrittlement have not been taken into consideration, so the strength analyses must be further developed, which may lead to new requirements on NDT.

SKB will pursue further development of insert fabrication at several suppliers in order to ensure delivery of the 200 inserts needed annually. The insert will be inspected by nondestructive testing to find discontinuities in the material. In order to be able to

show that canisters that comply with the design requirements can be fabricated, different testing methods must be developed due to the complex geometry of the insert. Requirements on NDT methods must in particular be established and verified. If the casting process cannot be improved, some other type of material must be used.

Sealing of the canister

The reference method, friction stir welding (FSW), is a solid-state thermomechanical process, while an alternative welding process, electron beam welding (EBW), is a fusion welding method. A large number of FSW welding tests have been performed, and the results have shown that the process is stable with high repeatability. Optimization of the FSW method is being pursued by determining the process window and demonstrating the potential of the process for production. It must be shown for the reference method, FSW, how the microstructure (cold working, very fine-grained areas, dissolution of sulphides and lines of oxide inclusions), properties and residual stresses of the weld metal differ from those of the parent metal, and how any impurities in the weld, such as increased oxygen content, and different types of weld defects affect quality. Different tests have been performed on FSW lid welds to assess their mechanical and chemical properties. FSW has produced good results in short-term tests (metallography, strength testing, corrosion testing, creep testing, chemical analyses, nondestructive testing etc.). Verification of the mechanical long-term properties of the weld metal is being done by continued creep testing. The influence of oxides and metal particles in the weld metal is being studied, and methods for minimizing different discontinuities as well as oxides and metallic particles are being investigated. The possibilities of using FSW for repair of defects in welds that do not satisfy the requirements are being explored by means of local rewelding. Detailed criteria for acceptable deviations for FSW welds have not yet been arrived at.

The reliability of electron beam welding is not yet satisfactory, and continued development work is being pursued. Various tests have been performed on the electron-beam-welded (EBW) lid welds to determine their mechanical and chemical properties with tests similar to those used for FSW welds. Grain size and probably

also residual stresses in EBW welds are large compared with the parent metal and FSW weld metal, while the mechanical and corrosion properties determined in short-term tests are acceptable. Results of long-term tests are needed with regard to creep and corrosion properties of EBW weld metal as well.

Nondestructive testing

Nondestructive testing (NDT) is of crucial importance for ensuring that the canister requirements are met. SKB has started working with different NDT methods for inserts. Ultrasound is the most suitable technology and is being used in the development work as a tentative testing method for discontinuities. In the case of nodular iron, the microstructure of the material affects ultrasonic testing and the nodular iron is difficult to investigate. It is nevertheless also possible to measure nodularity in nodular iron by means of ultrasonic methods. Future development work is aimed at developing testing methods for the nodular iron insert. In order to qualify these techniques, expected discontinuities must be known and preliminary acceptance criteria established. In order to better understand the results, it is necessary to examine microstructure, geometry and testing systems in order to gain an understanding of any limitations in the testing procedure. The reliability of the chosen methods should be studied as a basis for the qualification of methods for nondestructive testing of inserts. The qualification process requires analysis of a number of reference bodies with simulated defects in order to show how big defects the system can detect reliably.

All copper components are inspected by NDT in order to find any nonconformances and discontinuities in the material and to verify that fabrication works acceptably. Ultrasound is the best technology for copper components, but the microstructure of the material (mainly the grain size) affects ultrasonic testing. Local microstructural variations in copper tubes and copper lids cause uneven attenuation in ultrasonic testing. The extrusion and forging process must therefore be further developed by, for example, optimization and improved process control. Existing ultrasonic and radiographic methods will be studied, optimized and qualified in the future by practical trials and modelling for NDT of the copper shell and welds. Besides ultrasound and radiography, eddy-current

testing will also be used to detect defects on or near the surface of the copper canister. This method is not planned to be used by SKB because near-surface defects are not expected to lead to problems for long-term safety in the repository. Since the canister surface has to resist corrosion, it is important that there not be any near-surface defects in a finished canister. Surface testing is nevertheless very important, and SKB must decide which testing methods will be used for this purpose.

7.2 Long-term properties of the canister

Background

The design premises include both requirements on safe handling and lifting of the canister during encapsulation and deposition and fundamental requirements on long-term safety in the final repository. After deposition, the canister will stand in air with high humidity at a temperature of 90–100 °C, the maximum temperature of the copper canister in the final repository, before water saturation of the surrounding bentonite has occurred, which takes 10–15 years (initial state). Salt deposits are not expected to occur on the surface of the canister. The thermal conductivity of a metal is hundreds of times higher than the thermal conductivity of the bentonite and the rock. The canister is therefore expected to have an even temperature that gradually declines to the ambient temperature within 10,000 years.

SKB is investigating how the canister's insert and shell are deformed due to external forces such as hydrostatic pressure, earthquakes and glaciation and internal forces generated by the formation of corrosion products in the canister. The radiation dose to which the nodular iron insert is subjected can lead to material embrittlement, which is being studied. Questions regarding copper corrosion – general corrosion, microbial corrosion and stress corrosion cracking – still remain to be answered. Creep takes place in response to mechanical stresses on the copper canister, which can be divided into four phases: the water saturation phase, the temperate and permafrost phase, the glacial phase and the postglacial phase. The water saturation phase occurs soon after closure of the repository. Isostatic pressure build-up occurs around the canister due to groundwater pressure and swelling of the

bentonite. Pressure differences can arise in the canister as a result of uneven swelling of the bentonite or differences in bentonite density, causing flexural stresses in the canister, up to 55 MPa, and local plasticizing of the copper shell. During the glacial phase, ice formation causes a slow isostatic pressure build-up in the repository, up to 45 MPa. According to strength calculations and high-speed compression tests, the canister can withstand an external pressure of 110 MPa. The probability of canister collapse is therefore judged to be small, but sudden and unexpected time-dependent effects can occur during the glacial phase as a result of creep in the nodular iron insert and the copper canister during the very long span of time. During the postglacial phase, a slow decline in pressure takes place in the repository and earthquakes can occur, which can affect the canister mechanically when existing fractures in the deposition holes are activated and cause shear strains.

Corrosion

Oxidation of copper occurs already during the deposition and handling phase as well as the initial temperate phase. In the final repository, the copper canisters will be exposed to both general and local corrosion of different types in complex chemical, microbial and mechanical environments which furthermore vary in time and space. Stress corrosion cracking (SCC) in copper takes place in the presence of special conditions such as tensile stresses, an aerobic environment and certain impurities (ammonium, nitrite etc.) as well as a very slow strain rate. SCC also occurs in the presence of a $\text{Cu}_2\text{O}/\text{CuO}$ complex film on the copper surface. Recently, experimental results were published suggesting that stress corrosion cracking can also occur in a sulphidic environment. It is particularly important to quantify the stress state in the copper shell and in welds and to analyze, both experimentally and mechanically, different chemical conditions around the canister in order to rule out the risk of SCC under reducing conditions.

Copper can oxidize in the presence of oxygen, chloride, sulphate and nitrate ions in the groundwater. The most important process for general corrosion is sulphide corrosion, which occurs in the repository during the entire time. Sulphide ions in the groundwater react with copper to form copper sulphide. The importance of different copper oxide films, particularly in chloridic

and sulphidic water, as well as the ability of microbes to survive in the buffer and the possibility and importance of biofilm on the canister surface will be investigated. Microbial processes can give rise to the formation of sulphide (sulphate-reducing bacteria), which causes copper corrosion by the formation of copper sulphide. Copper corrosion in anaerobic chloride solutions that contain sulphide must be further investigated from both geochemical and microbial viewpoints. The goal of these corrosion investigations is to develop a corrosion model that can be used in the safety assessment.

Copper corrosion in water requires the presence of dissolved oxygen, high chloride concentrations, low pH or dissolved sulphide. Szakalos et al. ("Corrosion of Copper by Water". *Electrochemical and Solid-State Letters*, 10(11) C63-C67, 2007) recently announced that copper corrosion due to hydrogen evolution can also occur in pure, deionized, oxygen-free water at 73 °C. The researchers believe that their new results show that the corrosion properties of copper canisters in the final repository for spent nuclear fuel are not good enough and that the KBS-3 concept should be partially re-evaluated. According to the researchers, the corrosion rate of copper in pure oxygen-free water is on the order of microns per year. It is now important that the new issue of copper corrosion in oxygen-free water be thoroughly investigated.

Creep

Testing of the creep properties of copper has been under way for several years and recently investigations have begun for EBW and FSW welds. The effect of slow loading and creep in a multiaxial stress state is being investigated. A validated creep model must be developed so that different time-dependent processes can be taken into account, such as possible postglacial shearing of the canister. The impact of phosphorus on the creep strength of pure copper, the long-term stability of phosphorus and its role in creep properties must also be further investigated in order to achieve a satisfactory mechanical explanation. Along with the creep properties of copper, the creep properties of the nodular iron insert must also be explained together with other time-dependent phenomena, such as embrittlement and the effect of hydrogen on nodular iron. Cold-working effects in copper caused by fabrication

and handling must be thoroughly analyzed and evaluated with respect to creep properties, residual stresses and stress corrosion cracking.

Strength

It is of the greatest interest to study what discontinuities can be accepted in the nodular iron insert considering the stress level that may arise. The investigation provides a basis for inspection of the insert by nondestructive testing. Different types of damage that can occur during handling must also be analyzed so that the long-term integrity of the canister is not compromised by the effects of handling.

Postglacial earthquakes can cause shear loads and plastic deformation of the canister, affecting both the copper shell and the nodular iron insert. These shear strains are caused by both geological events and the mechanical properties of the bentonite buffer. The total combined stress level that can arise in the canister under different combined loads (simultaneous shear and isostatic load) should be critically established and a defect tolerance analysis, including both deterministic and probabilistic criteria, should be carried out. The shear rates are high, and subsequent time-dependent strain rates in copper and cast iron are slow. The influence of the strain rate on copper and cast iron must therefore also be investigated in future strength analyses. An overall strength analysis of the canister, including safety margins, in order to guarantee long-term safety is still lacking.

7.3 Swedish National Council for Nuclear Waste's conclusions

- The material and casting process for the nodular iron insert must be optimized so that specified requirements can be met. Otherwise some other type of material must be used.
- In order to guarantee reliability during canister fabrication and final disposal, quality requirements must be developed with respect to fabrication defects in all parts of the canister, including welds. These criteria should take into account material structure, material properties and defects in both the copper

shell and the cast iron insert. The quality requirements must be verified by methods for nondestructive testing (NDT).

- Continued corrosion studies are required in different areas: accelerated long-term stress corrosion cracking experiments, general corrosion in chloride- and sulphide-containing water with bentonite, and microbial corrosion.
- Mechanisms of copper corrosion in oxygen-free water must be investigated experimentally to determine whether corrosion of copper by hydrogen evolution can take place in pure, deionized, oxygen-free water and in groundwater with bentonite.

8 Buffer

8.1 Quality inspection of bentonite in final repository

Since the buffer is such a vital component in the final repository, expressions such as “sufficiently good properties” must be bolstered with specific requirements on the most important properties, such as swellability¹, hydraulic conductivity², chemical and physical stability³ etc. must be precisely defined (see more detailed description under the heading “Change of reference” below).

High montmorillonite content is important to ensure good swellability, but no initiatives have yet been described in the research programme for establishing limit values for acceptable montmorillonite content.

Other non-swelling secondary clay minerals that normally occur in bentonite are illite and kaolinite, though usually in low concentrations.

Other common primary minerals of importance in bentonite are quartz, feldspars, calcite, gypsum, siderite and pyrite.

The relative occurrence of these minerals and their respective particle size distributions affect the properties of the bentonite in different ways.

Among the minerals that occur, quartz and feldspars (silicates) are dominant (15–25%), and of these quartz is more stable against alteration and dissolution in contact with water. Reactions with water are strongly pH-dependent, and while quartz can for the

¹ Swellability entails that a high density can be maintained.

² Hydraulic conductivity entails low water permeability.

³ Chemical and physical stability entail less risk of transformation and good mechanical strength.

most part be expected to react at high pHs ($\text{pH} > 9$), dissolution and surface alterations occur on feldspars occur already in neutral and weakly acidic environments.

There are several different ways to define the surface charge of mineral particles, the most common of which is PZC (point of zero charge). PZC can be defined as the pH at which the surface has a net charge equal to zero. If the pH is lower than the PZC for a given mineral, the surface is positive, while it is negative at higher pHs.

PZC values for quartz and feldspars are approximately 2–2.5, which means that both minerals have negatively charged surfaces in the pH range in the final repository and can therefore adsorb positively charged ions in buffer and backfill.

However, particles of these minerals probably increase the porosity of bentonite due to their relative size in relation to particles of montmorillonite and the fact that they are less affected by water. This in turn affects the hydraulic conductivity of the bentonite.

Calcite and pyrite both affect the pH of the pore water, but in different ways. Calcite is relatively soluble and is a basic mineral that can neutralize acids and maintain alkaline conditions in the buffer, which is generally advantageous.

Pyrite reacts with and consumes oxygen dissolved in the water, making the environment less corrosive for the copper canister. However, the reactions with oxygen lower the pH, so the combination with calcite is desirable.

Gypsum is relatively soluble and assists in enabling calcium and sulphate ions to be transported in the pore water and cause precipitations of secondary minerals. However, it has little effect on the pH of the buffer. Like calcite, gypsum has the somewhat unusual property of being less soluble at higher temperature. This means it has a tendency to form precipitates near the copper canister (which has a higher temperature) in the buffer.

The groundwater often contains both calcium ions and hydrogen carbonate ions, and in view of the fact that very high pressures prevail in the buffer, ion transport will occur, followed by precipitation and formation of solid substances.

In the Council's opinion, SKB should present a quality programme regarding the bentonite used in the final repository. A quality inspection should include total mineral composition as well as the concentration of organic and inorganic compounds.

8.2 Some viewpoints on SKB's research programme with respect to buffer

The bentonite buffer is one of the most important components in the final repository. The properties of the bentonite and expected processes in buffer and backfill are of crucial importance for long-term safety and are important parts of the safety assessment. One of the most important functions of the buffer is to prevent or retard the transport of radionuclides from a leaking copper canister and the transport of corrosive substances to the canister.

In a series of previous reviews of SKB's research programme, the Swedish National Council for Nuclear Waste has called for a more sophisticated model for sorption of different ions in the bentonite buffer. Such a model is described in Appendix 3. In RD&D 2007, however, SKB says it does not consider sorption in bentonite to be a prioritized research area. Nevertheless, the Council urges SKB to set up models for transport through the bentonite of the most important positively and negatively charged radioisotopes.

Change of reference

For a very long time, SKB's research and development has been based on the assumption that sodium bentonite of the type Volclay MX 80 will be used, and its good properties with respect to swelling, "self-healing", gas permeability, hydraulic diffusion, hostility to microbes, retention capacity against ion transport, mechanical flexibility against minor movements in the rock and chemical stability have been thoroughly studied and described.

In RD&D 2004, SKB indicated that it intended to test other kinds of bentonite in order to obtain references for MX 80, as urged by the Council in its review statement (Nuclear waste – Barriers, Biosphere and Society, SOU 2005:47). However, the Council expressed concern at the fact that SKB concluded at a very early stage that calcium bentonite has virtually equally good properties, and in RD&D 2007 SKB has completely abandoned MX 80 as a reference material.

This is certainly a rapid reversal, and in RD&D 2007 SKB writes that "there are a number of sodium and calcium bentonites on the market that are very capable of meeting SKB's requirements."

Lower swelling potential

SKB admits that calcium bentonite has lower swelling potential but believes it has equivalent properties at the same buffer density.

In a previous state-of-the-art report (Nuclear Waste State-of-the-Art Report 2001, SOU 2001:35), the Council described the difference between sorption of water in sodium and calcium bentonite on a somewhat detailed level.

The literature data then showed that the difference in swelling potential is a factor of 2–3 lower for European bentonite than for MX 80.

A long-range advantage of calcium bentonite could be that the groundwater often contains calcium ions and that an ion exchange between sodium ions in the sodium bentonite and calcium ions in the groundwater could lead to some transformation.

If a calcium bentonite with a higher dry density is used to start with, such a long-range transformation could possibly be less dramatic than with equivalent sodium bentonite.

What properties are crucial?

There are, however, numerous other properties that are also important for long-term safety, and here the uncertainty is much greater.

For example, how are self-healing capacity (which is linked to swelling potential), hydraulic diffusion, gas permeability and retention capacity against radionuclides and other ions, as well as chemical stability, affected by which type of bentonite is used?

A very important factor in this context is the ability to resist erosion, i.e. the formation of very small particles (on the order of microns), which both depletes the buffer and can transport radionuclides from the repository.

As long as MX 80 was used as a reference material, it was possible to use its properties as a basis for comparison, but what can SKB do now?

How will different (perhaps sometimes conflicting) properties be prioritized and how will their limit values be determined?

Composition and structure of bentonite

The composition of bentonite with respect to mineral distribution and various kinds of impurities (organic and inorganic) is naturally also important to know and should be checked.

The Council has given its viewpoints on this in a special section.

In previous review statements the Council has recommended that SKB propose limit values for impurity concentrations in the bentonite buffer and combinations of these concentrations.

This recommendation still applies.

The composition of the pore water in both unsaturated and saturated buffer will be directly dependent on the composition of the bentonite, not least its impurities.

Research on montmorillonite structure

SKB states in RD&D 2007 that “a method for determining the structure of the montmorillonite was to be developed” and says that “the method for determining the structural formula of the swelling mineral will be further developed”.

Although it is always important to gain more knowledge through basic studies, it is nevertheless difficult to understand why SKB prioritizes this particular research.

In what way do they intend to use the results they expect to obtain?

Water saturation

The Council agrees with SKB that water transport in the unsaturated buffer is a complex process. Water transport is dependent on the composition of the buffer with respect to swelling and non-swelling components, the temperature gradient that arises from the canister through the bentonite, how homogeneously the water is supplied and at what rate.

It is undoubtedly one of the key processes in the repository and therefore requires a great deal of research and development in the form of both experiments and simulations, above all with the type of bentonite to be used in the buffer. As far as the Council knows, the tests and model calculations performed so far are based on MX

80, and now a long series of tests have to be done with other types of bentonite.

Inhomogeneous water saturation and swelling in different parts of the bentonite along the copper canister generate different compressive and shear stresses that could disturb the vertical and/or lateral position of the canister.

During the water saturation phase, the swelling pressure may temporarily be quite different in different parts of the deposition hole.

This undesirable process is also affected by the material properties of the bentonite such as hydraulic conductivity and swelling properties.

Piping and erosion

Water transport and swelling of the bentonite also mean that there is a risk of piping and erosion. An uncontrolled erosion process is undeniably a threat to the long-term function of the bentonite and must be kept to a minimum.

In these contexts, the strength of the bentonite is vital (rings, blocks and pellets) and is in turn dependent on mineral composition, type and amount of impurities and density on compaction.

The Council urges SKB to regard resistance to erosion as an important parameter in the final selection of the type of bentonite.

Ion exchange/diffusion and speciation of radionuclides

One of the buffer's most important roles as an engineered barrier is dependent on its ability to transport radionuclides as ions or colloids from a damaged copper canister.

The transport of radionuclides through bentonite has been investigated very thoroughly, and a review of possible diffusion pathways and mechanisms is provided in KASAM's 2001 state-of-the-art report (SOU 2001:35).

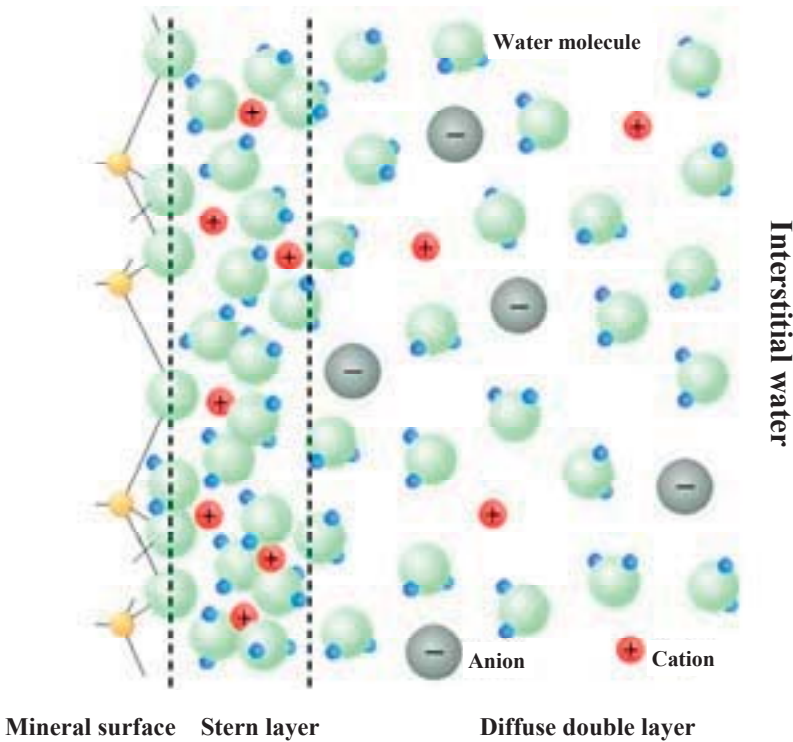
The Council has also described several of the mechanisms that are involved in the transport of different substances through clay minerals in a special section of this review statement.

In general, the transport of positively charged ions (cations) is fundamentally different from the transport of negatively charged ions (anions) in that the cations diffuse via surface diffusion in the Stern layer, i.e. the layer of water molecules closest to the mineral surface, while anions only diffuse through the interstitial water further out from the mineral surfaces (see Figure 8.1).

Because the transport mechanisms for positive and negative ions through the buffer are completely different, speciation of radionuclides is of great importance.

The studies of redox kinetics for different oxidized forms of radionuclides that are announced in RD&D 2007 therefore have the full support of the Council.

Figure 8.1 Transport of positively and negatively charged ions



Formation of colloids by canister corrosion products (such as magnetite), and associated adsorption and transport of radionuclides, is also a critical factor. Large colloidal particles could reduce the number of flow paths by clogging the pores of the bentonite, while tiny uncharged colloidal products that are unaffected by charge effects could increase the mobility of radionuclides.

The size distribution of the pores in the buffer is therefore an important parameter, which in turn is also dependent on the composition of the bentonite. It is via these pores that undesirable radionuclide transport takes place.

The choice of bentonite is thus far from unimportant.

Experimental data suggest that the diffusion coefficients are roughly ten times higher in calcium bentonite than in sodium bentonite (Choi & Oscarson, 1996), which shows that composition is of great importance for the properties of the bentonite.

Montmorillonite transformation

A special section in this review statement is devoted to transformation from smectite to illite.

A special property of montmorillonite is that there is a low exchange of tetravalent silicon in the tetrahedral sheets (siloxane sheets) in the mineral.

Illite is characterized by an exchange of trivalent aluminium for tetravalent silicon in these sheets, which gives rise to negatively charged surface sites and a stronger adsorption of cations, of which potassium ions are of by far the greatest importance and cause the clay to lose its property of swelling in water.

The transformation from smectite to illite can be expected to take a relatively long time, but the higher temperature nearest the canister and increased availability of potassium ions from leaching of crushed rock and concrete can hasten the process.

The Council has in previous statements urged SKB to study the importance of a limited illitization and this recommendation remains.

8.3 Swedish National Council for Nuclear Waste's conclusions

- The most important properties of the buffer material should be specified and limit values should be determined with respect to swelling potential, retention capacity against radionuclides, chemical stability, hydraulic diffusion, resistance to erosion and level of impurities (inorganic as well as organic).
- Mechanical strength and chemical stability must be guaranteed for compacted components in the buffer.
- Models should be set up for transport of the most important radioactive isotopes (with positive and negative charge) through the bentonite.

9 Backfilling and closure

9.1 Backfilling of deposition tunnels

SKB plans to backfill deposition tunnels and the uppermost parts of the deposition holes with naturally swelling clay (Friedland Clay) in the form of blocks, pellets and granules. Compaction and swelling are crucial for controlling the size of the water flow. A delicate balance must be struck between providing enough water flow to wet the buffer and limiting the water flow to prevent erosion. All experience of compaction in column experiments – including with bentonite – shows that unforeseen wall effects and piping can easily occur, even in columns with completely smooth walls. The problems are not less in blasted tunnels with rough walls, roofs and floors and point inflows of water. Tests have now been started in the new Bentonite Laboratory on Äspö.

The Council considers the ongoing tests to be very urgent and believes that tests must also be conducted with the water flows that can be expected in the deposition tunnels.

Backfilling is a critical process in the final repository. The requirements specification for backfilling has not been changed in a long time (the same requirements are given in RD&D 2004 and RD&D 2007), but SKB has not yet decided which concept will be used. The impression is that SKB has for a long time underestimated the difficulties that will be encountered in connection with backfilling of bored deposition holes and blasted tunnels and now has to work with several concepts in parallel.

The final choices of materials and method must in any case be made by the time an application to build the final repository is to be submitted. Backfilling of deposition holes takes place directly following deposition of copper canisters in the holes, which means

the two activities are closely connected to each other in time and space.

Material selection and water saturation

In a technical report from 2006 (TR-06-14), model calculations of water saturation were carried out for three different concepts: a mixture of bentonite and crushed rock (30/70), pure Friedland Clay and a backfill consisting of alternate layers of bentonite and crushed rock (the sandwich concept). The conclusion is that the time for water saturation of the backfill varies depending on the material and is much longer (about 10 times) for pure compacted Friedland Clay than for a mixture of bentonite and crushed rock.

If compacted blocks of Friedland Clay are used, the differences are even greater. The hydraulic conductivity in the backfill will in any case be much higher than in the fractured rock, but the advantage of compacted blocks of Friedland Clay is that it is much easier to verify the chemical composition than in a mixture of bentonite and crushed rock, whose composition is less homogeneous and whose content will be more varying.

The mineralogical composition of Friedland Clay is given in TR-06-18, and Table 1–8 shows that the clay contains about 30 weight-% swelling materials (smectites). Other constituents are quartz, kaolinite, mica, feldspars and illite, all of which are non-swelling minerals. They can, however, fill another important function, namely to give the backfill the stability that is required to resist the swelling of the buffer when it is water-saturated. This property of the backfill has been prioritized by the Swedish National Council for Nuclear Waste in previous review statements concerning SKB's research programme. In the Council's opinion, it is therefore important that SKB conduct research during the coming period to ensure that the chosen concept can meet this criterion.

Interfaces are critical

SKB intends to seal interfaces against roofs and walls in the deposition tunnels with bentonite pellets. It can be expected that the water saturation of the backfill will take place via the

surrounding rock and that seeping water will run along roofs and walls. The first contact with the backfill will thus take place through the gap with bentonite pellets, which naturally enough cannot have the same density as the compacted blocks of Friedland Clay located inside.

It is therefore vital that the bentonite not be carried away with the water before it has time to swell and leave a void, enabling the water to flow more freely. SKB should explain how long-term safety is affected by the creation of such voids. According to TR-06-18, Table 1–6, 20% of the tunnel area will consist of pellets. Accordingly, in the opinion of the Council, the interfaces against the rock and the buffer are the critical areas with regard to water saturation and therefore require special research.

Processes under saturated conditions

According to SKB's own calculations, water saturation may take a very long time (hundreds of years). It can hardly be expected that the hydraulic conductivity will be as low after saturation as in surrounding (fracture-free) rock. The mean density can also be expected to be lower in the backfill than in the buffer, due to the fact that the smectite content is lower and it is considerably more difficult to achieve as tight compaction as in the deposition hole. What will the consequences of this be? The conditions for bacterial growth can be expected to be better than in the buffer. This may in turn increase the solubility of certain minerals and there may be a risk of piping and erosion. Erosion can of course also be brought about by other processes, such as repeated freezing and thawing of the backfill. If radioactive colloids and radionuclides escape through the buffer, their transport through the backfill can take place much more easily than in surrounding rock, assuming the rock is fracture-free. The pores in the backfill can be expected to be larger and the specific ion exchange capacity lower than in the bentonite buffer.

Radionuclide transport in the backfill is dependent, as in the buffer, on the composition and charge of the radionuclides, i.e. their speciation. This is another reason for SKB to determine the speciation and redox reactions of the most important radioactive isotopes in the final repository. The Council urges SKB to conduct such research.

9.2 Closure – Backfilling of other openings than deposition tunnels

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

Choices of materials and method for closure are defined by a number of specific requirements given in section 16.2 of RD&D 2007. The requirements state that the closure must ensure that the backfill in the deposition tunnels is held in place and that the upper parts of shafts and ramp are designed to withstand a period of permafrost.

It remains to be shown how these requirements necessitate the choice of a given design and material. RD&D 2007 mentions a number of alternatives such as crushed rock, mixtures of crushed rock and bentonite and mixtures of quartz sand and bentonite. It can probably be assumed that the bentonite grade that will be used for closure will be of lower quality than the buffer with respect to composition and content of swelling components (smectites). This is a question of cost.

In order to meet the requirements defined in RD&D 2007, different materials can be used in different parts of the closure. The area nearest the deposition tunnels should be characterized by a certain stiffness in order to resist the swelling of the clay that will be used in them, while other areas in the closure mainly have to be tight to prevent water flows. The Council finds it surprising that the problems that can arise during the expected climate change (due to the greenhouse effect) are not discussed, for example higher levels and flows of groundwater as well as altered water chemistry and higher sea levels, probably already during the construction period.

The requirement that the closure should withstand periods of permafrost probably entails that at least the area nearest the ground surface should have a relatively low water content so that it does not freeze and burst. The closure can thus be designed with different sectors with somewhat different properties that all meet the stipulated requirements. The exact design of the closure should be determined by the properties of the rock with respect to e.g.

fractures of different depths, but then it is important to know which properties are possessed by different materials – and mixtures of materials – and how they can interact for best effect.

As far as can be judged, the closure activities lie far off in time, perhaps 2–3 generations. It has therefore not been considered necessary so far to allocate resources to make a final decision on method and materials for the process. It is, however, important that SKB can present a reference design for the closure line in such a way that the initial values that are needed for the safety assessment calculations can be considered credible. A clear account of this must be given no later than in the safety assessment (SR-Site) that will be appended to the application for the final repository.

9.3 Swedish National Council for Nuclear Waste's conclusions

- The final choice of materials and method for backfilling must be ready by the time the application to build a final repository is submitted.
- Special research is required on the interfaces between backfill and buffer and between backfill and rock.
- SKB needs to consider the problems that can arise during the expected climate change (due to the greenhouse effect), for example higher levels and flows of groundwater as well as altered water chemistry and higher sea levels, probably already during the construction period.
- The final design of the closure should be determined by the properties of the rock with respect to e.g. fractures at different depths and salinity. However, this presumes knowledge of what properties different materials – and mixtures of materials – have and how they can interact to best effect.

10 Geosphere

10.1 Rock engineering

Swedish rock engineering is presented in a very positive light (“long experience”, “development of world-leading technology”), but it would also have been appropriate to point out the shortcomings in technology and execution that have been revealed in recent years, particularly in tunnelling projects. The fact that the development need in these contexts is great is clearly evident from Figure 12.1, where only four subareas have known and proven technology, while eleven subareas have technology that must first be tested and two or three subareas have technology that is not known or sufficiently proven. In comparison with the other areas of technology in RD&D 2007, the development need is thus greatest in rock engineering, according to SKB’s own assessment. It can then be asked why this has not been realized earlier, and whether there is enough time to fully develop the technology. The final repository project involves executing advanced rock works with great precision and safety – there is no room for failure!

The requirements on the methods and equipment to be used in building the final repository appear to be realistic. There is an implicit requirement that could be formulated as follows:

Operation of the repository must be arranged so that the depositions of the different canisters do not interfere with each other.

SKB mentions two proven methods for stabilization of boreholes: installing perforated stainless steel plates, or stabilizing them with cement. It should be noted that in the case of cement stabilization, the cement must be of the low-pH type, the same type as has been developed for grouting, so as not to raise the pH

of the groundwater. Another thing is that all boreholes within the area create potential short-circuits for the groundwater (i.e. contact is created between different groundwater-bearing horizons), so the boreholes should be grouted as soon as possible.

Bedrock mapping

Bedrock mapping of tunnels and deposition holes is of great importance, and it is therefore very gratifying that new methods such as laser scanning provide faster and more accurate mapping and that geophysical borehole instruments, e.g. for ultrasonic measurement, have been developed that permit geological interpretation of the properties of the bedrock, for example identification of fracture orientation. Hopefully, this may also lead to development of methodology for systematic classification of bedrock heterogeneity.

The Council has pointed out the need for such methodology in two previous RD&D reviews (2002:63, 2005:47). Such classification is required in order to make an objective comparison between different subareas or tunnel sections and to verify the statistical approach used in modelling.

Rock stress measurements

Rock stress measurements are of particular importance. The same methods have been used in both areas and they have performed as intended in Oskarshamn and down to a depth of 250–400 m in Forsmark (according to the report “Site Investigation Forsmark 2002-2007”), but unfortunately not at greater depths in Forsmark, where the unique bedrock conditions have influenced the results of the measurements (SKB’s Report R-07-26). The overcoring method works poorly in the quartz-rich rock in Forsmark, resulting in elevated temperature during drilling with micro-cracking, which interferes with the measurement results, particularly in the thin-walled overcore cylinder that has been used. Report R-07-26 notes that only 30% of the tests of the overcoring method were successful and that the overcore cylinder should be modified. The hydraulic methods have also proved to have serious limitations. The conclusion in the aforementioned report is that

the method involving hydraulic fracturing in vertical boreholes to measure horizontal stresses is not applicable in the geological environment in Forsmark! According to the report “Site Investigation Forsmark 2002-2007”, there are only a “few credible measurement results at a depth of 500 m”, but the results are nevertheless deemed to agree well with the “estimated stress” obtained from indirect observations. It is stated on p. 345 of RD&D 2007 that the methods “appear to provide a similar picture of the stress situation down to levels around or slightly above the depths studied for a final repository” (cf. 250–400 m and 450–500 m), while it says in Report R-07-26 that the results from hydraulic fracturing were significantly lower than the results from overcoring! The statements about the results of the rock stress measurements are thus somewhat contradictory and furthermore uncertain. This is a very troublesome situation for SKB, which nevertheless believes that further development of methods for rock stress measurements in boreholes from the ground surface is not warranted and that switching to larger-diameter boreholes is far too costly. It is better to wait for information on the stress state obtained from deformation measurements during tunnelling. But then the site has already been selected and may be the wrong one!

There are also difficulties with deformation measurements in connection with tunnelling. In our stiff Scandinavian rock types and with the stress states that can be expected at the repository level, it is very difficult to obtain representative measurements of the stress state. A better alternative could be a system based on hydraulic fracturing at a short distance, about 15 to 30 m, where a large number of measurements could be made and spread and uncertainties could be statistically corrected.

The Council finds it troubling that rock stress measurements carried out to date in Forsmark are few and uncertain at the planned repository depth (450–500 m according to RD&D 2007 p. 68). The far-reaching conclusions drawn from the results can affect both site selection and the design and construction process, as well as in the longer term the durability of the repository. The Council therefore considers it imperative that existing knowledge of the rock stresses, particularly at repository depth in Forsmark, be considerably improved before a final choice of site is made. However, results that could clarify certain uncertainties have reportedly not yet been published.

Hydrotests

Two types of hydrotest equipment will be developed, including for quick measurement in probe holes.

There are existing methods for hydrotests. One problem with them is that it takes a relatively long time to obtain results, since the water flow in low-conductivity bedrock is also low. The measurement time can cause difficulties for planning of the construction work.

Another problem is the effect of open boreholes on the groundwater balance in the bedrock. There is a great deal of saline groundwater below the planned repository level in all planned areas. If boreholes penetrate this area, there is a certain risk that the saline water will rise. This increases the risk of corrosion in the repository.

Measurements of water flows in ramp and tunnels are proven: simple measurement systems known as measuring dams. The fine material problem involved with these dams can be solved with the right design.

Another problem is that some of the incoming water evaporates and never reaches the floors and dams. The quantity of water is not great, but with strict goals for watertightness in the openings, this effect can nevertheless be significant. SKB should study the magnitude of this effect.

Sealing by grouting

The Swedish National Council for Nuclear Waste commented in connection with the review of RD&D 2001 (SOU 2002:63) that new findings from grouting with silica fume should be studied, as well as different methods for grouting in fractures to achieve “a long-lasting limitation of water permeability in the bedrock that will surround the deep repository without adversely affecting the chemical environment”. But SKB did not arrive at the same conclusion until in RD&D 2004, and since then R&D efforts have been devoted to grouting methods as well as grouting materials. Nevertheless, many problems remain to be examined, for example the fact that grout does not penetrate into the finest fractures, and methods remain to be developed, for example for monitoring of the water inflow. These needs are shown in Figure 12.1. A

comprehensive programme has been presented for research, e.g. on erosion and the durability of grout, both under SKB's own auspices on Äspö and at universities and other institutions.

Together with Posiva, SKB has largely succeeded in meeting the requirements established for grouting materials and results on a laboratory and pilot scale. Fine-grained low-pH cement and silica fume/sol seem to be workable solutions. But they must be tested on a full production scale.

The Council believes that further research and development within this area is necessary and urgent, and a detailed timetable should be presented detailing what steps need to be finished at what times.

Drilling and blasting

SKB has done a great deal of work on optimization of drilling and blasting. It looks as if the method can be used to advantage in order to achieve stipulated goals regarding the EDZ (excavation-damaged or excavation-disturbed zone) and tunnel shape.

It is possible by means of controlled blasting to control microcracking caused by the borehole charge so that it does not form an interconnected system and thereby does not markedly increase the permeability of the bedrock in tunnel walls. But this remains to be proven by full-scale tests.

The emulsion explosive SSE (Site Sensitized Emulsion) has a number of advantages. But there are still unsolved problems. Today's charging machines are not yet sufficiently reliable to enable the charging factor in different holes to be regulated in the desired fashion. Charging machines have to be further developed and tested before than can be put into operation in the construction of the final repository.

For rock support, SKB can in principle use the same proven methods as in infrastructure tunnels. The only difference is the need for a low-pH cement, which has already been discussed in section 12.4.

Reverse raise boring is an established technology that easily meets the requirements stipulated for deposition holes. Chamfering of the deposition hole is more problematical. Both proposed methods, wire sawing and water jet, can be time-consuming. SKB should explore the possibility of depositing canisters

without chamfering of the deposition hole, which requires a higher tunnel or another type of deposition machine.

In its review of RD&D 2004, SKI said that SKB should consider tunnel boring machine (TBM) for deposition tunnels and deposition holes. It is therefore remarkable that an exhaustive comparison between conventional drill-and-blast and TBM boring has not been presented. Based on extremely weak evidence, controlled drilling and blasting is recommended in all tunnel systems in the final repository. This entire section deals with newfound knowledge of the excavation-damaged zone or excavation-disturbed zone (EDZ) and what fracturing looks like in this zone. Measures to reduce the scope of the zone and to control the extent and properties of the zone, above all its hydraulic properties, and to seal the zone are of central importance for the function and safety of the repository. The hydraulic properties of the zone will now be studied in a large-scale measurement experiment around a drill-and-blast tunnel with realistic conditions. Geophysical measurement methods ought to be tried and developed. A special group will be established on Äspö specialized in tunnelling with grouting. Development of methods for rock support and boring of deposition holes will be included in the programme.

The Council wishes to emphasize that these are absolutely necessary measures that should be scheduled in detail and carried out in a qualified manner. The Council demands an explanation as to why TBM boring has been abandoned and a better description of the extent and properties of the excavation-damaged zone in connection with drilling and controlled blasting.

10.2 The geosphere

Thermal conductivity of the bedrock

The thermal conductivity of the bedrock is of great importance for the dissipation of heat from the canister and thereby for the deposition geometry, particularly the spacing between the canisters. A general relationship between density and thermal conductivity has been demonstrated and verified by means of laboratory investigations on drill cores. Borehole logging with

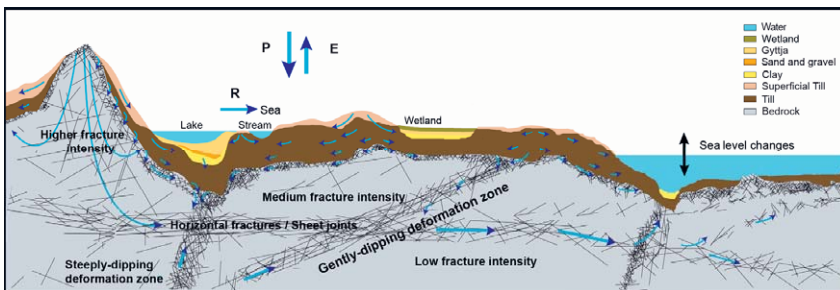
gamma probes has been tried for measurement of density variations.

The Council finds that continued development of efficient and inexpensive field methods, particularly full-scale methods, is urgent.

Groundwater flow

The programme for groundwater flow in RD&D 2004 was ambitious, and furthermore the regulatory authorities and the Council contributed suggestions and viewpoints that have been taken into account to some extent, although not the Council's suggestion regarding determination of the magnitude of groundwater recharge at great depth by means of several independent methods. The comprehensive programme has been carried out in conjunction with the site investigations and the safety assessment, as well as in the form of separate projects. Many valuable results have been achieved in terms of both model development and site-specific conditions. For example, new, interesting knowledge has been gained regarding the near-surface hydrogeology (see Figure 10.1) and the relationship between geosphere and biosphere. Simulations of the influence of an open repository on the impact area with regard to lowered groundwater table, inflows of groundwater to the repository and upward transport of saline water have provided important information for future design and construction.

Figure 10.1 Conceptual model of the near-surface groundwater conditions in a cross-section from the inland to the coast at Forsmark



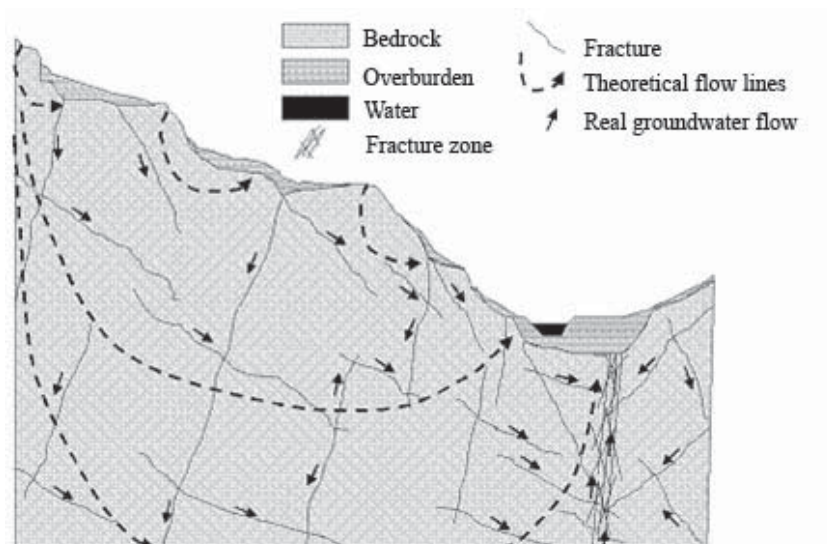
Source: SKB Report R-07-49.

The figure is based on a very large body of facts. It shows how the groundwater flow pattern is controlled by the topography and by mainly horizontal and gently-dipping fracture and deformation zones, but also by steeply-dipping fracture zones.

The Council believes that additional aspects of changes associated with an open repository should be examined, including both changes in groundwater chemistry due to oxygenation and “short-circuiting”, i.e. interconnection of different groundwater-conducting zones, which can lead to other salinities, and altered rock stress conditions.

Super-regional groundwater flow is a fundamentally important problem complex which, at the suggestion of the regulatory authorities and the Council, has been the subject of extensive modelling in eastern Småland. The results show that the topographic conditions in the landscape are the most important factors for this flow, causing the formation of a large number of recharge and discharge areas for groundwater in this undulating landscape, in other words mainly local flow processes even from repository depth. The median length of the flow paths is about two kilometres, whereas there are extremely few flow paths of more than ten kilometres. It is further evident that fracture zones and dolerite dykes are of importance for the local flow pattern, which has previously been noted in the Swedish National Council for Nuclear Waste’s state-of-the-art reports 2001 and 2004 (see Figure 10.2). Super-regional crushed zones do not appear to affect the large-scale flow pattern, however, which is surprising. The conclusion would thus be that an inland repository would not be preferable to a near-coastal repository – except with regard to salinity.

Figure 10.2. Recharge and discharge areas as well as groundwater flow patterns in a valley with varying topography and thin overburden (unconsolidated deposits) on fractured, hard bedrock.



Source: SOU 2004:67, Nuclear Waste State-of-the-Art Report 2004.

The actual flow pattern deviates considerably from the theoretical depending on fractures and fracture zones (Olofsson et al. 2001).

SSI has reviewed the report with the aid of two external experts and has certain objections, mainly that SKB has not had specific sites evaluated and compared, despite the identification of such sites.

SSI has therefore requested supplementary information on certain points, including sensitivity analyses of the modelling results, systematic analysis of how topographic scales affect the flow pattern on some specific sites and determination of the distribution of the flow and transport properties in some interesting areas.

The Council supports SSI's request and would like to stress the importance of studies of a small number of areas of differing character (topography; bedrock with varying permeability, barrier properties and major fracture zones; overburden conditions). In order to reduce uncertainties concerning such parameters in the terrain and e.g. the location of the groundwater table in recharge areas (of importance for the size of groundwater recharge and the

flow pattern) and the overburden in discharge areas, simple, supplementary field investigations would be of value within selected, limited areas. Perhaps the dominant effect of the topography can then be modified, for example if impermeable Quaternary deposits in low points in the terrain prevent discharge. Similarly, the lateral boundaries of the model can be checked in some points where fracture zones or dolerite dykes intersect the boundaries, which could mean that surface water divides (= lateral boundaries) and groundwater divides do not coincide. It should be added that the importance of the topography is also being studied in a doctoral project at KTH with support from SKI. It is of interest that areas with different topographies (Forsmark, Oskarshamn, Vetlanda and Älvdalen) are thereby being modelled.

SKB's programme for groundwater flow mainly discusses further development of the models used to date, for example a new routine for particle tracking, further improvements of identification of recharge and discharge areas and simulation of groundwater over one or more glacial cycles.

The Council finds the programme urgent, but would like to see programme points for modelling of the changed hydrological and hydrogeological conditions resulting from anticipated climate change due to the greenhouse effect, which are addressed in Nuclear Waste State-of-the-Art Report 2007.

Movements in intact bedrock

New valuable knowledge has been gained regarding the beneficial importance of light support (in experiments with a pressurized rubber bladder) to prevent spalling of the bedrock in deposition holes, while a negative effect can arise via thermally induced spalling in dry deposition holes if buffer and pellet fill do not absorb water rapidly enough. A serious remaining problem (previously mentioned in 10.1) is that the methods used for measuring rock stress have been found to work poorly at great depths in Forsmark. The overcoring method can give over-estimated values at great depths, and hydraulic methods only cause gently-dipping fractures.

The Council has previously pointed out (SOU 2002:63) that the relationship between the land uplift intensity in different areas and the openness of the fractures, and thereby their hydraulic

conductivity, should be studied. Norwegian studies have revealed a clear connection, as was pointed out in the Council's 2001 state-of-the-art report. The effect can above all be of importance in the long term and contribute to the discussion on north/south siting.

The Council finds it important to carry out general studies of what effect prevailing rock stresses have on hydraulic conductivity in fractures in different directions; in some directions conductivity can increase, in others decrease, which can be of importance for the detailed design of the repository.

Thermal movement capacity

There is relatively little risk that the canisters will cause any appreciable thermal movement. If the analyses should show this, however, the effect can be reduced by increasing the distance between the canisters.

Reactivation – movement along existing fractures

Newfound knowledge regarding maximum shear movements caused by earthquakes show that these movements will be considerably less than the current canister damage limit down to a distance of 200 metres from a magnitude six earthquake. In a radar satellite study, no movements were observed in any regional lineament or any fracture zone in the Forsmark area, but they were observed in loose sediments and fills.

In the final repository, the risk can be greatly reduced by not depositing any canisters in areas closer than 20 to 30 metres from such structures. The proposed simulation experiments and tests are well suited to their purpose.

The programme is continuing with – in the Council's opinion – urgent projects such as simulations of the effects of major earthquakes, development of the analyses of changes in hydraulic conductivity in fractures in the near-field in connection with construction, thermal impact and during a glacial cycle, and of stability conditions and stress development in the Earth's crust during a glacial cycle.

However, the Council finds it inappropriate that the Global Positioning System (GPS) measurements in Forsmark aimed at

recording any ongoing bedrock movements along certain zones are planned to be discontinued this year. The Council has previously maintained (SOU 2005:47) that the GPS measurements in both Forsmark and Oskarshamn should continue for a longer time as in Finland, but with fewer stations and measurement occasions than to date. The instrumentation and the processing method are being developed, resulting in more accurate and more reliable results. These results can be valuable as a basis for processing the site application, but the measurements should then continue at the selected site for monitoring during construction and operation of the repository.

An addition to the monitoring programme could be to install a microseismic monitoring system at the selected final repository site as soon as possible.

Fracturing

This problem was largely dealt with in 26.2.5. Modelling of fracturing is important, however, and progress has been made, particularly with the calculation code Fracod. This code could perhaps be applied in conjunction with tests proposed in section 26.2.5 in RD&D report 2007.

Time-dependent deformations

The proposed programme is good. Within the framework of the Finnish KYT (national nuclear waste research), some modelling and testing has been carried out concerning time-dependent deformations in bedrock. Coordination with this work could be of value.

Advection/mixing – groundwater chemistry

Site models have been constructed for both Forsmark and Laxemar utilizing both hydrogeochemical and hydrogeological data. The computer models have been updated. Verification of the mixing model M3 will be “concluded within the next few years”. The time required for this should be specified with greater precision, since the code is vital in many contexts. Calculations of the evolution of

salinity in connection with future climate changes over long time intervals will be carried out. Here again a more precise specification of the timespan is required. Are we talking about a glacial cycle or climate change due to the greenhouse effect?

Diffusion – groundwater chemistry

The Council finds it very laudable to try to utilize data from ice sheet conditions on Greenland to check the models for groundwater flow and salinity distribution.

Sorption of radionuclides

Important results have been obtained on sorption of uranium and technetium, but also regarding the fact that measurements using different methods yield different results, for example that ordinary batch sorption measurements are associated with great uncertainty and presumably overestimate sorption due to the fact that fresh surfaces are created in these experiments on crushed rock.

The Council finds it very urgent that the programme for radionuclide sorption be carried out as described in R&D 2007. It is thereby vital to carefully stipulate how and in what form (speciation) each radionuclide occurs – see special appendix on sorption.

Microbial processes

Valuable knowledge has been obtained on both different microorganisms in deep groundwaters and microbial processes, for example the fact that the majority of the investigated radionuclides were sorbed in lower quantities on rock surfaces with biofilm than on clean rock surfaces.

The Council would like to emphasize the need for further research on naturally occurring microbes in the Äspö HRL, and would like the results to be included in the continued modelling work, particularly on microbial processes, which can have both a negative (sulphate reduction) and a positive (oxygen consumption) impact on repository safety.

Colloids in groundwater

The Council would like to emphasize that colloid formation and transport of particles from bentonite with sorbing radionuclides are processes that should be thoroughly studied, along with colloid transport of precipitated radionuclides.

Integrated modelling – hydrogeochemical evolution

Hydrochemical and hydrogeological models (as well as a model for mineral reactions) have been used with success to give a detailed picture of the groundwater chemistry on both of the sites during the temperate period following repository closure.

The Council finds it remarkable that it is thereby assumed that “the present-day situation is expected to prevail during the coming 1,000-year period,” i.e. no climate change due to the greenhouse effect is assumed. The Council finds it necessary that the modelling work will be supplemented with different scenarios for climate change during this period in accordance with Bolin’s conclusions in the Swedish National Council for Nuclear Waste’s Report 2007:3e.

Integrated modelling – radionuclide transport

Very valuable results have been obtained from the extensive tracer tests carried out on Äspö with both sorbing and non-sorbing tracers. The results show that the retention properties of different flow paths differ, and that small fractures can be of great importance for radionuclide retention.

The Council finds it very valuable that the results of the tests are planned to be reported in scientific articles, that the developed methodology is being implemented in a program code that will be used in the safety assessment, and that a site-specific transport model for fractures on Äspö is being developed. It is also important that transport modelling continue in order to increase our understanding of transport in the near-surface deposits and in the interface zone between geosphere and biosphere.

10.3 Swedish National Council for Nuclear Waste's conclusions

- Improved knowledge is needed of rock stresses at planned repository depth in Forsmark. General studies should be conducted regarding what effect existing and altered rock stresses may have on hydraulic conductivity in fractures in different directions and the consequences for the detailed design of the repository. Furthermore, measurements of possible bedrock movements in both Forsmark and Oskarshamn should continue for a period during the processing of the site application and then on the selected site for an extended period during construction and operation of the repository.
- Additional R&D on grouting for sealing of fractures is necessary. A timetable should be given for different steps in this R&D programme.
- A better account should be given of the extent and properties of the excavation-damaged zone in conjunction with controlled blasting, along with an explanation of why the use of TBM boring has been abandoned.
- Additional aspects of changes associated with an open repository should be examined, such as changes in groundwater chemistry, "short-circuiting", i.e. interconnection of different groundwater-conducting zones, and altered rock stress conditions.
- The altered hydrological, hydrogeological and hydrochemical conditions associated with expected climate change should be modelled. Continued modelling should be done of transport and hydrochemistry in the near-surface groundwater and in the interface zone between geosphere and biosphere, taking into account different climate scenarios.

11 Biosphere

11.1 Background

The biosphere (or the surface ecosystems) is the part of the Earth where most organisms – plants, animals and humans – live. A possible release of radioactive substances from the repository will give a radiation dose to humans and other organisms. Knowledge concerning the transfer of radionuclides in the biosphere and the radiation doses caused by them is an important part of the safety assessment. The purpose of the biosphere programme is to provide better knowledge as a basis for the safety assessment. This knowledge is needed to show that the regulatory requirements regarding dose limits can be met and to permit the comparison of different sites, technical solutions and facility types.

The biosphere programme has taken an important step forward now that SKB can construct site-specific ecosystem-based models that simulate the flow of radionuclides in different ecosystems and that are also beginning to be able to take into account how the landscape changes in time and space. SKB is also calculating the radiation dose to man in a new way, based on flows of water and organic carbon in the ecosystems. Organically bound carbon is now being used as an indicator of how much radionuclides can be retained in and move between different ecosystems in process-based models. This is an interesting alternative to the models with compartments and transfer factors between them that have previously been used and that compared content per unit wet weight in different steps in the models. This new methodology has been used for the SR-Can safety assessment. Site data have been able to be used to a greater extent than previously.

The statements of comment that have been received regarding RD&D-Programme 2004 are reported and commented on. Many of the viewpoints have been taken into account in the formulation of the new programme, while for others there is a plan for subsequent action. Newfound knowledge is reported separately, which is good for the reader. The background reports contain a large body of material.

11.2 Swedish National Council for Nuclear Waste's considerations and assessment

The Council supports the overall goal of the biosphere programme to describe, with a modern knowledge base, 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.

The Council welcomes the continued and intensified efforts in the biosphere field. Chapter 27 in RD&D Programme 2007 continues and intensifies the work of RD&D Programme 2004. The studies that are now being conducted and planned will provide important support to both the safety assessment and the EIA process.

The question of using (today's) biosphere conditions as site selection criteria (for very long-lived waste) has been a topic of discussion against the background of changes in the biosphere in conjunction with climate change (the greenhouse effect), land uplift or sea level rise, etc. For very long times the geosphere offers a more stable barrier function. For shorter times (including land-based facilities and activities such as transportation that are linked to the final repository), however, it is important that consideration will be given to the biosphere conditions on the site. For the final repository itself there is also an initial period during which (current) biosphere conditions are of importance for safety. This is the case if there is a release of radionuclides during the operating period (with an open repository). SKB maintains that consideration is given to the biosphere in site selection. They have, for example, identified a number of biosphere-related factors that are being studied for the candidate sites. It is, however, still unclear how the results of the biosphere work will be integrated in the safety assessment and what importance the biosphere will have for

siting. It is therefore urgent that the modelling work be supplemented by sensitivity analyses of the modelling results. The Swedish National Council for Nuclear Waste also feels that SKB should, if possible, also conduct an analysis of how the results of site investigations in some other interesting areas affect the dose calculations. The Council would also like to see a programme for modelling of conditions in connection with an expected climate change due to the greenhouse effect.

As pointed out previously, it is in the Council's opinion that the data that are reported continue to be made readily available for national and international review. It is therefore positive that SKB's results will to an increasing extent be published in scientific journals. A special issue with eleven articles in the magazine *Ambio* has been one way to disseminate information on SKB's biosphere programme. In addition, some 30 articles and 80 reports have been published since RD&D 2004.

In a situation when both universities and regulatory authorities are being forced to cut back on their research activities, SKB itself is taking a leading role in research in the field and is also providing grants for a number of university-based research groups. It is good that SKB is raising its ambitions, but a threat to credibility that society has dwindling resources for independent review of the results.

Site investigation programme and model development, transport processes and hydrological relationships

SKB has done important work in these areas in recent years. The site investigations in Forsmark and Laxemar have resulted in two thorough descriptions of the ecosystems there from hydrological, oceanographic, geological, chemical and ecological viewpoints. As far as the Council knows, equivalent systems-ecological descriptions and model calculations are not available for Äspö, which would be desirable to further illustrate how the results of the site investigations affect the dose calculations.

The Council takes a positive view of the fact that SKB increased national cooperation via the Surfac Net network for surface ecosystems (with representatives of a number of research groups working in the area from different perspectives) and by supporting research projects at Swedish universities.

In cooperation with Posiva (Finland), SKB is developing a program called Pandora for dose calculations in the biosphere. The program, which was used in the SR-Can safety assessment, permits the use of the aforementioned process-based models. The Council views this development as an important and interesting complement to the compartment models used to date. But the reader would benefit from systematic comparisons between the results of the old and new models and the results of process-based models developed by other authors.

It is also important that transport modelling continue in order to provide a better understanding of transport in the interface zone between rock and soil (geosphere and biosphere). Similarly, better integration is required in the modelling of transport between near-surface waters (down to 150 m depth) and the groundwater at repository depth (which is done with models that go down to 2,000 m depth).

Terrestrial and aquatic ecosystems – importance of the ecosystems

SKB observes that terrestrial ecosystems – agricultural land, forests and wetlands – are characterized by the fact that they have a groundwater table that lies near the ground surface. The dominant transport processes to these systems are thereby root uptake, capillary force and fluctuations of the groundwater table. Along with wells, mires and wetlands are important recipients for the proposed sites. In the very long time perspective entailed by a final repository for spent nuclear fuel, big changes will occur on the repository site. This applies to the unconsolidated deposits, hydrological conditions and the biosphere.

The Swedish National Council for Nuclear Waste believes that deeper knowledge is needed regarding agricultural land as an ecosystem, with particular reference to the future cultivation of former accumulation beds in watercourses, lakes and seas, and use of wetlands which may contain elevated levels of radionuclides.

Uptake in forest products such as fungi (especially mycorrhizal fungi) and game can give considerable radiation dose contributions via food. Mosses and fine sediments are among the systems where radionuclides can be expected to be enriched.

The Swedish National Council for Nuclear Waste has in previous reviews also pointed out the importance of studying the variations in the biosphere parameters over time.

Aquatic ecosystems consist of running waters, lakes and seas. In the discharge areas, the radionuclides will pass sediment layers and accumulate there. In the short term, this can reduce the outflow but will gradually build up the radionuclide content of the sediments, which may later be liberated. Considerable basic research is being conducted with regard to hydrochemistry, seasonal dynamics, further development of systems-ecological models, bioturbation in sediments, inventories of fauna and flora in shallow bottoms, models of the sedimentation environment, etc.

It is urgent to keep track of the concentrations of radionuclides in the sediments in the Baltic Sea. The greatest accumulations of radionuclides will, for example, be found in shallow sea basins. These are areas that may be used for agricultural production when postglacial land uplift raises them out of the sea. Attention should also be given to transport of radionuclides from the Baltic Sea and along the south and west coasts of Sweden.

Radionuclides and other substances. Application of the biosphere models

The Swedish National Council for Nuclear Waste assumes that the overall environmental impact assessment that is to be done according to the provisions of Chapter 6 Paragraph 5 of the Environmental Code will also include an evaluation of the risks of chemical-toxic effects of leaking substances, such as heavy metals. SKB should therefore also apply its models to the turnover of stable substances, such as heavy metals, from the fuel which can, through their chemical toxicity, affect humans and the environment. The Council considers it important that the presentation of the results of the biosphere studies should be designed with a view to the interest of the public in understanding the total risks of a deep repository for spent nuclear fuel.

Environmental monitoring

The Council assumes that an environmental monitoring programme will be established in the repository environs, based on the extensive site investigations that are being done. The programme must be designed so that the impact of the repository can be distinguished from natural variations in the environment. An alternative can be to find organisms/species that can serve as suitable indicators for possible impact on the biosphere. The Council observes in this context that there are still certain uncertainties regarding how SSI's "Regulations on 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) are to be applied.

Monitoring in and around the repository

The Swedish National Council for Nuclear Waste addressed this issue already in its review of RD&D-Programme 98. There is very little in RD&D 2007 about verification of repository function (even though monitoring is mentioned in Figure 11.2). What SKB means by monitoring should be more precisely defined. The Swedish National Council for Nuclear Waste believes that this is an important issue when it comes to furnishing factual information to the public and that it is urgent that the regulatory authorities formulate their requirements here. The Council considers it urgent that the continued research and development work shed light on the options for selection of measurable parameters that can provide a picture of conditions in and around the final repository and trace possible releases of radionuclides. It should be clearly evident from the account how any guideline values for the different parameters have been arrived at.

11.3 Swedish National Council for Nuclear Waste's conclusions

- SKB must show more clearly how the results of the biosphere work are integrated in the safety assessment and the EIA process and what importance the biosphere will have for siting.

- SKB should conduct sensitivity analyses of the modelling results regarding the biosphere.
- SKB should prepare a programme for modelling of conditions in connection with expected climate change.

12 Climate evolution

It can initially be noted that the approach used in the safety assessment of defining three climate systems that are of importance for the repository – *temperate domain*, *permafrost domain*, *glacial domain* – is sound. The duration of these domains during the most recent glacial cycle (Weichselian) is, as properly noted, mainly important in more absolute terms, not exactly how they actually occurred in specific age intervals, in order to provide an analogue of how a future glaciation could affect a final repository.

The Swedish National Council for Nuclear Waste would, however, like to note that according to Bert Bolin in the Council's report 2007:3e, it is helpful to differentiate between the following three timescales: climate change in the 20th and 21st centuries, the following c. 1,000 years and the nearly c. 100,000 years following that.

12.1 Ice sheet dynamics and glacial hydrology

A thermodynamic ice sheet model has been used for a reconstruction of the Weichselian glaciations. Such a model is based on climate data taken from e.g. ice core archives and sea level change data, in contrast to an “inverse” modelling, which is based on geological “limit values” in the form of known, dated ice advances determined by e.g. ice margin positions and dated stratigraphic sequences. The weakness in the modelling method is apparently recognized, but the choice of method cannot be criticized since we have very poor geological data to go on regarding both the Early and the Middle Weichselian, particularly due to the difficulty of dating material beyond the limit of the ^{14}C method. It is, however, stated in the RD&D programme that “SKB plans to study the course of events during specific parts of the

most recent glacial cycle in Scandinavia in order to reduce the current uncertainty in the geological interpretations. Datings and correlations of existing interstadial sediment samples and stratigraphies from selected key localities in Sweden are therefore planned.” How this research is to be initiated and conducted and by whom is not stipulated, however.

It should therefore be pointed out that such work has recently been initiated or is currently being initiated at several of our universities, particularly with regard to MIS¹ 3 and the relationship of this interstadial to landice advance during MIS 4. On several points, new geological results indicate that the presented modelling result with an landice advance during MIS 4 down in southern Sweden, followed by deglaciation far up in northern Sweden during MIS 4 is correct, but this scenario as yet rests on very few datings. Such a scenario differs considerably from our view only 5-6 years ago, when the view was that the landice sheet first reached southern Sweden during MIS 2 and that northern Sweden was covered with landice for most of MIS 3.

It is further stated that SKB plans to initiate a project in cooperation with Posiva on Greenland aimed at using the Greenland landice as an analogue, mainly with regard to hydrological and geochemical conditions. The description is very rudimentary and provides only a vague picture of what is planned to be done, by whom, and when. The Council finds the planned project to be highly urgent and recommends that it be carried out.

12.2 Isostatic changes and shoreline displacement

The section is brief, and to understand the underlying reasoning it is necessary to penetrate the technical report TR-03-23. It is obvious that a great deal of work has been done to predict future sea level rises on the basis of available land uplift data and modelling. The Council finds the proposed programme for refinement of predictions of sea level rise in the scenario for a warmer climate to be excellent.

¹ MIS = Marine Isotope Stage (see further SKB Technical Report TR-06-36).

12.3 Permafrost growth

The proposed programme for a better understanding of permafrost growth in different scenarios and its importance for hydrogeology is ambitious and of great interest. The Council would particularly like to stress the importance of the studies of the effect of freezing of the backfill material in the deposition tunnels.

12.4 Climate and climate variations

Two projects have been initiated: one to quantitatively study extreme climate situations by climate modelling, and the other to study extreme climate situations during the last glacial cycle by studies of lacustrine deposits. Very little background information is given, especially about the latter study.

The Council considers both projects to be of great importance, especially simulating the future climate evolution with an increased concentration of greenhouse gases. As pointed out in the introduction to this chapter, three separate timescales should be taken into consideration. The changes during the next 100 years may have practical consequences for the investigated repository areas due to the fact that precipitation may increase and thereby surface runoff and groundwater recharge. Similarly, vegetation and land use may change. There is a considerable risk of sea level rise, which is however partially offset by the ongoing process of land uplift. It is more difficult to predict what will happen during the ensuing thousand years, but according to Bert Bolin (in the Council's Report 2007:3e) the trend towards a wetter and warmer climate will continue in the region, creating a climate similar to that during the Eemian warm period. The sea level rise may be up to six metres.

12.5 Swedish National Council for Nuclear Waste's conclusions

- SKB's climate research should be developed according to three time scales: the next 100 years, the subsequent 1,000 years and the 100,000 years following that

- The results obtained must be taken into account in the planning, design and construction of the final repository. As pointed out at various places in the review report, new knowledge concerning climate change has not always been taken into account.

13 Retrieval

13.1 Background

The question of retrieval of deposited spent nuclear fuel or other forms of nuclear waste is a question that has long been the subject of discussions in Sweden and internationally (e.g. in the IAEA and the NEA). In general, it can be said that the question is of interest for several reasons. The spent nuclear fuel may come to be regarded as a resource and therefore be of interest to recover, for example if new technology is developed. It may also be desirable to retrieve the deposited fuel for safety reasons. Many issues related to technology and safety but also to ethics have been discussed (see SOU 2007:38).

There is no requirement on retrieval in Swedish law, but since SKB maintains that retrieval is possible, SKB should nonetheless shed light on the possibilities and risks of retrieval. The Swedish National Council for Nuclear Waste has in several comments in conjunction with RD&D reviews returned to the so-called KASAM principle, which was formulated back in the late 1980s: A final repository should be designed to render inspection and measures unnecessary, but not impossible. If the possibility of inspection means that long-term safety is less than if we refrain from such inspection, then we should prioritize long-term safety.

13.2 Swedish National Council for Nuclear Waste's conclusions

- SKB's level of ambition in shedding light on possibilities and risks with retrieval is satisfactory.

14 Social science research

14.1 SKB's social science research programme

The Swedish National Council for Nuclear Waste has in its activities continuously addressed different societal and ethical issues and has previously drawn attention to the need for social science and humanities research in the process of finding a solution for the final disposal of spent nuclear fuel. The need for further studies of the societal and democracy-related aspects of the nuclear waste issue has also been noted by the concerned municipalities.

SKB conducts and funds research with a social science and humanities orientation within the framework of its "Social science research programme". The first call for proposals for funded research went out to a number of universities the spring of 2004 inviting proposals within four research fields (see below).

In 2003, as preparation for the establishment of a programme for social science research, SKB conducted a survey of social science research with a bearing on the nuclear waste issue. Two preparatory research seminars were held by SKB in 2002 and 2003, where researchers and representatives of municipalities and regulatory authorities were given an opportunity to offer viewpoints on the structure and content of the research programme.

SKB has held seminars in 2005, 2006 and 2007 on the theme of the research programme and has also published more popularly oriented annual reports for these years (*Samhällsforskning 2005, 2006, 2007*). The purpose of the social science research supported by SKB is described in R&D Programme 2007 (p. 409) as being to:

1. Get a broader perspective on the societal aspects of the spent nuclear fuel programme. This will facilitate evaluation and assessment of the programme in a larger context.

2. Provide deeper knowledge and a better body of data as basis for site- and project-related studies and analyses. The results of the social science research will thereby raise the quality of the basis for various decisions.
3. Contribute with data and analyses to research on the societal aspects of large industrial and infrastructure projects. In this way, experience gained from the nuclear fuel programme can benefit other similar projects.

SKB has focused on the following four “*general areas of research*” (p. 410) as being relevant:

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

SKB writes in RD&D 2007 that “*The main emphasis in the research areas supported by SKB should be on applied research, but there may also be interfaces with basic research*” (p. 410).

14.2 Swedish National Council for Nuclear Waste’s viewpoints

Points of departure

In its government terms of reference, the Swedish National Council for Nuclear Waste has been tasked to give “its independent assessment” of the RD&D programmes. The review of SKB’s social science research programme in RD&D Programme 2007 is based on the Council’s previously presented viewpoints or studies regarding the need for and thrust of social science and humanities research linked to the final disposal issue in general. The review presents new viewpoints and includes an assessment of what direction and role SKB’s social science research programme has and should have from the Council’s perspective.

The Council's previous viewpoints can be found in:

- The Swedish National Council for Nuclear Waste's review of RD&D Programme 2004 (SOU 2005:47) and
- The Swedish National Council for Nuclear Waste's "Nuclear Waste State-of-the-Art Report 2007 – responsibility of current generation, freedom of future generations" (SOU 2007:38).

Furthermore, the Council's Report 2007:5 (in Swedish only) is used as background material in the Council's review of RD&D 2007. It is a survey of the scope and orientation of current Swedish social science and humanities research on the nuclear waste issue that is funded by the actors in the nuclear waste sector and other research funding bodies.

SKB's formulation of the purpose of the social science research programme

The Swedish National Council for Nuclear Waste has the following viewpoints on how the purpose is formulated in its entirety in RD&D 2007.

The formulations of the target group for the research results are unclear. The purpose under point 2 above (p. 409 in RD&D 2007) is said to provide a better body of data as a basis for site- and project-related studies and analyses. We interpret this as referring to SKB's own studies and analyses. At the same time, SKB says in a later text section (p. 410) that the main target group for the research programme is decision-makers, local and national. The purpose of the research programme as stated under the heading "socioeconomic impact" is also said to be to gain better knowledge and understanding of the impact of the repository on the local community's economy and population structure. It is further pointed out in RD&D 2007 that the societal research is not primarily municipality-specific, which contradicts the purpose in point 2 above. In SKB's report from 2007 on the social science research programme (*Samhällsforskning 2007, Betydelsen för människorna, hembygden och regionen av ett slutförvar för använt kärnbränsle* ("Societal research 2007, The importance for the people, the local community and the region of a final repository for spent nuclear fuel") (SKB 2007, in Swedish only) it is also said that: "Society demands that SKB provide answers to questions

concerning how the siting of a final repository affects the community where the facility is built,” (SKB 2007 p. 6).

Nor does the Swedish National Council for Nuclear Waste find any description or discussion of how SKB itself intends to use the results of the research, beyond what is said in point 2 above.

The Council finds the three purposes stated above to be reasonable in principle for a social science research programme, but considers the formulations to be far too vague to contribute to a deeper understanding of the programme’s role in SKB’s work and to the solution of the nuclear waste issue. The Council would like to see formulations to the effect that the research programme should contribute to meeting the legal requirement for research results that shed light on societal aspects (voiced by the Council in connection with the review of RD&D Programme 2004) and to the effect that the viewpoints expressed by the Government, regulatory authorities, concerned municipalities and NGOs etc. (regarding the need to shed light on societal aspects and ethical issues) can be complied with.

We do not find any clear references to other parts of RD&D 2007. The Swedish National Council for Nuclear Waste notes that SKB’s social science research programme and its results are entering into the planning and licensing process at a very late date. This makes it even more urgent that RD&D Programme 2007 could have shown how the social science research results can support the solution of the nuclear waste issue and contribute to permit applications by showing the consequences in various respects linked to the choice of site and technical solutions, etc. Nor does the Council find that SKB describes or discusses in RD&D 2007 how far into the future the social science research programme can or should be conducted. This has, in contrast, been described for the RD&D programme’s technical and scientific parts. RD&D 2007 thus lacks a programme describing social science research in the future. The Swedish National Council for Nuclear Waste finds that the formulations of the purpose could been clearer and linked to specific knowledge needs in SKB’s own work, for example with the Environmental Impact Statement (EIS).

Does the social science research programme fill SKB's purpose?

In the opinion of the Swedish National Council for Nuclear Waste, SKB's social science research programme contributes to SKB's formulated purpose no. 1, i.e. a "broader perspective on the societal aspects of the nuclear fuel programme" and facilitates "evaluation and assessment of the programme in a larger context" compared with if the research programme did not exist. However, our review shows that there are a number of substantial gaps in the programme. Some of these gaps can and should be filled by SKB's social science research programme. We judge that other gaps will not be filled due to the focus of the research programme on the projects included today. These gaps should be filled by research funded from other sources than SKB.

The Swedish National Council for Nuclear Waste believes that SKB's social science research programme fills a very important function when it comes to generating knowledge for direct application in development, planning and discussions of solutions etc. to the final repository issue. The Council considers SKB's primary role to be to support applied sectoral research of direct practical benefit for development, planning, applications etc., i.e. the research referred to under points 1 and 2 above. As far as point 2 is concerned, however, the Council finds it difficult to see that SKB has as yet succeeded in linking together the different parts of the research programme and the results with different site- and project-related investigations.

We judge that SKB can contribute to research of a general nature as well, i.e. the research envisioned under point 3. However, such research has been and will continue to be limited and have large gaps. SKB also says that their sectoral research has a more limited focus than, for example, research funded by Riksbankens Jubileumsfond (the Bank of Sweden Tercentenary Foundation) could have had (SKB 2007 p. 12), which supports the Council's assessment.

Viewpoints on SKB's social science research programme in relation to the needs identified by the Swedish National Council for Nuclear Waste

The Swedish National Council for Nuclear Waste has the following viewpoints on the knowledge needs not covered by SKB's social science research programme:

1. Future perspectives and economic analyses with a regional and national perspective are lacking. There is, for example, no treatment of such important parameters as the long-term resource need for alternative solutions of the waste issue.
2. Research on economic, political and other global changes is lacking. This viewpoint was voiced by municipalities and the Council in the review of RD&D 2004 against the background of the fact that SKB spoke in RD&D 2004, Appendix A of fast, far-reaching and unpredictable societal changes. Here we are referring to the need for research on changes in society that are of importance for safety in the final repository with regard to human intrusion, preservation of knowledge concerning the location of the final repository, supply of materials during the construction phase, technology development, etc. The research may concern e.g. the consequences for the nuclear waste programme of a change in national energy policy, for example regarding the future of nuclear power. The point of departure in the RD&D programme is that the present-day policy to phase out nuclear power will remain unchanged. The environmental debate of the past six months has, however, led to renewed discussion of the nuclear power phase-out issue. The research may also concern possible future societal changes of importance for the final disposal problem. The Swedish National Council for Nuclear Waste's state-of-the-art report deals with issues of safety and the three barriers: natural, engineered and social (SOU 2007:38e, p. 82). All three barriers contribute to preventing the spent nuclear fuel from harming man and the environment. Research on the social barrier has to do with e.g. the safety culture of implementing actors, the decision process, attitudes, collective memory, protection in the form of participation, preservation of information and societal control. The need for such research has not been adequately met by SKB's social science research programme.

3. There is a lack of broader, more critically investigative and reflective research. The research may focus on the roles of different local, regional and national actors, interaction, norms, values, ethics, view of knowledge, generation and use of knowledge, choices, actions, power, etc. linked to the final repository process in the past, present and future. A specific issue when it comes to generation and use of knowledge etc. is the role of the environmental impact statement in SSI's, SKI's and the environmental court's judgements in connection with their assessment of SKB's application. Another example is an analysis of the norms and values that underlie SKB's risk and safety assessments, SKB's safety philosophy, and the choices made in the planning process. Furthermore, this research may examine the roles of different actors (media, authorities, NGOs, etc.) and the balance of power among them in opinion formation, decision-making, democracy, etc. specifically in relation to the final disposal issue. This research may also include international comparisons and comparative perspectives on the Swedish nuclear waste programme. Finding a solution to the final disposal issue is of such importance – from the viewpoint of risk to human health and the environment as well as from the economic, ethical and political viewpoints – that it deserves broad treatment aimed at contributing to societal development and learning.

Additional viewpoints held by the Council on SKB's social science research programme are the following:

- There is a research project in the programme that has shown that SKB as the activity operator has played a dominant role in the consultations. But there is nothing in RD&D Programme 2007 to suggest that SKB plans to change the consultations.
- SKB emphasizes the need for knowledge of risk perception in order for communication between planners and decision-makers and private citizens to work. However, the Council's report 2007:4e makes it clear that the need for research on risk perception has been met relatively well in general.
- A large part of the social science research programme is concerned with how opinions and attitudes are formed and change. However, the Council's overview of ongoing research in Sweden (Report 2007:4e) makes it clear that there are

already relatively many projects in this field. The Council's report instead calls for in-depth studies of conflicts between different risk assessments, how they are made, and how they are communicated.

14.3 Swedish National Council for Nuclear Waste's conclusions

The Council observes that the research programme has been started late in the final repository programme and that the programme has consequently not been able to fulfil its knowledge-producing potential in contributing to the societal aspects of the permit applications compared to if the programme had been started at an earlier stage. The Council therefore makes no recommendations for changes in the purpose of the programme in preparation for the submission of applications. However, the research programme has an important role to play during the review phase as well when it comes to presenting research results of benefit to municipalities, the Government, regulatory authorities and other actors. Furthermore, the construction and operating phases for the final repository will last a long time, which is a reason for some parts of the social science research programme to continue as proposed below.

The Council concludes that there are urgent research questions that will not be answered by SKB's social science research programme, as enumerated in point 3 in section 14.2. In the Council's opinion, this points to the need for research in the social sciences and the humanities linked to the final repository issue that has a broader and more critically reflective orientation than SKB's social science research programme and that is funded by another actor than SKB.

- The social science research programme should be supplemented by studies of future economic consequences of the handling of the nuclear waste issue, mainly cost-benefit analyses. This is needed in order to judge what societal resources are needed for alternative solutions.
- We consider research projects on global changes and safety culture (see point 2 in section 14.2 for details) to be a very

urgent research field, since such research can shed light on the social barrier for safety in the final disposal solution.

- SKB's social science research programme should continue after an application has been submitted in 2010 and be developed in a similar manner as the RD&D programme for natural science and technology.

15 LILW and decommissioning

15.1 Background

RD&D Programme 2007 gives only a very general account of issues related to low- and intermediate-level waste (LILW) and decommissioning. However, SKB says that they will provide a more detailed account of these issues in the next RD&D programme, RD&D Programme 2010.

The LILW programme embraces all low- and intermediate-level waste that will be disposed of in SKB's facilities. The facilities covered by the LILW programme are SKB's own existing and future facilities for final disposal of waste from the Swedish nuclear power plants. Interim storage of long-lived low- and intermediate-level waste from the nuclear power plants in BFA (rock cavern for waste at the Oskarshamn nuclear power plant) is also included in the programme.

In preparation for decommissioning and dismantling of the nuclear power plants, SKB intends to carry out decommissioning studies for the purpose of estimating costs and waste quantities, both radioactive and non-radioactive, as well as free-release material. The studies are based on the strategies and technologies that are developed in cooperation with the power plant owners. SKB will only dispose of the radioactive waste, but in the studies SKB calculates the volumes and the costs of decommissioning waste.

In RD&D Programme 2004, SKB states that the timetable for decommissioning of the Swedish nuclear power plants has not been finalized. The power companies estimate that the operating time of the reactors could end up being 60 years or more. SKB's planning and cost estimates are based on the assumption that the power

plants will be operated for about 40 years and then decommissioned as soon as possible.

The Swedish National Council for Nuclear Waste has said the following in previous review statements:

- Planning by SKB and licensees needs to be further concretized, e.g. including regard to decommissioning logistics.
- The Government should ensure that more light is shed on issues relating to the need for Environmental Impact Statements for a large-scale phase-out of nuclear power, including decommissioning of the nuclear power plants. The implications of current EU directives and provisions of the Environmental Code need to be clarified prior to decommissioning of nuclear power plants.

SKI and SSI as well as the Council have also maintained that issues related to LILW and decommissioning should be given greater attention. This includes both timetables for decommissioning (for example the question of immediate dismantling of the already shutdown Barsebäck reactors, and dates for completion of final repositories for different types of decommissioning waste) and division of responsibilities between the reactor owners and SKB. In a Government decision on RD&D Programme 2004, the Government gave its support to this view. The Government points out (along with SKI and SSI) that SKB should reconsider the reasons for waiting to build a final repository for long-lived waste until the majority of the nuclear power plants have been decommissioned.

15.2 Swedish National Council for Nuclear Waste's considerations

There are a number of issues which SKB (as well as SKI and SSI) have highlighted that need to be dealt with more thoroughly than they have been so far. They include e.g. classification of waste types, an account of where the different waste categories are to be disposed of, nuclide measurements, correlations between different radionuclides, etc.

Furthermore, the question of strategies for decommissioning should be discussed, for example immediate dismantling when the

final repositories are available for the decommissioning waste or immediate dismantling that can create a need for interim storage facilities. There may be different interests here, for example with regard to the already shutdown reactors in Barsebäck and other aspects of the reactor programme.

Even though it is clear that the division of responsibilities for decommissioning essentially entails that SKB is responsible for R&D and planning, construction and operation of the necessary facilities and that the nuclear power plants are responsible for the actual decommissioning work, the question of division of responsibilities between the nuclear power plants and SKB needs to be discussed further, in particular what this division of responsibilities entails in the practical work of preparing and executing decommissioning and dismantling.

These questions were discussed at the hearing arranged by the Swedish National Council for Nuclear Waste on decommissioning in November 2007 (see Council report 2007:7e). At the hearing, the importance of inviting concerned municipalities to participate in the dialogue when a nuclear power plant is to be decommissioned was emphasized.

In the opinion of the Council, it would be valuable to know how all types of nuclear waste (and spent nuclear fuel) can be disposed of in Sweden and what activities and facilities are needed for this. The delimitation to the KBS-3 system that is now being done by SKB with regard to systems analysis entails a focus on how the spent nuclear fuel is disposed of but does not include how operational or decommissioning waste from facilities and activities inside and outside the KBS-3 system is disposed of (e.g. low- and intermediate-level waste from the reactors or from Clab). According to the Swedish National Council for Nuclear Waste, systems analysis should be regarded as a valuable tool that can be used to study interactions between different components in complex systems. A systems analysis of the system of facilities included in the LILW and decommissioning programme should be of value for a broad understanding of the need for R&D and for prioritizations within this area. Questions of this kind were discussed at the hearing on systems analysis arranged by the Swedish National Council for Nuclear Waste in April 2008.

15.3 Swedish National Council for Nuclear Waste's conclusions

SKB should give a more detailed account than they have given to date of the planning for the disposal of low- and intermediate-level waste (LILW) and how the decommissioning of nuclear facilities will be carried out. Such an account is planned by SKB in conjunction with RD&D Programme 2010. The Swedish National Council for Nuclear Waste would particularly like to draw attention to the following questions:

- SKB should specify when different facilities can be decommissioned and give reasons for this. The desire for immediate dismantling can be evaluated in relation to the need to have final repositories ready to receive decommissioning waste before the dismantling work is begun. The Swedish National Council for Nuclear Waste therefore believes that there is a need for a systems analysis encompassing all the facilities and activities covered by SKB's account of LILW and decommissioning.
- Questions concerning the decision process for decommissioning and disposal of the waste need to be studied. The need for environmental impact assessments of decommissioning of nuclear power plants should be illuminated. The implications of current EU directives and provisions of the Environmental Code need to be clarified prior to decommissioning of nuclear power plants.
- The Swedish National Council for Nuclear Waste wishes to emphasize the importance of a transparent decision process with regard to decommissioning and dismantling where the municipalities are invited to participate in the dialogue.

Appendix 1

The Swedish nuclear waste programme

Presentation and review of programme for research and development

According to Section 12 of the Act (1984:3) on Nuclear Activities (the Nuclear Activities Act), the reactor owners shall prepare or have prepared a programme for the comprehensive research and development work and other measures needed for “ensuring the safe management and final disposal of nuclear waste arising in the activities or nuclear material arising therein that is not reused” (Section 10 Paragraph 2) and for “safely decommissioning and dismantling plants in which activities are no longer to be conducted” (Section 10 Paragraph 3). The programme shall be prepared every three years, cover a period of six years and be submitted to the Swedish Nuclear Power Inspectorate (SKI).

The reactor owners have assigned SKB the task of preparing this programme. The most recent programme, “RD&D Programme 2007 – Programme for research, development and demonstration of methods for the management and disposal of nuclear waste,” was published by SKB in September 2007.

Every RD&D programme is reviewed by SKI, which circulates it to a large number of organizations and invites them to offer viewpoints. These viewpoints are compiled by SKI, which submits its own viewpoints and comments to the Government.

In parallel with this thorough review by SKI, the programme is also reviewed by the Swedish National Council for Nuclear Waste, which submits its own review statement to the Government. Based on SKI's and the Council's review statements, the Government then decides whether the programme meets the requirements of the Nuclear Activities Act (including with regard to comprehensiveness). The Government can prescribe conditions for the continued research and development activities that are considered necessary. Provided that SKB complies with the stipulated conditions and otherwise takes into account the comments made by the Government and its authorities, the RD&D programme can be regarded as having received the support and approval of society. It should, however, be pointed out that the Government, in its examination of future applications for permits under the Nuclear Activities Act and permissibility under the Environmental Code, is not formally bound by what has been pronounced in previous decisions with regard to the RD&D programmes.

Fundamental principles for the division of responsibilities between the state and the nuclear power companies

The division of responsibilities between the state and the nuclear power companies when it comes to management and final disposal of spent nuclear fuel etc. is based on four fundamental principles that have been established by the Riksdag (Swedish parliament). These principles are reflected today mainly in the Nuclear Activities Act and the Act (2006:647) on Financial Measures for the Management of Waste Products from Nuclear Activities. Some of the principles are also expressed in international conventions to which Sweden has acceded and is thereby bound to comply with.

The four principles can be expressed as follows¹.

- The costs for final disposal of spent nuclear fuel and nuclear waste must be covered by revenues from the production of energy which has given rise to them. Considering the long time periods required for management and disposal, expenses will arise long after production at a nuclear power plant has ceased. This means that funds for future expenses for the management and disposal of spent nuclear fuel etc. must be continuously taken from the revenues from the energy production and set aside for later use.
- A reactor owner must take responsibility for ensuring that spent nuclear fuel and nuclear waste are managed and disposed of in a safe manner. This means that the reactor owners must ensure that the requisite measures for management and disposal are actually implemented. They must ensure that the necessary technical know-how, skills, equipment, manpower etc. are available and are utilized.
- The state has overall responsibility for spent nuclear fuel and nuclear waste. This includes overall responsibility to ensure that final disposal is implemented plus ultimate responsibility for final disposal in the sense that the state is compelled to assume responsibility for procurement and financing if the nuclear power industry is not able to get the job done or abstains from doing so for other reasons.
- Every country has to take responsibility for the spent nuclear fuel and nuclear waste generated in that country. From this it follows that final disposal of spent nuclear fuel and nuclear waste from nuclear activities in another country may not occur in Sweden other than in exceptional cases.

The questions surrounding nuclear waste management are not just technical; they also require political decisions. And, as noted in the Swedish National Council for Nuclear Waste's 2007 report on the state-of-the-art in the nuclear waste field, these decisions must be made under some uncertainty, where a non-decision also entails taking a position (cf. SOU 2007:38e, pp. 21–24, 84 and 88–92).

¹ For a more detailed account with source references, see a report published by the Swedish Nuclear Power Inspectorate in December 2006, *Statens ansvar för slutförvaring av använt kärnbränsle*. (SKI Rapport 2007:01, pp. 3–4, in Swedish only).

Handling, planning and financing

The foundation for the development of the Swedish nuclear power programme began to be laid back in the late 1940s. This work continued during the 1950s and 1960s. An application for a concession for what would be the first nuclear power reactor in Sweden, Oskarshamn 1, was submitted in 1965. That reactor was put into commercial operation in 1972. During the period 1969–1972, the owners of the future nuclear power plants in Oskarshamn, Ringhals, Barsebäck and Forsmark ordered an additional seven reactors.

Questions regarding how the waste from nuclear power production would be managed were only raised sporadically in the public debate during this period of growth and development. But a change occurred in the early 1970s. After a few years – roughly at the same time the first reactor at Oskarshamn was put into service and seven other reactors were ordered – the waste issue was suddenly at the focus of the energy debate.

At the beginning of 1973, the Government formulated the terms of reference for a joint parliamentary committee to investigate matters “pertaining to high-level waste from nuclear power plants”. The committee – known as the AKA Committee – proposed in the mid-1970s a system of facilities similar to the system which now exists in Sweden in certain parts and which SKB plans to develop. The complete system includes the existing waste facilities CLAB (central interim storage facility for spent nuclear fuel) and SFR (final repository for low- and intermediate-level operational waste) plus planned final repositories for, among other things, high-level waste. The AKA Committee never led to any Government bill, but its work had a very great influence on the planning of the management of the waste from the Swedish nuclear power plants and from other nuclear activities.

The Stipulations Act, which entered into force in 1977 and was abolished when the current Nuclear Activities Act entered into force in 1984, required an “absolutely safe” final disposal of the spent nuclear fuel in order for a fuelling permit to be issued for a reactor. The Nuclear Activities Act requires a “safe” management and final disposal of spent nuclear fuel and nuclear waste and imposes responsibility for research, development and execution on

the reactor owners². According to the Act, they have to present a research and development programme every three years. In order to prepare and develop this programme (now called an RD&D programme) and to manage the radioactive waste and the spent nuclear fuel from the reactors, the owners of the Swedish nuclear power reactors have formed the aforementioned company SKB, which is owned by them jointly.

In the early 1980s the Riksdag decided on a special financing of the future costs for safe management of the spent nuclear fuel and decommissioning of the nuclear facilities. The financing system basically entails that the nuclear power companies pay a special fee to a state-administered fund, the Nuclear Waste Fund. The fee is levied at a given rate per kWh of electricity delivered by the nuclear power plants. In 2008 the fee amounted to about 0.8 öre/kWh (100 öre = 1 krona). The nuclear power companies are entitled to reimbursement from the Fund for any costs they incur for measures aimed at safe management and disposal of the spent nuclear fuel. The remaining assets are held in the Fund for future needs. In addition to the fee, the nuclear power companies must pledge certain financial guarantees for the calculated costs. Current provisions are found in the Act (2006:647) on Financial Measures for the Management of Waste Products from Nuclear Activities and an associated ordinance (2007:161).

So far the funding system has worked well. Up to and including 2007 it has covered costs for management and disposal of spent nuclear fuel, including research and development of a final disposal system, amounting to nearly SEK 21 billion (at current prices)³. According to the latest cost calculations, an additional around SEK 67 billion (2007 prices) will be needed. Of this amount, around SEK 39 billion is in the Fund today. According to the calculations,

² In the travaux préparatoires leading up to the Nuclear Activities Act (see Gov. bill 1983/84:60 p. 46) the Government emphasized that extremely strict requirements regarding safety and radiation protection must be made on management and final disposal of the spent nuclear fuel and continued: "It is therefore urgent that the research and development work concerning the waste issues continue to be pursued after a fuelling permit has been issued. Against this background it would appear unfortunate if a method were to be designated 'absolutely safe' – as in the Stipulations Act – which could give the impression that further research and development work is not as urgent. The expression 'absolutely safe' should therefore not be carried over into a new law."

³ The figure is taken from the 2007 Annual Report for the Nuclear Waste Fund. The amount given for costs to date for the Swedish nuclear waste programme in RD&D Programme 2007 (p. 37) is around SEK 27 billion, and for the total costs from the start around SEK 94 billion. The remaining costs thus amount to about SEK 67 billion. It should be observed that the amounts given in RD&D Programme 2007 are in 2007 prices.

the difference, about SEK 28 billion, will be covered by the return on existing Fund assets and by continued fee payments as long as reactors are in operation⁴.

Choice of alternative disposal methods

In the international exchange of ideas around final disposal of nuclear waste, five different strategies have been considered:⁵

- Ultimate removal by launching into space.
- Disposal in inaccessible areas on Earth, for example beneath the Antarctic ice sheet or in deep sea sediments.
- Long-term storage of the spent fuel in a monitored repository – possibly pending the further development of other strategic and technical alternatives, sometimes called the “zero alternative”.
- Nuclear transformation, transmutation, of the waste to reduce its radiotoxicity.
- Final disposal of the waste deep down in the bedrock.

The first two strategies have been dismissed from the discussion for obvious reasons (unacceptable safety risks and/or breaches of international conventions). The third strategy entails leaving it to those who will live in future centuries to arrive at a satisfactory long-term solution. Large research and development efforts have been launched internationally around the fourth strategy, transmutation. But with today’s knowledge of the technology and economics of this strategy, it has so far not been considered acceptable in this country that it would constitute the basis for a long-term solution. Instead, the strategy in Sweden has been focused on the fifth alternative, final disposal of spent nuclear fuel deep down in the bedrock. There is also a broad international consensus among technical experts that geological disposal (in the bedrock or in other geological formations) is the most suitable

⁴ In conjunction with the presentation of RD&D Programme 2004, the future costs were calculated to be about SEK 55 billion. The most important reasons why the costs calculated in 2007 are much higher (SEK 67 billion) is that the volumes of spent nuclear fuel are now projected to be greater than before, because the industry now assumes that the remaining reactors will be in operation longer than has previously been assumed, that the costs for future decommissioning of the nuclear power plants have been calculated to be higher, and that the most recent calculation is done in 2007 prices.

⁵ For a more detailed account of these strategies, see the Swedish National Council for Nuclear Waste’s report *Nuclear Waste State-of-the-Art Report 2007 – responsibility of those now living, freedom of future generations* (SOU 2007:38e pp. 37–47).

method for disposal of the most hazardous forms of radioactive waste. This is the strategy preferred by most countries with a research and development programme for high-level waste or spent nuclear fuel.

Over the years SKB has presented several different alternative methods for final disposal of spent nuclear fuel in the Swedish bedrock:

- The KBS-3 method (see further below).
- Long tunnels (Very Long Holes), where encapsulated fuel is emplaced spread out in a number of approximately 5-km-long tunnels.
- WP-Cave, where encapsulated fuel is emplaced in a cage-like rock structure at a depth of 300–500 metres.
- Deep boreholes (Very Deep Holes), where encapsulated fuel is deposited in holes drilled from the ground surface at a depth of 2–4 km.

The KBS-3 method (which involves placing the spent nuclear fuel in copper canisters with a cast iron insert and emplacing the canisters in holes, with a surrounding barrier of bentonite clay, in a tunnel system in rock at a depth of 400–500 metres) has been developed gradually over several decades with periodic presentation and review of the results. The KBS-3 method has been accepted by the Government as the main alternative in the continued development work. In a Government decision in November 2001 in response to SKB's supplement to RD&D Programme 98 (known as the RD&D-K report), the Government approved this method as a "planning premise" for the site investigations which SKB is currently conducting in Forsmark (Östhammar Municipality) and Laxemar (Oskarshamn Municipality). However, in the same decision the Government underscored "that final approval of a specific method for final disposal cannot be given until a decision is made on applications under the Environmental Code and the Nuclear Activities Act for a permit to build a final repository for spent nuclear fuel".

Selection of alternative sites for final disposal

From the late 1970s to the mid-1980s, deep boreholes were drilled and measurements performed in some ten areas (later designated *study site investigations*) in different parts of Sweden. These field investigations were interrupted in the face of protests by the local population in several localities. In the early 1990s, SKB initiated a site selection process based on voluntary participation with a number of municipalities where *feasibility studies* were conducted. The purpose of these feasibility studies was to clarify whether there were good geological and other prospects in the investigated municipalities for identifying sites suitable for locating a final repository for spent nuclear fuel. In 2000, SKB identified three sites as being suitable for further studies and asked the three concerned municipalities for permission to conduct *site investigations*. Two of the municipalities, Oskarshamn and Östhammar, granted permission. In both of these municipalities, a virtually unanimous municipal assembly had supported the decision to grant permission, but at the same time they formulated a number of conditions.

The geological investigations which SKB has carried out to obtain data as a basis for selection of a site for a final repository for spent nuclear fuel – with the KBS-3 method as a planning premise – were thus originally conducted for the purpose of surveying the geological conditions in large parts of Sweden. Such a site must satisfy fundamental requirements in accordance with the provisions of the Nuclear Activities Act, the Environmental Code and regulations issued by the Swedish Nuclear Power Inspectorate and the Swedish Radiation Protection Authority. But site selection must also have political support, i.e. both the concerned municipality and the Government must accept the siting.

The Government's decision to accept the KBS-3 method as a planning premise made it possible for SKB to start the site investigations in Forsmark and Laxemar. These site investigations were concluded at the turn of the year 2007/2008.

Appendix 2

Description of the chemical composition of the buffer

Names of clay minerals are used in different contexts in RD&D 2007 in describing different processes in the bentonite buffer. Examples of such names are *montmorillonite*, *pyrophyllite*, *smectite*, *illite* and *chlorite* together with inorganic compounds (minerals) such as *quartz*, *feldspars*, *mica*, *plagioclases*, *amorphous silicon*, *calcite*, *pyrite*, *siderite* and *gypsum*. The latter are regarded in this context as impurities in the bentonite, even though most of them are natural components in clays.

It may therefore be useful to sort out the terminology in order to make it easier to understand the processes described in the research programme. A clay (such as bentonite) is a general name for an inorganic material consisting of tiny particles (< 0.002 mm). Clay generally contains primary clay minerals, of which the most important ones are different types of *feldspars*. Feldspars can be divided into two main groups called *alkali feldspars* and *plagioclases*. Alkali feldspars consist of a mixture of KAlSi_3O_8 (orthoclase) and $\text{NaAlSi}_3\text{O}_8$ (albite) and the composition of the plagioclases varies between the two extremes $\text{NaAlSi}_3\text{O}_8$ (albite) and $\text{CaAl}_2\text{Si}_2\text{O}_8$ (anorthite).

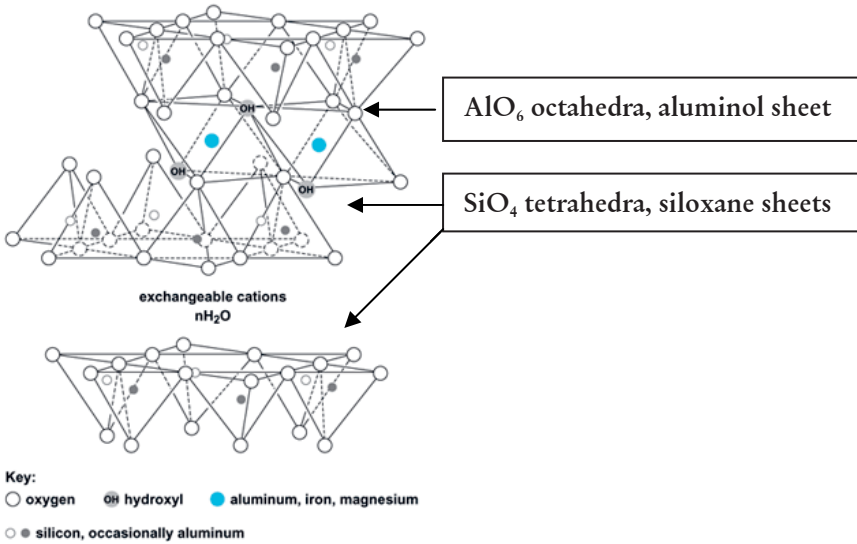
Clay also contains secondary clay minerals, such as *smectite*, *montmorillonite*, *pyrophyllite*, *illite* and *chlorite*.

There are a relatively large number of different types of secondary minerals grouped under the heading “phyllosilicates” (sheet silicates).

One subgroup consists of the 2:1 minerals, which consist of two sheets with interlinked SiO_4 tetrahedra (siloxane sheets). The crystal structure is built up in such a way that a sheet with AlO_6

octahedra (aluminol sheet) is sandwiched in between the siloxane sheets (see Figure 1).

Figure 1 Crystal structure of clay minerals (smectite)



The chemical formula of an ideal 2:1 clay such as *pyrophyllite* is $\text{Si}_8^{\text{IV}}\text{Al}_4^{\text{VI}}\text{O}_{20}(\text{OH})_4$, but different variations are common.

Between the siloxane sheets, different types of cations (positive ions) are often coordinated either via hydroxyl groups (OH groups), in which case they are called *chlorites*, or as individual cations with or without a surrounding water shell, for example in *smectites*.

In general, neither the tetrahedral siloxane sheets nor the octahedral aluminol sheet sandwiched between them are completely intact. In the SiO_4 sheets, some of the Si^{4+} may be exchanged for Al^{3+} and in the AlO_6 sheet, Al^{3+} may be substituted for Fe^{2+} , Fe^{3+} , Mg^{2+} , Ni^{2+} , Zn^{2+} or Cu^{2+} . The process is called isomorphous substitution. If the substituted ions have a higher positive charge than the substituting ions (e.g. $\text{Al}^{3+} \leftrightarrow \text{Mg}^{2+}$), the net effect may be that the sheet becomes negatively charged.

Montmorillonite, which is the main constituent of bentonite, belongs to the smectite group. In montmorillonite, the substitution has mainly occurred in the octahedral sheet, i.e. Al^{3+}

has been partially replaced with Mg^{2+} and Fe^{2+} , which gives rise to a negative surface charge. This takes place in the octahedral aluminol sheet, while the tetrahedral siloxane sheet is preserved more or less unaffected. The negative charge is compensated for by adsorbed cations (positive ions) between the siloxane sheets. They can be exchanged relatively easily, and together with water they give the montmorillonite its unique properties as a swelling and shrinking clay mineral.

The ideal chemical formula for montmorillonite is $M_{0.33}H_2OAl_{1.67}(Fe^{2+},Mg^{2+})_{0.33}Si_4O_{10}(OH)_2$, where M stands for adsorbed and exchangeable cations (Na^+ , Ca^{2+}) between the layers.

In other types of smectites, the substitution has instead taken place in the siloxane sheet ($Si^{4+} \leftrightarrow Al^{3+}$), which means that the negative charge arises there. This also means that adsorbed cations are generally more tightly bound to the surfaces and are not as readily exchanged.

Illite is an intermediary between *smectite* and *mica mineral*, for example muscovite with the chemical formula $K_2Al_2(OH)_2(AlSi_3O_{10})$. Illite contains more Si^{4+} , Mg^{2+} and H_2O but less Al^{3+} and K^+ than muscovite. K^+ is, however, the dominant cation between the layers together with Ca^{2+} , Mg^{2+} and sometimes NH_4^+ (ammonium ion).

Illite swells very little in water.

Quartz or silicon dioxide occurs in several forms with different crystal structures. The SiO_4 tetrahedra have common corners and form molecules that extend into three dimensions.

Silicon dioxide is an acidic oxide that is attacked by alkaline solutions (high pH).

Amorphous silicic acid has the formula $Si(OH)_4$ or better $SiO_2 \cdot 2H_2O$.

Calcite consists of calcium carbonate and has the formula $CaCO_3$. When calcium carbonate is precipitated in an aqueous solution at room temperature, calcite (calcspär) is formed, while precipitation at higher temperature gives another phase (aragonite) with the same composition but another structure.

Calcite is an alkaline mineral that reacts with and neutralizes acidic solutions (low pH).

Siderite or iron spar has the chemical formula $FeCO_3$ and is thus iron carbonate and contains divalent iron ions (Fe^{2+}) that can be oxidized in air to Fe^{3+} to form $FeO(OH)$.

Both siderite and calcite dissolve in water containing carbon dioxide.

Another ferrous mineral occurring in bentonite is *pyrite*, FeS₂. Pyrite is also oxidized by oxygen in air, forming sulphate ions and making the solution acidic (low pH).

Gypsum consists of calcium sulphate and has the formula CaSO₄·2H₂O.

The mineralogical composition of *Friedland Clay* looks completely different. Friedland Clay contains much more *quartz*, *mica*, *kaolin*, *illite* and *feldspars* and does not have the same capacity to swell as bentonite, with a much poorer ion exchange capacity.

Kaolin is a non-swelling clay mineral of the 1:1 type, i.e. its crystal structure contains one siloxane sheet and one aluminol sheet.

Appendix 3

Sorption and surface chemical reactions in the buffer

In conjunction with its review of RD&D 2007, the Council would like to suggest what could be included in a more sophisticated model and how such a model could contribute to a better understanding of sorption processes in the buffer and the backfill.

The buffer is supposed to prevent colloids and radionuclides from escaping from a damaged canister (RD&D 2007 p. 318).

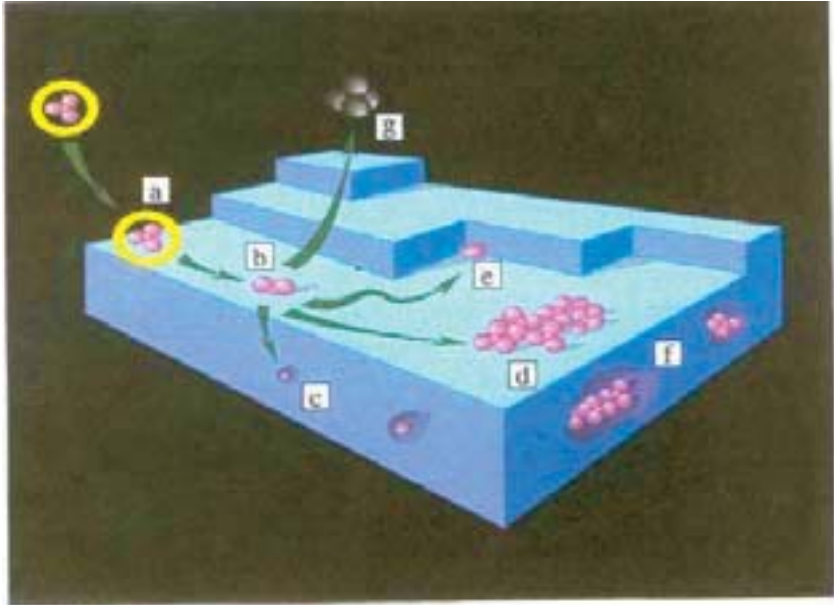
Adsorption is one of the primary processes that affect transport of impurities as well as radionuclides in clays (e.g. in the bentonite buffer). Both physical and chemical forces are involved in adsorption. The physical causes include electrostatic effects (charge effects) due to the fact that opposite charges attract while like charges repel.

The most important chemical forces for adsorption are different types of chemical bonds.

The buffer and the backfill in a final repository can be described as a highly concentrated mineral suspension, at least when it has been water-saturated. The surfaces of the mineral particles together comprise adsorbents with a very large total surface area. It is these surfaces, in contact with surrounding water, that constitute the active part of the buffer and backfill, and it is also the properties of these surfaces that determine how well the buffer can perform its intended function.

There are a variety of different mechanisms for adsorption of an ion in the mineral/water interface (Figure 1).

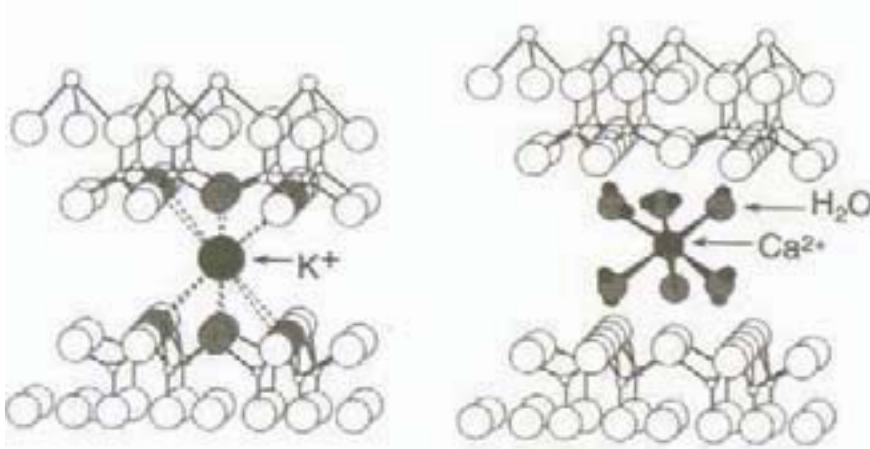
Figure 1 Different mechanisms for adsorption of ions on clay mineral



From Charlet and Manceau 1993 CRC Press Boca Raon, FL.

- a) Adsorption of ions via outer-sphere complex formation.
- b) Reaction with specific surface sites on the mineral particle and inner-sphere complex formation.
- c) Diffusion through the surface followed by isomorphous substitution.
- d) Diffusion along the mineral surface and surface precipitation.
- e) Diffusion on the surface to one site (ledge or irregularity), which maximizes the number of bonds to the adsorbed ion.
- f) If the mineral particle grows, the surface precipitate can be embedded in the crystal structure.
- g) The adsorbed ion can diffuse back to the surrounding solution as a result of dynamic equilibrium or as a result of redox reactions (e.g. change from oxidizing to reducing conditions).

Figure 2 and Figure 3. Example of inner-sphere and outer-sphere complexes



Positive ions (cations) can be adsorbed both as inner-sphere and outer-sphere complexes, depending on the properties of the ion, for example ion size, charge, hydration energy (the energy that is liberated when the ion is surrounded by a water shell), etc. An ion that is adsorbed as an outer-sphere complex often retains its shell of water molecules. Compare, for example, the potassium ion and the calcium ion in Figures 2 and 3.

Another crucial factor is the pH of the solution (suspension) and the fact that same ion can form an outer-sphere complex at a lower pH and an inner-sphere complex at a higher pH. A high ionic strength also favours the formation of inner-sphere complexes, which means that the ion is more tightly bound to the surface. This applies, for example, to the adsorption of lead ions (Pb²⁺) on montmorillonite, where outer-sphere complexes are formed at low ionic strength (0.006 M) if pH < 6.5 and inner-sphere complexes are formed at higher ionic strength (0.1 M) and higher pH (pH > 6.7).

Thus, potassium ions (K⁺) form inner-sphere complexes with the surface, while calcium ions (Ca²⁺) form outer-sphere complexes with the same surface (see Figs. 2 and 3). Potassium ions are chemically bound to the surface, while calcium ions are electrostatically bound and the surface has a different charge. The

potassium ions then shed their surrounding “shell” of water, while the calcium ions retain it. As a result, the potassium ions are difficult to leach out and adsorption causes the mineral to lose much (most) of its swelling capacity. Illite contains adsorbed potassium ions.

Mechanism b) can give rise to negative charges on the particle surfaces due to the fact that ions with a lower positive charge, such as Mg^{2+} or Fe^{2+} , are adsorbed and then replace an ion with a higher charge, such as Al^{3+} , in the mineral. The net effect is a reduced positive charge and thus a surplus of negative surface charge. As a result, most clay minerals, such as montmorillonite, have a negative total charge and the pH theoretically needs to be reduced to about 2.5 in order for the surface to become positively charged. The negative surface charge is compensated by positive ions (cations) between the siloxane sheets (see Figure 3). It may be hydrated sodium ions or calcium ions, i.e. ions with a surrounding “shell” of water.

Mechanisms d), e) and f) in Figure 1 are some of the reasons why minerals such as calcite, gypsum and pyrite occur as impurities in the bentonite.

Mechanism g) entails that if conditions – such as pH, ionic strength, temperature and redox level – change (e.g. from oxic to anoxic redox level), adsorbed ions can diffuse back to the surrounding solution and be transported to a new location in the buffer and one or more of the other mechanisms can once again enter into play.

Transport depends on ion charge

Transport of radionuclides and other ions through the bentonite varies greatly depending on their charge.

The negative charge of the mineral particles at the pH values that occur in the final repository causes positive ions (cations) to be adsorbed and transport to be retarded, while negative charged ions (anions) are repelled and in general diffuse more rapidly through the buffer (or the backfill).

The situation when it comes to adsorption of negative complex ions (anions) is more complicated. Since the dominant mineral surfaces in the buffer and the backfill are negative, electrostatic effects due to different charges are not an issue.

However, anions can be adsorbed onto certain surface sites due to ion exchange with hydroxyl (OH) groups from the surface or due to hydrogen bonding, whereby water molecules or hydroxyl groups (OH groups) on the mineral surface interact with the water molecules that surround the anion.

As far as the bentonite is concerned, the siloxane sheets between the layers of montmorillonite consist of Si–O–bonds that make the surface relatively hydrophobic (water-repellent). These surfaces interact with different ions mainly via electrostatic attraction due to different charges between adsorbent and adsorbate. The edges of the layers are, on the other hand, more hydrophilic and contain =AlOH sites whose charge is dependent on the pH of the suspension. The edges can therefore react with negative ions either via specific chemical (covalent) bonding or via hydrogen bonding.

There are a number of equilibrium-based adsorption models based on the fact that a mineral surface in an aqueous suspension is surrounded by a layer of water molecules that are more or less structured depending on the charge of the surface. The reason for this is that the water molecule is a dipole, i.e. it contains both a positive and a negative part. This layer of water molecules is called the electrical double layer and its thickness is dependent on, for example, the size of the surface charge and the ionic strength of the suspension (thicker layer at low ionic strength). Reactions in and around the EDL are crucial for the adsorption of different ions on the surfaces. (For an illustration of the EDL, see Figure 8.1 in the Chapter entitled Buffer.)

The charge distribution from the mineral surface through the EDL can be described by a number of different models which serve as a basis for creating a thermodynamic adsorption model that can describe complexation on the surfaces as a function of different concentrations and pHs. This model describes the formation of surface complexes that are thermodynamically motivated and can be used together with data for formation of complexes in solution and dissolution/precipitation of poorly soluble compounds.

This is thus a brief description of what the Council in previous reviews has referred to as a sophisticated adsorption model.

Appendix 4

A systems analysis approach to the safety assessment

In this appendix we use a systems analysis approach to provide perspective on the safety assessment. According to Checkland, systems can be divided into four classes:

Natural systems (NS). Natural systems can be studied, described and predicted by the natural sciences. Man as a creature of nature is included in these systems, but also has the ability to create and utilize the following three systems.

Designed physical systems (DPS). The origin is man and a purpose. A DPS has thus comes about as a result of a purposeful act. For example, man has developed nuclear power plants to produce electricity. DPS can be described with the same theories as NS.

Designed abstract systems (DAS). Like a DPS, the origin of a DAS is in man and a purpose. The difference compared with a DPS is that a DAS is an abstract system. A good example is a model system for safety assessment.

Human activity systems (HAS). The origin is our self-reflective capacity and our resultant ability to establish goals, for example to build a final repository or to develop a model system for safety assessment. An HAS reflects over and determines the goals of its activity as well as the means to achieve the goals.

Here we choose to treat the safety assessment as an activity, in other words a human activity system which we designate HAS(safe). The HAS(safe) builds up a DAS(safe) and uses it to describe the safety of a DPS (final repository) embedded in an NS (surrounding rock). An HAS cannot be described and predicted in

the same way as other systems. In lieu of constitutive models for HAS, CATWOE serves as a tool which has been shown by experience to work for defining such systems. It consists of the following parts:

- Customers: Those who utilize the results of the activity (actually the transformations, see below).
- Actors: Those who carry out the transformations.
- Transformation: Change of the system from one state to another.
- Weltanschauung: Worldview that makes the transformations meaningful in a context.
- Owners: Those who can stop the system, i.e. its transformations.
- Environment: The surrounding world with its environmental constraints.

The implications of these concepts for the final repository programme terms are described below.

Customers

During the research and development phase of the final repository programme, the customers for the safety assessment consisted primarily of two categories:

- R&D personnel employed or engaged by SKB, SKI and SSI.
- Board members of SKB, SKI and SSI as well as KASAM.

Later, SKB's programme entered a new phase with preliminary investigations within a number of municipalities for the purpose of finding possible sites for a final repository, followed by site investigations in two municipalities. The safety issue thereby became a topical subject for debate at the local level on a much greater scale than before. The circle of customers has thereby been widened to include concerned municipalities.

A judgement of SKB's future application, including the choice of site for a final repository, will in the end be a decision at the highest political level and be based on a complex body of background material. It is important that agreement can be reached on

what this background material should consist of and that the decision be preceded by a broad discussion that should also include environmental groups. They also then become customers for the safety assessment. Over the years SKB, the regulatory authorities and the municipalities (each acting in its respective role) have tried, by means of both informal and formal methods, to involve environmental groups and concerned private citizens in a joint accumulation of knowledge regarding the problem complex surrounding the final repository project.

Ultimately, the results of the safety assessments also comprise background material for Government decisions on e.g. siting of a final repository. The Government can thereby also be said to be a customer, albeit an indirect one via the Swedish Radiation Safety Authority and the environmental court.

Actors

The group of actors has been stable since the early 1980s and has consisted of relatively small but steadily growing groups of R&D personnel employed or engaged by SKB, SKI and SSI.

Transformation

Opinions on what the safety assessment transforms may differ. It may, for example, be technical-scientific information:

T1 *HAS(safe) transforms independent information on all relevant technical-scientific areas to coherent information on the total safety of the facility and the importance of the different areas for safety.*

Other conceivable transformations may be (particularly with a view to the new customers):

T2 *HAS(safe) transforms the R&D staff's pictures of the importance of all relevant technical-scientific processes for the safety of the final repository into confirmed or new pictures of their importance.*

T3 *HAS(safe) transforms persons who are unsure about the safety of a proposed repository into persons who are convinced of the safety of*

the repository or persons who are convinced that the repository is not safe.

T4 *HAS(safe) transforms incomprehensible and detailed technical and scientific information and assessments concerning the performance of the final repository into a body of background material which decision-makers dare to use to justify the issuance of a permit to safe facilities (or the non-issuance of permits to unsafe ones).*

Transformation T1 is mainly used by R&D personnel at SKB and the regulatory authorities to create a picture of safety for themselves and to convince one another. The reason why other transformations are needed is that worldview W1 can in part be called into question (see below). In short, T1 assumes a belief in the scientific-technical positivism described in W1.

T2 has roughly the same customer category as T1, but is mainly motivated by a more modest attitude to what a safety assessment is capable of doing (i.e. slightly less scientifically positivistic). T3 is aimed at new customer categories (interested persons in concerned municipalities, officials at the Government Offices, aware private citizens), while T4's direct customers are board members, municipal politicians and even the Government.

Worldview

The worldview that dominated in the early phase of the safety assessment was the following:

W1 *Safety assessment is a rational and efficient way to target information gathering and process information to improve risk management. It is also a rational and efficient way to resolve conflicts between different specialists regarding the importance of "their" systems and specialist knowledge for total safety.*

This is the worldview of technical positivism, against which a number of objections can be raised, for example:

i) The safety assessment spans over many disciplines, and it is impossible for one person to know whether all parts are being carried out with the desired scientific and technical rigour.

- ii) Completeness and certainty are unattainable goals in a safety assessment – it must be based on judgements. This means that the transformation can be called into question.
- iii) The safety assessment is difficult to understand for the uninitiated. There is a risk that its results will only be accepted by those who have been involved in its production.

Objections i) and ii) may be reasons for switching to a somewhat “softer” worldview:

W2 The safety assessment is a verifiable and objective procedure for compiling and processing large quantities of information in order to assess the safety of a final repository.

The new customer categories affected by transformations T3 and T4 will certainly be affected by objection iii). Depending on their attitude, the customers in T3/T4 may possibly accept worldview W2. But there is a risk that they will consider the following worldview to be more relevant:

W3 Safety assessment is an incomprehensible, unverifiable and thereby easily manipulated system of computer models and procedures for processing the information which the user thinks is important and which the models can handle.

In order to prevent the customers who are dependent on safety assessment in transformations T3 and T4 from developing a worldview such as W3, conscientious efforts are required to make the safety assessment comprehensible and transparent. If this cannot be done in a dialogue between actors and customers, there is a clear risk that the importance of the safety assessment as background material for decision-making will be undermined and that the support of the “owners” will cease.

Owners

The system can cease to exist if its 1980s customers (SKB, SKI and SSI) cease to use it. As suggested above, there is also a risk that the safety assessment will be massively discredited by its new customers so that the original owners will stop using it.

Environment

The environment consists of the waste-producing system, and in a broader perspective the political debate on nuclear power.

Summary

The safety assessment's circle of customers has been widened from being limited to groups with expert knowledge and a fundamentally positivistic worldview to including decision-makers and interested private citizens. This increases the need to make it more comprehensible and transparent. This also means it now has two roles. One role is internal within the expert groups and is represented by transformations T1 and T2 above. The other role, which is mainly manifested by transformation T4, is external and aimed at political decision-makers and thereby also the general public, primarily in concerned municipalities but also in a broader sense.

The Swedish National Council for Nuclear Waste (Kärnavfallsrådet) is a scientific committee attached to the Ministry of the Environment and tasked to study matters relating to nuclear waste and the decommissioning and dismantling of nuclear installations and to advise the Government on these matters. Furthermore, the Swedish National Council for Nuclear Waste is supposed to identify and analyze issues in the nuclear waste field that are of significant importance for the decision process and the assessment of the long-term safety of the final repository and ensure that these issues are thoroughly illuminated. Its main tasks are to:

- present an independent assessment of the state-of-the-art in the field of nuclear waste,
- review the Swedish Nuclear Fuel and Waste Management Co's (SKB's) Research, Development and Demonstration (RD&D) programmes, and
- contribute to transparency and dialogue in the nuclear waste field by arranging hearings and seminars.

The members of the Swedish National Council for Nuclear Waste are qualified scientists from Swedish and Nordic universities and institutes of technology. They represent independent expertise in fields that have a bearing on the management and final disposal of spent nuclear fuel and other radioactive waste, such as engineering and natural science, as well as ethics, the humanities and the social sciences.

This report describes the Swedish National Council for Nuclear Waste's review of the Swedish Nuclear Fuel and Waste Management Co's (SKB's) RD&D Programme 2007 — "Programme for research, development and demonstration of methods for the management and disposal of nuclear waste".

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