Technical Report

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# Planning report for the safety assessment SR-Can

Svensk Kärnbränslehantering AB

June 2003

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# Planning report for the safety assessment SR-Can

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# Preface

This document outlines the methodology for SKB's next assessment of long-term safety for a KBS 3 repository. The assessment, SR-Can, is to be finished by the end of 2005 and will be used for SKB's application to build an Encapsulation plant for spent nuclear fuel. Apart form outlining the methodology, the report discusses the handling in SR-Can of a number of important issues regarding the near field, the geosphere, the biosphere, the climatic evolution etc. The report has previously, e.g. in SKB's RD&D Programme 2001, been referred to as the Methodology report. As its purpose has since been expanded so that it, apart from outlining methodology, also serves as a planning tool, it is now called a planning report for SR-Can.

While the ambition has been to address the most relevant issues for an assessment of long-term safety, the suggested methodology and treatment of specific issues are neither definite nor exhaustive. The methods and the list of issues will develop as the project progresses. Furthermore, the level of detail in the present report varies, often as a reflection of varying maturity of the current planning rather than as an indication of the relative importance of different issues.

The undersigned has been responsible for the planning project, for the methodology development described in Chapter 2 and for editing the report. Kristina Skagius, Kemakta Konsult AB has had the main responsibility for the development of the data base discussed in section 2.5, in collaboration with Johan Andersson, JA Streamflow AB and the undersigned. Johan Andersson has provided input for the treatment of initial states and for the management of input data uncertainties. Both KS and JA have given valuable comments on the overall methodology. Fred Karlsson provided input for the discussion of natural analogues in section 2.12.4.

The following persons have provided input to chapters 3 to 8: Kastriot Spahiu fuel); Lars Werme and Håkan Rydén (canister); Patrik Sellin (buffer and backfill and partly fuel); Jan-Olof Selroos (geosphere flow and transport); Harald Hökmark, Clay Technology AB (geomechanical issues); Ignasi Puigdomenech (geochemistry); Lena Morén (climate and intrusion issues); Ulrik Kautsky (biosphere) and Fredrik Vahlund (integrated radionuclide transport modelling). Thanks are due also to Ola Karnland and Lennart Börgesson, Clay Technology AB for comments on buffer and backfill issues.

Stockholm, June 2003

Allan Hedin

# Summary

This document is a planning report for SKB's next assessment of long-term safety for a KBS 3 repository. The assessment, SR-Can, is to be finished by the end of 2005 and will be used for SKB's application to build an Encapsulation plant for spent nuclear fuel. Apart form outlining the methodology, the report discusses the handling in SR-Can of a number of important issues regarding the near field, the geosphere, the biosphere, the climatic evolution etc.

The Swedish nuclear safety and radiation protection authorities have recently issued regulations concerning the final disposal of nuclear waste. The principal compliance criterion states that the annual risk of harmful effects must not exceed $10^{-6}$ for a representative individual in the group exposed to the greatest risk. There are also a number of requirements on methodological aspects of the safety assessment as well as on the contents of a safety report. The regulations are reproduced in an Appendix to this report. Inserted in the Appendix are references to relevant sections of the report where the intended handling of the regulatory issues in SR-Can are described.

## Methodology for SR-Can

The repository system, broadly defined as the deposited spent nuclear fuel, the engineered barriers surrounding it, the host rock and the biosphere in the proximity of the repository, will evolve over time. Future states of the system will depend on

- the initial state of the system, e.g. at the time of deposition,
- a number of thermal, hydraulic, mechanical and chemical processes acting within the repository system over time and
- external influences acting on the system.

The primary safety function of the KBS 3 system is to completely isolate the spent nuclear fuel within copper canisters over the entire assessment period, which will be one million years in SR-Can. Should a canister be damaged, the secondary safety function is to retard any releases from the canisters. The two issues of isolation and retardation are thus in focus throughout the assessment.

The safety assessment SR-Can will consist of a number of main steps, which will be carried out partly consecutively, partly in parallel. The main steps of the assessment are the following:

1. Qualitative system description, FEP processing

   This step consists of defining a system boundary and of describing the system within the boundary on a format suitable for the safety assessment. KBS 3 specific and international databases of relevant features, events and processes influencing long-term safety are structured and used as one starting point for the assessment.

2. Initial state descriptions

   Possible initial states of the system are described, including uncertainties and open design issues. A site specific description of the geosphere and the biosphere forms an important part in this step.

3. Process descriptions

   In this step all identified processes within the system boundary involved in the long-term evolution of the system are described in detail. Some of the process understanding will be provided by the site description.

4. Description of boundary conditions

   This step is a broad description of the evolution of the boundaries of the system, focussing mainly on *i*) the climatic evolution and its influence on the repository system and *ii*) future human actions. The site description will consider the historical evolution, which is a key input to future development of the system and its boundaries.

5. Preliminary analyses

   In this step, a number of analyses are carried out to understand the broad features of the system evolution for several combinations of initial and boundary conditions. The analyses are often of a simplified nature. Sensitivity analyses are carried out to determine what input data to the analyses are important for safety so that particular care is taken in determining these data. Another important aim is to inform the selection of scenarios in the subsequent step. Focus is on both the isolating and retention potentials of the system.

6. Scenario selection

   In this step, a number of scenarios for detailed analysis are selected, drawing on information from the preceding steps of the analysis and other relevant sources.

7. Input data selection

   In this sub-task, data to be used in the quantification of the repository evolution and dose calculations are selected and reported in a dedicated Data Report.

8. Analysis of scenarios

   The temporal evolution of the system is analysed for each scenario in this step. The isolating and retarding potentials of the repository are analysed. Probabilistic hydrology, transport and dose calculations are at the core of the analyses.

9. Integration of results and conclusions

   This step includes integration of the results from the various scenario analyses, conclusions regarding safety in relation to acceptance criteria and feedback concerning design, continued site investigations and R&D programme.

The initial state, the internal processes and the external influences and the way they together form the repository evolution, can never be fully determined, understood or described. There are thus uncertainties of various nature associated with all aspects of the repository evolution and hence with the evaluation of safety. A central theme in any safety assessment methodology must therefore be the management of all relevant types of uncertainty. The management amounts to classifying and describing uncertainties, as well as handling them in a consistent manner in the quantification of the repository evolution and of the radiological consequences to which it leads. A preliminary plan for the management of uncertainties in the different steps of SR-Can is given.

Another issue permeating much of the assessment is the approach to risk calculations, since the primary compliance criterion is risk based. Such an approach is outlined and matters like overestimation of risk, time dependencies and risk dilution are discussed.

## Climate issues

The future climate evolution is an essential part of the description of the external conditions to the repository system. Past climate changes including permafrost and glacial conditions are highly likely to occur also in the future. The time sequence of these changes is governed by cyclic astronomical phenomena affecting insolation. Although the future insolation can be well predicted, it is difficult to estimate the response of the climate due to limited understanding of the climate system and also due to additional uncertain driving forces like human induced greenhouse effects. Three principal climate domains can be distinguished:

- The glacial domain.
- The permafrost domain.
- The temperate/boreal domain.

A number of possible future climate evolutional pathways will be considered in the selection of scenarios in SR-Can. Together, the different scenarios/variants should give a good coverage of possible evolutions.

The report gives an overview of major issues related to the selection of scenarios/variants and to the descriptions of the three climate domains along with a plan for their management in SR-Can.

## Biosphere issues

The biosphere chapter discusses the treatment of the general development of the biosphere, from the initial state as described by data from site investigations and onwards in different time periods. Thereafter the handling of groundwater discharge points is treated, followed by a description of modelling of radionuclide turn-over based on process understanding. Numerical modelling methods and ecosystem models are presented, as are the management of generic data and the handling of exposure to humans and the environment.

## Geosphere issues

Mechanics: The impact of geomechanical processes on the repository system might range from slight alterations of the hydraulic properties of the geosphere to jeopardising the integrity of the canister itself. Starting from a discussion of the initial state from a mechanical point of view, this section of the geosphere chapter discusses the thermal pulse, glacial load, earthquakes, time dependent deformations, tectonic movements and impact of mechanical processes on the host rock permeability.

Hydrology and transport: Groundwater flow and radionuclide transport modelling in the geosphere is discussed in detail for current climate conditions and for altered climatic situations. Modelling of transient and density driven flow situations are discussed as is the management of different scales through nested modelling, simulation of wells and near-surface hydrology. Several conceptual aspects of radionuclide transport in fractured media are addressed. Radionuclide transport in deposition tunnels and colloid facilitated transport are given particular attention.

Geochemistry: The chemical evolution of the buffer, backfill and rock is ultimately governed by the composition and flow of groundwater. In the long term, the chemical properties of the groundwater, together with the properties of the buffer and the copper canister, determine for how long the buffer and canister will function properly. This sub-section treats first the handling in SR-Can of the geochemistry of the repository system at closure, focussing on the spatial extent and composition of perturbed groundwaters, effects of drawdown and up-coning, of grouting, shot-creeting and concrete leachates and of organic materials. Thereafter the handling of the temporal evolution during the first 1,000 years after closure is discussed, in particular the evolution of the salinity distribution around the repository and the subsequent modelling of groundwater composition, mainly as a consequence of mixing of different groundwater types. Finally, the handling of the evolution during the first glacial cycle is discussed. Since a detailed modelling of this phase is not realistic, the aim is to enclose the groundwaters within two extreme types: the “saline ice-front” and the “non-saline melting zone”. The main components in glacial melt-waters will be evaluated and the issue of penetration of $O_2$-rich waters will be addressed.

## Near field issues

General near field issues addressed concern the near field temperature and the impact of earth quakes on the near field.

Regarding the fuel, particular attention is given to fuel dissolution which will be thoroughly addressed in a state-of-the-art report as a supporting document to SR-Can. Other issues concern athermal diffusion, fuel colloid formation, radionuclide inventories, radionuclide chemistry, cladding tube integrity and criticality.

The derivation of input data regarding frequencies and sizes of initial canister sealing defects from test series of the canister production and quality control systems is discussed thoroughly. Other canister matters include the further evolution of defective seals, the internal evolution of a damaged canister, the isostatic collapse load of the canister insert and canister corrosion.

Regarding the buffer and backfill, a number of different materials and backfilling concepts to be analysed in SR-Can are presented. Plans for modelling the initial THM unsaturated phase and the long-term chemical evolution of the saturated buffer and backfill are briefly outlined. Other matters addressed are radionuclide transport properties, colloid formation/erosion, gas issues and canister sinking.

## Intrusion issues

The handling of future human actions, most notably intrusion into the repository, will in SR-Can be restricted to actions that are carried out after the sealing of the repository, take place at or close to the repository site, are unintentional and that impair the performance of the repository's barriers. The methodology for handling intrusion issues resembles that used in SKB's earlier safety assessment SR 97.

## Integrated modelling

Available tools for integrated modelling are presented. A new, simplified model for the integrated simulation of the repository system evolution is available. The model mimics a number of separate models used in SR 97 for e.g. the thermal evolution of all repository components, for buffer and backfill rheology, for the long-term chemical evolution of the buffer, for copper corrosion and for the internal evolution of the interior of a damaged canister.

Regarding radionuclide transport and dose calculations, simplified, fast analytical models are now available and the numerical tools used in SR 97 have been further developed, in particular as regards numerical platforms and representations of the biosphere.

# Contents

# 1 Introduction

## 1.1 SKB's program for spent nuclear fuel

Nuclear waste in Sweden is handled by the Swedish Nuclear Fuel and Waste Management Co, SKB. Within SKB's program for spent nuclear fuel, an interim storage facility and a transportation system are today (June 2003) in operation. Several decades of research and development has led SKB to put forward the KBS-3 method for the final stage of the spent nuclear fuel management. In this method, copper canisters with a cast iron insert containing spent nuclear fuel are surrounded by bentonite clay and deposited at approximately 500 m depth in saturated, granitic rock, see Figure 1-1.

Two principal remaining tasks in the program are to locate, build and operate *i*) the deep repository and *ii*) an encapsulation plant in which the spent fuel will be emplaced in canisters to be deposited in the deep repository.

SKB is currently pursuing site investigations for a deep repository in the municipalities of Östhammar and Oskarshamn. The investigations are conducted in two stages, an initial phase followed, if the expected site suitability is confirmed, by a complete site investigation phase. The aim is to build a deep repository at one of these candidate sites, provided that the bedrock and other relevant conditions are found suitable. An application to build a deep repository will be made at the end of 2008 according to current time plans.

The favoured alternative for the location of the encapsulation plant is at Oskarshamn, in conjunction to the existing interim storage facility. An application to build an encapsulation plant will be made in 2006.

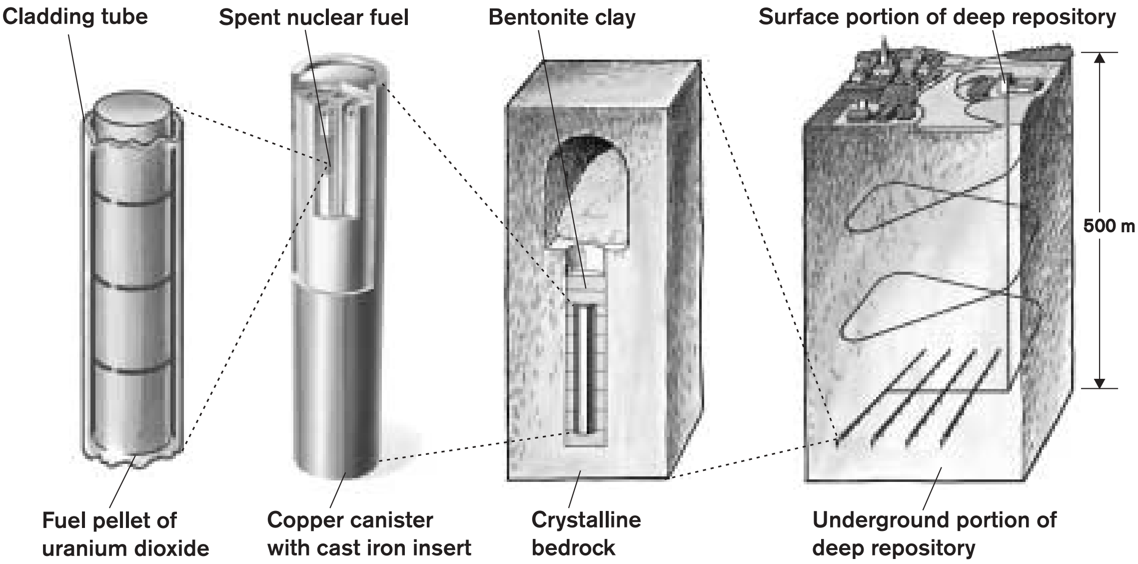

***Figure 1-1.*** *The KBS-3 concept for storage of spent nuclear fuel.*

### 1.1.1 Reporting of long-term safety during the current program stage

The two applications foreseen in the current stage of SKB's program for spent nuclear fuel will each require a report on long-term safety for the deep repository. This is an obvious requirement for the application to build the repository. Also the application to build the encapsulation plant will require such a report since, in that application, it must be demonstrated that a repository with the sealed canisters to be delivered from the encapsulation plant will meet the requirements on long-term safety set up by Swedish authorities.

Two safety reports will thus be produced within the next five years; one for the application to build an encapsulation plant and one for the application to build the repository. They will hereafter be referred to as SR-Can and SR-Site, respectively. SR-Can will be based on site data from the initial site investigation phase and SR-Site on data from the complete site investigation.

After an initial phase of the SR-Can project, an SR-Can Interim report will be produced, with the main purpose of demonstrating the adopted methodology, so that this can be reviewed before it is used for the applications. It is e.g. desirable to demonstrate that the major part of the review comments concerning methodological issues in SKB's previous safety assessment, SR 97 /SKB, 1999a/, have been adequately addressed. The interim report will tentatively be published in August 2004, but a detailed plan for the extent of the report, and hence when within the SR-Can project it should be produced, remains to be established in consultation with relevant authorities.

Also, preliminary safety evaluations /SKB, 2002/, of each site will be made as sub-tasks within the SR-Can project. The main purposes of those evaluations are to determine whether earlier judgements of the suitability of the candidate area for a deep repository with respect to long-term safety holds up in the light of borehole data and to provide feed-back to continued site investigations and site specific repository design.

## 1.2 Purpose of the safety assessment SR-Can

As mentioned, SR-Can will be used for SKB's application to build an Encapsulation Plant. The purpose of the safety assessment SR-Can is to be precisely defined early in the SR-Can project. Preliminarily, it can be described as being essentially twofold:

1. SR-Can should assess the potential of a repository of the KBS 3 type at the candidate sites to being able to comply with applicable regulatory criteria in Swedish legislation, given data from the initial site investigations.
2. SR-Can should provide feedback to design development, to SKB's R&D programme, to further site investigations and to future safety assessment projects.

## 1.3 Purpose of this report

The purpose of this report is to serve as a basis for the planning of the safety assessment SR-Can. In so doing, the report outlines the methodology to be used in SR-Can and discusses a number of issues related to different components of the repository system and its surrounding.

The plans regarding methodology and the treatment of specific issues outlined in the report are in most cases relatively mature, but may be modified during the course of the project. It has furthermore been the intention to treat all major methodological and technical issues relevant for SR-Can, but the set of issues is not exhaustive.

## 1.4 Regulations

The form and content of a safety assessment, and above all the criteria for judging the safety of the repository, are defined in regulations issued by the Swedish Nuclear Power Inspectorate, SKI, and the Swedish Radiation Protection Authority, SSI. The regulations are based on framework legislation, the most important being the Environmental Code, the Nuclear Activities Act and the Radiation Protection Act. Radiation protection matters are handled by a number of international bodies, and national legislation is often based on international rules and recommendations.

Regarding long-term safety of nuclear waste repositories, there are two more detailed regulations of particular relevance, issued by SSI and SKI, respectively:

- "The Swedish Radiation Protection Institute's Regulations concerning the Protection of Human Health and the Environment in connection with the Final Management of Spent Nuclear Fuel or Nuclear Waste" (SSI FS 1998:1)
- "The Swedish Nuclear Power Inspectorate's regulations concerning safety in final disposal of nuclear waste" (SKIFS 2002:1)

The two documents are included in their entirety in an Appendix to this report. The way in which SKB intends to fulfil the requirements are indicated by references to relevant sections in chapter 2, inserted in the regulatory text in the Appendix.

### 1.4.1 Regulations for final disposal of spent nuclear fuel, SSI FS 1998:1

These regulations are reproduced in section A.2.1. The parts of SSI FS 1998:1 most relevant to an assessment of long-term safety imply the following:

- Protection of human health shall be demonstrated by compliance with a risk criterion stating that "the annual risk of harmful effects after closure does not exceed $10^{-6}$ for a representative individual in the group exposed to the greatest risk".
- Regarding environmental protection, biological effects of ionising radiation in living environments and ecosystems concerned shall be described, based on available knowledge.
- The consequences of intrusion into a repository shall be reported and the protective capability of the repository after intrusion shall be described.
- SSI requires a more detailed assessment for the first 1,000 years following repository closure.

SSI has also issued a report with background discussions and comments to SSI FS 1998:1. There, some further guidance regarding the implementation of the regulation is given. Excerpts from that report, relevant to an assessment of long-term safety are also given in the Appendix.

Furthermore, SSI is planning to issue General Recommendations concerning the application of SSI FS 1998:1.

### 1.4.2 The Swedish Nuclear Power Inspectorate's regulations concerning safety in final disposal of nuclear waste, SKIFS 2002:1

These regulations are reproduced in section A.1.1. The parts of SKIFS 2002:1 most relevant to an assessment of long-term safety imply the following:

- The safety assessments shall comprise features, events and processes which can lead to the dispersion of radioactive substances after closure.
- A safety assessment shall comprise as long time as barrier functions are required, but at least ten thousand years.
- Requirements on reporting of analysis methods
  - for system description and evolution,
  - for the selection of scenarios (including a main scenario that takes into account the most probable changes in the repository and its environment),
  - the applicability of models, parameter values and other conditions used in the analysis,
  - handling of uncertainties and sensitivity analysis.
- Regarding analysis of post-closure conditions SKI require descriptions of the evolution in the biosphere, geosphere and repository for selected scenarios; the environmental impact of the repository for selected scenarios, including the main scenario, with respect to defects in engineered barriers and other identified uncertainties.

SKI has also issued General Recommendations concerning the application of SKIFS 2002:1. There, more detailed discussions regarding the e.g. classification of scenarios and uncertainties are given. Excerpts from the Recommendations, relevant to an assessment of long-term safety are also given in the Appendix, along with indications of how SKB intends to fulfil the requirements.

# 2 Methodology

## 2.1 Introduction

This chapter outlines the methodology to be used for SR-Can. It is written for planning purposes, but can also in parts be seen as an early version of a methodology chapter in the final report of SR-Can. The methodology will be further developed during the project and this will be reflected in the final report.

The main purpose of a safety assessment of a deep repository is to investigate whether the repository can be considered radiologically safe over time. In principle, this is obtained by comparing estimated releases and doses from the repository to regulatory criteria.

The repository system, broadly defined as the deposited spent nuclear fuel, the engineered barriers surrounding it, the host rock and the biosphere in the proximity of the repository, will evolve over time. Future states of the system will depend on

- the initial state of the system, e.g. at the time of deposition,
- a number of thermal, hydraulic, mechanical and chemical processes acting within the repository system over time and
- external influences acting on the system.

Internal processes are e.g. the decay of radioactive material, leading to the release of heat and the subsequent warming of the fuel, the engineered barriers and the host rock. Groundwater movements and chemical processes involving the engioneered barriers and the groundwater are other examples. External influences include effects of the climate and future climate alterations, land-up lift and the build-up of mechanical energy due to plate tectonic movements. Also future human actions may influence the repository.

The initial state, the internal processes and the external influences and the way they together form the repository evolution, can never be fully determined, understood or described. There are thus uncertainties of various nature associated with all aspects of the repository evolution and hence with the evaluation of safety. A central theme in any safety assessment methodology must therefore be the management of all relevant types of uncertainty. The management amounts to classifying and describing uncertainties, as well as handling them in a consistent manner in the quantification of the repository evolution and of the radiological consequences to which it leads.

The primary safety function of the KBS 3 system described in Figure 1-1 is to completely isolate the spent nuclear fuel within the copper canisters over the entire assessment period, the length of which needs to be defined. Should a canister be damaged, the secondary safety function is to retard any releases from the canisters. The two issues of isolation and retardation are thus in focus throughout the assessment.

The safety assessment SR-Can will consist of a number of main steps, which will be carried out partly consecutively, partly in parallel. From a project management point of view, many of the steps can be seen as sub-projects in a larger integrated safety assessment project. The steps are also a suitable structure for much of the presentation of the methodology in this chapter as is reflected in several of the subsections to follow. The methodology is a development of that used in SR 97. Figure 2-1 is a graphical illustration of the steps and the main products resulting from them.

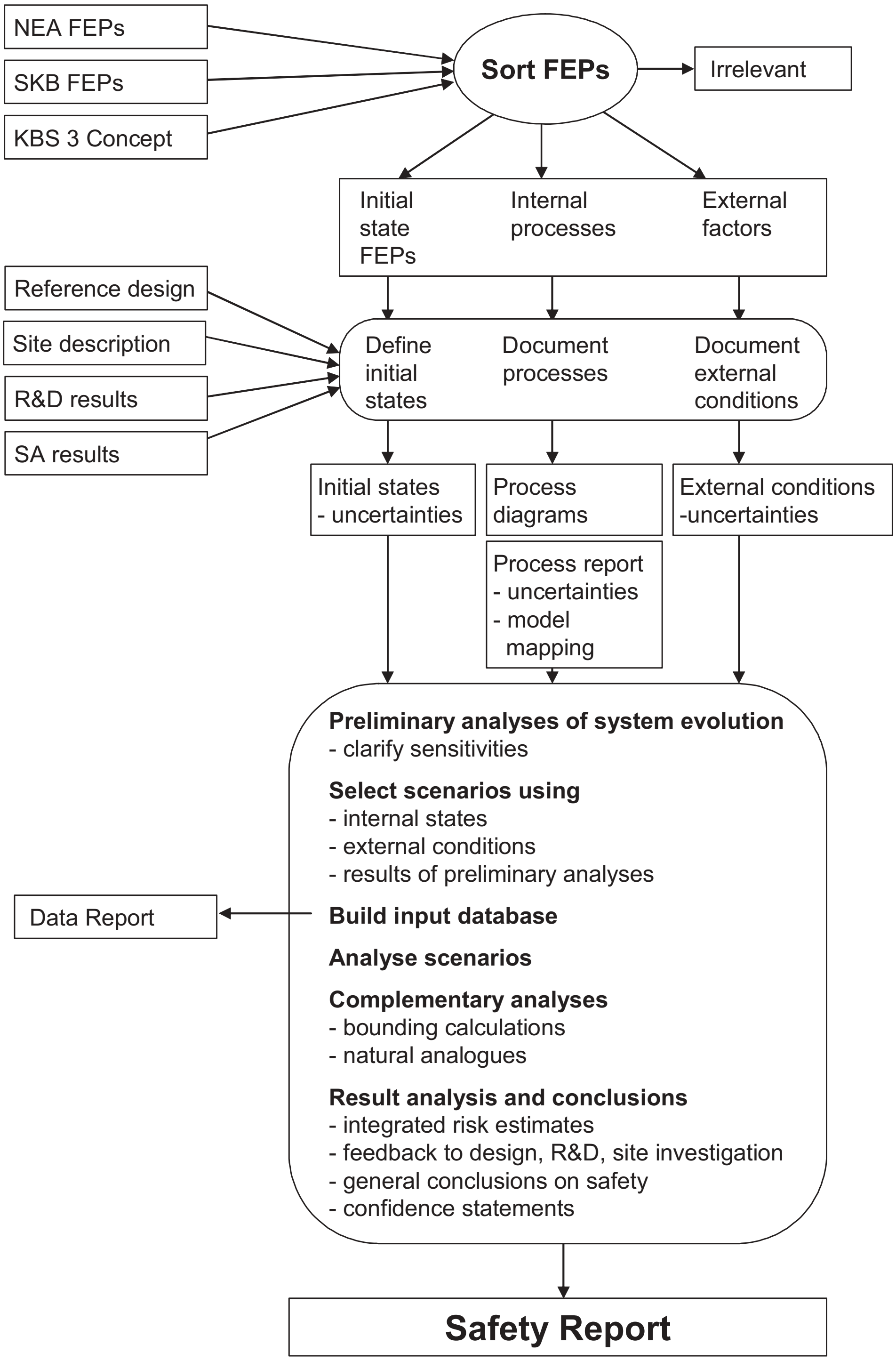

***Figure 2-1.*** *An outline of the main steps of the safety assessment SR-Can. Activities are represented as ellipses, input information and products as rectangles.*

The main steps of the assessment are the following:

1. Qualitative system description, FEP processing

   This step consists of defining a system boundary and of describing the system within the boundary on a format suitable for the safety assessment. KBS 3 specific and international databases of relevant features, events and processes influencing long-term safety are structured and used as one starting point for the assessment.

2. Initial state descriptions

   Possible initial states of the system are described, including uncertainties and open design issues. A site specific description of the geosphere and the biosphere forms an important part in this step.

3. Process descriptions

   In this step all identified processes within the system boundary involved in the long-term evolution of the system are described in detail. Some of the process understanding will be provided by the site description.

4. Description of boundary conditions

   This step is a broad description of the evolution of the boundaries of the system, focussing mainly on *i*) the climatic evolution and its influence on the repository system and *ii*) future human actions. The site description will consider the historical evolution, which is a key input to future development of the system and its boundaries.

5. Preliminary analyses

   In this step, a number of analyses are carried out to understand the broad features of the system evolution for several combinations of initial and boundary conditions. The analyses are often of a simplified nature. Sensitivity analyses are carried out to determine what input data to the analyses are important for safety so that particular care is taken in determining these data. Another important aim is to inform the selection of scenarios in the subsequent step. Focus is on both the isolating and retention potentials of the system.

6. Scenario selection

   In this step, a number of scenarios for detailed analysis are selected, drawing on information from the preceding steps of the analysis and other relevant sources.

7. Input data selection

   In this sub-task, data to be used in the quantification of the repository evolution and dose calculations are selected and reported in a dedicated Data Report.

8. Analysis of scenarios

   The temporal evolution of the system is analysed for each scenario in this step. The isolating and retarding potentials of the repository are analysed. Probabilistic hydrology, transport and dose calculations are at the core of the analyses.

9. Integration of results and conclusions

   This step includes integration of the results from the various scenario analyses, conclusions regarding safety in relation to acceptance criteria and feedback concerning design, continued site investigations and R&D programme.

These steps will be discussed in further detail below, together with other relevant issues regarding methodology.

### 2.1.1 Structure of Safety Report

The structure of the safety report to be produced as the final product from the SR-Can project will essentially follow that of the main steps of methodology. Many of the parts of the project will be documented in dedicated reports that are summarised in the main report.

The structure will to some extent be influenced by requirements in applicable regulations. For example, SKIFS 2002:1 state in an Appendix a number of items that must be reported regarding analysis methods and analysis of post-closure conditions.

Furthermore, the contents of the safety report should be consistent with international consensus in this field as e.g. expressed in /NEA, 1997a/.

## 2.2 Handling site information

A considerable part of the basis for the safety assessments SR-Can and SR-Site will be provided from SKB's ongoing site investigations in the municipalities of Oskarshamn and Östhammar.

Field data from the site investigations are analysed, within the site investigation project, by a **site analysis group** that produce a **site descriptive model** of the geosphere and the biosphere. The site descriptive model is a synthesis of observations of the current state of the site and of the understanding of past and ongoing e.g. hydraulic and geochemical processes driven by phenomena such as land up-lift and the changing long term climate. Model simulations of the historical evolution of the site are an important part of the synthesis work carried out by the site analysis group. The resulting geosphere 3D model of current conditions provides thermal, hydraulic, mechanical, chemical and transport properties of the rock, within a geometrical framework describing major structures of the site. The biosphere part of the model contains a description of the ecosystems at the site. The model is accompanied by a thorough description of the inter-disciplinary analysis and interpretation work underpinning it.

The site descriptive model will provide essential parts of the initial state descriptions of the geosphere (see section 2.6.3) and the biosphere (section 4.2.1) for the safety assessment. The model however describes the situation prior to rock excavation for the deep repository, whereas the initial state of the safety assessment refers to the time of deposition of waste containing canisters. Analyses of how the excavation activities affect the undisturbed, natural state of the rock are thus needed and essential parts of this work will be done by a **repository engineering group** in conjunction with their determination of a suitable repository layout in the site model.

Apart from providing the basis for the initial state description of the geosphere and the biosphere, the site descriptive model provides an understanding of past and ongoing processes at the site. This information will be crucial for the description and modelling 5of the future development, the results of which should be compatible with the understanding of the site history.

The safety assessment will use the hydraulic simulation models set up by the site analysis group. Whereas these are essentially used to simulate the site history by the site analysis group, the future evolution will be in focus in the safety assessment.

The results of the safety assessment will provide feedback to both further site investigations and design work. Regarding the site model, an overall assessment of the confidence in the site descriptive model will be made within the safety assessment. The focus will here be on the aspects of direct relevance for safety, see further section 2.13.

## 2.3 Timescale of the Assessment

### 2.3.1 Regulatory requirements and guidance

The SKI regulations SKI FS 2002:1 state that the safety assessment should cover the time period during which the barrier functions are needed, though at least 10,000 years. The recommendations accompanying the SKI regulation suggest that the timescale of an assessment should be related to the hazard posed by the inventory in comparison to naturally occurring radionuclides. In the recommendations it is also noted that "…it should also be possible to take into consideration the difficulties of conducting meaningful analyses for extremely long time-periods, beyond one million years…".

SSI's regulations state that "For the first thousand years following repository closure, the assessment of the repository's protective capability shall be based on quantitative analyses of the impact on human health and the environment." "For the period after the first thousand years following repository closure, the assessment of the repository's protective capability shall be based on various possible sequences for the development of the repository's properties, its environment and the biosphere."

SSI's regulation thus distinguishes two phases for the analysis, but does not indicate an upper limit for the assessment time.

### 2.3.2 Implications for SR-Can

In the case of spent nuclear fuel, an assessment period longer than 10,000 years is required. After approximately 100,000 years, the radiotoxicity of the spent nuclear fuel is comparable to that of the natural uranium ore once used to produce the fuel /Hedin, 1997/. Also the sum of toxicity of all fractions in the nuclear fuel cycle is comparable to that of the utilised uranium ore after 100,000 years, see Figure 2-2. The latter comparison is roughly equivalent to comparing the radiotoxicity of the amount of U-235 consumed by fission in the reactor to the radiotoxicity of the products of the fission process.

Another criterion that may be used to justify a timescale for a safety assessment is that the time period analysed should go beyond the point in time at which peak doses from the repository occur. In SKB's latest safety assessment for the KBS 3 system, SR 97, the peak dose occurred within one million years in most of the calculation cases. One million years was also the assessment period used in SR 97. However, there are also examples where the peak dose occurs at the end of the assessment period due to ingrowth of the naturally occurring nuclide Ra-226. Since the KBS 3 concept is aiming at complete isolation of the waste for time periods very far into the future through encapsulation, the peak dose criterion is deemed as less suitable.

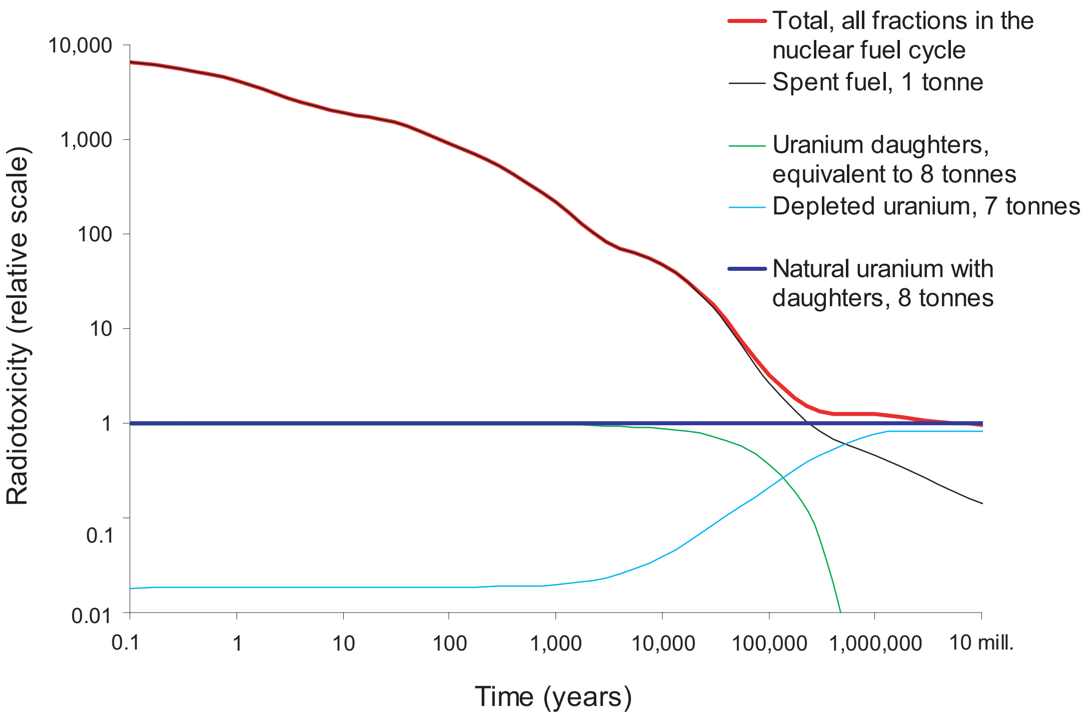

*Figure 2-2.* *Radiotoxicity on ingestion of uranium ore (blue line), and of the sum of all fractions that arise when the same quantity of uranium mineral is used in the nuclear fuel cycle (red line). The different fractions comprise the spent fuel (38 MWd/kg U SVEA 64 BWR), the depleted uranium and the uranium daughters that are separated in the uranium mill. From /Hedin, 1997/.*

In SR-Can the timescale for the assessment will be one million years. This timescale is longer than what is needed to reduce the radiotoxicity of the inventory to a level comparable to that of the corresponding amount of natural uranium ore and also in accordance with the suggestions in SKI's recommendations cited above. Tentatively, a brief general discussion of the evolution beyond one million years will also be given in SR-Can.

## 2.4 Format for system description

The repository system encompasses the spent nuclear fuel, the canisters, the buffer, the tunnel backfill, the geosphere and the biosphere in the proximity of the repository, see Figure 1-1. In the development of a FEP database (see below), the system boundary was defined in more detail. The following is noted from that definition:

- Roughly the portion of the biosphere studied in site investigations, i.e. an area of the order of 100 km$^2$ above the repository, is regarded as part of the system, whereas the biosphere on a larger scale is regarded as external.
- Roughly the portion of the geosphere covered by a local model (around 2–6 km$^2$ of the surface above the potential repository), is regarded as part of the system. Depending on the analysis context these boundaries may be further extended.
- Future human behaviour on a local scale is internal, but not issues related to the future society at large.

- A general, strict boundary definition is neither possible nor necessary, and that the same boundaries will not necessarily be relevant in all parts of the safety assessment.
- The boundary of the backfill system component is defined in geometrical terms as all rock excavation volumes except deposition holes. The definition thus includes the volumes of deposition tunnels, access ramps/shafts, ventilation shafts, exploration bore-holes, drilling for rock support etc. All materials within these boundaries are included, e.g. the backfill itself, plugs and rock support. Injection materials belong to the geosphere since it is injected primarily into the naturally occurring fractures.
- With the separation of buffer and backfill, the system description is no longer (as in the SR 97 assessment) one-dimensional in the sense that a system component can have only one inner and one outer neighbour. This sacrifice of simplicity of the system description was deemed necessary to obtain an adequate treatment of the backfill. The backfill has no inner boundary, but interacts with both rock and buffer over its "outer" boundary and the rock interacts with both the buffer and the backfill over its inner boundary.

For the purpose of the safety assessment, a detailed description of the system is needed, on a format not only suitable to describe the repository as built, but also the changes the repository will undergo with time. Such a *system description* must thus be able to account for the changing state of the repository and the processes and interactions causing these changes. The format adopted here is a development of that used in the safety assessment SR 97 /SKB, 1999a/.

The system is divided into the system parts fuel, canister, buffer, backfill, geosphere and biosphere. Each system part is characterised by a number of time dependent variables. The buffer is e.g. characterised by the variables temperature, density, swelling pressure, chemical composition etc. The variables are generally functions of both space and time. Within a certain system part, a number of processes act over time to alter the state of the system. Examples from the buffer are heat transport, water uptake, swelling, chemical decomposition and ion exchange.

Variables and processes are represented in a *Process Diagram*, one for each system part. Figure 2-3 shows the process diagram for the buffer. The diagram also shows which variables influence a certain process as well as the influences a particular process has on the set of variables. Also interactions over the boundaries of the system part are described.

Associated with the process diagram is the *Process Report* which contains a thorough documentation of the scientific understanding of all the processes, of how they are treated in the safety assessment etc. More detailed accounts of the identification of relevant processes and the contents of the process report are given in sections 2.5 and 2.7, respectively.

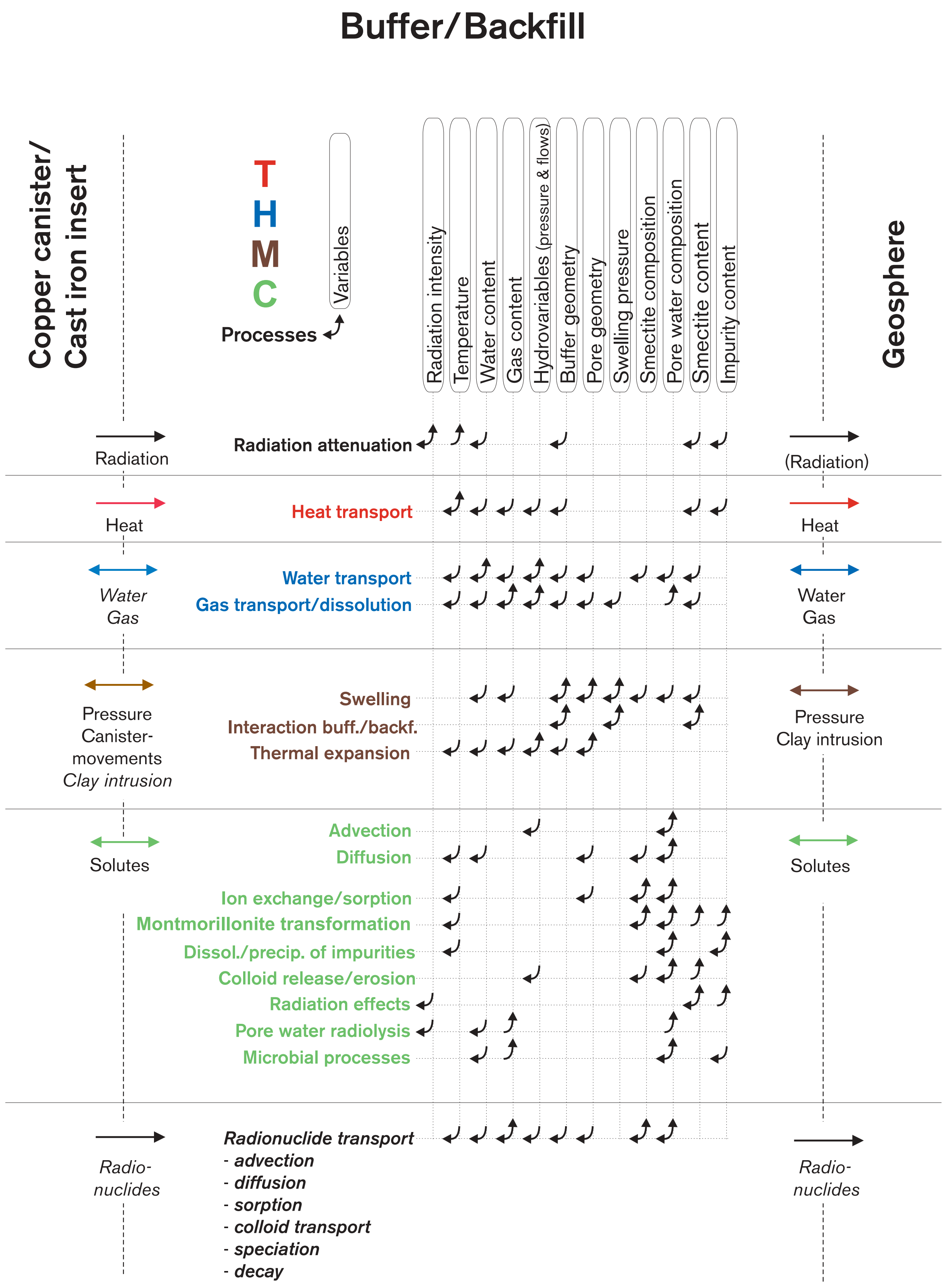

***Figure 2-3.*** *The SR 97 version of the process diagram for the buffer. Thermal, hydraulic, mechanical and chemical processes are listed in the left column, the variables are given in the top row. Influences between variables and processes are described by arrows in the diag ram. Processes and interactions in italics only occur isolation of the copper canister is broken.*

## 2.5 FEP database

In preparing for the safety assessment SR-Can, SKB has further developed its database of features, events and processes (FEPs) relevant to the long-term safety of a nuclear waste repository. Documentation of this work is in progress and will be presented as a Technical Report when the database is in more final form. The SR 97 version of the database has been compared to the NEA international FEP database to ensure that all relevant factors in the latter are taken into account. The structure of the database is closely related to the format for the system description described above. The database is thus structured around

- Processes within the system boundaries relevant to long-term safety.
- Factors affecting the initial state of the repository, either directly related to a specific variable or to the initial state in general.
- External factors relevant to long-term safety, e.g. climatic evolution and human intrusion.

Virtually all FEPs in the NEA database could either be mapped to one of these categories or be deemed as irrelevant for the KBS 3 system.

For all processes treated in the SR 97 Process Report, i.e. the majority of processes in the new database, the relevant parts of the SR 97 Process Report has been stored in the database as a starting point for an updated documentation.

More FEPs will be handled in SR-Can compared to SR 97. The treatment of both initial state FEPs and external FEPs has been considerably more elaborate and the results of these efforts will be propagated to the selection of scenarios. The list of internal processes is similar to that in SR 97 but the processes will be treated in a more systematic manner.

Further work regarding the FEP database will be carried out as part of the work to define initial states of the repository, to update the process documentation and to manage the evolving boundary conditions of the system, see further the descriptions of these activities below.

## 2.6 Initial state

An essential part of the safety assessment SR-Can will be the definition of the initial state of the repository system, i.e. the state of the system from which the analysis of the long-term evolution starts. Here, some principles for handling the initial state in SR-Can are outlined.

For many aspects of the assessment of long-term safety it is convenient to let the initial state be that in which the canister, buffer and backfill is left immediately after deposition. However, as discussed e.g. in SR 97, it is not straightforward to define a point in time for the initial state since the repository will be built and taken into operation gradually. Nevertheless, most features important for long-term safety around a deposition hole will be rather similar irrespective of the time of deposition and the SR 97 analysis demonstrated that it is meaningful to define an initial state in this way for many aspects of the long-term evolution.

There are however aspects that will evolve during the gradual construction, disposal and backfilling activities in the repository. These include the groundwater flow and composition as well as the rock mechanical effects of the excavation activities. For those aspects, the time of deposition is not necessarily a natural point of departure for an analysis of long-term evolution.

For the purpose of the long-term safety assessment, the repository system will be characterised as a number of time and space dependent variables describing e.g. the geometry, temperature, hydraulic conditions etc, see section 2.4 and further the SR 97 Main Report Volume I, chapters 5 and 6 /SKB, 1999a/. The task of describing the initial state can therefore be said to amount to assigning initial values to these variables. This is straightforward regarding e.g. the dimensions of a deposition hole whereas e.g. the task of describing initial defects in the canister sealing is a major undertaking for SKB as is indeed the description of the initial state of the host rock and the biosphere at the site.

### 2.6.1 Requirements and factors to be considered

The initial state descriptions should capture not only "normal" or "specified" conditions but also reflect the results of an analysis of what deviations from these conditions that can be reasonably expected. There are a number of factors that need to be considered in the definition of initial states:

- A reference design of the KBS-3 system including specifications of fuel, canister, buffer, backfill, geosphere and biosphere.
- Open design issues. These include choice of buffer and backfill materials, selection of excavation techniques, in particular for deposition tunnels (boring or drilling/blasting), material specifications for tunnel plugs and determination of grouting practices. Modelling implications and data needs for the different design variants need to be established.
- Possible deviations from specifications in reference design. Note though that e.g. a certain (small) number of initially defective canisters may be included in the reference design, see section 6.4.1. In this context, a decision is needed as to whether SR-Can should treat long-term consequences of incomplete closure/extended operational phase of the repository.
- Transfer (and possibly transformation/interpretation) of relevant data from the site descriptive model (geosphere and biosphere).
- A repository layout within the site model.
- Treatment of the evolution of bedrock conditions, such as groundwater flow and the groundwater composition, during the gradual construction, disposal and backfilling activities in the repository.
- Mishaps during repository operation with consequences for the initial state.
- Results of FEP analysis.

Some of these factors and their further handling are discussed in more detail below.

It is urgent that the definition of the initial state is carried out early in the SR-Can project as subsequent steps require that the initial state(s) have been defined. The task will require a sub-group within the SR-Can project with participation of safety assessment generalists and design specialists.

### 2.6.2 Results of FEP analysis

The FEP analysis for SR-Can has to date resulted in a number of issues that need to be considered in the definition of the initial state. These are recorded in the SR-Can FEP database. Many of them concern the effects on the initial state of the evolution of the system during excavation and operation.

FEPs identified as being related to the initial state in general or to particular variables have been reviewed. The general initial state FEPs were further classified as either belonging to a particular variable, or as “Design deviations”, “Mishaps” or left as “General”.

In the further planning of the work the following will be considered:

- All FEPs mapped to the initial state should be revisited and a course of action decided, and documented for each of them.
- Depending on the type of FEP (affecting variable, design deviation or mishap) the discussion on the course of action should consider the general approach for handling *i*) evolution of the bedrock conditions during repository operation, *ii*) design deviations and *iii*) mishaps, as will be discussed below. That is, the FEPs will add to the list of issues under these categories.
- Typical decisions for a FEP would be that it is *i*) already handled, *ii*) that it is not relevant in light of other decisions taken or *iii*) there is a need to update the planned analyses for evolution/design deviation or mishap.
- The exact modelling/data implications of those FEPs requiring updates of analyses will be explored/decided.

### 2.6.3 Information from the site description

Transfer (and possibly transformation/interpretation) of relevant data for the site descriptive model of the host rock will be a major task in defining the initial state of the geosphere. The Site Descriptive Model is an integrated description of the site and its regional environments with respect to current state and naturally ongoing processes, covering geology, rock mechanics, thermal properties, hydrogeology, hydrogeochemistry, transport properties and ecosystems. The description is made in regional and local scale and should serve the needs for Safety Assessment and Rock Engineering /SKB, 2000/.

As the investigations progress, different versions of the Site Description will be produced, where a certain version of the description is related to a defined “data freeze”. SR-Can will initially utilise the Forsmark version 1.1 description as an example whereas the 1.2 versions for the Forsmark and Simpevarp sites will be used in the final stage of SR-Can. SR-Site will be based on the latest available Site Description at that time. Although the models will be updated over time, the intent is that already version 1.1 should have the same principal content as the later versions. The main difference between early versions and later ones will be the confidence in the description and also that a later version may contain more rock domains and other geometrical details. Still, most data on tunnel scale (and below) will be given in statistical terms also in the later versions. Only large features will be given deterministically. This means that procedures developed and shown workable for version 1.1, should be readily applicable also when later versions of the Site Description are used.

In SR-Can it will be necessary to develop and demonstrate a procedure for how to use the Site Description in defining the initial state. The transfer of data should generally be quite straightforward. Several descriptions, like fracture networks, transmissivity distributions etc will already be implemented in the Safety Assessment computer codes, since the Site Description and Safety Assessment partly will use the same codes. However, there are some issues requiring specific attention:

- Repository construction and operation may alter the conditions in the site description. Some of the alterations may be reversible, whereas other needs to be taken into account. This issue is further discussed in the section below.
- The elaborations on the data transfer given in chapter 3 of /SKB, 2002/ should be re-assessed, in order to explore potential problems and other issues to be resolved for SR-Can. The scale of input data needed and specific uncertainty implications (is it possible to formulate "pessimistic cases", how to use "generic data" etc) has to be determined. The uncertainty treatment should be in line with the overall approach to data uncertainty to be applied for SR-Can.
- An important part of the Site Description will be a confidence statement. Safety Assessment needs to put this into perspective and review the plausibility of the arguments. Are confident parts of the site description relevant to the safety case? Are the parts of the description where confidence is low really important for safety? Also, are the confidence statements well supported? If not – how could they be improved? For SR-Can it is needed to start some preparation for how to take care of confidence statements. Also the site descriptive modelling would need feedback (help) in how to formulate their confidence statements. A starting point may be to consider the structure given by /SKB, 2002/ section 4.3.1.

### 2.6.4 Evolution of bedrock conditions during repository operation

The gradual construction, disposal and backfilling activities in the repository will affect conditions like groundwater flow and groundwater composition. The main tunnel system will remain open for the entire repository operation, whereas different deposition tunnels will be explored, excavated, used for disposal and then backfilled within much shorter time (5 years or so).

The unavoidable drainage and inflow to the open parts of the repository will be the main hydraulic sink in the repository volume as long as there are open underground facilities. This will affect the groundwater flow directions, the flow rates and also groundwater composition. Surface waters with dissolved oxygen and organic matter will be drawn downwards. Deep saline waters will be drawn towards the repository. The extent of these changes will depend on the actual flow rates into the open tunnels, which in turn may also depend on grouting efficiency, and how well the tunnels are connected to the surface and to deep lying saline waters (if they exist). Information about the site conditions is to be available in the Site Description.

When a repository tunnel is backfilled and pumping ceases, the direct inflow to these parts will stop, but the surrounding rock mass will still be affected by the drainage of the other, open, tunnel parts. When the entire repository is closed and backfilled a general re-saturation will start. The re-saturated state will probably be similar to the conditions prior to excavation, but some remnant effects may have been imposed, and the time for reaching this "natural state" depends on the actual rock conditions, the time variation of boundary conditions etc.

In the near-field of individual disposed canisters, the surrounding groundwater pressure will probably increase rather fast. Thus, for deposition hole re-saturation and thermal analyses, the fact that other parts of the repository remain open may possibly be disregarded.

Tunnel construction will have mechanical effects on the near-field rock, both through coupled THM effects and by grouting and other means for sealing the rock. The effect is probably only local – and in previous analyses this has been considered by assuming an EDZ with increased permeability in the tunnel direction. However, past assumptions on the EDZ have been rather poorly supported – reassessing the foundation of assumptions is needed.

Even if the open repository may have quite a large impact on the bedrock conditions, the need for treating this in the safety assessment is also linked to whether there will be any radionuclide releases during the "transient time" or not. If early releases could occur it would be necessary to analyse migration in a rather different field of migration paths (and with different properties) compared to the "saturated case". However, if the prime object is to explore the impact on the isolation function during the operational phase, the ambition level on how accurate to describe the operational and re-saturation phase may diminish.

In the further planning of the work the following will be considered:

- Establish the expected timing of disposal tunnel excavation, operation and closure (i.e. will they only be open for 5 years etc).
- Consider whether there will be a need for 'early' radionuclide migration analyses or if the focus should be on exploring effects with potential impact on long term isolation and migration properties.
- Together with "repository engineering" discuss the need for groundwater flow (and transport of major components) for an open repository and plan further actions.
- Reassess the rationale for EDZ-assumptions and how to handle near-field THM effects and grouting in the long term.
- Consider whether it is possible to select some 'type situations' (like different TDS levels, different groundwater pressures, different near-field permeability etc), which may cover the outcome of analyses on what the near-field environment may actually be. Possibly the repository system is robust to a wide range of environments, implying that a prediction of the exact evolution of conditions is not needed.
- Assess implications to near-field evolution, groundwater flow and groundwater composition over time considering all relevant initial state FEPs. Are the implications of the repository operation covered by the actions taken? If not what additional actions should be taken?

### 2.6.5 Mishaps

A preliminary approach for handling mishaps would be to exclude severe mishaps like fire, explosions, sabotage and severe flooding. The reasons for this are *i*) the probabilities for such events are low and *ii*) if they occur, this will be known prior to repository sealing so that mitigation measures and assessment of possible effects on long-term safety can be based on the specific real event.

The list of mishaps resulting from the FEPs analysis will be considered and a final decision made whether the approach of not analysing severe mishaps is acceptable. In case not, selection of mishaps to be explored and modelling implications needs to be assessed.

### 2.6.6 Selecting initial states

An initial state for the safety assessment is defined in detail by assigning initial values to all variables described in the SR-Can database. Often, the values will be given as intervals covering uncertainties of the initial state of the variable in question.

For SR-Can a reference initial state with variants and potentially a selection of alternative initial states will be analysed. The principal criterion determining whether an initial state should be regarded as an alternative or as merely as a variant of the reference state is its impact on long term safety in comparison to the reference initial state. The detailed classification of initial states is to some extent arbitrary. This is however not problematic as long as all relevant states are covered either as variants or as alternative states.

Again, it is noted that the reference state will cover the entire ensemble of canisters and deposition holes in the repository. It should thus include such barrier imperfections that could be statistically expected within the ensemble. This could e.g. mean that a certain small number of initially defective canisters are included in the initial state, see further section 6.4.1; and that a whole range of groundwater flux situations around deposition holes should be covered. This is in agreement with the design specifications of the repository and also with the definition of the main scenario in SKIFS 2002:1.

## 2.7 Process descriptions

A cornerstone in the SR 97 safety assessment was the so called Process Report /SKB, 1999b/, containing a thorough description of all identified, relevant long-term processes for fuel, canister, buffer/backfill and geosphere. Using a prescribed format, each process was described with respect to general understanding of the process, remaining uncertainties and treatment of the process in the safety assessment for a number of scenarios.

For SR-Can a new, developed version of the Process Report will be produced. As described above, for each process, the text in the SR 97 version of the Process Report has been stored in SKB's FEP database. This documentation is a starting point for the new version. As also described above, the list of relevant processes has been reviewed and slightly extended by comparison to other databases. Furthermore, the backfill has been included as a system part of its own, rather than being described together with the buffer as in SR 97.

The updated process descriptions will thus be stored in the database, and an up-to-date version of the Process Report can always be produced more or less automatically by requesting a report on a specified format from the database software. An SR-Can version of the report will be defined and stored in the database.

### 2.7.1 Structure for Process Descriptions

In the new version, all identified processes will tentatively be documented and treated using the following template, where many of the headings are the same as those used in the SR 97 report:

#### *Overview/General description*

Under this heading, a general description of the knowledge regarding the process will be given. For most processes, a basis for this will be the contents of the SR 97 Process Report. All that text will however be reviewed and updated as necessary.

#### *Influencing/influenced variables*

For each variable in the relevant system part, it will be discussed and documented whether it influences the process in any significant way. Similarly, variables influenced by the process will be systematically discussed and documented. The database software will be used to enforce completeness in the influence documentations.

#### *Boundary conditions*

The boundary conditions for each process will be discussed. These refer to the boundaries of the relevant system part. For e.g. buffer processes the boundaries are the buffer interfaces to the canister, to the walls of the deposition hole and to the backfill. The processes for which boundary conditions need to be described are in general related to transport of material or energy over the boundaries. For e.g. chemical processes occurring within a system part, e.g. illitisation in the buffer, the discussion of boundary conditions will be referred to the boundary conditions of the relevant transport processes occurring in the buffer i.e. advection and diffusion.

#### *Model studies/experimental studies*

Model and experimental studies of the process are summarised. This documentation will be the major source of information for many of the processes.

#### *Time perspective*

The time scale on which the process occurs is documented if such a timescale can be defined.

#### *Natural analogues/observations in nature*

If relevant, natural analogues and/or observations in nature regarding the process is documented under this heading. See further section 2.12.4 for the use of this information in the safety assessment.

### *Handling in safety assessment*

Under this heading, one of the following options for treating the process in the safety assessment will be selected (the decisions, and the experts involved in it are documented):

1. The process is neglected. Based on the information summarised in the description of the process under the previous headings, a decision to neglect the process is taken.
2. The process is conceptually simplified in a pessimistic manner so that it does not need a quantitative treatment in the safety assessment. An example of this in SR 97 is the process "Metal corrosion" in the fuel system part. Metal parts are assumed to be fully and immediately corroded if and when water penetrates a damaged canister and contacts the fuel. Their contents of radionuclides are assumed to be immediately dissolved in the contacting water.
3. The process is included in an integrated modelling exercise in the safety assessment. An example of this is the integrated modelling of radionuclide releases from the fuel, followed by radionuclide transport in canister, buffer, geosphere and biosphere leading to dose consequences for man. In these cases the available modelling tools need to be referred to.
4. The process is studied in a separate model which is not directly integrated in the safety assessment. The results of the separate study are used in the analysis of the different scenarios to assess the impact of the phenomenon in question on the evolution of the system. Also in this case the modelling tool or the modelling exercise will be documented. An example of this is the treatment of the deformation of the cast iron insert. This has been separately modelled for a number of load situations including high isostatic loads expected during glaciations, dynamic loads potentially caused by earth quakes and uneven static loads due to uneven swelling of the buffer. The load situations in these separate studies can be compared to those occurring over time in the different scenarios of the safety assessment. From these comparisons conclusions regarding the canister integrity over time can be drawn when the different scenarios are analysed, using in this way the Process Report as a reference.

In many cases the decisions on how to handle a particular process will depend on site specific information.

As a result of the information under this subheading, a mapping of all processes to method of treatment and, in relevant cases, applicable models will be produced. A first version of such a mapping, partly covering the processes in the SR 97 Process Report is shown in Table 2-1.

### *Uncertainties*

Given the selected handling in the safety assessment, different types of uncertainties associated with the process will be summarised.

***Uncertainties in mechanistic understanding:*** The uncertainty in the general understanding of the process is discussed based on the preceding documentation and with the aim of answering the question: Are the basic scientific mechanisms behind the process understood? Alternative models may sometimes be used to illustrate this type of uncertainty.

**Table 2-1. Mapping of processes in the SR 97 Process Report on available tools for quantitative treatment in the safety assessment. This version of the table is incomplete and for demonstration purposes only. Abbreviations used: S: System model, see section 8.1, N: neglected, P: separate process model, C: simple calculation (could potentially be included in system model), H: hydro model, see sections 5.2 and 5.4, NF: near field radionuclide transport model, see section 8.2.2, FF: far field radionuclide transport model, see section 5.3, AT: analytic transport model, see section 8.2.**

| | Neglected | System Model | Separate Process Model | Simple Calculation | Hydro Models | Near Field RN Transport Model | Far Field RN Transport Model | Analytic RN Transport Model | Notes |
|---|---|---|---|---|---|---|---|---|---|
| **Fuel** | | | | | | | | | |
| Radioactive decay | | S | | | | NF | | AT | |
| Induced fission | | | P | | | | | | P: See TR-02-07 |
| Radiation attenuation/heat generation | | S | P | | | | | | Heat generation: TR-99-02 |
| Heat transport | | S | P | | | | | | TR-99-02 |
| Water and gas transport; boiling/condensation | | | | | | | | | |
| Thermal expansion/ cladding failure | | | | | | | | | Cladding failure pessimistically exaggerated, no modelling |
| Advection | | | | | | NF | | AT | Cavities treated as mixed tank |
| Diffusion | | | | | | NF | | AT | Cavities treated as mixed tank |
| Residual gas radiolysis/ acid formation | | | | C | | | | | |
| Water radiolysis | | | | C | | | | | |
| Metal corrosion | | | | | | | | | Pessimistically simplified, no modelling |
| Fuel dissolution | | | P | | | NF | | AT | |
| Dissolution gap inventory | | | | | | NF | | AT | |
| Speciation Fe corr prod | | | P | | | | | | P: TR-97-33 |
| Speciation radionuclides | | | P | | | | | | P: TR-97-33 |
| Helium production | | S | | | | | | | |
| Radionuclide transport | | | | | | NF | | AT | |
| | | | | | | | | | |
| **Canister/Insert** | | | | | | | | | |
| Radiation attenuation | | | P | | | | | | |
| Heat transport | | S | P | | | | | | |
| Deformation Fe insert | | | P | C | | | | | P: Isostatic collapse load see PPM-95-3420-11, complex static uneven load cases see PPM-98-3420-33, dynamic load see TR-92-30; C: Simple static uneven load cases |
| Deformation Cu canister | | | P | | | | | | |
| Thermal expansion | | | | C | | | | | |

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Corrosion Fe | | S | | | | | | | |
| Stress corrosion Fe | | | | | | | | | |
| Radiation effects Fe | | | | | | | | | Neglected based on experimental data |
| Galvanic corrosion | | | | | | | | | |
| Corrosion Cu | | S | | | | | | | |
| Stress corrosion Cu | | | | | | | | | |
| Radiation effects Cu | | | | | | | | | Neglected based on experimental data |
| | | | | | | | | | |
| **Buffer** | | | | | | | | | |
| Radiation attenuation | | | | C | | | | | |
| Heat transport | | S | P | | | | | | P: Integrated with fuel and canister, see e.g. TR-99-02 |
| Water transport | | S | | | | | | | P: Saturation phase see TR-99-41; Water intrusion into defective can see TR-97-19 and TR-99-34 |
| Gas transport/dissolution | | | P | | | | | | |
| Swelling | | S | P | | | | | | P: TR-99-41 (unsaturated phase) |
| Interaction buff/backf | | S | P | | | | | | P: TR-99-41 (unsaturated phase) |
| Thermal expansion | | | P | | | | | | P: TR-99-41 (unsaturated phase) |
| Advection | | | P | | | | | | P: TR-99-41 (unsaturated phase) |
| Diffusion | | S | P | | | | | | Incorporated through Qeq;<br>P: TR-99-29 |
| Ion exchange/sorption | | S | P | | | | | | P: TR-99-29 |
| Montmorillonite transformation | | | | C | | | | | Mass balance calc., see Process Report |
| Dissol/precip impurities | | S | P | | | | | | P: TR-99-29 |
| Colloid release/erosion | N | | | | | | | | Neglected based on experimental data |
| Radiation effects | N | | | | | | | | Neglected based on experimental data |
| Pore water radiolysis | N | | | | | | | | Neglected based on experimental data |
| Microbial processes | N | | | | | | | | Neglected if buffer density exceeds 1,800 kg/m$^3$ |
| Radionuclide transport | | | | | | | | | |
| - advection | N | | | | | | | | Neglected for saturated buffer |
| - diffusion | | | | | | NF | | AT | |
| - sorption | | | | | | NF | | AT | |
| - colloid transport | N | | | | | | | | Neglected for saturated buffer of density above 1,700 kg/m$^3$ |
| - speciation | | | P | | | | | | |
| - decay | | | | | | NF | | AT | AT: Chain decay not treated |
| | | | | | | | | | |
| **Backfill** | | | | | | | | | **Most backfill processes are not explicitly treated in SR 97** |
| Radiation attenuation | | | | | | | | | |
| Heat transport | | | | | | | | | |
| Water transport | | | | | | | | | |
| Gas transport/dissolution | | | | | | | | | |
| Swelling | | | | | | | | | |

|  |  |  |  |  |  |  |  |  |  |
|---|---|---|---|---|---|---|---|---|---|
| Interaction buff/backf |  |  |  |  |  |  |  |  |  |
| Thermal expansion |  |  |  |  |  |  |  |  |  |
| Advection |  |  |  |  |  |  |  |  |  |
| Diffusion |  |  |  |  |  |  |  |  |  |
| Ion exchange/sorption |  |  |  |  |  |  |  |  |  |
| Montmorillonite transformation |  |  |  |  |  |  |  |  |  |
| Dissol/precip impurities |  |  |  |  |  |  |  |  |  |
| Colloid release/erosion |  |  |  |  |  |  |  |  |  |
| Radiation effects |  |  |  |  |  |  |  |  |  |
| Pore water radiolysis |  |  |  |  |  |  |  |  |  |
| Microbial processes |  |  |  |  |  |  |  |  |  |
| Radionuclide transport |  |  |  |  |  |  |  |  |  |
| - advection |  |  |  |  |  |  |  |  |  |
| - diffusion |  |  |  |  |  | NF |  |  |  |
| - sorption |  |  |  |  |  | NF |  |  |  |
| - colloid transport |  |  |  |  |  |  |  |  |  |
| - speciation |  |  |  |  |  |  |  |  |  |
| - decay |  |  |  |  |  | NF |  |  |  |
|  |  |  |  |  |  |  |  |  |  |
| **Geosphere** |  |  |  |  |  |  |  |  |  |
| Heat transport |  | S | P |  |  |  |  |  | P: Integrated with buffer, see e.g. TR-99-02 |
| Groundwater flow |  |  |  |  | H |  |  |  | H: Calculates also transport properties, several models available |
| Gas flow/dissolution |  |  |  |  |  |  |  |  |  |
| Movement in intact rock |  |  |  |  |  |  |  |  |  |
| Reactivation |  |  | P |  |  |  |  |  |  |
| Fracturing |  |  |  |  |  |  |  |  |  |
| Time-dependent deformations |  |  |  |  |  |  |  |  |  |
| Thermal movement |  |  | P |  |  |  |  |  |  |
| Advection/mixing |  |  | P |  |  |  |  |  |  |
| Diffusion |  |  |  |  |  |  |  |  |  |
| Reactions groundwater/rock | N |  |  |  |  |  |  |  |  |
| Diss./prec. frac.filling minerals minerals |  |  | P |  |  |  |  |  |  |
| Microbial processes |  |  |  |  |  |  |  |  |  |
| Decomposition inorg. mtrl |  |  |  | C |  |  |  |  |  |
| Colloid formation | N |  |  |  |  |  |  |  |  |
| Gas formation/gas dissolution |  |  |  |  |  |  |  |  |  |
| Methane ice formation | N |  |  |  |  |  |  |  |  |
| Salt exclusion | N |  |  |  |  |  |  |  |  |
| Radionuclide transport |  |  |  |  |  |  |  |  |  |
| - advection |  |  |  |  |  |  | FF | AT |  |
| - matrix diffusion |  |  |  |  |  |  | FF | AT |  |
| - sorption |  |  |  |  |  |  | FF | AT |  |
| - colloid transport |  |  | P |  |  |  |  |  |  |
| - transport in gas phase |  |  |  |  |  |  |  |  | Geosphere pessimistically short-circuited |
| - decay |  |  |  |  |  |  | FF | AT | AT: Chain decay not treated |

***Model simplification uncertainties:*** In most cases, the quantitative representation of a process will contain simplifications. These may entail a significant source of uncertainty in the description of the system evolution. This aspect of the quantitative treatment will be discussed for the available tools. Alternative models may sometimes be used to illustrate this type of uncertainty.

***Input data and data uncertainties:*** The set of input data necessary to quantify the process will be documented. The further treatment of important input data and input data uncertainties will be described in an Input Data Report, to which reference will be made if relevant. The plans for the Input Data Report are developed in section 2.11.

### *References*

A list of references used in the process documentation.

Expert judgements will permeate all steps of the process documentation. This needs to be clearly acknowledged and documented.

Biosphere processes will be documented separately in a biosphere process report on a partly different format, see further chapter 4.

In chapters 3 through 6, the handling of issues related to many central processes in fuel, canister, buffer, backfill, geosphere, biosphere and climate alterations are discussed. Much of the developments sketched in those chapters will result in updated information in the Process Report for SR-Can.

## 2.8 Handling of changing external conditions and external events

The external conditions of the system defined in section 2.4 are likely to change dramatically during the one million year assessment period. In particular the global climatic evolution will induce changing conditions of an uncertain nature. Today's climate is likely to be followed by several cycles of permafrost and glacial conditions during the assessment period. The time sequence of these changes is likely governed by cyclic astronomical phenomena affecting insolation. Although the future insolation can be well predicted, it is difficult to estimate the response of the climate due to limited understanding of the climate system and also due to additional uncertain driving forces like human induced greenhouse effects. Another large scale phenomenon affecting the boundaries of the system is the so called ridge push caused by tectonic plate movements and resulting in a gradual increase of stress in the bedrock.

The further development of the analysis requires a more thorough description of the boundary conditions in order to *i*) choose a set of scenarios that give a reasonable coverage of possible future evolutions and *ii*) allow analyses of these scenarios with respect to repository safety in subsequent steps of the assessment, bearing in mind that the risk associated with the repository is to be estimated.

The description of future climate and other external conditions is a prerequisite for the biosphere descriptions and those of several future conditions in the bedrock like temperature, groundwater flow, pressure and composition as well as mechanical load situations and their consequences.

There are also a number of external events like human intrusion that could affect the repository.

The broad features of the expected long-term evolution of the boundaries of the repository system have been described in several previous safety assessments, most recently SR 97, and in a number of reports from R&D projects. The further handling of changing external conditions and external events will be pursued along three lines in SR-Can:

a) With the SR 97 climate scenario as a starting point, available information regarding future climate evolution will be compiled together with the external FEPs related to climate in the SR-Can database. The aims are *i*) to define a set of time dependent external conditions to be used in the selection of scenarios and *ii*) to manage the analyses of consequences these boundary conditions will have on the repository system. This work is further detailed in chapter 3.

b) The consequences for the repository for a number of crucial, often stylised external conditions will be analysed as a part of the preliminary analyses described in section 2.9.

c) Further analysis of external events. The treatment of future human intrusion in SR 97 and FEPs relating to external events in the SR-Can database are two important points of departure for the further handling of these issues. Regarding the management of intrusion, more details are given in chapter 7.

As regards point b) above, section 2.9.3 provides some examples of crucial external conditions which need to be specified and for which the consequences of in particular the engineered components of the repository will be analysed.

## 2.9 Preliminary analyses

### 2.9.1 Aims

As a number of initial states and boundary conditions emerge from the steps above, preliminary evaluations of the safety related implications of these will be made, primarily in order to be able to make an informed choice of scenarios in the subsequent step and to optimise the efforts spent on determining input data with uncertainties.

The focus in these analyses will be on the entire evolution of the system. Both the isolating potential of the canisters and the retarding capacity of the system will be analysed. The aim is to include as many processes as possible in the preliminary analyses, in order to understand the broad features of the system evolution.

Parts of the preliminary analyses will be included in the formal scenario analyses later in the project, whereas other parts will be refined using more sophisticated simulation models and/or data from e.g. the site to be analysed.

An ambition already in the preliminary analyses will be to conduct sensitivity analyses since this will inform not only the choice of scenarios but also the efforts spent on determining input data values for the final scenario analyses.

The safety functions of the repository are to isolate the waste and to retard radionuclides should the isolation be breached. Early in the project, preferably as part of the preliminary analyses, the barrier properties contributing to the safety functions should be described in detail. Examples of such properties are the diffusion barrier characteristic of the buffer and that the reducing conditions provided by the geologic environment. Such a description is useful in e.g. the selection of scenarios which must be informed by the understanding of the safety functions of the repository. The description will build on that given in SR 97 and in other relevant sources.

Another aim is to clarify the different time scales on which the repository evolves, and the types of analyses required on the different time scales.

The role of the results of the preliminary analyses in the final safety report remains to be determined. In cases where the results are directly used in the selection or subsequent analysis of scenarios, they must be thoroughly documented in the final reporting. Preliminary analyses not used as the bases for decisions and/or that are superseded by more detailed studies within the scenario analyses may be left out in the final report.

### 2.9.2 Methods for preliminary analyses

Three main methods will be used for the preliminary analyses:

1. Separate detailed analyses of specific issues. These are often studies that were initiated as results of earlier assessment and which have been on-going for some time. Examples are bounding estimates of the effects of earth quakes including the rock, buffer and canister as well as effects of isostatic loads on the canister.
2. Integrated system evolution model. SKB is currently developing a simulation model, see section 8.1, which integrates a number of processes of the repository evolution. The model can be used to study the thermal evolution of the entire system, the chemical evolution of the buffer and backfill for various initial and boundary conditions, canister corrosion for a number of conditions, etc. Some processes are treated in a simplified manner, but results of bench-mark tests indicate that much of the model predictions are very similar to those obtained from more sophisticated models. See Table 2-1 for a preliminary account of processes handled in the integrated model.
3. Preliminary, simplified radionuclide transport analyses.

Also, results from earlier assessments, in particular SR 97, will be utilised as appropriate.

### 2.9.3 Issues to address

The following are examples of boundary or bounding conditions that will be addressed in the preliminary analyses.

#### *Intrusion of different groundwaters*

The intrusion of groundwater *i*) of glacial origin (low ionic strength and possibly oxygenated), *ii*) of varying degrees of salinity on the backfill, buffer and canister will be studied. These are not direct boundary conditions but rather extreme and in some cases unrealistic consequences of flow boundary conditions that may be difficult to quantify throughout a glacial cycle. The results of these analyses can thus be used as bounds on possible impacts of such flow boundary conditions. Also the impact of present day groundwater composition and cement pore water will be analysed.

#### *Consequences of earthquakes*

The consequences of physically maximum possible earth quakes in major structures at the candidate sites are analysed. Emerging studies of field observations of earth quake effects and model simulations of earth quake consequences in rock, buffer and canister will be used in this analysis where the application of respect distances to major fracture zones will be an important part of the methodology.

#### *Consequence of maximum groundwater pressure*

A maximum ground water pressure during a glaciation and its consequence on in particular the canister integrity are studied. The maximum pressure in the SR 97 assessment was estimated at around 30 MPa at repository depth, to which should be added the swelling pressure of the betonite to obtain a total isostatic load on the canister. The assumptions leading to this value will be revisited and the response of the canister will be analysed in the light of results from new calculations of canister strength taking into account inhomogeneous material properties of the load bearing canister insert.

#### *Maximum possible permafrost depth*

A compilation of available information on maximum expected permafrost depth during a glacial cycle at the two candidate sites is made. Consequences of freezing backfill and, if found relevant, also of freezing buffer are studied.

Apart from these, also steady state present day conditions will be analysed. Reference initial conditions, initially defective barriers and dry deposition holes will be considered. Several of the issues mentioned above are further discussed in chapters 3 through 6.

### 2.9.4 Example of probabilistic transport and dose calculations

Since SR 97, SKB’s capability of performing probabilistic hydrology, transport and dose calculations has been developed. This is further discussed in subsequent chapters. Here, some results obtained with simplified analytic transport and dose models, with input data further developed from those used in SR 97 are presented. The most important developments since the probabilistic calculations reported in SR 97 are:

- Uncertainty regarding the fuel dissolution rate is included by assuming a 90 percent likelihood of the rate being $10^{-8}$/year and a 10 percent likelihood of it being $10^{-4}$/year. The SR 97 calculations used a constant value of $10^{-8}$/year.
- All distributions assumed to be discrete in SR 97 are now log-normal, preserving mean values and standard deviations.[1]

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[1] This is not necessarily a “more true” distribution. It is however continuous so that also parameter values between the two used in the discrete distributions are included. Furthermore, it has been demonstrated that the two yield very similar results /Hedin, 2003a/.

- Distributions of biosphere dose conversion factors are taken directly as the output distributions from the biosphere modelling, rather than being based on statistics of those results. Not only the detailed distributions but also correlations between conversion factors of different radionuclides are in this way propagated to the integrated modelling.
- 17 radionuclides are modelled, rather than 9 in the SR 97 probabilistic calculations and a number of variables given pessimistic constant values in SR 97 are now treated probabilistically, based on the SR 97 input database.
- The number of initial canister failures is a binomial distribution with an average of $10^{-3}$·NCan where NCan is the number of canisters in the repository and $10^{-3}$ is the design specification value for the probability of a defective canister leaving the encapsulation plant.

These and other modifications of the SR 97 calculations are results of the ongoing efforts to improve the basis for the probabilistic dose estimates in upcoming safety assessments. An important factor not yet included in this example is the spatial distribution of release points in the biosphere. In the above modelling, all releases are pessimistically assumed to occur at the same point in space, in this particular case to a small peat bog giving high concentrations of in particular Ra-226. This is a pessimistic treatment of release points that could influence the result considerably. Ongoing efforts to improve the treatment of near surface hydrology will allow a better treatment in SR-Can. Also a less pessimistic, site specific description of the characteristics of the fractures intersecting deposition holes would likely have a significant influence on the results.

The results in the form of cumulative peak dose distributions for the three sites analysed in SR 97 are shown in Figure 2-4. The inset indicates which radionuclides give important contributions to the peak doses for the entire ensemble of realisations, for the realisations yielding the highest peak doses.

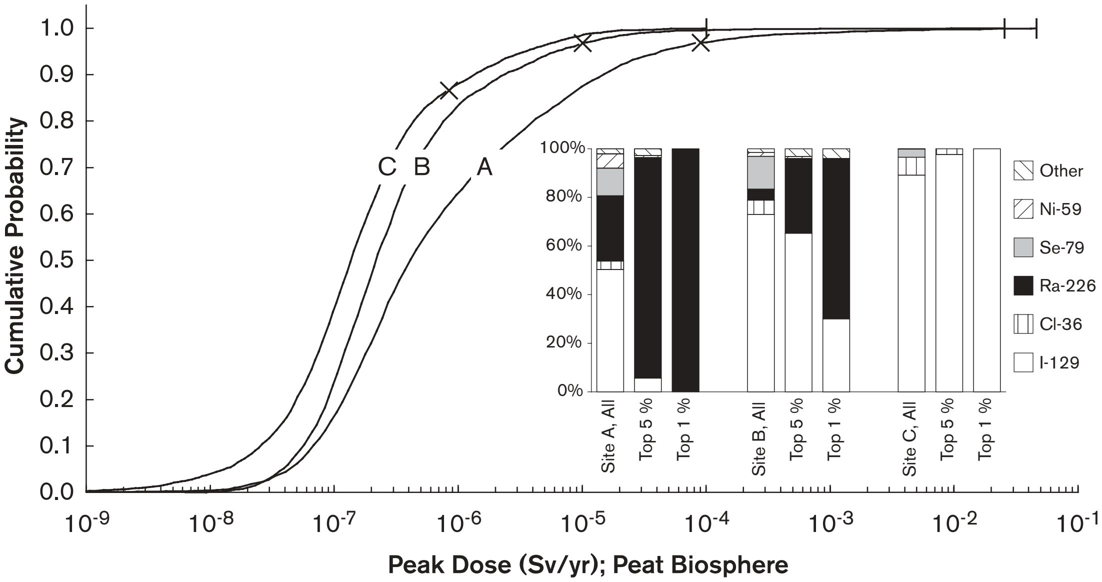

*Figure 2-4. Cumulative peak dose distributions for the three sites assuming a peat biosphere. Mean values are marked by crosses, maximum values by vertical bars. The inset shows the distribution of dominating nuclides for the entire set of realisations, and for the sub-sets of realisations yielding doses above the 95th and 99th percentiles, respectively.*

### 2.9.5 Sensitivity analyses

Sensitivity analyses of the results of the preliminary assessments are important for understanding system safety and in order to focus the efforts in the subsequent steps of the safety assessment, in particular the choice of scenarios and the selection of input data for various model calculations.

The aim of the sensitivity analyses is to determine which uncertain factors have significant impact on safety. Both results regarding the isolating capacity and the retarding capacity of the system will be subject to sensitivity analyses.

A first task for a sensitivity analysis is to determine the safety related calculation endpoints for which sensitivity to input data will be determined. The most obvious endpoint is the annual radiological dose to individuals in the vicinity of the repository, the primary entity of regulatory concern. There are however a number of other conceivable safety related release criteria, e.g. the total release of $\alpha$-emitters and $\beta$-emitters from the geosphere, see further section 2.12.3.

#### *System evolution*

From the point of view of understanding the system evolution, it is also interesting to study the sensitivity of a number of intermediate measures of safety. Such safety related time dependent properties include:

- canister integrity (corrosion, mechanical impacts),
- peak canister temperature,
- buffer density,
- buffer swelling pressure,
- backfill hydraulic conductivity.

These are examples of entities for which sensitivity to input data uncertainties could be studied in order to inform subsequent steps of the analysis.

These aspects of the system have not been treated by systematic sensitivity analyses in earlier assessments. Methods for doing this will have to be selected as the project progresses. It is noted that a primary issue in the study of the evolution is the canister integrity for which the outcome in a particular calculation case is either that it is maintained or not (and if not, the time at which this occurs). In many cases it will likely be concluded that canister integrity is maintained with any reasonable set of input parameters (e.g. corrosion studies) and in such cases the results of the sensitivity analyses will be that the calculation endpoint is not sensitive to estimated uncertainties in the relevant input data. This may well also be the result for other calculation endpoints like peak canister temperature and buffer swelling pressure.

### *Transport and dose calculations*

As mentioned above, the primary safety related time dependent model output for which sensitivity analyses are performed is *the total radiological dose*. Not only the total dose, but also doses from selected individual radionuclides are of interest as calculation endpoints for the sensitivity analyses. As calculated doses are strongly dependent on a number of highly uncertain circumstances in the biosphere, it is motivated to also perform sensitivity measures on one or several alternative safety indicators. Tentatively the *radionuclide releases from the geosphere* will be used as an alternative safety indicator.

A first aim of the sensitivity analyses is to determine which uncertain input parameters give the most significant contribution to *the width of the output distribution*. It is also relevant to determine which uncertainties have a significant impact on *the mean value of the output entity*. This is particularly the case for the dose indicator since the mean dose is directly proportional to the risk, i.e. the regulatory target in Swedish legislation.

A range of developed methods for this type of sensitivity analysis exist, and suitable methods for the KBS 3 system have been selected in recent work /Hedin, 2002b, 2003a/, where also example applications using SR 97 data are given.

Several studies and reviews have demonstrated that standardised rank regression is a suitable method for sensitivity analysis of non-linear systems where the calculation end point is a monotonous function of the input variables. This applies also to the present non-linear and monotonous system /Hedin, 2003a/, and the standardised rank regression coefficient (SRRC) is thus suitable to identify the most important variables contributing to dose uncertainty.

This method was applied to the results of the probabilistic calculations described in section 2.9.4. The SRRC was determined by step-wise regression, see Figure 2-5a. Dominating variables are the fuel dissolution rate, FuelRate ($yr^{-1}$), the groundwater advective travel time, $t_w$ (yr), the number of initially defective canisters, $N_{Can}$ (–), the fracture flow wetted surface, $a_w$ ($m^{-1}$), the diffusivity of Ra-226 in the groundwater, DeRockRa-226 ($m^2/yr$) and the ecosystem specific dose conversion factors, EDF (Sv/Bq) of several nuclides. This gives a good indication of the key uncertainties for this system given current knowledge and available information for the three sites. (The flow wetted surface, $a_w$, has now been superseded by the geosphere transport resistance, F, as one of the most important parameters in the transport modelling.)

The top few percent of the realisations play an important role in determining the mean value and these realisations are dominated by partly different nuclides than the full distribution. To determine which input variables determine the high dose outcomes, the fractions of the input distributions related to the one percent of the realisations yielding the highest peak doses were selected for each input variable. The mean values of these fractions can then be determined and evaluated according to

$$\alpha_{99} = \frac{\text{mean}_{\text{Top Percentile Related Fraction}} - \text{mean}_{\text{Full Input Distribution}}}{\text{standard deviation}_{\text{Full Input Distribution}}}$$

Figure 2-5b shows the $\alpha$99 values for logarithmically transformed data. $\alpha$99 values above 0.4 were considered significant. Further details are given in /Hedin, 2002b/.

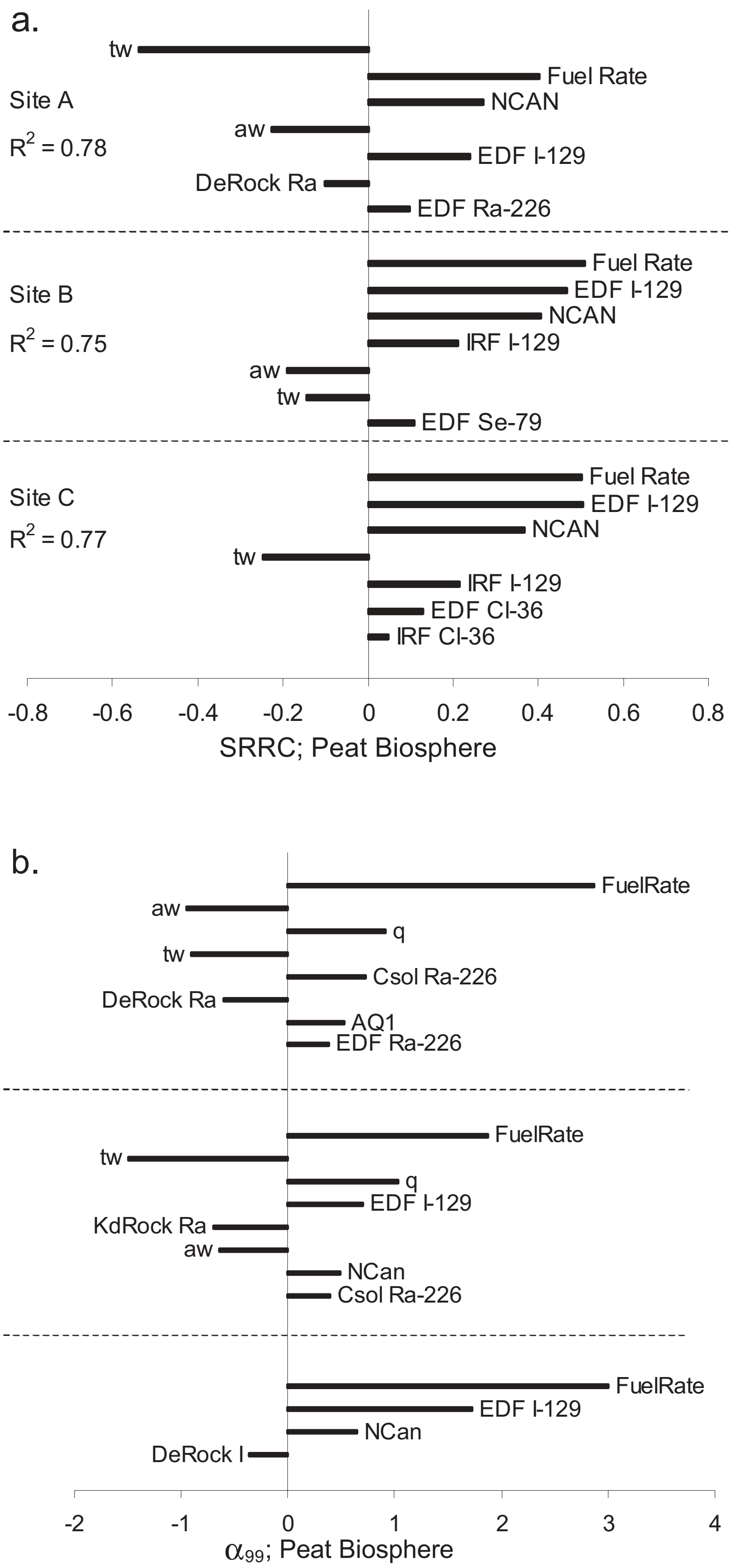

***Figure 2-5.*** *Sensitivity analysis results for the three sites; a) SRRC and b) $\alpha$99 values. Note that the calculation endpoint is the peak dose over the entire one million year assessment period. The same method can though be applied at different specified points in time; an important uncertain factor appearing in such a study is the time at which an initially small canister defect suddenly increases to a large defect due to the evolution inside the canister.*

### *Verification of sensitivity analysis results*

An important part of any sensitivity analysis exercise is to verify that all major sensitive parameters have been identified. This can e.g. be done *i*) by assigning constant central values to all identified sensitive input parameters keeping the full distributions for remaining input data and study the reduction in output distribution width and *ii*) by using full distributions for only the sensitive parameters keeping other constant at central values which should not give any significant reduction in output distribution width.

### *Selection of data and ranges for preliminary sensitivity analyses*

The final data set for the safety assessment will not be available for the sensitivity analyses carried out as part of the preliminary analyses. Indeed, the results of these sensitivity analyses are intended to be used to allocate resources for the determination of the final data set. Input data distributions for this first step will essentially be taken from earlier assessments, in particular from SR 97.

Sensitivity analyses will be carried out also on calculation results based on the final data set, see section 2.12.2. It will be necessary to confirm that the results of those sensitivity analyses are consistent with the ones based on preliminary data, thereby verifying that the preliminary analyses were a sound basis for decisions in e.g. the allocation of resources for the determination of data uncertainties.

## 2.9.6 Examples of expected results

Apart from yielding an overall understanding of the temporal evolution of the repository system, specific issues to be handled are for example the following:

- Bounding calculations of the consequence of intrusion of oxygenated glacial melt water on canister corrosion.
- Bounding estimates of earth quake effects, given the design rules to be applied.

If already bounding calculations of canister corrosion due to glacial melt water indicate that this would not jeopardise the isolating potential of the canister, this is an indication of how thoroughly the issue needs to be treated in the scenario analyses to follow. On the other hand, if such calculations indicate the opposite, this is a signal to treat the issue thoroughly in the selection and analysis of scenarios.

If bounding estimates of earth quake effects indicate that this phenomenon is unlikely to lead to canister ruptures under any reasonable circumstances, this simplifies the scenario selection and analyses. If the opposite is indicated, this is a signal to develop a more sophisticated treatment of earth quakes in the remaining parts of the assessment.

## 2.9.7 Timescale for repository evolution

As a part of the preliminary analyses a discussion on relevant time frames for the repository evolution will be developed. In the process descriptions, time perspectives are discussed for each process, see section 2.7.1. This information will be put together in a diagram showing which processes and which external conditions are active on different time frames during the assessment period.

## 2.10 Scenario selection

As discussed above, the system evolution is associated with many different types of uncertainties. It is not possible to cover all these in a single evaluation of the evolution. Rather, a number of different possibilities for the future evolution of the system are studied. At the highest level of this differentiation of evolutionary pathways is the choice of a number of scenarios.

### 2.10.1 Regulatory requirements and recommendations

There are several issues concerning applicable regulations that have to be taken into account in the selection of scenarios. The quantitative criterion for repository safety in Swedish regulations is a risk limit and from the analyses of the defined scenarios it must thus be possible to draw conclusions regarding risk.

SKI's regulations SKIFS 2002:1 require that scenarios be used to describe future evolutions of the repository and that among these, there should be a main scenario that takes into account the most likely changes within the repository and its surroundings.

The recommendations accompanying SKIFS 2002:1 describe three types of scenarios: the main scenario which includes the expected evolution of the repository system; less probable scenarios, which include alternative sequences of events to the main scenario and also the effects of additional events; and residual scenarios, which evaluate specific events and conditions to illustrate the function of individual barriers.

According to SKI, the main scenario should "be based on the probable evolution of external conditions and realistic, or where justified, pessimistic assumptions with respect to the internal conditions. It should comprise future external events which have a significant probability of occurrence or which cannot be shown to have a low probability of occurrence during the time covered in the safety assessment. Furthermore, it should be based, as far as possible, on credible assumptions with respect to internal conditions, including substantiated assumptions concerning the occurrence of manufacturing defects and other imperfections, and which allow for an analysis of the repository barrier functions…".

The less probable scenarios cover "…variations on the main scenario with alternative sequences of events as well as scenarios that take into account the impact of future human activities such as damage inflicted on barriers."

Residual scenarios should "…include sequences of events and conditions that are selected and studied independently of probabilities in order to, *inter alia*, illustrate the significance of individual barriers and barrier functions. The residual scenarios should also include cases to illustrate damage to humans intruding into the repository as well as cases to illustrate the consequences of an unclosed repository that is not monitored."

Regarding scenario probabilities the SKI recommendations state: "The probabilities that the scenarios and calculation cases will actually occur should be estimated as far as possible in order to calculate risk."

SSI's comments on SSI FS 1998:1 state: "The chosen scenarios must in their entirety give a full picture of the risks attributable to the final repository."

"The description shall include a case, which is based on the assumption that the biospheric conditions which exist at the time that an application for a licence to operate the repository is submitted will not change." In the comments it is stated that "In this context, known trends must also be taken into consideration, such as land elevation…"

SSI's risk criterion applies in the case of a repository which is undisturbed by human activity. However, SSI FS 1998:1 also states that "consequences of intrusion into a repository shall be reported… The protective capability of the repository after intrusion shall be described."

### 2.10.2 Application in SR-Can

In SR 97, no systematic selection of scenarios was done as an integrated part of the project. Rather, a number of scenarios were chosen from results of earlier assessments and reports produced by SKB and others. As noted both in the SR 97 main report and in reviews of SR 97, a more integrated and thorough method for scenario selection will be required in future analyses.

In SR-Can, scenarios will be distinguished from each other through one or several of the following factors:

- Essential safety related differences in initial state, due to e.g. uncertainties in the site descriptive model or regarding an important aspect of the initial state of a barrier. It is to be noted that the initial state will encompass the entire repository and thus all canisters and deposition holes.
- Essential safety related differences in boundary conditions, due to e.g. uncertainties in the climatic evolution.
- The occurrence of safety related, sudden events which are in principle impossible to predict from the knowledge of the system today, e.g. future human intrusion events or earth quakes.

An appropriate choice of scenarios thus requires both insights into what possible variations in initial and boundary conditions that can be reasonably expected and also which of these may have an essential impact on safety. Another requirement is a comprehensive list of safety related events that need to be taken into account to obtain a reasonable coverage of such events among the selected scenarios.

The choice of scenarios will draw on the results from the previous steps of the analysis, in particular the contents of the FEP database, the description of initial states and of external conditions and the results of the preliminary analyses.

Within the definition of each scenario, a number of variants may be defined as necessary to cover

- variants of initial states, e.g. in the site description,
- variants of external conditions,
- conceptual uncertainties and
- input data uncertainties, although a standard way of treating these will be to evaluate the scenario evolution probabilistically.

Guiding principles in the selection of scenarios is that scenarios should be mutually exclusive and that they together should be exhaustive in the sense that they should cover all reasonable future evolutions. A main reason for this is that it should be possible to logically calculate the risk associated with the presence of the repository as a probability-weighted sum of risk contributions from the set of scenarios, see further section 2.15.

It is premature to forecast the actual selection of scenarios at this planning stage of the SR-Can project. Apart from the principles discussed above, the following can however be said already now concerning the selection:

- A high probability or "main" scenario will be selected along the lines of SKI's recommendations. It is however unclear if *any* high probability scenario can be defined for time periods far into the future, when in particular the climatic evolution will be highly uncertain.
- Several alternative climate evolutions will have to be covered in the scenario selection.
- A scenario where today's biosphere prevails will be included since this is explicitly required by SSI. It remains however to be determined what probability should be associated with such a scenario.
- Earth quakes, which were analysed in a separate scenario in SR 97, will likely be integrated in the high probability (and other) scenario(s) in SR-Can.
- Several "bounding cases" covering much of the intentions expressed in SKI's recommendations concerning "residual scenarios" will be analysed, see further section 2.12.1. These will though not necessarily be included in the definition and selection of scenarios described above, since they are not derived with the same methodology or for the same reasons as those scenarios.

Scenario probabilities will be estimated to the extent possible, it can though already now be concluded that these will often have to be pessimistically overestimated. A main purpose for estimating probabilities is to allow a risk calculation, see further section 2.15 for a discussion of scenario probabilities in the risk calculations.

## 2.11 Compilation of Input Data

All input data to quantitative aspects of the safety assessment will exhibit uncertainties. The quality of the results of any calculation in the assessment will, among other factors, depend on the quality of the input data and on the rigor with which input data uncertainties have been managed. A common and methodological philosophy for the determination of input data and the subsequent management of data uncertainty is therefore required.

The set of input data parameters to a full safety assessment is very large. Some input data uncertainties will have a decisive influence on safety related output uncertainty whereas others will essentially not influence output uncertainty at all. An obvious example of the latter are transport properties of those radionuclides that never give a significant contribution to the total dose. It is thus appropriate to identify input data to which output is sensitive and use these insights in allocating resources to the determination of input data uncertainties.

Also the sensitivity analyses do however require input data with uncertainty estimates and there is thus a need to proceed in steps where a preliminary data set is used for a preliminary sensitivity analysis. The result of that analysis is then used to determine data uncertainties in a more rigorous manner, with emphasis on the input data to which output is most sensitive. A preliminary input data set will be determined from the SR 97 input data base, and other appropriate sources.

### 2.11.1 Inventory of data

The mapping of safety relevant processes on models, see section 2.7, yields a set of models which are used to quantify the system evolution. The data requirements of these models in principle constitute the input data inventory to be managed in the safety assessment. The importance of different parameters however differs markedly.

### 2.11.2 Procedure for assigning values

In SR 97, a standardised procedure was employed for all input data to radionuclide transport calculations. The outcome was presented in the SR 97 Data Report /Andersson, 1999/. The uncertainty treatment in SR 97 is discussed by the SKI/SSI review /SKI and SSI, 2001/. The authorities have since conducted some investigations on Expert Judgement /e.g. Wilmot and Galson, 2000; Wilmot et al, 2000; Hora and Jensen, 2002; Hora 2002/. Also SKB has continued development work /Hedin, 2002b, 2003a/.

A new procedure, based on the one used in SR 97 and taking into account review comments is under development. It takes the form of a protocol to be used for all relevant data for the safety assessment. The protocol needs to be flexible so that anything from a well motivated estimate of a single data value to a full expert elicitation of probability distributions can be handled depending on the nature of the input data and needs of the safety assessment. It will include areas like

- Context; the use of the input data in SR-Can, results of sensitivity analyses, correlation to other input data.
- Sources of information (experimental data, site investigation data, model calculations etc).
- Qualitative uncertainty assessment (a description of what types of uncertainty affect the data).
- Quantitative uncertainty assessment (the actual assigning of e.g. data values, data intervals or probability distributions).

The protocol will be tested before it is finally adopted in SR-Can.

### 2.11.3 Allocation of resources

Sensitivity analysis is a key tool for the allocation of resources regarding determination of input data, see section 2.9.5. As discussed in that section, a number of calculation end-points regarding both isolation and retention will be considered and sensitivity of these will be determined.

It is also important to understand some general features of how the models transform input to output. The output dose distributions in the SR 97 assessment are e.g. highly skewed, as is often the case in this type of calculation. The skewness is primarily due to the way in which the input data are transformed by the model, which has been demonstrated by selecting varying input distribution shapes, preserving mean values and standard deviations. The skewness of the output distribution is only slightly affected by the selection of input data shape. This is an aid in the determination of input data since it informs the analyst that calculation results are often not sensitive to the detailed shapes of the tails of input distributions. There are however also examples where only the extreme values of an input distribution have an effect on calculation results.

## 2.12 Analysis of scenarios

The system evolution will be modelled for the scenarios selected according to the procedures described in section 2.10. If the evolution implies canister ruptures or if canisters are assumed to be initially damaged, radionuclide transport and dose consequences will also be modelled. In general, the latter will be modelled for constant barrier properties which are derived, often pessimistically, from the results of the studies of the overall system evolution for each scenario. Such barrier properties are e.g. buffer density, chemical composition and swelling pressure.

The tools for the modelling are described in the process mapping, see Table 2-1. Not all modelling exercises will be actually carried out as part of the scenario analyses, but will refer to results obtained in separate studies. Much of the modelling approaches and tools are further described in chapters 3 through 8.

Input data and data uncertainties will essentially be taken from the Data Report, see section 2.11.

A number of modelling exercises will be made for each scenario. Since the definition of the scenario encompasses all deposition holes and all canisters, it will be necessary to cover the entire range of initial conditions concerning barrier states that is expressed in the initial state for a particular scenario. It may thus be necessary to model both initially intact and initially damaged canisters, initial buffer state as specified and initial buffer states deviating from the specifications, “wet” and “dry” deposition holes etc within the same scenario. This will in general be covered by a number of separate analyses that will together form the results of the analysis of a particular scenario.

### 2.12.1 Bounding calculation cases

As a complement to the calculation cases for each scenario discussed above, a number of bounding calculation cases for hypothetical conditions will be made. These serve several purposes: The relative importance and role of the different barriers or safety functions can be elucidated. They can aid in building the safety argumentation. Hypothetically, an upper bound on the consequences of a post-glacial earth quake could be given by assuming that all canisters break after 100,000 years. Similarly, the consequences of a fundamental, unrealistic, omission of a canister damaging process could be given an upper bound. A maximum consequence of e.g. having misunderstood the geosphere retention properties could be given by assuming that releases from the buffer immediately reach the biosphere.

Also, these cases are designed to cover the residual scenarios mentioned in the recommendations accompanying SKI’s regulations, see further section 2.10.1.

Examples of cases that could be considered include:

- No geosphere retention.
- No solubility limits inside canister.
- No backfill, no buffer.
- All canisters break at time $t_1$, $t_2$, etc.
- Unsealed repository.

To the extent possible, these cases should not only analyse radionuclide transport and dose but also the system evolution in general.

#### *Development of a design basis*

It may also be necessary to include cases that contribute to the further development of a design basis for the repository. The recommendations to SKIFS 2002:1 state: "Based on scenarios that can be shown to be especially important from the standpoint of risk, a number of ***design basis cases*** should be identified. Together with other information, such as on manufacturing method and controllability, these cases should be used to substantiate the design basis such as requirements on barrier properties."

This should certainly be possible for many barrier properties, based on the calculation cases defined within the selected scenarios. Several important barrier properties, like the thickness of the copper shell of the canister or the diameter of the deposition hole, are however not regarded as open design issues, and are thus not necessarily included as variants of the initial state. Additional calculations cases may therefore be needed to develop the design basis.

### 2.12.2 Sensitivity analyses

Sensitivity analyses are an important part also of the scenario analyses. Furthermore, SKIFS 2002:1 require a sensitivity analysis that "shows how the uncertainties affect the description of barrier performance and the analyses of consequences to human health and the environment".

Sensitivity analyses will thus be performed as a part of the scenario analyses. The tasks and methods will resemble those applied in the preliminary analyses, see section 2.9.5, but now the analyses will be applied to the results of some of the final calculation cases of the SR-Can assessment.

### 2.12.3 Alternative safety indicators

The dose/risk safety indicator provides a direct measure of consequences for man due to the existence of the repository. As discussed in section 2.14.1, several aspects of the biosphere evolution are highly uncertain, also in a relatively short time perspective. The evaluation of safety will depend on a number of assumptions made in order to handle these uncertainties. Therefore it could be interesting to complement the dose/risk indicator with alternative indicators which do not require detailed assumptions about the biosphere or of human habits.

The recommendations accompanying SKIFS 2002:1 mention that for distant futures, the dose indicator can be complemented with other safety indicators, e.g. concentrations in the ground or near-surface waters of radionuclides from the repository or the calculated flux of radionuclides to the biosphere.

A problem with alternative indicators is that there is in general no obvious criterion to which the calculated entities can be compared. In some cases, calculation results can be compared to natural concentrations or fluxes. These criteria are however site specific and do not include man-made radionuclides. The latter problem can be partly overcome by comparing naturally occurring sum concentrations/fluxes of ±- and ²-emitters to the corresponding repository induced entity.

A related question concerns quantitative measures of biological effects on biota other than man. This is briefly discussed in section 4.5.

### *EU SPIN Project*

A recently reported EU project /EU, 2002/ concludes that two alternative indicators could preferably be used to complement the dose indicator. These are:

- Radiotoxicity concentration in biosphere water: preference for medium time frames.
- Radiotoxicity flux from geosphere: preference for late time frames.

The project also reports on reference values that could tentatively be used for comparisons to calculated concentrations and fluxes of radionuclides from the repository.

### *Finnish activity constraints*

The Finnish Radiation and Nuclear Safety Authority STUK has recently issued activity release constraints to the environment /STUK, 2001/.

The nuclide specific constraints are defined for long-lived radionuclides only. The effects of their short-lived daughters have been taken into consideration in the constraints defined for the long-lived parents. The nuclide-specific release rate constraints are

- 0.03 GBq/y for the long-lived ±-emitting isotopes of Ra, Th, Pa, Pu, Am, Cm.
- 0.1 GBq/y for Se-79, I-129, and Np-237.
- 0.3 GBq/y for C-14, Cl-36, Cs-135, and the long-lived isotopes of U.
- 1 GBq/y for Nb-94 and Sn-126.
- 3 GBq/y for Tc-99.
- 10 GBq/y for Zr-93.
- 30 GBq/y for Ni-59.
- 100 GBq/y for Pd-107 and Sm-151.

The constraints apply to activity releases which arise from the expected evolution scenarios and which may enter the environment after several thousands of years, while dose rate constraints are applied in the shorter term. In applying the above constraints, the activity releases can be averaged over 1000 years at the most. The sum of the ratios between the nuclide specific activity releases and the respective constraints shall be less than one. It should be noted that the Finnish regulator has derived these constraints partly based on a set of reference biospheres considered possible in the future at the planned disposal site, Olkiluoto at the coast of the Baltic Sea, and partly on natural fluxes of radionuclides established for similar environments. The reference values of the Finnish regulatory guide are thus not directly applicable for other disposal concepts and sites /EU, 2002/. However, both the disposal concept and the sites considered in Sweden are similar to those for which the Finnish activity constraints have been developed.

#### *Other studies*

An SKI/SSI study /Miller et al, 2002/ compiles from the published literature a substantial database of elemental abundances in natural materials and, using these data, calculates a range of elemental and activity fluxes arising due to different processes at different spatial scales. It is concluded that these fluxes should be comparable to results from safety assessment calculations.

IAEA has published a study entitled "Safety Indicators in Different Time Frames for the Safety Assessment of Underground Radioactive Waste Repositories" /IAEA, 1994/ and is currently conducting a research programme on natural concentrations and fluxes, that is expected to be concluded in 2003.

#### *Implications for SR-Can*

The material presented above will be evaluated with respect to applicability to Swedish conditions and to the SR-Can assessment. Preferably one or two alternative indicators will be used in the evaluation of part of the calculation results emerging from SR-Can.

### 2.12.4 Use of natural analogues

#### *Background*

References to natural analogues have been made in SKB:s safety reports since 1978 but they have in general had a limited role in the overall evaluation of safety. Most successful, so far, have been the material analogues; uranium oxide, copper, bentonite, cement, etc, used to illustrate safety relevant processes. The SR 97 Process Report refers to natural analogues for 14 of the processes presented, for example, copper corrosion, gas transport in clay, illitisation, silica precipitation in clay, microbial activity in clay, tectonic reactivation or neoformation of rock fractures, matrix diffusion, etc.

An overview of the analogue field was presented in RD&D-programme 2001. SKI's recommendations concerning SKIFS 2002:1 state: "The validity of assumptions used, such as models and parameter values, should be supported, for example through … field experiments and studies of natural phenomena (natural analogues)."

#### *Summarising analogues used in the Process Report*

The Process Report with its references to analogue studies will be updated in connection within SR-Can, see section 2.7.1. It may be worthwhile to present analogues also more "up front", in addition to the treatment in the Process Report. A way of doing that would be to go through the barriers and summarise the analogue applications mentioned in the Process Report, in a descriptive and illustrative way, as a chapter/section in the main report. The following is a rough list of processes based on the content of the previous Process Report:

- Spent fuel: criticality, fuel dissolution.
- Canister: copper corrosion.
- Buffer and backfill: Gas transport, illitisation, silica precipitation, microbial activity.
- Host rock: Reactivation of rock fractures, neoformation of rock fractures, matrix diffusion, influence of cement (pH-plume).

Weight will automatically be put on the material analogues (spent fuel, copper, bentonite), since they provide useful arguments for safety assessment and are therefore well represented in the Process Report. The examples above were taken from the SR 97 Process Report. The new and updated version, which will be produced for SR-Can, is likely to contain additional examples.

#### *Illustrating basic conclusions*

Illustrative analogues, where text can be easily combined with pictures and diagrams may be particularly useful in this context. An example could be the medieval helmet from York, made of steel with brass ornaments and preserved in an old well under reducing conditions. Such an example could be used to address the issue of galvanic corrosion.

#### *Discussing "negative analogues"*

This chapter/section could also be a forum for commenting "negative analogues", i.e. analogues which indicate seemingly contradictive results to other conclusions of the safety assessment. An example is the measurement of plutonium migration at the Nevada Test Site. Such cases should preferably be discussed in a visible place of the report and brought into context. For example, in SR 97 the negative colloid analogues from Krunkelbach mine and Nevada Test Site were both discussed in the Main Report (SKB TR-99-06, Vol. II, p. 279 /SKB, 1999a/). Another example is the Boda Caves phenomenon discussed in SKB's RD&D-programme 2001 /SKB, 2001/.

## 2.13 Integration of results and conclusions

### 2.13.1 General discussion and risk summation

This step of the assessment will contain an overall summation and discussion of the results of the analyses of the different scenarios. An important part of the discussion will be a risk summation according to section 2.15 in order to reach a conclusion regarding compliance with the regulatory risk criterion.

Another important part of the discussion of results is to provide feedback to site investigations, design development and R&D efforts. A general instrument for this would be the results of the sensitivity analyses carried out as part of the scenario evaluations.

### 2.13.2 Feedback to site investigations

Feedback concerning the site description will primarily be communicated to the site modelling group that provided the site description. They may then, in turn, assess to what extent this feedback also has implications for the actual investigations during continued site investigation.

In general, an evaluation will be made of the confidence in site description as a whole. The following, more specific, feedback may be expected:

- The calculated migration paths will designate a volume of the explored rock where it is particularly important to have high confidence in the Site Description. This could be compared with the current confidence and would thus lead to assessments of the need to increase borehole density etc.
- Similarly, the distribution of discharge points will indicate which portions of the surface environment are of most interest, at least for radionuclide turn-over modelling for present day conditions.
- The transport calculations and sensitivity analyses will provide similar feedback of higher precision. They will also help in putting the site specific uncertainties in a broader perspective.
- Exploring the impact of different alternatives will suggest if there is a need to spend efforts (critical measurements and modelling) in decreasing the span of alternatives in the Site Description, both regarding geometry and properties.
- Assessing importance of (potential) heterogeneous rock type mixture will provide feedback to site investigations on the ambition level and approach for describing the rock type variability.
- Earthquake analyses on different alternative description could give indications as to what extent efforts would be needed to discriminate among the alternatives.
- Indication whether further attention is needed as regards colloid levels.
- If the results of the safety assessment suggest there is a problem with indications of mineral deposits found, this may require a more careful assessment of the extent of the deposits.

Much of this feedback will be given also in the preliminary safety evaluations of the candidate sites to be produced within the SR-Can project, see further section 1.1.1 and /SKB, 2002/. In those evaluations comparison with criteria as given in /Andersson et al, 2000/ will be made and, based on this, a general recommendation of whether site investigations should continue.

### 2.13.3 Feedback to design development

Regarding feedback to design modification/improvements, feedback will obviously be provided in comparing the results of analyses of open design alternatives (e.g. choice of backfill material, choice of buffer material, TBM drilling or blasting) which are defined as alternative initial states.

Also a discussion of the design basis, see section 2.12.1 in the light of the safety assessment results should be included in the feedback given to design development.

### 2.13.4 Feedback to Research & Development

The results of sensitivity analyses should give direct implications on those crucial uncertainties regarding individual processes or system features that have been expressed as data uncertainties.

A more qualitative approach would be to go through the descriptions of uncertainty regarding mechanistic understanding and model simplifications in the Process Report and the subsequent analyses of the consequences of these uncertainties in the scenario evaluations. This would identify needs for improved mechanistic understanding and modelling tools.

### 2.13.5 Feedback to future safety assessments

Also, a number of experiences from the safety assessment project itself are expected to be useful in planning and carrying out future assessments. These will be discussed as part of the feedback from the assessment.

## 2.14 Overall information/uncertainty management and QA plan

A safety assessment handles a vast amount of information of qualitative and quantitative nature. The management of the body of information to a large extent amounts to the management of qualitative and quantitative uncertainties that are inevitably associated with the information. This section gives an overview of a plan for information and uncertainty management in SR-Can. Since this issue permeates the entire analysis, the overview is in part a summary of the different steps of the methodology described in the preceding sections, but with emphasis on information/uncertainty management and quality assurance.

The plan is a starting point and will be further developed as the project progresses.

As a background, the section below gives a brief description of the different types of uncertainty that have to be managed in the safety assessment.

### 2.14.1 Classification of uncertainties

There is no unique way in which to classify uncertainties in a safety assessment. The classification adopted below is however compatible with international practice /NEA, 1991, 1997a/ in this type of analysis. SKB has previously discussed the classification and nature of uncertainties in detail, see e.g. /SKB, 1996, section 3.4/ and /Andersson, 1999, section 2.1/. Here, only a brief discourse is given, setting the frame for the presentation of the management plan.

The safety assessment is built on the analysis of how a system with an initial state evolves as a result of the action on the system by a number of internal processes and external influences/events. From this description, a number of issues regarding uncertainties can be identified:

- How well is the initial state known, qualitatively and quantitatively, i.e. are all important aspects of the initial state identified and how well can they be quantitatively described?
- Have all relevant internal processes been identified? How well are they understood mechanistically?

- Have all relevant external events and phenomena been identified? How well can they be quantified?
- How can a representative account of the system evolution be made, given all the uncertain factors given above? How well can the internal processes be represented mathematically to give a realistic account of the system evolution? How well are all the input data necessary for the quantification of the system evolution known?

In finding a structure for a more rigorous approach to the above issues, it is customary /NEA, 1997a/ to describe uncertainty in the categories system/scenario uncertainty, conceptual uncertainty and data uncertainty. A general conclusion from international collaboration efforts in the area of assessment methodology is that there is no unique or correct way to describe or classify uncertainty. Rather, in any safety assessment, it is important to make clear definitions of the use of different terms in this area, in the light of the results of international efforts like /NEA, 1997a/.

In SR-Can, the following broad definitions will be used:

*System uncertainty* concerns completeness issues, i.e. the question whether all aspects important for the safety evaluation have been identified and the way the analysis is capturing the identified aspects in a qualitatively correct way, e.g. through the selection of an appropriate set of scenarios. In short, have all factors, FEPs, been identified and included in a satisfactory manner?

*Conceptual uncertainty* essentially concerns the understanding of the nature of processes involved in the repository evolution. This concerns not only the mechanistic understanding of a process or set of couple processes, but also how well they are represented in a simplified mathematical model of the repository evolution.

*Data uncertainty* concerns all quantitative input data used in the assessment. There are a number of aspects to take into account in the management of data uncertainty. These include correlations between data, the distinction between uncertainty due to lack of knowledge (epistemic uncertainty) and due to natural variability (aleatory uncertainty) and situations where conceptual uncertainty is treated through a widened range of input data. Also, there are many degrees of freedom in determining a strategy for deriving input data. One possibility is to strive for pessimistic data in order to obtain an upper bound on safety in compliance calculations, another option is the full implementation of a probabilistic assessment requiring input data in the form of probability distributions. These aspects are further discussed in section 2.11.

It is noted that the distinction between system and conceptual uncertainty is vague. It would certainly be possible to use only the term conceptual uncertainty and include in its definition the aspects termed system uncertainty above.

The plan presented in section 2.14.3 below demonstrates how all the discussed types of uncertainty will be managed in the safety assessment. It is intended to be applied in detail to the fuel, canister, backfill and the parts of the geosphere that lie within the system boundaries.

### 2.14.2 Need for stylised examples

The local biosphere is by definition a part of the system, i.e. it lies within the system boundaries and biosphere uncertainties should thus be managed in the same way as for other internal parts. However, in the biosphere, the list of processes determining the system evolution is in principle very long and the system in which they occur is highly inhomogeneous, including a number of different ecosystems each with a large number of more or less complex components. Furthermore, the time scale on which the biosphere changes is in general considerably shorter than for other parts of the system, and the interactions with man are much stronger and associated with partly irreducible, large uncertainties. Although some aspects of the evolution of the biosphere at a particular location can be reasonably forecasted in maybe a 1,000 year perspective, a large part of the description of particularly human behaviour will have to be through stylised examples. The management of uncertainties in the biosphere will be further developed as the SR-Can project emerges.

Also regarding external conditions the uncertainty management will largely have to be through stylised examples aiming at covering possible future evolutions, e.g. regarding the climate. A detailed treatment of all the processes involved in the climatic evolution is out of the scope of the safety assessment. It is furthermore a rapidly evolving field of science, where uncertainties are fundamental and in part irreducible. The approach will instead be to follow the development of the field, and derive a number of stylised possible example evolutions that together give a reasonable coverage of what could be expected in the future. In particular extreme conditions with respect to repository safety need to be captured in these examples. These conditions include

- maximum glacial overburden and the resulting hydraulic pressures and hydraulic loads on the bedrock,
- infiltration of waters of extreme composition like oxygenated glacial melt water of low ionic strength and
- extreme surface boundary conditions for groundwater flow possibly leading to high groundwater fluxes at repository level or groundwater movements that could cause infiltration of deeply lying saline groundwaters.

The inner parts of the system, which are responsible for the safety functions isolation and retardation are thus treated most strictly in the management of uncertainty whereas the biosphere and the external conditions are handled in a more stylised manner.

### 2.14.3 Plan for uncertainty management

The purpose of the safety assessment will affect the management of uncertainties. In this context, the purpose of the assessment is essentially two-fold:

- to assess compliance with Swedish regulation and
- to give feedback to design modifications, research and development program and further site investigations.

The first purpose can, if there are sufficient safety margins, be largely accomplished by a pessimistic handling of many uncertainties. The second however requires a more sophisticated management in order to determine quantitatively which uncertain factors and open design issues affect safety most.

A plan for the structured and well documented management of uncertainties is an important part of an overall QA plan for the safety assessment. The following is a first attempt to present such a plan for the management of uncertainty. The plan is broadly structured according to the different main steps of the safety assessment project. As mentioned above, it will have to be developed as the SR-Can project progresses.

### *Derivation of a comprehensive set of internal processes and variables*

Method: Derive SR-Can Process Diagrams in a structured way from the SR-Can FEP database. The SR-Can database contains the SR 97 Process Diagrams, the SR 97 Process Report, the SKB Interaction Matrix documentation and the NEA FEP database which encompasses a number of national FEP databases. By mapping the contents of the NEA FEP database onto the processes and variables in the SR 97 Process Diagrams, allowing for new processes and variables to be included if appropriate, it is ensured that no known relevant processes/variables are omitted from the safety assessment.

Type of uncertainty addressed: Completeness regarding internal processes, variables and couplings between process and variables.

Documentation: Electronic version of SR-Can database (mapping activities and resulting Process Diagrams), report describing working procedures and essential results like Process Diagrams.

QA procedures: a) Automated database software check that all FEPs in NEA database have been considered in the mapping, and that b) all possible combinations of process/variable influences have been considered, c) recording of experts and dates for decisions regarding all SR-Can database manipulations in the database.

### *Compilation of Process Report*

Method: Document each process present in the process diagram, according to a pre-determined format, see section 2.7.1 for a tentative structure. Hereby, a thorough account is obtained of the current state of knowledge of the process, of influencing and influenced variables in the Process Diagrams, of boundary conditions (if relevant), of uncertainties regarding mechanistic understanding, of suggested treatment in the safety assessment and of model simplification uncertainties in that treatment. The documentation along with a list of references is stored in the SR-Can database.

Type of uncertainty addressed: Conceptual uncertainty regarding mechanistic understanding, model simplifications and exclusion of insignificant processes from further modelling.

Documentation: The Process Report, which is automatically generated from the SR-Can database. A mapping of processes onto models/methods used to quantify the process in the safety assessment, se section 2.7.1 for an example.

QA procedures: Through the database management, it is ensured that all identified processes are documented using a predetermined format, that all variable influences are documented. Possibly a software checking routine in the database should be developed for this. Recording of experts and dates for decisions regarding all SR-Can database manipulations in the database. It is further noted that a methodological updating of the documentation of scientific understanding is the key to the quality of the Process Report.

### *Derivation of a set of initial states that cover all relevant safety related features*

Method: a) Collect all FEPs in the NEA and SR 97 FEP databases related to the initial state. Document further treatment in the database. b) Consider relevant open issues in the KBS 3 design and other factors discussed in section 2.6.1. c) Select a number of initial states, drawing on understanding of safety relevant features. d) Ensure that each variable in the Process Diagrams is assigned a value in each initial state applying, for the important input data, methods for describing data uncertainties. Selection of important data is based on sensitivity analyses.

Type of uncertainty addressed: Completeness regarding selection of initial states. Data uncertainties in the descriptions of initial states.

Documentation: Electronic version of SR-Can database (management of FEPs related to initial state), database report describing working procedures and essential results like a summary of initial state FEPs, Initial state report, describing selection of initial states, Data report for relevant data uncertainties

QA procedures: a) Automated database software check that all FEPs in NEA and SR 97 databases have been considered in the mapping of initial states, b) recording of experts and dates for decisions regarding all SR-Can database manipulations in the database, c) well recorded expert judgements in the initial state report, d) procedures for managing input data uncertainties in the Data Report, see further section 2.11 below.

### *Derivation of external conditions*

Method: Collect all FEPs in the NEA and SR 97 FEP databases related to external conditions. Further treatment according to section 2.8 and chapter 3.

Type of uncertainty addressed: Completeness in the management of external events and factors in boundary conditions,

Documentation: Electronic version of SR-Can database (management of FEPs related to external conditions), database report describing working procedures and essential results like a summary of external FEPs,

QA procedures: Automated database software check that all FEPs in NEA and SR 97 databases have been considered in the mapping of initial states, recording of experts and dates for decisions regarding all SR-Can database manipulations in the database.

### *Compilation of input database*

Method: Derive inventory of input data from models used in quantitative assessments of system evolution, allocate resources spent on each datum drawing on results of preliminary sensitivity analyses, apply predefined protocol in compiling information relating to data uncertainty and to the quantification of uncertainty.

Type of uncertainty addressed: Data uncertainty, conceptual uncertainty in cases where this is managed by an appropriate selection of input data.

Documentation: Data report, including an account of the inventory of data, the protocol with instructions to authors and filled out protocols for data being treated in the report.

QA procedures: a) mapping of processes on models as recorded in process documentation in the SR-Can database, b) documented use of protocol for derivation of input data in Data Report.

### Selection of scenarios

Method: Consider results of initial state descriptions, of process structure, of description of external conditions and the results of preliminary analyses. Select a number of scenarios and variants for further analysis.

Type of uncertainty addressed: Completeness in the choice of evolutional pathways

Documentation: Scenario selection documentation/report

QA procedures: Document how all decisions are taken, how results of initial state selection, external conditions and results of preliminary analyses are propagated to and further managed in the selection of scenarios. A structured procedure for this needs to be developed.

### Model evolution for each scenario

Method: Use relevant set of models, describe uncertainties in Process Report, map process on models, use quality assured input data. Derive calculations cases covering uncertainties, either probabilistically or by selecting an appropriate set of deterministic cases.

Type of uncertainty addressed: Integration of much of the uncertainty described in the previous steps.

Documentation: Process Report, process mapping, documentation of modelling exercises.

QA procedures: Documentation of models and input data in sufficient detail so that calculations crucial to the safety case can be reproduced. A large part of the input data will be documented in the SR-Can Data Report.

### Bounding calculation cases

Method: Exclude important safety features like geosphere retention or canister isolation potential. Otherwise, proceed as above.

Type of uncertainty addressed: Broad conceptual uncertainty in system understanding, completeness.

Documentation: Documentation of modelling exercises.

QA procedures: Documentation of models and input data in sufficient detail so that calculations can be reproduced. A large part of the input data will be documented in the SR-Can Data Report.

### 2.14.4 Summary

With a proper implementation of the plan outlined above, it should be possible for a reviewer to

- follow and review the identification of processes, variables and dependencies between these,
- follow and review the management of internal processes, the selection of initial states and external conditions and the way these are used in the selection of scenarios and
- repeat calculations, in particular those crucial to the safety evaluation.

## 2.15 Approach to Risk Calculations

### 2.15.1 Regulatory requirements and guidance

The quantitative acceptance criterion in Sweden for long-term safety of a nuclear waste repository is a limit on annual risk. SSI FS 1998:1 states the following: "A repository for spent nuclear fuel or nuclear waste shall be designed so that the annual risk of harmful effects after closure does not exceed $10^{-6}$ for a representative individual in the group exposed to the greatest risk." The conversion between dose and risk is to be carried out using ICRP's probability coefficient for cancer and hereditary effects of 0.073 per Sievert. An annual risk limit of $10^{-6}$ thus corresponds to a dose limit of about $1.5 \cdot 10^{-5}$ Sv/yr.

The dose component of a risk is an integration or summation over all exposure pathways of the product of the probability of the pathway occurring times the magnitude of the dose. This sum or integral is multiplied by 0.073 per Sievert to obtain the risk, which is thus dimensionless.

It is furthermore important to note that SSI's risk criteria "concerns a repository undisturbed by man" according to the background comments issued by SSI.

### 2.15.2 Application in SR-Can

In principle, the product of dose consequences and likelihoods of all possible future evolutions of the repository should be weighed together and presented as a time dependent risk. The spectrum of possible evolutions is however immense and can not be captured in a detailed sense. This is also recognised in SSI's regulations and associated background comments.

The usual approach taken in safety assessments, and also in SR-Can, is to work with scenarios and variants that are meant to capture the broad features of a number of representative possible future evolutions. Together these should give a reasonable coverage of possible future exposure situations. Conditional risks will be calculated for each scenario and variant and these are then weighed together using the probability for each scenario/variant. Furthermore, each variant, represented by a specific calculation case may be evaluated probabilistically in order to determine the mean exposure given the data uncertainties for the particular variant.

The approach of calculating risk as a weighted sum over a number of scenarios constrains the way in which scenarios are selected and defined. It must be possible to logically explain the determination of probabilities. In short, the scenarios should be mutually exclusive, and the set of scenarios complete in the sense that all relevant future evolutions are covered.

A “normal evolution” scenario with a high probability of occurrence must e.g. contain initially defective canisters and other barrier insufficiencies if such are likely when the entire ensemble of canisters and deposition holes in the repository is considered. Furthermore, in evaluating less likely scenarios treating disruptive events due the course of the repository evolution, the consequences of these need to be superimposed on those of the normal evolution scenario. This does not mean that the calculation case for the latter must include also the normal evolution, but it must be possible to superimpose the two in order to correctly represent the disruptive scenario in the final risk calculation.

Since SSI’s background comments state that the risk criterion concerns a repository undisturbed by man, at least scenarios involving direct intrusion into the repository will be excluded from the risk summation.

### 2.15.3 Overestimation of risk

The formulation of scenarios, variants and calculation cases, and the subsequent weighing together of these to a total risk will not aim at a realistic calculation of risk. SSI’s regulation requires that the annual risk should be *less than* $10^{-6}$. There are a number of uncertainties that cannot be managed quantitatively in any other rigorous manner from the point of view of demonstrating compliance than by pessimistic assumptions. An example is the handling of uncertain immobilisation phenomena in the geosphere. The present knowledge base does not allow credit to be taken for such processes in estimating the safety of a repository and they have to be pessimistically neglected.

Another situation where risk will have to be overestimated concerns scenario probabilities. For scenarios and variants where defendable probabilities are difficult do derive, a scenario or variant giving high consequences might pessimistically be assigned unit probability and other scenarios and variants yielding lower dose impacts may be “subsumed” under the one with the more severe consequences.

Although the primary aim with risk calculations is to demonstrate compliance, there is also the clear ambition of clarifying the sensitivities of the calculation results. For this aim, the calculation cases should in principle be as realistic as possible in capturing uncertainty. The main quantitative tool for this is the use of probabilistic evaluations of calculation cases followed by sensitivity analyses of the results.

It is concluded that pessimistic simplifications should be avoided where a sound scientific bases exists for a quantitative treatment and further that the pessimistically neglected features of the system should be included in a discussion of sensitivities.

### 2.15.4 Time dependent risk or peak over entire assessment period?

In SKB’s latest safety assessment, SR 97, an upper bound on the peak of the time dependent risk was calculated in the following way for a particular probabilistic calculation case: In each realisation the peak dose over the one million year assessment period was determined. The mean value of the so determined distribution of peak doses was then compared to the dose criterion. While this is a correct way of putting an upper bound on risk, it is however more informative and also in agreement with the regulatory requirements /SKI and SSI, 2001/ to calculate the mean annual dose at each point in time and require that this entity never exceeds the dose corresponding to the risk criterion of $10^{-6}$. The two methods are sometimes referred to as “the mean of the peaks” and “the peak of the mean”. In SR-Can, it is thus SKB’s intention to use the latter, i.e. to present risk as a function of time.

An example of the two types of results is given in Figure 2-6.

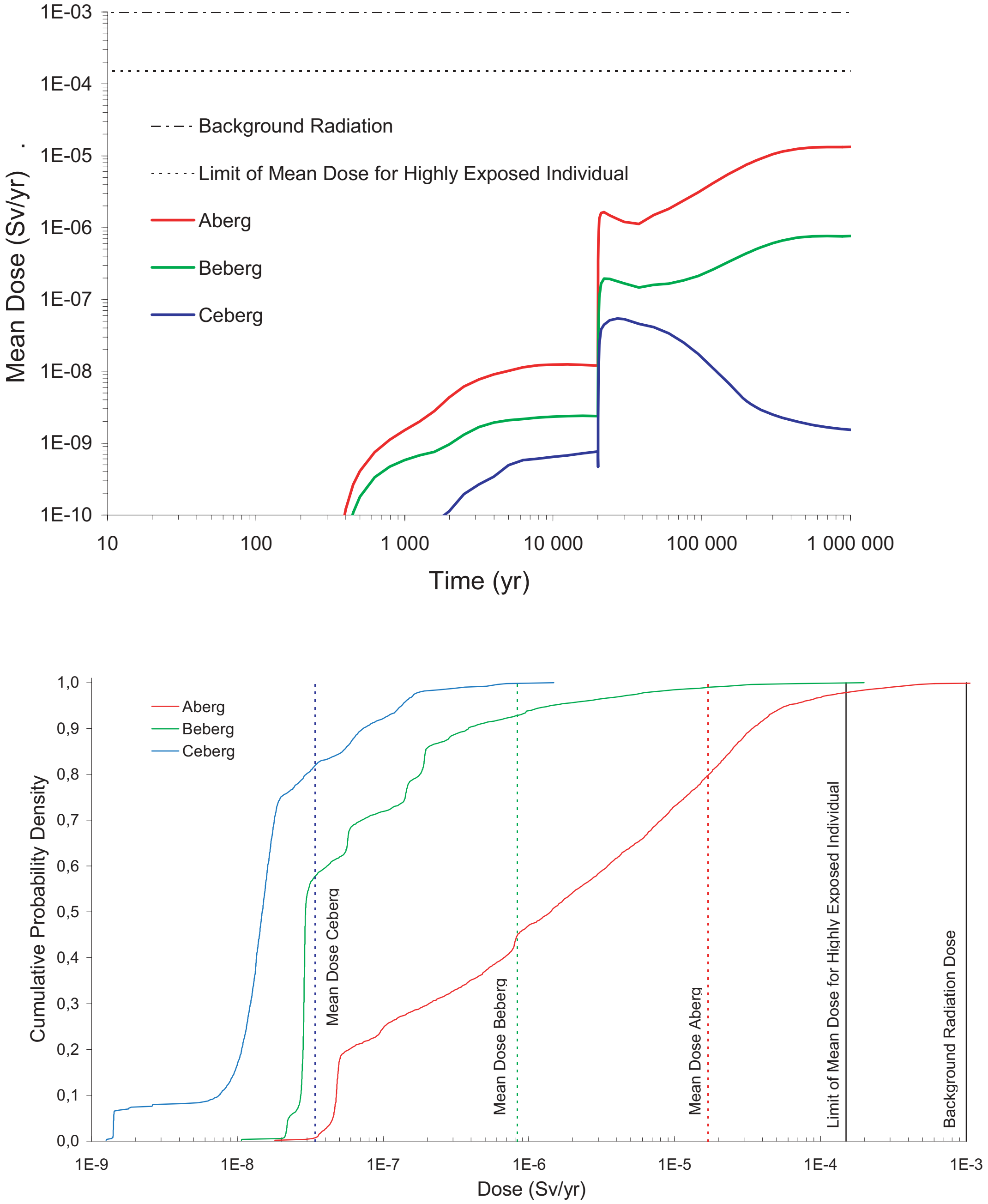

***Figure 2-6.*** *Probabilistically determined mean doses as a function of time for the three sites analysed in SR 97 (upper). Probabilistically determined peak dose distribution for the three sites analysed in SR 97 (lower). Both figures are derived from the results of the same probabilistic calculation.*

### 2.15.5 Risk dilution

The term “risk dilution” is sometimes used to denote a situation where a *higher* degree of uncertainty in input parameters, i.e. a broader input distribution leads to a *lower* mean value of an output quantity e.g. mean dose or risk /NEA, 1997b/. A seemingly paradoxical situation arises where less knowledge implies a more safe repository if the mean value is used as a safety indicator. This can e.g. be the case when there is uncertainty concerning the point in time of an event that would lead to canister ruptures. The dose consequence for a given point in time could then depend strongly on the assumed time at which the rupture occurred. Averaging over alternative situations in which the canister rupture and thus peak dose occurs at different points in time would reduce the resulting mean value at any point in time and more so the larger the span of possible rupture times.

This effect is inherent in the concept of risk and is thus an inevitable consequence of a risk criterion which is to be applied as a function of time and where the entity to be determined is the mean value considering all relevant uncertainties. The above effect should thus be tolerable given the Swedish regulations.

Nevertheless, from an implementing point of view several conclusions can be drawn from the above:

- A broader input data distribution is not necessarily pessimistic, not even if it is broadened towards the high consequence end. Thus care must be taken in assigning input data distributions so that input data that might influence the calculation end-point in this way are not unduly broadened.
- The above risk dilution effect can be illustrated by complementing a “peak of the mean” calculation with a “mean of the peaks” calculation, see the previous section.
- Disaggregated calculations and disaggregated discussions of the results of more integrated calculations are necessary from the point of view of capturing risk dilution.

### 2.15.6 Issues needing clarification

There are some issues regarding SSI FS 1998:1 that need clarification. SKB’s view on these matters has been expressed in a Memo to SSI. Some examples of questions are

- Time frames for risk calculations.
- Time dependencies and probabilities in biosphere models.
- Delimitations of exposed groups and individuals.

SSI is currently developing general advice concerning SSI FS 1998:1, in which hopefully these issues can be clarified.

# 3 Climate issues

## 3.1 Introduction

As stated in section 2.8, the future climate evolution is an essential part of the description of the external conditions to the repository system. Past climate changes including permafrost and glacial conditions are highly likely to occur also in the future. The time sequence of these changes is governed by cyclic astronomical phenomena affecting insolation. Although the future insolation can be well predicted, it is difficult to estimate the response of the climate due to limited understanding of the climate system and also due to additional uncertain driving forces like human induced greenhouse effects.

Based on knowledge about past climate and of the earth's climate system, the possible variations of the Scandinavian climate can be bounded. The extremes within which the climate can vary can be predicted with reasonable fidelity. Within these limits characteristic climate conditions can be identified.

Warmer climate than the present will move the current border between cold temperate, boreal, conditions and warm temperate conditions in a northerly direction.

Colder climate will affect flora and fauna. Deciduous forest will be replaced by coniferous forest, which in turn may be replaced by shrub tundra. In areas where the mean annual temperature falls below –1°C permafrost will possibly start to develop. Mountain glaciers will start to grow into ice sheets that eventually may cover large parts of Scandinavia. The growth and decay of ice sheets will alter the shoreline due to changes in sea level and depression/upheaval of the earth crust.

The climate-driven environmental changes mentioned above can be represented as *climate-driven process domains* /Boulton et al, 2001/ defined as *a climatically determined setting on the earth surface in which a series of processes habitually occur together* and in the following referred to as *climate domains*. The identified climate domains are:

- The glacial domain.
- The permafrost domain.
- The temperate/boreal domain.

The purpose of identifying climate domains is to create relatively simple characterisations of the processes associated with a particular climatically determined surface environment.

### 3.1.1 Strategy for managing varying climate conditions in SR-Can

A number of possible future climate evolutional pathways will be considered in the selection of scenarios. Together, the different scenarios/variants should give a good coverage of possible evolutions. These descriptions will be mainly qualitative in nature. *Tentatively*, the following evolutions could be sketched in a 100,000 year time frame:

- a "best estimate" represented by a characteristic Quaternary glacial cycle,
- a future climate altered by human impact including green-house effect,
- a continuation of today's climate.

Each evolution studied in the assessment will then be described as a time sequence of climate domains.

The climate domains will be studied generically and the important issues for each domain will be addressed. Also effects reaching over the domain boundaries need to be addressed. In the analyses of selected scenarios/variants, the generic information will be put together to yield an integrated, time-dependent view of the evolution.

In the following, an overview of major issues related to the selection of scenarios/variants and to the descriptions of the three climate domains along with a plan for their management in SR-Can is given.

## 3.2 Selection of possible future climate evolutions

It is widely accepted that during the last 2 million years, i.e. the Quaternary period, repeated vast glaciations have occurred on the Northern Hemisphere /e.g. Holmgren and Karlén, 1998; Ruddiman, 2001/. During the last 800,000–900,000 years or so a characteristic evolution with successively colder climate giving rise to successively larger ice sheets abruptly terminated by a transition to a warm climate similar to the present have occurred. The length of these characteristic climate cycles is about 100,000–150,000 years. According to the astronomical climate theory, also referred to as the Milankovitch theory, the growth and decay of ice sheets are triggered by variations in insolation caused by the variation of the Earth orbit around the sun /e.g. Emeliani, 1955; Hays et al, 1976; Imbrie and Imbrie, 1980; Berger et al, 1980; Imbrie et al, 1984; Berger and Loutre, 1991/. In spite of some ambiguities this theory is widely accepted. As a best estimate it may be assumed that the characteristic glacial cycles of the past 800,000 years will continue into the future. New findings regarding the astronomical climate theory will be followed.

The presence of ice sheets is of vital importance not only for the thermal, hydrological, mechanical, chemical and biological boundary conditions for the repository but also for the climate itself. The growth of ice sheets caused by changes in temperature and precipitation and the growing ice sheet affects temperature and precipitation. The growth of ice sheets will also cause alterations of the shore-level due to depression of the earth crust and changes in sea level. The vicinity to the sea also affects the climate at a site. Presence of large lakes and sea also affects the occurrence of permafrost.

The growth and decay of ice sheets is thus of vital importance for the climate conditions. The extension of ice sheets given different climate conditions and properties of the ice sheet and subsurface have been studied by means of modelling by Boulton /Boulton and Payne, 1993; Boulton et al, 2001/. Both past and future ice sheet extensions have been calculated.

The best known of the past glacial cycles is the last, the Weichselian. The use of a well documented ice sheet (computer) model calibrated it against geological evidences of ice sheet extensions during the Weichselian is believed to provide information on ice sheet dynamics and characteristics such as ice thickness, ice temperature and melt rates. Based on the calculated Weichselian evolution earlier glaciations can be simulated. If the simulated ice sheets agree with geological evidences they will bound the possible conditions occurring during a characteristic Quaternary glacial cycle /Näslund et al, 2003; Näslund and Jansson 2003/. It is anticipated that in the spring of 2004 a well calibrated and validated simulation of the Weichselian will be at hand. The results will be compared to Boulton's results and other simulations of past ice sheets available in the literature /e.g. Berger et al, 1996/.

The ice sheet model referred to above contains a module for calculating isostatic movements of the crust. In spite of the simplified earth model used in this module it provides a time history of the isostatic movements during the Weichselian. The modelled isostatic movements can be compared with empirical observations. A compilation of empirical data from the late Weichselian and the Holcene is provided in the empirical model of Påsse /Påsse, 2001/. Combined with known records of sea level change /Shackleton, 1987; Lundberg and Ford, 1994/ this will provide a picture of the evolution of the shore-level which can be used to bound magnitude and rate of shore-level displacement.

The growth of ice sheets will cause changed surface mass distribution on earth. The earth will respond by changed relative sea levels, surface deformation and altered geopotential and rotation vector. This is referred to as glacial isostatic adjustment (GIA). Isostatic movements and sea level change must be considered in a global perspective. Studies of these processes have been performed by means of GIA modelling. GIA modelling can be used to constrain possible shore-level displacements based on realistic earth models. GIA-modelling also contributes to development of rheological Earth models and the understanding of rock stress alteration during a glacial cycle. The possibility of including also GIA studies as a basis for SR-Can is being investigated.

Human impact on climate is a debated issue. /Berger and Loutre, 1997/ have by means of modelling showed that the emission of greenhouse gases may lead to a warming of the climate that may perturb the glacial cycles that have occurred the last million years. A European project with the objectives to develop strategies for representing climate changes in biosphere systems and to explore and evaluate the potential effects of climate change on the nature of biosphere systems was initiated in 2000 /Calvez, 2001/. Within this project modelling of the future climate using the same model as referred to above has been performed /BIOCLIM, 2001/. The modelling indicate that the greenhouse effect may extend the current interglacial period for as long as 50,000 years. Although these predictions are highly uncertain the possibility of a human altered climate evolution can not be excluded.

The selection of possible future climate evolutions will be based on knowledge of past climate changes known from various biological and geological records (see further sections 3.3 and 3.4) and on results from modelling efforts. As the ice sheet extension is of mayor importance for climate and biosphere conditions the ice sheet modelling mentioned above will provide the basis for the descriptions of alternative climate evolutions. Biological and geological records will be used to calibrate, validate and also to supplement results from the ice sheet modelling. Relevant published results regarding climate evolution and dynamics will be reviewed. In this context the work within the BIOCLIM project by Loutre & Berger at the University Louvain-la-Neuve will be an important source of information. Climate related features, events and processes (FEP) included in the SR-Can FEP database will also be considered.

## 3.3 Temperate/boreal domain

The main process occurring in the temperate/boreal domain affecting repository performance as well as biosphere conditions is shore-level displacement. Further variations in temperature and precipitation will affect the biosphere and the salinity in the inland sea or lake east of Sweden, the current Baltic Sea. Shore-level displacement and changes in salinity will alter the geohydrological and geochemical conditions in the host rock.

The main factors of importance both for the repository performance and biosphere conditions are magnitude and rate of shore-level displacement and the contemporary salinity of the water covering the repository. All these factors can be bounded based on the ice sheet modelling and empirical studies mentioned in section 3.2.

Climate conditions during the Holocene are known from various biological and geological records such as tree rings, pollen, sea and lake sediments, stalagmites and stalactites etc. There are also some records from the Late Weichselian. It is believed that the current climate variation in a north southerly direction together with known variations during the Holocene provides a picture of the possible climate conditions within the temperate/boreal domain. Human induced climate change is believed to lie within the magnitude of change seen during the Holocene. A compilation of available climate records and based on that a synthesis of the climate evolution during the Holocene will be finished late 2003.

## 3.4 Permafrost domain

The occurrence of permafrost will alter the geohydrological and geochemical conditions in the host rock. The cold climate required for the development of permafrost will also affect the biosphere conditions. The main factors affecting repository performance are the permafrost depth, the duration of a permafrost layer and the rate of aggradation and degradation.

The occurrence and depth of permafrost mainly depend on the temperature and the occurrence of large water bodies. Factors such as snow cover, vegetation and topography also affect the occurrence of permafrost /French, 1996; Vidstrand, 2003/. Little is known about the temperatures in Scandinavia during a glacial cycle. There are some records from northern France /Guiot et al, 1989; De Beaulieu et al, 1991; Guiot et al, 1992/ that can be used for estimations of temperature and precipitation. These records can be compared to the climate drive used in the ice sheet modelling mentioned in section 3.2 to provide a picture of possible temperature variations. There are also other climate records for instance sea sediments from the sea east of Norway that can be used to bound the possible temperature variations. Even in very cold climates there is no permafrost beneath large water bodies. If a site is covered by the sea there will most possibly be no permafrost. The shore-level displacement is discussed in section 3.2.

Modelling of the development of permafrost given plausible temperature conditions and earth layer thickness and properties and bedrock properties is being planned. Site studies at a gold mine in the permafrost area in Canada /Ruskeeniemi et al, 2002/ will provide data that can support assumptions and modelling efforts.

## 3.5 Glacial domain

The presence of an ice sheet will alter the thermal and mechanical conditions in the bedrock. The hydrological conditions will also change, and as a consequence of that the chemical conditions in the bedrock are altered. Of course the presence of an ice sheet also impacts the biosphere. The main factors of importance for the subsurface conditions are the ice thickness and the basal conditions of the ice. The latter determine whether there is fluent water present at the ice/bed interface which in turn affects mechanical, hydrological and chemical conditions within the bedrock. Parameters of importance besides ice thickness are melt rate, duration of the ice load and depth of sub glacial permafrost.

An advancing or retreating ice sheet give rice to altered rock stresses. The effective stresses depend both on ice load and occurring water pressures. The water pressures beneath an ice sheet depend on the basal conditions of the ice sheet. If the ice is frozen to the bed there is no fluent water present, neither within the ice sheet nor at the ice/bed interface. The temperature of the ice is below the pressure melting point and there is permafrost in the bed. The ice sheet gives rice to a vertical load proportional to the ice thickness and no water pressure. The ice is frozen to the bed and there is no or very limited erosion.

If the ice sheet is warm based – that is the temperature at the ice/bed interface is at or above the pressure melting point – there is fluent water present at the ice/bed interface. The ice sheet gives rice both to a vertical load proportional to the ice thickness and a water pressure with a maximum corresponding to the ice thickness. The ice slides at the ice/bed interface and the erosion can be significant.

The basal hydrological system of a warm based ice sheet comprises two components. One obtains its water from melting basal ice and the other obtains its water from melting of ice at the ice sheet surface and from precipitation. The first occurs everywhere where the temperature is at, or above, the pressure melting point. The melting is accomplished by geothermal heat flux and deformation energy released by the internal movements of the ice sheet. The melt rate is small and the process is continuous with no fast variations over time. The surface melt rates can on the contrary be very large and vary significantly both daily and annually. At the frontal-near parts of the ice sheet the two hydrological systems overlap.

The ice sheet modelling described in section 3.2 will provide a well documented glacial history for the Weichselian. This history will include the variation of all parameters of importance for the repository performance. It will be the basis for sensitivity tests using different climatological and geothermal input. Sensitivity analysis and model runs comprising several glacial cycles will provide bounds for the possible variation of the important parameters. The output from the ice sheet modelling will be used as input in analysis of the thermal, mechanical, hydrological and chemical conditions in the bedrock.

It is believed that the addition of vertical load during a glaciation will suppress seismic activity. When the ice melts and the vertical load disappears an unstable situation where both large and frequent earthquakes may occur is expected. An analysis of the stress situation in the crust and its importance for the seismic activity during and after a glaciation is planned. The study will be initiated with a sensitivity analysis which will provide an understanding of the parameters of most importance for the occurrence of post glacial faulting. The analysis will use results from the ice sheet modelling concerning ice thickness, duration of the load and water pressures.

The knowledge on the hydrology of continental ice sheets is limited. We lack information on the formation of subglacial melt water channels and the pressure around them as well as of the interaction between the two hydrological systems mentioned above. A literature review on the present knowledge of glacial hydrology based on glaciological, hydrological, geomorphological and quaternary geological publications will be finished in early 2004. The hydrology of ice sheets will also be studied by means of modelling and field observations.

# 4 Biosphere issues

## 4.1 Introduction

This chapter is a summary of two reports treating the methodology for treatment of biosphere safety assessment issues /Kumblad and Kautsky, 2003 in manuscript/ and the strategy for the analysis of biosphere site data /Löfgren and Lindborg, 2003/.

The text discusses the treatment of the general development of the biosphere, from the initial state as described by data from site investigations and onwards in different time periods. The subsequent section considers how groundwater discharge points will be handled, thereafter modelling from process understanding is discussed. Numerical modelling methods and ecosystem models are presented, as is the management of generic data and finally exposure to humans and the environment.

In the safety assessment of SR-Can, several improvements and changes from earlier assessments will be made for the biosphere. The experience from the safety assessment of SFR (SAFE project) is the major driving force for the changes. For SR-Can not all important biosphere data from the site will be available for the safety assessment as it is intended to in SR-Site. Moreover, for available data supporting reports summarising the understanding of the site and corroborating working hypotheses will not be ready for SR-Can to motivate all data selections or estimates of uncertainties.

A number of actors are involved in the management of the biosphere for the safety assessment. There is a *site investigation group* that collects site specific data, an *analysis group* that interprets the data and builds an understanding and a biological model of the site and a *safety assessment group* that uses the knowledge compiled by the analysis group for assessments of the long-term development of the biosphere and for radionuclide transport and dose calculations. These will be referred to where relevant in the following.

## 4.2 General biosphere development

The current status and future development of the biosphere has to be described in different time spans, where the highest degree of confidence is for the first 1000 year, whereas for longer time period critical instances should be identified. The intention is to produce a series of snapshots with maps of different occasions from the past to the future in different time resolutions, with a structure similar to that of the reasonable biosphere introduced in the SAFE project. The general development of the climate as depicted in the different scenarios to be chosen in SR-Can will serve as the basis for the descriptions of the biosphere development.

### 4.2.1 Current status

The description of the current status of the site will include estimations of the major flows of water, dissolved inorganic matter (e.g. inorganic nutrient compounds and trace elements), dissolved and particulate organic matter (e.g. carbon, nitrogen and phosphorous) and the migration of organisms.

To obtain a good description of the current status at the sites, good site data are required. The site data will be used to produce maps describing the structure/morphology of the relevant catchment areas including distribution of various types of matter and parameters for flows of matter (cf. Figure 4-1 and Figure 4-2).

The site data will be averaged in time for a yearly or longer time perspective.

The data collection will be performed according to the site investigation program and the required data are described in /Lindborg and Kautsky, 2000/. Some data may need to be obtained from research projects. The collected data from the site has to be compared with regional and national data for justification.

The collected integrated data will be reported in maps describing the current status of the sites. The maps will be based on the measured high-resolution topography made in the site investigation program and the surveys of the seafloor. The major work is done by the analysis group, cf /Lövgren and Lindborg, 2003/, but a dedicated group will be working with the interface of data handling between the site analysis and safety assessment groups (Figure 4-2).

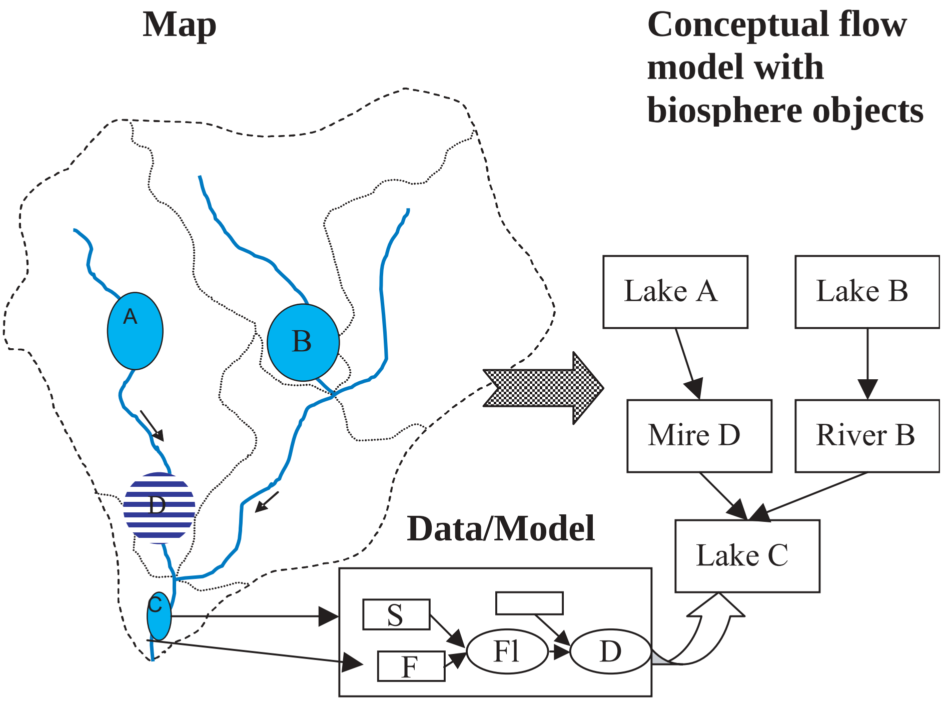

*Figure 4-1. Biosphere mapping and conceptual models. Left side show the maps produced by the site investigation and analysis group subdivided in discharge areas, lakes and rivers. The maps are simplified into different biosphere objects used for the dose modelling. The model describing the objects can be transfer factor models or ecosystem models. Site specific data for the parameters are obtained from the properties of the maps integrated over time and space (bottom box, cf Figure 4-2).*

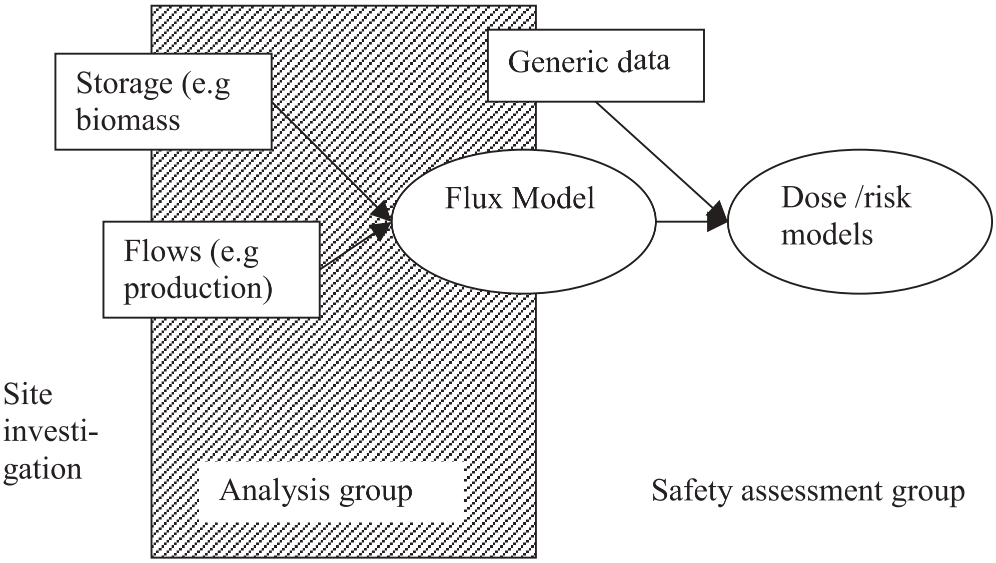

***Figure 4-2.*** *Schematic biosphere model. Boxes are parameters and circles models. The site investigation group measures the magnitude of the variables e.g. biomass for different species. The analysis group estimates the fluxes if not measured in field and compiles a flux model (e.g. carbon and water flow) which is used in the safety assessment. This flux model is refined for an exposure and dose model for radionuclides by the safety assessment group. Generic data are mainly collected from the literature, but some can be compiled from the site studies.*

### 4.2.2 The first 1,000 years

According to SSI FS 1998:1 and comments from SSI on the SR 97 assessment, special emphasis in safety assessments should be on the development during the first 1,000 years.

The expected major driving forces during the coming 1,000 year period are the shore-line displacement, biosphere succession (mire and forest development), sediment redistribution (sedimentation and resuspension/erosion) and potential climate change caused by global warming.

The future shoreline displacement and sedimentation processes are inferred, as part of the safety assessment, from the historical development of the site and the understanding of the future development, see section 3.2 for the latter.

The historical data on shoreline displacement and sedimentation processes are obtained in the site investigation program and compiled by the analysis group.

The future ecosystem, vegetation and associated fauna are gradually modified in accordance with the shore-line displacement. Some processes will interact, e.g. peat development and forest succession, which also can be inferred from existing data.

The development during the first 1,000 years will be described by a series of maps, each capturing the situation at a defined point in time. The interval between the maps will be dependent on the rate of changes for different ecosystems. The methodology for establishing the maps will be developed in the first phase of treatment of data from the Forsmark site and as far as possible utilized for SR-Can. However, there will be data gaps regarding understanding of regolith processes and regolith vegetation interactions, and these gaps will not be filled until the completion of SR-Site (cf. Figure 4-3).

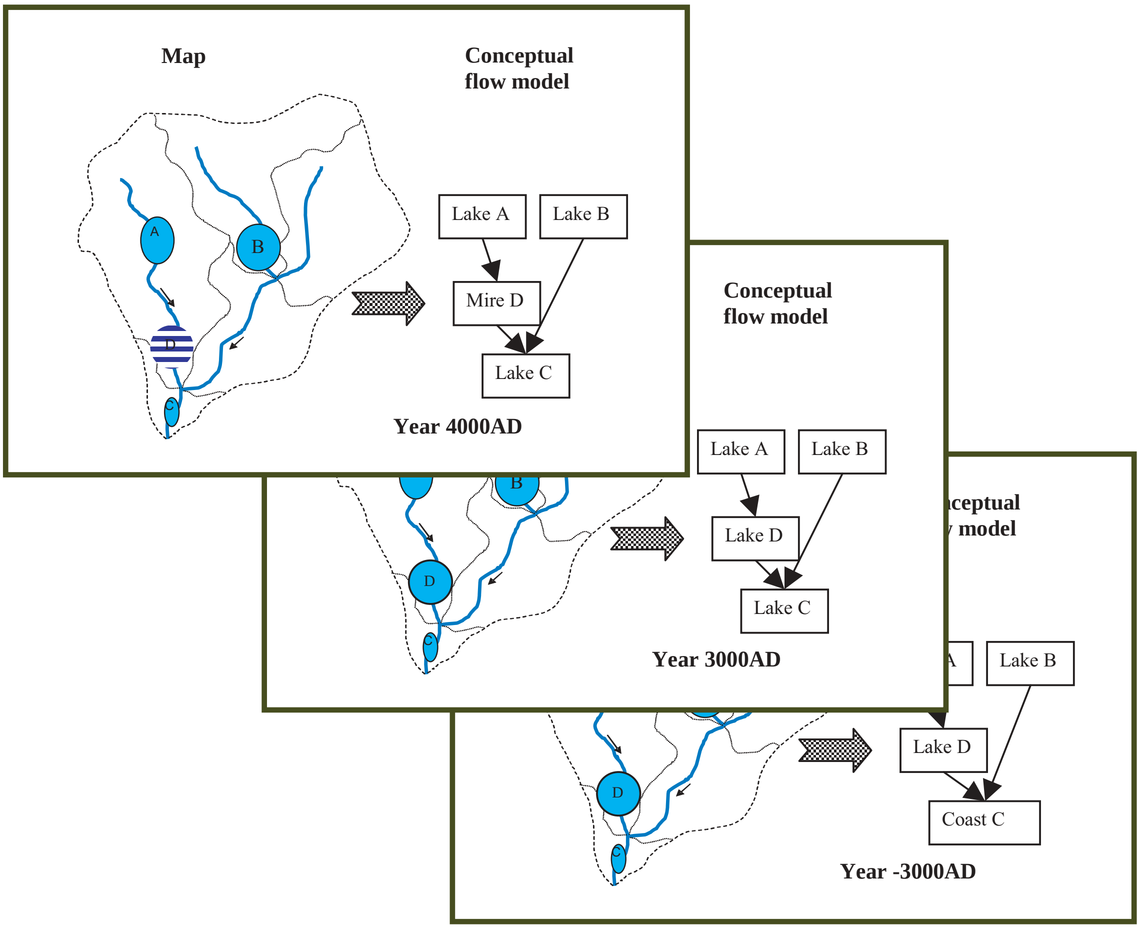

***Figure 4-3.*** *Biosphere maps for different time periods. The maps represent different time periods with different biosphere objects and data. A new map is compiled for new state when a relevant change from the previous biosphere has occurred.*

Future human exploitation of the environment at the sites in terms of e.g. farming, fishing, hunting, collecting berries and mushrooms, is estimated by the prediction of availability of suitable soils and water and their productivity. The maps developed for the coming 1000 years will provide a basis for estimating the constraints of possibilities to use the area for different purposes, e.g. agriculture.

Climate change or variability due to the greenhouse effect the coming 1,000 years is more difficult to put in the context of a continuous changing environment, due to the large uncertainties associated with these phenomena. The implications of a potential climate change on the hydrology and oceanography e.g. sea level and salinity, will be described. In SR-Can an analysis of the variability due to possible climate change, see section 3.2, will be used to vary the hydrology and oceanography. Since the research is still in quick progress in this area it is not meaningful to make larger compilations of the results in SR-Can although it should be done for SR-Site. However, the methodology for how to incorporate the variability in hydrology and oceanography into the assessment will be developed during the first phase of SR-Can.

### 4.2.3 The period up to the next glaciation

During the period beyond the first 1,000 years and until next glaciation large-scale climate changes to a cooler climate is expected to affect the ecosystems as well as the shore-line displacement. One of the major events that need to be considered for this time period is the transition to a tundra ecosystem with permafrost conditions. Important factors to evaluate are the geosphere-biosphere interface (e.g. talliks), erosion processes and human exploitation of the environment (e.g. exposure pathways). Shore-line displacement will cause dramatic changes of the land–sea distribution and we can expect that present-day coastal sites will be "inland" sites with altered discharge points. It may also imply changed exploitation of the ecosystems, e.g. when previous lakes have become agricultural areas. The implications of a possible extended interglacial period (see section 3.2) on soils and ecosystems must also to be considered.

The characteristic feature of this longer time period is the permafrost and tundra situation. This situation will be described and discussed in a report. During the first phase of SR-Can the method for how to handle these conditions will be established. A preliminary implementation will be made for SR-Can and finalised for SR-Site.

### 4.2.4 The glacial period

During the next expected glacial period the surface ecosystems is expected to contain few species and food chains and the human population is likely to be absent or sparse and therefore, the doses from potentially discharged radionuclides are expected to become very limited.

A report describing glaciated and ice-margin surface ecosystem and its human exploitation will be compiled for SR-Can to justify the inclusion or exclusion if dose calculations for this period.

### 4.2.5 Next interglacial period

The best prediction of the next interglacial period will be to use Holocene as an example. To achieve that, characteristics of the historical development produced by the analysis group will be merged with the prediction of the future development of the sites.

## 4.3 Discharge points

A fundamental piece of information for safety assessments of a deep repository for nuclear waste is the positions of discharge points of radionuclides in the biosphere. The positions for such discharges are determined by the transport in the geosphere, the geo-biosphere interface, the transport in quaternary deposits and the surface hydrology. Other, perhaps more unusual transport pathways to the biosphere is the transport of radionuclides in gaseous or particulate form (e.g. from drilling). Thus, descriptions of the hydrological and oceanographical processes from the repository to the final endpoints are needed. Moreover, the special case of wells as an exposure pathway is important.

### 4.3.1 Hydrology

The hydrology of the geosphere, the surface ecosystems and the interface between them needs to be addressed in a safety assessment. In this section, the surface hydrology including oceanography and the interface between the geosphere and the ecosystems are considered. The geosphere aspects of hydrology are described in sections 5.2 and 5.4.

For the safety assessment, the water turnover is a fundamental parameter, which usually is driven by the precipitation–evaporation (P-E) in the drainage area (i.e. runoff), and water level fluctuations (mainly in the sea). Thus, both variables are sensitive to the climate. The runoff, together with water volume in lakes and other reservoirs, determines the water turnover time, which is an important parameter in biosphere models. These variables are relatively easy to estimate from available data or data collected in the site investigation program for surface hydrology and oceanography. A compilation of the data is made within the analysis group /Löfgren and Lindborg, 2003/.

The hydrological and oceanographical variables will be put in context of the biosphere development (e.g. shoreline displacement and climate change) by the analysis group and safety assessment.

Today, both regional and site specific data are available, but these data need to be integrated for the relevant catchment areas. This can be done in SR-Can. However, newly collected data and understanding will not be possible to include until the SR-Site analysis, since the major part of surface hydrology of the site will be available in later site model versions than those on which SR-Can will be based.

The hydrological processes in the regolith (soils and quaternary deposits) are important in order to estimate the mixing of shallow ground water with deep groundwater. The ground water fluxes in the quaternary deposits is also of importance for the horizontal radionuclide transport at the depth where they are inaccessible for biota. Finally, since the discharge points to surface ecosystems seems to be sea- and lake floors, the vertical transport in the quaternary deposits towards these ecosystems as well as to areas with high abundance of roots are important to estimate. These issues are addressed in section 5.2.

### 4.3.2 Wells

Wells are an important exposure pathway for humans. The use of wells is dependent on the climate and surface hydrology as well as on the quality of the water, i.e. its chemical composition. It is necessary to analyse the well archive, evaluate its data quality and interpret the information. There is also a need to assemble information on the spatial distribution of wells in the region, as well as the history of drilled wells and to estimate the future development of wells, i.e. the number of wells that could be expected to be drilled in correlation to the population etc.

Furthermore, the establishment of a model that describes the dilution of radionuclides discharged in wells is also needed. The well hydrological model is further discussed in section 5.2.

## 4.4 Processes and FEPs

In the modelling of radionuclide transport and dose calculations in the biosphere, a number of features, events and processes (FEPs) need to be addressed. In earlier assessments, a major part of all identified important biosphere processes and phenomena have been collected in a so called interaction matrix. The matrix and its documentation was then used to motivate the models used for the quantitative treatment of the processes, or to motivate the exclusion of less relevant processes from further treatment.

The latest version of SKB's biosphere interaction matrix was developed within the SAFE project. This matrix will be reviewed and transferred to a Process Report where the FEPs will be documented. The Process Report will have a structure resembling that of the other parts of the repository system, see section 2.7. A first draft of the process report and the interaction matrix should be finished for the first phase of SR-Can. This report will continuously be improved and updated during the second phase of SR-Can and during SR-Site.

It is expected that for a major part of the processes in the biosphere it is not necessary to develop numerical models. The documentation and scientific reasoning in the process report and the numerous reports from the sites is expected to be sufficient to simplify the calculations or to motivate that the process is neglected. This understanding will mainly evolve during the final part of the site investigation when a sufficient amount of data has been produced. Thus the numerical models used can change from SR-Can to SR-Site.

## 4.5 Modelling of radionuclide transport, doses to man and concentrations in biota

In the coming safety assessment for the deep repository, the intention is to use two parallel model chains for the modelling of radionuclide transport and doses to man. The two options are improved versions of the existing transfer models (as in SR 97 and SAFE) and ecosystem models.

The existing transfer factor models (SR 97 and SAFE) were developed for seven typical ecosystems or cases (mire, lake, running water, coastal area, agricultural land, wells and irrigation). In the ecosystem modelling two models will be used, an aquatic and a terrestrial model. The aquatic model will be applied for lakes, streams and the sea but with different parameterisation in terms of habitat distribution, water transport, characteristics of sediments and quaternary deposits and biota. Similarly, the terrestrial model will be used for forest, wetlands, pasture, agriculture and other terrestrial ecosystems.

SSI FS 1998:1 states the following: "Biological effects of ionising radiation in living environments and ecosystems concerned shall be described…"

To assess effects on the environment, ecosystem models are necessary in order to calculate radionuclide concentrations in biota. However, although further developed ecosystem models would allow estimates of such concentrations to be made, the knowledge of how to transform concentrations into effects on biota, so that quantitative assessments of these can be made, is very limited today. This is also acknowledged in SSI's background comments to SSI FS 1998:1. Further discussions with or advice from SSI is required in order to develop a manageable way of handling this issue given the limited knowledge concerning radiation effects on biota other than man. As far as possible, SKB's intends to make use of the experience from the EU-project ERICA and FASSET in this matter.

### 4.5.1 Spatial modelling

In SR-Can the biosphere will be defined in specific biosphere objects from different ecosystem categories (cf. Figure 4-1). The objects have different spatial extension and properties that can be regarded as an ecosystem with an intrinsic turnover. That is, instead of describing e.g. a lake as several 250 m by 250 m squares (as in SR 97), the lake itself will be described as a homogenous ecosystem with a certain geometric extension and ecological properties. The stream-tubes entering the lake will thus be added to the same ecosystem. Thus, the position of the discharge point (x, y, z) will be overlaid by the polygon describing the biosphere object.

The next step is to model the accumulation of the discharge downstream if there are several stream-tubes entering the same catchment basin but in different biosphere objects. For example, one stream-tube in the forest, one in the river at the forest, one in the lake downstream the forest and river (Figure 4-1). This will be done by connecting the different biosphere objects together based on site-specific maps. The maps will not only describe how the biosphere objects are interconnected with each other, but will also provide estimates of important parameters such as water turnover, accumulated runoff and information on how the biosphere can be utilised by humans. Since the amount of stream-tubes are limited in each area, “wiring” the fate of discharges from each stream-tube though the biosphere objects manually will be easier. The wiring needs to be repeated for each identified critical time period in the biosphere (e.g. reasonable biospheres, cf. Figure 4-2).

The implementation of the idea is quite easy but needs to be tested with site data to identify gaps in data or tool capabilities. In the test a set of the high-resolution maps with topography from e.g. one of the sites can be used together with hypothetical stream-tubes and assumed interconnections. This should be done jointly by the analysis and safety assessment groups. In the next step the exposure models are wired to the map (see below), which should be done by safety assessment.

### 4.5.2 Tools

The most important tools with which the models will be built and calculations made are described in section 8.2.4.

### 4.5.3 Aquatic models

Aquatic models are used for the lakes, rivers and coast. The lake model was improved in SAFE. In SR-Can existing models for lakes, rivers and coast will be reviewed and as far as possible site data used for parameterisation.

Parallel to transfer factor models, the ecosystem models will be developed for the same systems and as far as possible used as alternative models. However, they might not finally be documented and validated within SR-Can.

### 4.5.4 Terrestrial models

Terrestrial models are used for modelling the mire, agricultural land, meadows and forest. In SR-Can the existing model for the mire and agricultural land will be reviewed and as far as possible site data used as parameters.

For the forest an existing model will be tested and adopted for the assessment. Parallel to this, ecosystem models will be developed and as far as possible used as alternative models (c.f. aquatic models).

The irrigation model used in earlier assessment will be updated with the latest information gathered in the EU-program BIOPROTA.

## 4.6 Generic data

In all models, generic data are used, e.g. radionuclide half-lives, distribution coefficients such as $K_d$-values and uptake coefficients such as bioconcentration factors (BCF). Moreover, generic assumptions about human behaviour, diet and dose factors are included in the models. In addition, several constants for organisms, hydraulic conductivity, density etc are used in the calculations. All these data must be reviewed and updated, either from sources as ICRP or SSI or from site data that are generalised.

### 4.6.1 Radionuclide data

Data on radionuclide half-lives needs to be reviewed and used consistently through all steps of the assessment. $K_d$-values should also be updated and used consistently as far as possible within the entire assessment. Similarly, the BCF-values and root uptake factors, which are important for the existing transfer factor models should be updated and evaluated for their application for the assessment sites. Dose factors for human ingestion, inhalation and external radiation needs to be updated with ICRP recommendations. This is ongoing work in BIOPROTA and a draft will be available for the initial phase of SR-Can and subsequently further updated.

The FASSET and ERICA projects will hopefully give some guidance on dose factors for biota.

### 4.6.2 Humans

Many human activities and behaviour e.g. the daily intake of food, need to be stylised due to the large variation in human habits. However, the maximum exploitation base for humans can be constrained by the actual size and conditions of the site, e.g. in terms of fish production and amount of available water.

It is rather straightforward to calculate the size of a sustainable population in an area, using data on the present situation, existing data from the past and a theoretical maximum on how large a population can live in a sustainable way in a region.

A report on food consumption and diet in Sweden treating also the coastal population relevant for the sites will be produced for SR-Can.

## 4.7 Probability estimates for risk calculations

The approach to risk calculations is presented in section 2.15. For the biosphere, the probabilities for different conditions will to some degree need to be estimated. Such probabilities can be obtained from e.g. estimates of life times of a particular biosphere types or the statistical representation of the current landscape pattern.

For the initial phase of SR-Can an example will be provided based on Forsmark data. The treatment will be further refined for the final SR-Can report. Furthermore, the issue of probabilities for different biosphere conditions needs to be clarified in further discussions with SSI, as mentioned in section 2.15.6.

# 5 Geosphere issues

## 5.1 Mechanical issues

### 5.1.1 Introduction

The impact of geomechanical processes on the repository system might range from slight alterations of the hydraulic properties of the geosphere to jeopardising the integrity of the canister itself.

Some processes are initiated due to the excavation of the tunnel system. Other processes initiate as a response to the deployment of canisters which generate a thermal pulse. Yet other processes are only likely to occur under very specific circumstances. Moreover, many processes cannot be treated separately from others i.e. many, if not most, processes are coupled.

Below, the treatment of some critical geomechanical processes in SR-Can is discussed. The primary aim is to provide a useful input for the planning of SR-Can interim report, due July 2004 and for the SR-Can final report.

Though geomechanical processes might alter the retention capabilities of the geosphere, the primary concern of the discussion is the integrity of the canister. In particular shear movements along fractures that intersect deposition holes have the potential of substantially altering the geometry of deposition holes in such a way that canisters may be damaged. Therefore, the focus is here on this particular process and on ways to quantify the extent to which it will impact canister integrity under different load regimes.

Within the context outlined above, the following issues are considered:

- The initial state.
- Thermal pulse.
- Glacial load.
- Earthquakes.
- Time dependent deformations.
- Tectonic movements.
- Impact of mechanical processes on the host rock permeability.
- General issues.

In SR 97, canisters in deposition holes intersected by fractures that moved 0.1 m or more, counted as damaged. Work is now being done to revise that criterion, but there are no indications so far that any modifications will have to be made.

### 5.1.2 Initial state

#### *Description*

To understand how various geomechanical processes interact and affect the repository, it is essential to first describe the initial mechanical state in the repository system.

The initial state of stress is here defined as the compound effect of tectonic-, isostatic- and lithostatic loads on an existing tunnel system, itself exerting some stress redistribution with high tangential stresses around tunnels and deposition holes.

From a mechanical point of view the initial state is characterized not only by the rock stresses, but also by the deformations and changes in mechanical properties that have taken place during excavation. The excavation work will cause some direct damage to the rock walls. High tangential stresses may induce additional fracturing close to the walls. The combined effects of direct damage and stress-induced fracturing will result in excavation damaged zones (EDZ's). The extent and character of the EDZ's depend on the undisturbed pre-mining state of stress, the near field rock mechanical properties and the excavation method.

Though there will be an impact on the near-field rock permeability with possible importance for the retention properties, the high tangential stresses and the EDZ formation do not directly affect the canister integrity. However, the initial state description constitutes a very important input to various geomechanical analyses and models.

#### *Plan*

Several studies exist that describe the initial state of the repository in a general sense. These studies were used as reference for the initial state description made in SR 97. However, there are no recent studies that take into account the present-day repository lay-out and design and that make use of the significant code development that has taken place during the last 5–10 years.

This can be achieved by setting up a modern, near-field rock model of a tunnel with a small number of deposition holes, and with design, layout, stress state etc according to the Forsmark model v. 1.1 and other prerequisites for SR-Can. It is necessary that the model is created such that the canister spacing is consistent with relations between spacing, rock thermal conductivity and canister power. Such relations will be at hand in early autumn 2003 /Hökmark and Fälth, 2003/.

The models that will be created for actual design will probably be adequate and sufficient to use as input in SR-Can. This means that models do not have to be created specifically for the safety assessment project. In early autumn 2003 a format for co-ordination of the design work with safety assessment work will be established. One aspect of the co-ordination work is to ensure that the models, or at least one representative model, can be used for analysis of subsequent stages (analysis of thermal stresses, of stresses induced by future loads etc, see "Thermal pulse" below).

### 5.1.3 Thermal pulse

#### *Description*

The canisters generate heat during a considerable time resulting in the development of thermal stresses. The characteristics of the pulse are governed by, among other factors, rock properties and repository layout.

The thermal pulse induces stresses that, under unfavourable circumstances, will cause slip along fractures that intersect deposition holes. If sufficiently large, such shear displacements may jeopardise the integrity of the canister.

The issue of canister damage caused by thermally induced fracture shear displacements has been constituently addressed since the appearance of SR 97, /Hakami and Olofsson, 2002/. There is however still a need for a modern thermo-mechanical near field rock analysis, taking site specific data and the most actual design of canisters and tunnels under consideration. The canister power, the deposition hole diameter and the canister spacing are parameters that will have different values from those used in previous studies.

#### *Plan*

The general model(s) suggested above under “initial state” should be configured to include or be complemented by thermal analyses. The format for coordination of projecting work and safety assessment work will be applied also for near field analyses of the thermal pulse.

### 5.1.4 Glacial load

#### *Description*

Future glaciations will considerably alter the stress state in and around the repository. This in turn will have the following consequences:

1 Similar to the stresses induced by the thermal pulse, the stresses induced by the quasi-static ice load may produce shear movements on fractures that intersect deposition holes.

2 The nature of the glacial load will, among other factors, govern the postglacial state of stress and the possible earthquakes (see below) resulting thereof.

3 The glacial load will increase stresses and possibly affect the hydraulic properties of the rock. There may for instance be some additional fracturing in already highly stressed rock around deposition holes.

There is currently a general lack of understanding concerning the mechanical interaction between an ice sheet, the crust and the mantle. As a consequence thereof, there is an uncertainty regarding the mechanical boundary conditions for large scale models of the rock volume hosting the repository.

#### *Plan*

A study that sets bounds to the mechanical loads caused by ice growth, constant ice load and ice retreat will be initiated according to the following:

- Generic study of how simple earth models are affected by simple ice sheet models. In these models, variations in layer thicknesses, elastic and viscoelastic parameters, initial states and various stability measures are studied, first by 2D-models, then expand into 3D models. Results of these activities may be at hand in January 2004.
- A construction of a realistic 2D earth model, a transect through Nordkalotten, that includes topography and variations in the properties of the earth’s crust and lithosphere. A test of realistic ice sheet models including different scenarios governing variations in pore pressure. These activities are followed up by a sensitivity analysis and validation against empiric stress and uplift data. The studies aim at answering the following key questions: Where do glacio-isostatic faulting occur? Are deformations zones required in the model to be consistent? Results of these activities are expected to be at hand June 2004.
- A construction of a 3D model of the entire region aiming at properly modelling the 3D aspects of the ice sheet withdrawal. Results of these activities are expected to be at hand June 2005.
- Construction of 3D site-specific models that include the site geology. The aim is to estimate the risk for future glacio-isostatic faulting at the sites. Results of these activities are expected to be at hand June 2006.

### 5.1.5 Earthquakes

#### *Description*

Earthquakes occur as a response to sudden reactivations (slip) along fractures as trapped forces exceed the strength of the rock. Three, quite different, kind of earthquakes can be anticipated:

1 Tectonic earthquakes. These result from the compound effect of stresses accumulated from ridge push and remnant stresses from the latest glaciation.

2 Induced earthquakes. These earthquakes are triggered by the presence of an underground opening and might occur in rock volumes with high stresses, usually at greater depth than planned for the repository, and low degree of fracturing.

3 Glacio-isostatic earthquakes. Such faults, commonly referred to as “post-glacial faults”, are anticipated to occur during or shortly after deglaciation of any future glaciation.

Of these earthquakes, only glacio-isostatic earthquakes are considered to be of immediate relevance. Such earthquakes might affect a repository, from a geomechanical point of view, in the following ways:

- An earthquake can be triggered within the repository area by reactivation of deformation zones. However, it is believed that this effect can be avoided by the use of proper respect distances to deformation zones.
- An earthquake in the vicinity of the repository can trigger secondary slip along larger fractures within the repository.
- An earthquake can induce fracturing (in pristine rock) within the repository.

Since SR 97 a set of supplementary studies has been initiated that can be used to estimate respect distances between repository fractures of a relevant size (200 m diameter) and deformation zones with potential of hosting earthquakes of different magnitudes (consistent with their extension). The approach of trying to arrive at respect distances may, if successful, mean that the safety analysis will not have to depend heavily on forecasts of the future seismic activity in the Swedish bedrock.

### *Plan*

The first steps of the supplementary studies have been finalised /Hökmark et al, 2003, in prep./. The results have been used as the point of departure for the next steps:

- FEMSOL II study to find max induced displacement on a 200 m target fracture, subjected to Magnitude 6 earthquakes driven by a post glacial type stress field.
- FLAC3D study with the same general objectives as the FEMSOL II study, but also with the additional objective of finding ways of extending the magnitude range.

The FLAC3D study is now (June 2003) close to completion. The planning of following steps will be carried out during summer 2003. When the results of the continued analyses are at hand, these models will be elaborated and used to find realistic, yet conservative, respect distance estimates. The intention is to confirm, by use of numerical models, that respect distances are on the orders of magnitude (i.e. short) found from studies of actual cases /Bäckblom and Munier, 2002/. Parts of this work will be ready in due time for inclusion in the SR-Can 2004 interim report. All will be ready for inclusion in the SR-Can 2005 final report.

A study is currently being performed, “Review of postglacial faulting – directions for future studies, Arvidsson”, to document current understanding, or baseline knowledge, on these issues. The task may possibly be completed in time for inclusion in the SR-Can interim report.

A study will be initiated that concerns the possibility for the repository itself to act as a plane of weakness (i.e. similar to a potential fracture zone), such that strain energy is released through slip along the plane of the repository rather than along existing nearby zones. At present (June 2003) there is no work statement defined for the study and no contractor has been assigned. The task should be completed in due time for the SR-Can 2005 final report.

Similarly, a study should be initiated that targets the conditions necessary to generate large fractures through pristine rock, i.e. through blocks bounded by local deformation zones. At present (June 2003) there is no work statement defined for the study and no contractor has been assigned. The task should be completed in due time for the SR-Can 2005 final report.

As an additional possibility, the contour plot technique used by /LaPointe et al, 2000/ to present results of static Poly3D calculations should be applied to a more relevant target fracture size (200 m rather than 2000 m). If this way should be tried is dependent on the outcome of dynamic analyses: the preliminary results suggest that the static effects on target fracture overshadow the dynamic effects. If this holds true systematically, it may be worthwhile to consider a new Poly3D study. The decision should not be taken much earlier than October 2003. The task should be completed (if decided) in due time for the SR-Can 2005 final report.

### 5.1.6 Time dependent deformations

#### *Description*

Inherent time-dependent material properties cause creep deformations. These may lead to convergence of deposition holes and tunnels. The nature of such deformations and their possible impact on repository performance needs to be further explored.

#### *Plan*

A literature study on rock mass creep in general and creep along fractures in particular is close to being completed and reported /Glamheden and Hökmark, 2003/. This study will give hints on expedient ways to set bounds to creep effects by use of numerical models. The literature study, including suggestions for actual numerical studies should be ready in due time for inclusion in the SR-Can 2004 interim report.

The results of the literature study will be applied to near field discrete fracture models during spring 2004. The contractor will probably be FB Engineering AB. The task should be completed in due time for inclusion in the SR-Can 2005 final report.

### 5.1.7 Tectonic Movements

#### *Description*

In the long time perspective, the load on the repository host rock may change because of slow and continuous large scale deformations of the Baltic Shield. The horizontal compression caused by “ridge-push” at the western plate boundary is assumed to have contributed to the development of the present-day stress state with the major principal stress being horizontal and oriented NW-SE, and may continue in the future. In SR 97, estimates of tectonic compression effects were made. These estimates gave very modest load changes. The conclusion made in SR 97 was that the risk for canister damage because of future slow tectonically induced load changes can be neglected.

#### *Plan*

The state of knowledge regarding future load changes needs to be documented to improve the confidence in the estimates that have to be made to rule out the possibility of canister damage. This should be done by use of a literature study. Probably this does not have to be a very comprehensive study, but some time will be needed to initiate and specify the work. The study should be possible to conclude in time for inclusion in the SR-Can 2005 final report.

### 5.1.8 Impact of mechanical processes on the host rock permeability

#### *Description*

In SR 97, reference was made to general and qualitative views on how stress changes impact the permeability of the near field rock. The issue of permeability changes needs to be treated in a more quantitative way. Since the appearance of SR 97, work has been done in different contexts, for instance within the DECOVALEX project.

### *Plan*

At present (June 2003) there is no picture of the applicability of the results obtained during development and testing of coupled MH models. Such a picture must be established early autumn 2003. Based on that picture it will be possible to decide if additional numerical analyses have to be performed for the particular purpose of the safety analysis. Should this be necessary, the results of these analyses may be at hand in due time for inclusion in the SR-Can 2005 final report, provided that work is initiated soon after a clear picture of the state of knowledge has been established.

## 5.1.9 General issues

### *Description*

There are a few very general questions that are relevant to most load cases. Regarding canister integrity the following questions need attention:

- Relevance of relation between fracture size and fracture displacement.
- Fracturing and coalescence of fractures.

In SR 97 general relations between fracture size and possible fracture shear displacement were used to support numerically derived conclusions regarding maximum possible shear movements under different load conditions (glacial loads, tectonic loads etc). For 2D conditions analytical expressions can be derived provided that the medium surrounding the fracture is linearly elastic, isotropic and homogeneous, (Figure 5-1).

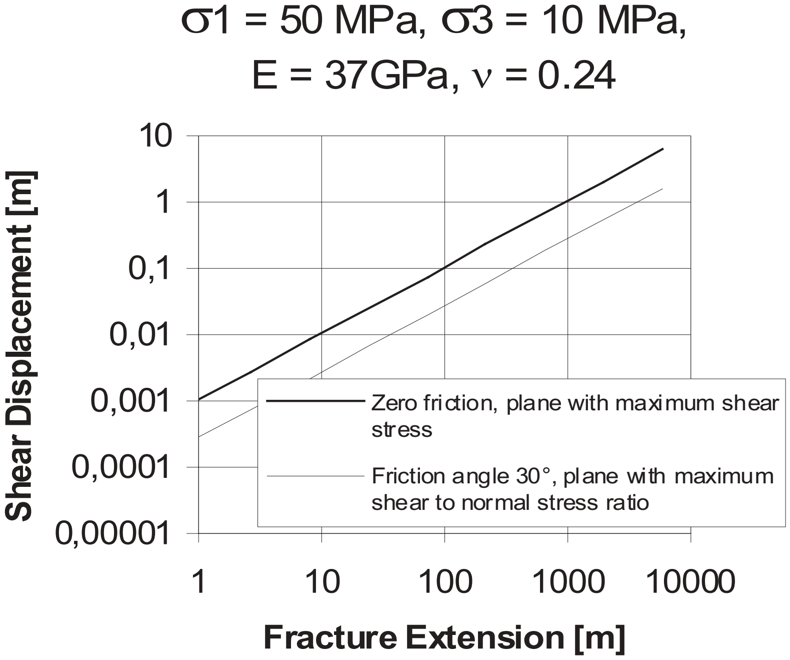

***Figure 5-1.*** *Relationship between shear displacement and fracture extension for idealised conditions.*

The relevance of the size/displacement relation needs to be investigated for realistic conditions (in particular for fractured media). For the safety analysis this issue is relevant on a fairly large scale, since only large fractures will be able to deform sufficiently to damage canisters.

The fracturing/coalescence issue is relevant on all scales. On the deposition hole scale and on the tunnel scale, fracturing may change the near field permeability. Coalescence of large fractures into even larger fractures may create possibilities of canister damage.

### *Plan*

A study should be initiated that has the following objectives:

- Find out how the size-displacement relation is affected if the rock is not elastic.
- Find out how the displacement is affected if a fracture with given extension is in actual fact part of a mechanically interconnected fracture system, such that there is a risk that the effective extension has been underestimated.

A present (June 2003) there is no work statement defined for this study. Probably the 3DEC code should be used. The task should be completed in due time for inclusion in the SR-Can 2005 final report.

## 5.2 Flow modelling for current climate conditions

Groundwater flow modelling provides some key entities for the subsequent radionuclide transport calculations in the SKB Safety Assessment model chain. These entities are:

- Groundwater flux (Darcy velocity at repository depth/representative canister locations).
- Flow paths from representative canister locations to the biosphere.
- Transport resistance and advective travel time along the flow paths.

Groundwater flow modelling in previous safety assessments, e.g. SKB 91 /SKB, 1992/ and SR 97 /SKB, 1999a/, has been heavily based on the use of HYDRASTAR /Norman, 1992/, a stochastic continuum code. A number of shortcomings with HYDRASTAR were identified specifically in conjunction to SR 97; the main ones include:

- Lack of density driven flow.
- Limitations with transient flow solutions.
- Mass balance problems when transferring boundary conditions from regional to local (HYDRASTAR) scale models.
- Limitations to assess the transport resistance due to fractures not being described in a discrete manner.

The shortcomings listed above prompted a development of new tools. The need for new tools was magnified by the explicit desire to use the same groundwater flow model tool not only for safety assessment applications, but also for Site Characterisation studies and Design issues within the SKB Site Characterisation Programme. Thus, versatile and flexible tools are needed that can address the specific issues of the different end-users.

In this section we discuss primarily a situation where boundary conditions and included processes reflect the expected development of the geosphere from present day conditions up to the next glaciation period. The main transient process to consider for groundwater flow is the shore-line displacement due to land up-lift. Furthermore, density dependent flow and the salinity field development need to be addressed due to the proximity of the repository sites to the Baltic Sea.

Several scales are of interest for the flow modelling, from the regional (length scale 10 km), via the local (length scale 1 km) to the repository/block scale (length scale 10–100 m). Flow modelling is to be performed at all scales within the Site Characterisation Programme (however, not necessarily all scales for all end-users).

Groundwater flow modelling for site characterisation applications is managed through Site Analysis projects. The modelling will result is site-descriptive models, expressed through the RVS tool and accompanying reports. The historical development of the groundwater flow regimes are of prime interest in these analyses.

The Site Analysis projects have decided to use two separate groundwater flow codes handled by two independent modelling teams. The reason is twofold: first, similar results by two independent codes/teams lend credibility to the analysis; second, independent modelling efforts are seen as a quality control of data handling and modelling practice. The two codes chosen are CONNECTFLOW (NAMMU+NAPSAC) /Marsic et al, 2001, 2002/ and DarcyTools /Svensson, 2002a, b/.

CONNECTFLOW, specifically the NAMMU part, can be seen as a continuation of the stochastic continuum approach initiated at SKB by use of HYDRASTAR. Moreover, NAMMU has regularly been used in previous safety assessment studies for regional scales analyses (e.g. SR 97). DarcyTools (formerly PHOENICS) has been developed within the Äspö HRL framework and has successfully been applied for various field and laboratory scale modelling exercises. Thus, CONNECTFLOW and DarcyTools are based on a different set of experiences and usages within SKB. To show consistency in results between these two model approaches imply a quality assurance in itself.

The main developments performed in CONNECTFLOW since SR 97 include:

- Nested models on all relevant scales can be used. Possibility to nest continuum models within a continuum, discrete models within a continuum, or continuum models within a discrete model. The nesting is done based on constraint equations such that continuity is preserved between the different scales. Nested models enable e.g. the use of a smaller local scale, since path lines emanating from the local scale model freely can continue in the regional scale model. Also, the nested modelling approach automatically ensures mass balance.

- Possibility to perform transient, density dependent simulations in nested models (not in discrete models).

- The transport resistance can be calculated for each path line through the discrete fracture network within the discrete part of CONNECTFLOW. The integration of the transport resistance is exact in the sense that the local fracture surface area and corresponding flow rates are used in the calculation.

- Possibility to study design (tunnel and deposition hole) issues with a continuum representation of the engineered systems within a discrete representation of the fracture network on repository/block scales. Specifically, more detailed input to the near-field model COMP23 can be obtained (e.g. values for Q1 and Q2 in COMP23). Implications on radionuclide transport modelling of such detailed descriptions of the engineered barriers/near field are discussed below in section 1.2.1.

The main developments performed in DarcyTools since SR 97 include:

- Implementation of a technique to obtain stochastic continuum hydraulic conductivity fields based on underlying discrete fracture networks. The obtained continuum fields exhibit several desirable features such as more or less self-consistent scaling properties.
- Nesting of models at different scales possible. However, even if the nesting is automated, fluxes or pressures have to be transferred from one domain to the next.
- Possibility to calculate the transport resistance in the whole domain using the fracture network information available from the underlying discrete fracture network model.
- Introduction of a new solver (MIGAL) which enables the possibility to perform large models even at the super-regional scale (length scale 100 km).
- Transient, density dependent models were available already at the time of SR 97; however, DarcyTools now incorporates multi-rate diffusion as a process that also affects salt transport. This feature is thought to be essential in order to correctly model the salinity evolution.
- Introduction of a particle tracking routine (PARTRACK) that incorporates multi-rate diffusion as a main retention mechanism. PARTRACK is not intended for safety assessment use, but rather as an alternative means to analyse possible tracer tests performed during the site characterisation programme.

It is an open question whether the dual groundwater flow approach is to be applied also for safety assessment applications, or only for the site characterisation modelling. However, for SR-Can only one tool will be applied. The suggestion is to base the groundwater flow modelling for safety assessment applications on CONNECTFLOW. The reasons are mainly based on available resources rather that on technical considerations.

Remaining problems to be solved prior to SR-Site include (some of the issues are planned to be solved already prior to the finalisation of SR-Can and are indicated by ‘*’ below):

- Coupling of the site-descriptive model (as expressed through RVS) and the hydrogeological groundwater flow models. (*)
- Treatment of surface hydrology and near-surface hydrogeology, and coupling to deep groundwater flow and biosphere models, respectively. A proper understanding and handling of the surface hydrology will provide a means to obtain the correct water infiltration rate to the deeper models, and also provide a better description of flow path behaviour in the near-surface environment. The latter issue is of importance in order to predict correct radionuclide exfiltration locations in the biosphere. On-going research within SKB indicates that the existing groundwater flow models can be used, if a high resolution is applied close to the surface /Holmén and Forsman, 2003/. Specifically, the quaternary deposits need to be modelled with a high degree of realism. Implications of increased realism of near surface flow on radionuclide transport is discussed in section 5.3. (*)
- A number of conceptual issues concerning salt modelling need to be assessed. These include e.g. generation of salt in the model, application of relevant initial and boundary conditions for salt, and determination of simulation starting point in time for density-dependent groundwater flow simulations. (*)

- The handling of other climate related situations such as permafrost and glaciation periods. A discussion on these issues is provided in section 5.4.
- There is a need, as expressed in the review of SR 97, to utilize geochemical information in order to constrain groundwater flow models. This is partly dictated by the ample availability of geochemical data, and partly by a belief that such data in fact may improve site understanding and model confidence. A correct description of the salt evolution in groundwater flow models may be seen as a minimum level of compatibility between geochemistry and hydrogeology; however, more elaborate geochemical modelling can be pursued. The experience from Äspö Task Force (Task 5: Coupling of hydrogeology and geochemistry) indicates that such coupling may be hard to accomplish in practice. An assessment of ambition level for SR-Can is needed.
- Issues related to up-coning of saline waters, re-saturation after repository closure, and effects of back-filling material and EDZ properties on the groundwater flow situation in the repository have to be addressed in the safety assessment. Specifically, modelling of up-coning and re-saturation during the operational phase will provide results for the salinity distribution that may serve as initial conditions for simulations of the long-term evolution. Safety assessment may also need to address poorly sealed investigation boreholes. The codes should be able to handle all issues listed above, but detailed tests are needed. (*)
- In addition to up-coning and re-saturation, the fraction of useable deposition holes obtained for different assumptions regarding structural-hydraulic model will be of interest for Design. Furthermore, predictions of groundwater inflow to the tunnel system for different grouting situations, and issues related to what hydraulic requirements should be placed on different repository components (depositions tunnels, access tunnels, etc) are of interest for Design. Potential code modifications implied by these analyses remain to be investigated during the coming year(s); however, the expected workload mainly lies in applying the existing codes for these specific tasks. (*)
- Simulation of wells are of interest for safety assessment; specifically, the volume of rock influenced by a well (capture zone for migrating radionuclides) and dilution in the well are of interest. In principle, both DarcyTools and CONNECTFLOW can handle wells, but these features have not been rigorously tested for safety assessment applications. The addition of un-structured meshes in DarcyTools (planned for 2004–2005) will also aid in the implementation of wells in the model). Within SR-Can it will be demonstrated how a well affects the flow field and possibly also affects radionuclide breakthrough with examples. The major difficulty with this approach is that results are heavily dependent on problem configuration; i.e. widely differing results can be obtained by different choices of well location and corresponding hydrogeological conditions.

The time schedule for the development work is as follows:

- Both CONNECTFLOW and DarcyTools are in principle ready for safety assessment applications. During the spring of 2003, the final implementation of the transport resistance calculation in CONNECTFLOW is performed.
- Issues related to surface hydrology are currently investigated in /Holmén and Forsman, 2003/; however, implementation of (some of) the developed methodology in DarcyTools and CONNECTFLOW will be needed during 2004.
- Issues related to salt modelling and associated initial/boundary conditions are dealt with in the site-descriptive modelling projects, and no additional action will be needed within the realms of SR-Can.

- Coupling between geochemistry and hydrogeology is currently being pursued in a project within Deep repository technology (Äspö). The objective is to utilize all relevant data from Äspö and produce up-dated conceptual models relative to the 1997 models. Tentative project name: Revised hydrochemical Äspö models. Duration: Sept 2003–December 2004.

## 5.3 Transport modelling for current climate conditions

Radionuclide transport in the geosphere is in the SKB safety assessment model chain calculated using the code FARF31 /Norman and Kjellbert, 1990/. FARF31 is based on a one-dimensional stream tube concept, and includes the following processes: advection, dispersion, matrix-diffusion with equilibrium sorption, and radioactive decay (incl. decay chains). Immobilisation processes, known to occur in the field, are for conservative reasons not included. This is motivated by the fact that it is hard to convincingly show that these processes are valid over the spatial and temporal scales of interest for safety assessment applications. Furthermore, colloid facilitated transport is not included in FARF31 even though the presence of colloids could in principle imply non-conservative consequences for some relevant conditions. Colloids will instead be handled through separate analyses, see section 5.3.2 below.

Transport is calculated for multiple path lines (stream tubes) obtained from the groundwater flow modelling. Thus, field-scale dispersion is automatically accounted for through the usage of path lines that have experienced heterogeneous flow conditions.

Longitudinal dispersion along a stream tube is included in the FARF31 formulation through the usage of a Peclet number (the formulation based on a constant Pe-number rather than on a constant dispersivity implies that dispersion increases with travel length as observed in field tests). Dispersion, which is a model concept rather than a physical process in a true sense, is included in order to introduce spreading due to small-scale heterogeneity not resolved by the flow modelling.

A limitation with the 1D formulation is that mixing between stream tubes can not be accounted for. Thus, even if the conceptual picture of transport through discrete fractures supports such a formulation, frequent and fairly strong criticism has been raised against 1D transport formulations.

The link between the groundwater flow models described in section 5.2 and FARF31 is the advective travel time ($t_w$) and, more importantly, transport resistance (F) calculated by the flow models. These two entities serve as input for individual stream tubes in FARF31 in the form $t_w$ and $a_w = F/t_w$ where $a_w$ is the flow wetted surface per volume of water.

In addition to the semi analytical calculations in FARF31 (PROPER module and stand-alone version) where the transport equations are solved analytically in Laplace space and numerical routines are used for inversion and convolution, a finite volume based code has been developed to solve the transport equations (in the longitudinal and transverse direction) numerically. While the semi analytical solution puts limitations on what kind of problems that are possible to solve, the finite volume implementation allows for scoping calculations where the effect of different boundary conditions, matrix properties, additional transport mechanisms etc may be tested. The basic idea behind the finite volume method is to use an integrated form of the governing equations and to solve these over a finite number of elements representing the computational domain. For each of the elements, the activity may change either through an inflow/outflow of material over the boundaries of the elements or due to material being generated/destroyed inside the volume. Since the flux over the boundaries of the elements will be a function of the activity in nearby elements (depending on the problem, this approximation may have different degree of complexity), a system of equations is obtained that may be solved using a suitable conventional solver.

At present, the finite volume implementation has been done in the Matlab environment using built-in solvers with adaptive time stepping suitable for the long time scale the present problem possesses. These have been chosen for easy coding and there is nothing in principle that prevents the models from being implemented on other platforms/applications than Matlab for instance as standalone C or Fortran77 programs executed as part of the Proper computational chain. The finite volume implementation has been tested in a number of different scoping calculations.

The ability of performing scoping calculations to investigate effects of having changing matrix properties as well as colloidal transport are areas where the implementation have showed promising results. However, the present version of the finite volume implementation has been shown to be relatively computer intensive compared to the Proper FARF31 implementation. Hence, the code might be more suitable for scoping calculations than for probabilistic safety assessments. However, after better understanding of the physical problem and the relevant parameter intervals it is likely that the application will be faster and may even be suitable for the probabilistic calculations.

The possibility of connecting a number of Proper FARF31 modules in series to account for the effect of changing longitudinal properties (a so called segmented FARF31) has been developed. The segmented FARF31 has been compared to the finite volume FARF31 with good results.

Issues related to how the transport resistance should be defined and calculated in different flow models is a topic of the ongoing EU-project RETROCK. In principle, the transport resistance can, for individual fractures, be calculated as F=2LW/Q or F=tw/b where L and W are the fracture length and width, respectively, Q is the volumetric flow rate, and b is the fracture half-aperture. Even if the two formulations for obvious reasons are identical for fractures with given dimensions and flow conditions, SKB advocates that the first formulation should be used for safety assessment applications since it is more compatible with entities provided by the flow models. Furthermore, it offers a conceptual advantage since 2LW easily can be interpreted as the “flow-wetted surface”.

In the site-analysis projects, site-descriptive models for transport properties are derived. In short, these models provide different fracture (structure) and background rock types with given retention characteristics. The fractures (structures) subsequently populate a 3D structural-geologic description of the site. The population strategy can be based on various levels of complexity, where the simplest level would be that the same structure type populates the whole domain. A somewhat more complex strategy would e.g. be different structure types in different parts of the domain based on elevation or dominating geology. An even more complex strategy would be a case where structure type is correlated to some fracture property such as e.g. fracture length. The latter approach is currently tested in the on-going Task 6 of the Äspö Task Force.

The site-descriptive models for transport properties are likely to imply that the retention parameters (such as $K_d$-values, diffusivities and matrix porosities) will exhibit a spatial variability. For such cases, safety assessment needs to adopt a strategy for dealing with spatially variable matrix parameters. This can be done in two ways:

- A single realistic (typical) or pessimistic value is chosen for the whole domain. Simply taking average values of the retention parameters will not result in the mathematically correct values. Thus, the choices have to be based on other arguments.
- A correct average value can be calculated, but in this case the averaging has to be done in conjunction to the calculation of the transport resistance (F) in the flow models. In short, the product of F and a group of retention parameters needs to be integrated along the flow paths. This implies that the retention parameters need to be read into the flow model; furthermore, FARF31 will receive an input that already contains the matrix information. This implies code changes for both the groundwater flow and radionuclide transport models.

For Design (and safety assessment) applications, the discrete formulation of tunnels and canister deposition holes in the hydrogeological models will be of interest as discussed above, cf. section 5.2. Thus, transport in tunnels need to be accounted for. How to achieve this with FARF31 is discussed below in section 5.3.1. In short, the basic idea is to have two separate models, one for transport in tunnels, and one for transport in the rock. The output from the tunnel model subsequently serves as input for the rock model, i.e. the two models will be coupled in the same manner COMP23 and FARF31 are coupled today. The FARF31 describing transport in the tunnel will need to be modified in order to incorporate the correct processes. Since the backfill likely will consist of a granular material, the relevant processes are surface sorption (comparable to equilibrium sorption in aquifers), or possibly matrix diffusion into volumes (spheres) of finite extent with subsequent sorption on inner surfaces.

An open question is whether radionuclide transport close to the upper surface should be explicitly handled in the geosphere codes. The groundwater flow models will treat near surface hydrology to a certain extent in order to predict correct exfiltration points, see discussion above in section 1.1, but it is not clear that transport, and specifically retention, should be handled in a FARF31 like code. Rather, the processes may to a certain extent already be incorporated in the biosphere compartment models. Exactly where the interface between geosphere and biosphere is located when radionuclide transport processes are considered, is still unclear. The issue need to be addressed early in the SR-Can project.

Apart from the development work described above, two fundamental limitations with the described modelling strategy may imply additional supporting code development and calculations. These are:

- The stream tube concept is strictly valid only for steady-state flow conditions. Transient flow, resulting from to the shore-line displacement, violates the assumptions of the stream tube concept. In order to assess the effects of transient flow on radionuclide transport, scoping calculations are being performed using the code CHAN3D where flow and transport are solved simultaneously. The hypothesis is that the effects can be shown to be small (at least in a statistical sense) such that bounding situations/conditions can be defined. If the hypothesis is proven wrong, quite a development task lies ahead. In principle, the approach based on separate flow and transport models will collapse, and a new tool with integrated flow and transport needs to be incorporated into the safety assessment model chain.
- The integration of the transport resistance (F) in flow models is not correct when decay chains are considered. Also here bounding effects are to be studied. The tool for such an analysis is the recently developed segmented version of FARF31. In short, the standard FARF31 with integrated parameters is compared to the segmented FARF31 with uniform parameters for each sub-domain. By running several parameter

combinations, it should be possible to obtain a good knowledge of when the integrated approach works and when it does not work. How to finally deal with decay chains in SR-Can and SR-Site is an open question and depends on the outcome of the comparative exercises. From a feasibility point of view it is not attractive to replace the current standard, semi-analytical FARF31 with a segmented counterpart for the bulk of calculations to be performed within SR-Can and SR-Site.

The time schedule for the FARF31 development work is as follows:

- A possible numerical exercise to assess the 1D assumption in FARF31 is to model transport in DarcyTools by two different means. First, transport can be modelled by advective particle tracking, which corresponds to the Lagrangian-like stream tube formulation. Second, transport can be modelled by the advection-dispersion equation in a Eulerian sense for the same hydrostructural model. By using hydrostructural models with different properties, ranging from homogeneous porous media models to discrete networks close to the percolation threshold, it should be possible to demonstrate that the 1D formulation is appropriate for the discrete systems we are interested in. A modelling exercise of this type should be performed prior to finalization of SR-Site.
- The EU-project RETROCK will deliver its final report by the end of 2004. Already now (mid 2003) we have a fairly good knowledge of the results to be presented in the report. Thus, in principle we know how the calculation of the transport resistance will be formulated, i.e. for safety assessment applications we will use fracture surface LW and flow rate Q rather than advective travel time and fracture aperture for the calculation of F.
- The strategy to be used in the site analyses projects for obtaining site-descriptive models for transport properties will be finalized during the second (or third) quarter of 2003. Some later input may be received from Task 6 within the Äspö Task Force which will be finalized during 2005. However, the input from Task 6 will likely not challenge the strategy, but rather provide additional support.
- The scoping calculations concerning transient flow are on-going, and will be finalized during 2003. A presentation of preliminary results have been done at MRS 2003 /Moreno et al, 2003/ and further results are to be presented at Migration 03.
- The scoping calculations concerning decay chains and the implementation of colloids in the numerical version of FARF31will be initiated during autumn 2003.

### 5.3.1 Strategy for the modelling of radionuclide transport in deposition tunnels

In previous Safety Assessments, radionuclide transport in deposition tunnels has been neglected. The reason is twofold: first, the tunnels have been assumed to be back-filled with a material with a permeability at least as low as the average of the surrounding bedrock, second, the analysis tools have not been able to handle transport in tunnels.

The recently developed groundwater flow models can provide detailed input data to the near-field model COMP23 (in terms of Q1 and Q2), see Figure 8-3, section 8.2.2. Also, the detailed description of near-field flow conditions implies new requirements on the geosphere transport description as implemented in FARF31. Specifically, the correct retention phenomena have to be incorporated in FARF31, and multiple release paths from single canister position needs to be handled. These issues are further elaborated below. However, first a description of the different tunnel cases are presented.

Within SR-Can the following tunnel analyses are suggested:

1. Good back-filling properties. The hydraulic conductivity is $<10^{-11}$ m/s. Diffusion dominated transport in the tunnels.
2. Back-filling properties according to set requirements. The hydraulic conductivity is $\sim 10^{-10}$ m/s. Both diffusion and advection may be important transport mechanisms.
3. Poor back-filling properties. The hydraulic conductivity is $>10^{-8}$ m/s. Diffusion in tunnels can be neglected.
4. The back-filling lacks swelling properties. There are gaps between back-filling and surrounding rock. These gaps are highly conductive.

Case 4 may be combined with cases 1–3. The likely most conservative assumption is to combine case 4 with case 1.

The above listed cases can be analysed with slightly modified versions of COMP23 and FARF31 fed with input from CONNECTFLOW. From a CONNECTFLOW model with explicitly implemented tunnels and deposition holes (as continuum representations) within a discrete fracture network, information will be obtained on fracture intersections with the canister hole and associated flow in the fractures. This information will provide Q1. Also flow in the EDZ can be obtained, and provides input on Q2. COMP23 is discretised to include the deposition hole only; i.e. no part of the deposition tunnel is included in COMP23. In addition to the transport components described using Q1 and Q2, nuclides will be transported in the deposition hole to the tunnel by diffusion. Thus, COMP23 will produce three separate out-put fluxes to be handled by the geosphere transport model FARF31.

Different versions of COMP23 could also be used for different fracture intersection modes with the deposition holes. An open question is how the fracture cut-off in the generation of the discrete fractures will affect the calculation of Q1. Smaller cut-offs will result in a larger number of intersections, but some threshold should be attained where additional fractures will have such a low flow rate that their contribution is negligible compared to Q2. This issue will have to be addressed with sensitivity analyses.

The three outlets from COMP23 (i.e. based on Q1, Q2 and the diffusive transport from deposition hole to tunnel floor) would be handled by separate FARF31 models. This implies that particles would have to be released at the fracture/deposition hole intersection location, at the EDZ, and at the interface between deposition hole and tunnel floor. For all three starting positions, the path lines would be followed through the tunnel and rock system out to the model boundaries. Along each path line, one needs to integrate the F-factor and advective travel time. In practice, this would be done by keeping track of how much of the pathline is in tunnels, and how much in intact rock. In each sub-domain, the F-factor and travel time are integrated, and subsequently the models are coupled in the same manner as the segmented FARF31 version discussed in section 5.3. The FARF31 model describing tunnel transport would have to be up-dated with appropriate retention mechanisms. Two alternatives should be addressed: equilibrium sorption resulting in a simple retardation coefficient, and diffusion into a granular medium with subsequent sorption on the inner surfaces of the granular material. The latter conceptual model may be implemented using the multi-rate formulation available in DarcyTools.

The description above is valid for cases with advection in the tunnel, i.e. cases 2–3 above. For case 1, transport in the tunnel would be neglected for the analyses to be performed within SR-Can.

The above feasibility study requires significant resources. Preliminary results may be available for SR-Can, but a well-tested and documented strategy based on comprehensive analyses will not be ready until SR-Site. The above developments would, however, provide a more realistic estimate of the retarding capacity of the near field rock compared to that obtained with the low resolution in the old flow models.

It is important to remember that when CONNECTFLOW is run in a purely continuum fashion, we will still not be able to resolve transport on a near-field scale. The same holds true for DarcyTools, where a continuum formulation always is used. For these cases, COMP23 and FARF31 will be run in the old fashion, i.e. one flow value is fed into COMP23, and the transport model chain is run in similar fashion to the calculations in SR 97.

### 5.3.2 Colloid facilitated transport

In SR 97, colloid facilitated transport in the geosphere was not explicitly handled, but reference was given to earlier SKB work where it is argued that colloids are probably not problematic, primarily since their concentrations in Swedish groundwaters are sufficiently low.

In a recent report /Klos et al, 2002/ it is not excluded that colloids could be a problem. Kinetic sorption onto colloids is treated. It is demonstrated, using SR 97 Aberg data and more that, depending on the kinetic characteristics of the sorption process, the colloids could give significant contributions to dose for the cases studied. It is however only a restricted combination of parameter values that could yield such results and it is unclear if these are at all realistic.

A reasonable conclusion would be that colloid facilitated transport needs a more elaborate treatment in SR-Can than in SR 97. Both a more detailed mechanistic treatment and possible colloid concentrations for different groundwater situations (see section 5.5) need to be considered.

A possibility would be to include kinetic sorption on colloids in the recently developed numerical version of the transport model FARF31 (section 1.2) and study a number of cases. If possible, also chain decay (not treated in the mentioned report) should be included. A major sub-task would be to evaluate available data and to choose data for a pre-study and for SR-Can.

It remains to determine which features need to be included in modelling, what data this requires and how these data should be obtained.

It also remains to establish a time plan for how the issues discussed in this section (i.e. the entire 5.3) shall be implemented in transport modelling activities of the SR-Can project, bearing in mind a) the SR-Can interim report due Summer 2004 and b) the SR-Can final report due end December 2005.

## 5.4 Groundwater flow and radionuclide transport modelling for climate scenarios

Current tools and development needs concerning groundwater flow and radionuclide transport models are described below for the temperate, permafrost and glacial domains (i.e. climate driven process domains). Furthermore, handling of couplings/dependencies between the domains, and between hydrogeology/transport and other geo-scientific disciplines are briefly discussed.

### 5.4.1 The temperate (inter-glacial) domain

The temperate domain is typically handled in most detail in current Safety Assessment studies (relative to the other two domains). Thus, most modelling tools developed are specifically tailored to handle the conditions prevailing during the temperate domain. This is specifically true for the CONNECTFLOW (NAMMU-NAPSAC) and DarcyTools development that has been pursued at SKB since the end of SR 97, see section 1.1. The main new features, relative to SR 97, are the ability to handle transient and density driven flow conditions. The evolution in the geosphere due to the shore line displacement can thus be modelled in a realistic manner, see further section 5.2.

With the developments mentioned above, it is foreseen that the groundwater flow modelling is adequate for the temperate domain. However, concerning transport modelling it needs to be shown that the transient flow conditions stemming from the shore line displacement can be approximated as steady state such that a streamline (steam tube) approach still is a valid transport description, see section 5.3.

### 5.4.2 The permafrost domain

The permafrost domain does not imply any direct conceptual changes for the models, but rather changes in model parameterisation and possibly changes in boundary conditions. Specifically, the hydraulic conductivity will be reduced in the upper part of the geosphere where the ground is frozen, possibly up to few hundred meters depth.

Other issues to consider include the modelling of taliks where high solute concentrations may prevail, and the dilution at the surface during summer periods. The latter issue may be handled with time varying boundary conditions.

Also transport can be handled with modified parameters, e.g. $K_d$-values may need to be changed in order to reflect changes in groundwater chemistry.

### 5.4.3 The glacial domain

The changes in the geosphere and the geosphere's surrounding are likely much greater for the glacial domain relative to the permafrost domain. Two alternative options seem possible in order to handle this domain: a simpler version where changes are handled with changes in parameters and boundary conditions, or a more comprehensive analysis where the actual changes are directly simulated in the groundwater flow model. The two options are described below.

For the simpler option, the glacial domain primarily implies changes in parameters and boundary conditions. Hydraulic conductivities need to be modified where ice tunnels are formed, and boundary conditions related specifically to infiltration need to be changed. Again, transport can be handled with modified parameters, e.g. $K_d$-values may need to be changed to reflect changes in groundwater chemistry. The greatest development need for this version seems to be to obtain relevant boundary conditions reflecting the glacial conditions. Large-scale climate models to be developed should be able to provide the boundary conditions needed.

The more comprehensive option implies that current groundwater flow models are coupled with climate models such that the evolution of glaciers, ice tunnels and infiltration zones are described explicitly in the groundwater flow model. This is likely a rather time consuming task; furthermore, boundary and initial conditions for the climate processes in the coupled model are still needed from larger-scale climate models. This option seems to be more of a research topic than a realistic alternative to be implemented in SR-Can.

Therefore, the simpler option will be implemented in SR-Can. The possible development of the comprehensive option will be considered in SKB’s updated RD&D programme to be presented in 2004. Bilateral cooperation may be an option for the development work (OPG-Canada).

### 5.4.4 Coupling between different climate domains

The three climate driven process domains identified constitute a useful description in order to exemplify typical conditions during different time periods. However, in reality there is obviously a constant evolution within each domain, and no clear limit or distinction between the different domains. For example, during a temperate domain temperatures may slowly decrease such that permafrost regions slowly develop within parts of the geosphere.

From a modelling point of view it seems logical to describe the continuous change in parameters and/or boundary conditions such that the three domains result from the analysis (modelling) rather than form model input specifications. However, this may be hard to achieve in practice (long simulation times, not well known changes in parameters and boundary conditions etc), and hence we may be restricted to use separate models (specifications) for the different domains. If this is the case, it may be hard to explain what will happen during the transitions from one domain to the next. Likely, these transitions will be interesting from several aspects. Thus, it may prove problematic to build a robust safety case without being able to continuously describe the evolution in the geosphere.

The development of models that describe the continuous change in geosphere conditions thus should be developed within the SKB RD&D programme. Final results are not needed for many years, but we should be able to demonstrate that work is on-going. These types of models are currently being used in related fields outside the nuclear waste community, and it is very likely that our reviewers will expect us to take advantage of developments in the related fields.

### 5.4.5 Coupling between groundwater flow/transport and related disciplines

It is usually argued that coupled processes such as mechanical-hydrogeological are not relevant for normal conditions (i.e. for the temperate domain). However, for the glacial domain it is easy to envision that mechanical processes may influence hydrogeological processes. For example, the load of the glacier may imply a redistribution of the stress field with implications for the permeability of the rock mass, and subsequent unloading of the rock mass (i.e. melting of the glacier) may imply earthquakes with changes in fracture properties and/or formation of new fractures, see further section 5.1.5. Models that couple mechanical and hydrogeological processes are more of research tools today than models ready to be applied in a safety assessment context.

Also other couplings may be considered, e.g. between hydrogeology and hydrochemistry. Specifically during the glacial domain it seems likely that groundwaters with different characteristics can be introduced into the geosphere, and the implications for groundwater flow (e.g. changes in permeability due to precipitation/dissolution) and transport (changes in sorption characteristics due to changes in groundwater chemistry) are possible. The latter issue can probably be handled with changes in $K_d$-values in the transport model, whereas the former coupling remains more of a research topic (also the relevance can be questioned).

Of the above issues, only the influence of groundwater chemistry on transport can be directly addressed in the flow modelling within SR-Can. The importance of the remaining issues will have to be assessed by other means.

### 5.4.6 Summary

The available groundwater flow and radionuclide transport models seem adequate for the needs of SR-Can. However, a better understanding of changes in parameters (e.g. permeabilities) and boundary conditions is needed specifically for the flow models during the glacial and possibly also during the permafrost domains.

The coupling between the different domains may turn out problematic unless a continuous time evolution can be modelled. It is possible that transition periods from one domain to the next can provide conditions that are critical for repository performance. In principle it should be possible to model a continuous evolution with the current groundwater flow models.

For the glacial domain it may turn out important to couple mechanical and hydrogeological processes. Specifically, the impact of the ice load on permeability, and the impact of unloading on fracture characteristics, may be crucial to address.

It also remains to establish a time plan for how the issues discussed in this section shall be implemented in flow modelling activities of the SR-Can project, bearing in mind a) the SR-Can interim report due Summer 2004 and b) the SR-Can final report due end December 2005. A permafrost modelling study will be performed during the first half of 2004, see section 3.5. Such a study could provide boundary conditions and information on permafrost extent and depth for a subsequent hydrogeological modelling study. For the glacial domain, hydrogeological simulations are needed for subsequent use in hydrochemical analyses. Existing model results can be used. Updated models are to be run only if new boundary conditions are obtained.

## 5.5 Geochemistry

### 5.5.1 Introduction

The chemical evolution of the buffer, backfill and rock is ultimately governed by the composition and flow of groundwater. In the long term, the chemical properties of the groundwater, together with the properties of the buffer and the copper canister, determine for how long the buffer and canister will function properly.

Transport and reaction processes influence the chemical properties of groundwaters around the repository. The predominant transport process is advection, although diffusion plays also a role. Reactions occur among groundwater constituents, and between the groundwater and fracture surfaces in the form of dissolution/precipitation of fracture filling minerals. Furthermore reactions between the groundwater and the minerals in the rock take place, although very slowly. Microbial processes take place in the groundwater and in biofilms developed in fracture surfaces etc. Microbial processes influence the decomposition of materials from repository construction, colloid formation, gas production/consumption, redox reactions, etc.

Chemical reactions and microbial processes will be driven by concentration gradients and by changes with time. Climatic effects, shore-line displacements, etc, will influence the hydrology and consequently the geochemical composition of groundwaters around the repository. The changing climate will provoke dramatic movements of groundwater altering the geochemistry at and around the repository.

Below, the treatment of the geochemical issues in SR-Can is discussed. The following questions are addressed:

- geochemistry of the repository system at closure,
- initial time-evolution of groundwaters (0 to 1,000 years),
- further time-evolution of groundwaters during the first glacial cycle (1,000 to ~120,000 years).

The evolution of groundwater geochemistry for the subsequent glacial cycles is expected to follow the trends that will be discussed for the first glaciation, and it is not commented any further here.

In SR 97 the temporal evolution of groundwaters during a glacial cycle is mainly enclosed within two extreme groundwater types: the "saline ice-front" and the "non-saline melting zone". The saline waters in the ice front may occur as a consequence of hydraulic up-lifting effects.

### 5.5.2 Geochemistry of the repository system at closure

#### *Description*

Groundwater will suffer substantial changes in composition around the repository during its long operation time. Some changes will be caused by shore-line displacements and climatic variations, but also the presence of the repository will induce significant groundwater changes. It is essential to have a deep understanding of the chemical status of the repository system at closure in order to describe its immediate geochemical evolution after closure (i.e.: how fast does the system return to a "normal" state?).

- An important issue is the spatial extent and the composition of the perturbed groundwaters,
- effects of drawdown (increased meteoric water) and up-coning of saline waters,
- effects of grouting, shot-creeting and concrete leachates on pH, etc,
- the effects of organic material (urine, tobacco, plastics, cellulose, hydraulic oil, surfactants and cement additives).

The reducing capacity of the backfill is also of importance for the integrity of the copper canisters. The time for $O_2$ consumption in the backfill during the resaturation phase may be used to illustrate this reducing capacity.

During the operational phase, inflow of groundwater into the tunnel and mixing of groundwaters in fractures will probably result in precipitation of large amounts of $Fe(OH)_3$ and perhaps $CaCO_3$. The effects of these solids from a chemical and microbiological aspect must be established.

Another important question is the expected evolution of the microbial population during operation and through the resaturation phase. It could be envisaged that these changes in microbe populations could induce increased colloidal and organic matter concentrations.

#### *Plan*

Several reports are required as a basis for the evaluation of the geochemical state of the repository at closure. The aim is to have all the reports ready for the SR-Can interim report, due July 2004. The following studies are envisaged: the spatial extent of the repository perturbation on groundwater; the time for $O_2$ consumption during the resaturation phase; and the microbiological evolution of the repository.

The hydrogeochmical analytical group (HAG) of SKB's site investigation program will study the possible influence of precipitation of iron hydroxides and calcite around the repository during the operational phase. These calculations will be outside the site characterisation tasks, but will apply the same modelling tools used in establishing the site models.

### 5.5.3 Initial temporal evolution of groundwaters (0 to ~1,000 years)

#### *Description*

During this period of time a temperate climate is expected, and it is quite possible that this climate domain might extend further than one thousand years. Displacements of the Baltic shore line, and changes in the annual precipitation will influence the hydrology of the site and as a consequence the geochemical composition of groundwaters around the repository. It is expected that the meteoric water and perhaps the Baltic water components in the groundwaters will increase during this period.

Most of the existing flow and transport modelling tools are well suited to handle the conditions prevailing during the temperate domain. Codes such as CONNECTFLOW or DarcyTools have the ability to model transient and salinity driven flow conditions. The evolution of groundwater flow and salinity due to the shore line displacement should thus be possible to model in a realistic manner, see also Sections 5.2 and 5.4. Such calculations must consider the state of the groundwater around the repository at closure.

Results from a regional model of salt distribution as a function of time may be translated into mixing proportions of reference waters if the succession of events in the site is also known. In this case an influx of meteoric waters and/or Baltic waters will also be given from the hydrological modelling and its boundary conditions. All this knowledge will be used as input to the M3 model /Laaksoharju et al, 1999/ to calculate mixing proportions of different groundwater types: meteoric, Baltic seawater, deep brine, etc. The starting and final mixing proportions of waters may then be used to calculate rock-water interactions, e.g. calcite dissolution, using a well known code such as PHREEQC to provide other parameters such as pH, alkalinity, and redox potential.

#### *Plan*

A regional site model for the salinity distribution as a function of time for the temperate climatic domain will be obtained as indicated in section 5.4 of this report.

The HAG (hydrogeochmical analytical group of SKB's site investigation program) will use the regional hydrological and salinity model to evaluate the proportions of different water types and compute water-rock interactions. These calculations will be outside the site characterisation tasks, but they will apply the same modelling tools used in establishing the site models. The aim is to finish this evaluation by December 2004, depending on the outcome of the hydrological and salinity model.

### 5.5.4 Further temporal evolution of groundwaters during the first glacial cycle (~1,000 to ~120,000 years)

#### *Description*

During this period of time climatic changes are expected to be more dramatic than in the initial temperate phase of ~1,000 years or more. Three main climatic process domains alternate (Chapter 3): temperate, permafrost, and glacial. This will greatly affect the flow and composition of the groundwaters. However, as indicated in section 5.4 it does not seem appropriate to perform detailed hydrological calculations as a function of time. This would require the continuous time-changes in parameters and/or boundary conditions such that the three process domains result from the modelling. This is hard to achieve in practice due to long simulation times, and to large uncertainties in the changes in parameters and boundary conditions. Therefore the modelling will be restricted to using separate specifications for the different climatic domains.

The three climate-driven process domains are useful in exemplifying typical hydrological conditions during different time periods. In reality however there is a constant evolution between climate domains, and there is no clear limit between them. For example, during a temperate domain temperatures may slowly decrease such that permafrost regions slowly develop within parts of the region. Nevertheless, different groundwater types will prevail as a result of the different types of climate domains and their corresponding hydraulic conditions.

Therefore the groundwaters in the climate scenario will be enclosed within two extreme groundwater types: the "saline ice-front" and the "non-saline melting zone". The saline waters in the ice front may occur as a consequence of hydraulic up-lifting effects. Diluted meltwaters may penetrate the geosphere in certain circumstances as a consequence of high hydraulic pressures beneath the ice-sheet.

Some questions of importance for geochemistry that were addressed in SR 97 will be further evaluated in SR-Can:

- Continental ice: how fast does it grow/disappear; duration; thickness; will the repository be located below a sub-glacial lake?
- Hydraulic conditions under continental ice: penetration of $O_2$-rich waters; penetration of diluted melt waters; up-lifting of saline waters.
- Permafrost: how fast does it penetrate (can saline water accumulate beneath it?); probable depth and duration.

#### *Plan*

The penetration of diluted waters and up-lifting of saline waters has been described for example in SKB-R-03-04. This result will be the basis for calculations on water-rock interactions by the HAG (hydrogeochemical analytical group of SKB's site investigation program). This modelling exercise will be outside the site characterisation tasks, but will apply the same modelling tools used in establishing the site models. The aim is to present an evaluation of the chemistry of the main components in glacial melt-waters, to be finished during 2004. The results will also be the basis for calculations of the penetration depth of $O_2$ waters. This problem was already addressed in SR 97, but new information and new numerical codes are now available and this question must therefore be revisited. This task will be completed by the end of 2004.

The question of the accumulation of high salinity pockets beneath permafrost will be addressed using codes such as CONNECTFLOW or DarcyTools. This may be addressed simultaneously with the penetration rate of permafrost. Modelling of this problem will start at the beginning of 2004, with the aim to complete the study by the end of the same year.

### 5.5.5 Data and conceptual uncertainties in groundwater geochemistry

#### *Description*

All data is subject to uncertainties. Some arise from the measurements and they may be statistical or systematic. These uncertainties may be addressed by estimations from experts in the matter. In the field of groundwater chemistry there is the additional problem of sample representativity and of uncertainties in the geosphere and hydrological models, which affect the estimation of sample representativenes.

In addition to these uncertainties, calculation models used in groundwater geochemistry have additional uncertainties. These arise from uncertainties in thermodynamic data, in the assumptions of equilibrium, in the models for sorption or solid solutions, etc.

#### *Plan*

A workshop will be organised by SKB inviting experts in this matter to discuss how to deal with uncertainties in this field. The workshop will be arranged in early 2004.

# 6 Near field issues

In this chapter, a number of issues regarding the fuel, canister, buffer and backfill are discussed. The first two sections deal with two general near field issues, namely near field temperature and the impact of earth quakes on the near field. Radionuclide transport modelling of the near field is discussed in chapter 8, section 8.2.2. Radionuclide transport in deposition tunnels is discussed in section 5.3.1.

## 6.1 Near field temperature

The thermal evolution of the fuel, the canister, the buffer and the near field rock will depend on a number of factors, a few important ones being

- The heat generating power of the fuel.
- The thermal conductivity of the canister interior, in particular in the gap between copper canister and cast iron insert, see Figure 6-1.
- The emissivity of the copper canister's inner and outer surfaces.
- The thermal properties of a possible gap between canister and buffer, and, to a lesser extent, between buffer and the wall of the deposition hole.
- The rock thermal properties of the buffer and host rock.
- The spacing between deposition holes.

An important safety related requirement states that the temperature of the canister surface must not exceed 100°C in order to avoid enrichment of salts on the outer canister surface which may subsequently lead to chemical attacks on the canister that are difficult to predict. The requirement is fulfilled by a sufficiently large distance between adjacent canisters in the repository layout. In practice, the target has often been set to 90°C to account for uncertainties and inhomogeneities in the various properties influencing temperature.

Detailed analyses of the thermal evolution of the canister surface, buffer and near field rock will be done as a repository engineering activity, taking the above requirement into account.

In SKB's recently developed system evolution model, section 8.1, it has been demonstrated that the results of more detailed thermal models for both the buffer/rock system and for the canister and its interior, can be well reproduced. Figure 6-1 shows two examples of calculations with that model. The model will be used in SR-Can to verify the canister spacing calculations done by the repository engineering group, to study sensitivities of the fuel and canister temperatures to various assumption on gap properties like emissivities and gas heat conductivities, to estimate the thermal expansion of the cast iron insert and the copper canister, to estimate fuel temperature etc.

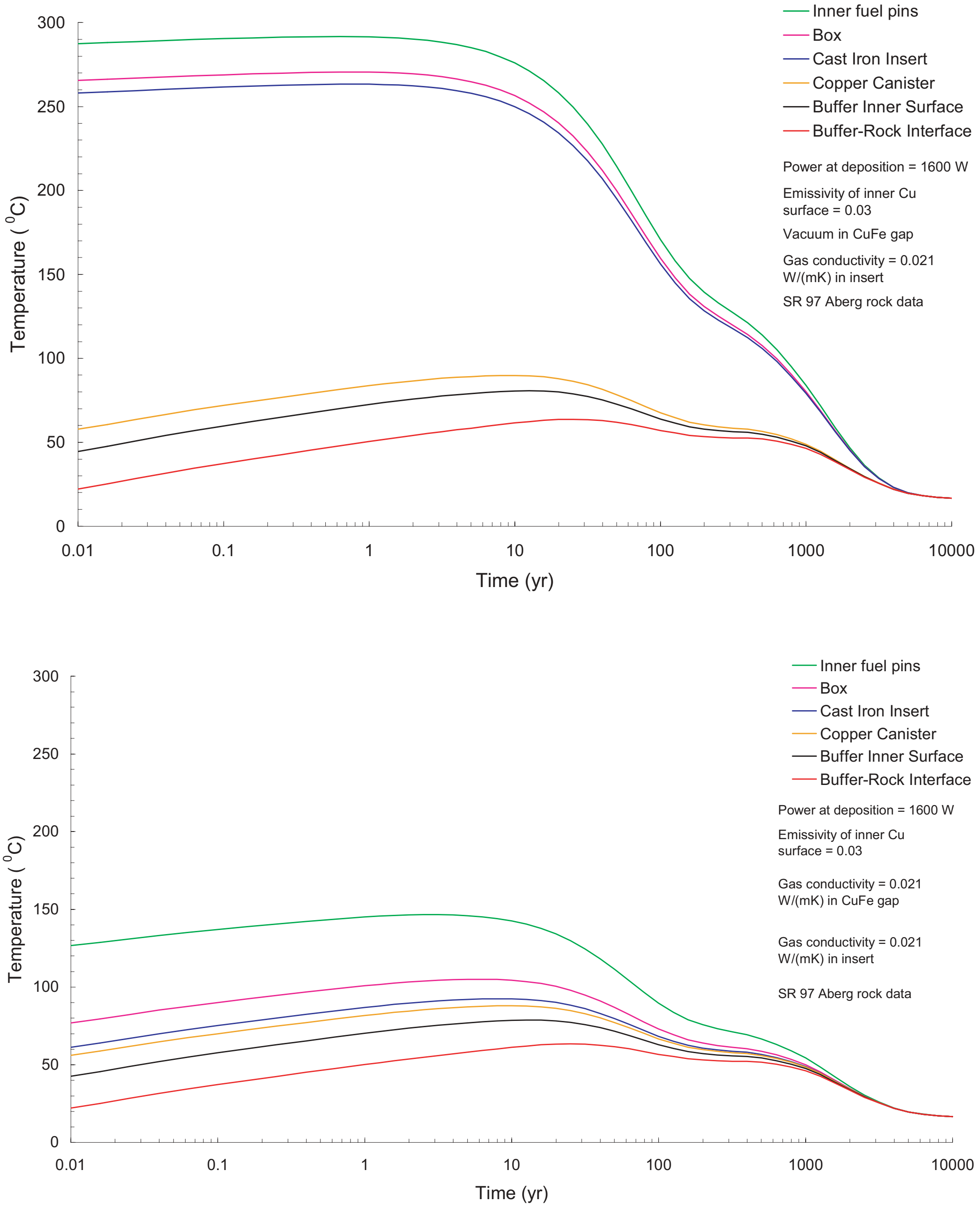

***Figure 6-1.*** *Two examples of possible thermal evolutions of various components in the near field. The upper figure illustrates the effect of vacuum between cast iron insert and copper canister, the lower shows the evolution for a gas filled gap between the two components. Note that all components outside the gap, e.g. the copper canister temperature, are unaffected by the conditions in the gap.*

## 6.2 Earthquake effects on near field

The effects on buffer, copper shell and cast iron insert of an earth quake induced shear movement of a fracture intersecting a deposition hole has recently been modelled /Börgesson et al, 2003/. Laboratory tests were performed to determine relevant material properties for the buffer for the modelled situation.

Shear rates up to 1 m/s, buffer densities up to 2.1 g/cm$^3$ and shear movements up to 20 cm are simulated, meaning that the present study is a more realistic representation than those referred to in e.g. SR 97. The results from the study indicate that the consequences of a shear movement across the deposition hole depend strongly on the density of the bentonite, but also on the location of the shear movement in relation to the centre of the canister. A shear movement hitting the middle of the canister is less severe than a movement off centre. In neither case is an immediate failure of the cast iron insert or the copper canister predicted.

The study yields the stress and plastisation state of the copper shell, the insert and the buffer immediately after shearing. It remains to be critically evaluated if this state could lead to canister failures of any type during the further course of events. A possible cause for later failure would be creep of the copper canister as a consequence of the deformations caused by the shear movement. Also the effects of future increased isostatic loads on canisters affected by an earth quake should be considered. Other issues concern the selection of realistic material properties for the cast iron insert and possibly the properties of the buffer in case of cementation.

Evidently, the results of this study need to be integrated with emerging results from studies of earth quake effects in the geosphere, see section 5.1.5, to determine which of the modelled cases above are relevant. Also the general evolution of the buffer needs to be considered in order to assess future buffer densities.

## 6.3 Fuel issues

This section treats some important fuel issues in SR-Can. Eventually, the outcome of much of the efforts indicated below will be summarised in the SR-Can Process Report.

### 6.3.1 Fuel dissolution

Uncertainties regarding the fuel dissolution rate if water contacts the fuel in an assumed damaged canister has a strong influence on the results of radionuclide release, transport and dose calculations for typical conditions for a KBS 3 repository. In the example of a sensitivity analysis of such results from calculations based on SR 97 data, see section 2.9.5, the fuel dissolution rate is the top ranking uncertain parameter to which the results are sensitive. This issue thus requires considerable attention in SR-Can.

A wealth of new experimental data on fuel dissolution is emerging from several organisations. In particular the effects of hydrogen, expected to be present due to cast iron corrosion inside a defective canister, are in focus in many studies. To ensure a comprehensive treatment of the fuel dissolution issue, taking all recent developments into account, a group of international experts in this area will, on SKB's initiative, produce a state-of-the-art report on several crucial questions related to fuel dissolution.

A series of meetings will be held during the course of the work. Tentative chapter headings of the report suggested during a first planning meeting are:

- Boundary Conditions.
- State of the fuel after 1000 years.
- Information about the fuel used in fuel leaching experiments.
- Discussion of experimental data.
- Review of fuel dissolution models previously used by SKB and their foundations.
- Model(s) to be used in SR-Can.

In an appendix, fuel dissolution models proposed by other and not used by SKB will be discussed.

A draft version, with recommendations for modelling of fuel dissolution SR-Can, will be delivered by the end of 2003 and the final report will be published in the spring of 2004.

### *Further considerations*

There are several results on spent fuel leaching and alpha doped $UO_2$(s) (simulating old fuel) in the presence of various amounts of dissolved hydrogen. All data show a large impact of dissolved hydrogen on spent fuel or $UO_2$(s) leaching.

In order to be able to use these data, a calculation of the rates of hydrogen production and diffusion out of the canister should be carried out. A variation of the parameters such as cast iron corrosion rates (i.e. hydrogen production rates), diffusion coefficients and canister defect dimensions would give a range of dissolved hydrogen concentrations in the groundwater inside the canister at different time periods. Then a hydrogen effect based model may be applied for e.g. $[H_2]_{diss} > 10^{-3}$ M, corresponding to a partial pressure of hydrogen slightly higher than 1 atm. Alternatives for modelling this case are e.g.: *i*) zero net dissolution, i.e. a solubility limited model, or *ii*) an upper limit of the dissolution rate measured under hydrogen atmosphere, e.g. $10^{-8}$/yr.

When the hydrogen concentration is lower than 1 mM, a dissolution model valid for 1,000 years old spent fuel dissolution under the influence of alpha radiolysis has to be considered. The available experimental data for such conditions are not extensive, however some exist and should be reviewed. An alternative could be to use a dissolution rate of $10^{-6}$/year, as in a relatively recent EU project /Grambow et al, 2000/.

## 6.3.2 Athermal diffusion

Fission products migrate in the spent fuel matrix by diffusion. This requires high temperatures or fissions. There is only one experimental work /Matzke, 1983/ where temperature independent diffusion of heavy atoms (as Pu and U) caused by fissions has been observed in in-reactor conditions. The so-called athermal diffusion is a process which has been forwarded lately as possible to occur in spent fuel due to alpha decay, by analogy with the athermal diffusion noticed in spent fuel due to fissions. This athermal diffusion or alpha self-irradiation enhanced diffusion is supposed to be related to the movement of the radionuclides within the defects of the lattice accumulated by the alpha decay) and driven by the alpha recoil. By analogy with fission induced athermal diffusion, athermal diffusion coefficients for alpha induced diffusion have been estimated as proportional to the number of defects created and the energy of the recoil nuclei.

These estimates are very approximate and span a range of a few orders of magnitude. The final calculated effect is an increase of the grain boundary fraction by up to 30 percent of the total inventory after 10,000 years, with consequences also for fuel grain cohesion.

Given the importance of the predicted consequences, the process should be considered in SR-Can. Further discussions on the handling of this issue in SR-Can will be found in the state-of-the-art report in progress, see section 6.3.1.

### 6.3.3 Colloid formation

An intact buffer is an effective colloid filter. However, if the buffer is altered, colloids could escape from the canister and potentially act as vectors for radionuclide transport in the rock. The possibility of colloid formation inside the canister therefore needs some attention.

#### *Colloids from dissolved radionuclides*

In a couple of recent studies /Knopp, 2000; Neck and Kim,1999/ the solubility of tetravalent actinide oxides as e.g. Th(IV) oxide has been determined at the pH value at which the formation of oxide colloids is detected. This means that the often discussed actinide(IV) oxide intrinsic colloids can not be formed from undersaturated solutions, i.e. in spent fuel leaching solutions with extremely low concentrations of the actinide(IV) ions in solution. The solubility measurements show also that at the neutral pH range the solid phase in equilibrium with the solution corresponds to a less crystalline higher solubility phase than at $pH < 4$. To reach oversaturation with such an oxide phase even higher soluble actinide ion concentrations should be necessary.

Preliminarily, it seems reasonable to exclude this mechanism for colloid formation under conditions expected inside a defective canister in a deep repository.

#### *Formation of Fe(III) colloids*

Another possibility is the formation of Fe(III) hydroxide colloidal particles through the oxidation of Fe(II) ions originating from iron insert dissolution by radiolytic oxidants. As discussed above, it is more probable that the dissolved hydrogen produced in the container by anoxic iron corrosion would consume radiolytic oxidants more readily than Fe(II).

The possibility for Fe(III) colloid formation will be further discussed in the state-of-the-art fuel report, see section 6.3.1.

#### *Formation of fuel colloids*

The formation of fuel colloids from spent fuel grains is discussed in the SR 97 Process Report, section 2.7.8. There is presently no additional information available to that cited in SR 97.

### 6.3.4 Radionuclide inventories for SR-Can

The radionuclide inventories used in SR 97 will be updated. The calculated values are reasonable, but a better discussion about the uncertainties is required. Also, the dependence on fuel type should be further elaborated on. Some observed differences between the SR 97 calculations and results reported by Nagra have to be resolved.

The treatment of the instantaneous release fraction, IRF, in SR-Can will be the same as that in SR 97. Information from recent studies will be added to the data set. High burn-up fuel is one area that may require special attention.

SR-Can inventories will be suggested in September 2003, along with a plan to further improve the suggested data.

### 6.3.5 Radionuclide chemistry in SR-Can

The structure of the background report on solubilities for SR 97 /Bruno et al, 1997/ is useful also for SR-Can. The areas that need major revision are:

- The definition of the reference water and the evolution with time. What groundwater conditions can be expected in the repository? This area requires integration with the chemical modelling of the porewater in the buffer.
- A better definition of “best-estimate” and “pessimistic” solubility values. Those definitions were introduced in SR 97 after the solubility report was completed and the values were somewhat arbitrarily selected.
- The importance of the corrosion of the iron insert was almost neglected in the solubility calculations in SR 97. This may push the redox conditions to very low values.
- There is a much better understanding of the actinide chemistry today. This has to be considered in the report.

A report on radionuclide solubilities for SR-Can (Forsmark site) will be provided by the end of January 2004, provided that the composition of the reference water for the Forsmark site can be delivered as an input to the project by September 2003. Uncertainties in the delivered solubilities will be discussed in the report according to the general plan for management of data uncertainties, outlined in section 2.11.

### 6.3.6 Cladding tube integrity

The scientific bases for cladding credit as a barrier to radionuclide release at the proposed Yucca mountain repository has been reviewed by /Ahn et al, 1999/. They identify as mechanical mechanisms for cladding failure rockfalls, creep and splitting due to spent fuel matrix oxidation. As other mechanisms they list corrosion and delayed hydrogen cracking (DHC) and failure prior to disposal due to damage during handling. The risk for rockfall is eliminated in a KBS-3 type repository since this kind of a repository is backfilled in contrast to the proposed Yucca mountain repository. Neither will splitting due to spent fuel oxidation occur because of the very limited amount of oxygen available in a sealed KBS-3 repository. Remaining identified mechanisms for cladding failure prior to canister failure in a KBS-3 type repository are creep failure, delayed hydrogen cracking (DHC), and failure due to damage during handling.

Creep failure requires high cladding temperatures. In dry storage of spent fuel the upper limit for safety against creep failure is set at 410°C (Germany) and 380°C (USA). According to Ahn, creep failure is unlikely during repository conditions, but if the cladding temperature is driven above ~350°C up to 5 percent of the cladding tubes may fail.

DHC is a crack propagation process under sustained load conditions. It results from hydrogen diffusion to the crack tip followed by the formation and fracture of hydrides. After irradiation, the zircaloy cladding contains circumferential hydrides, which has a limited effect on the risk for failure. Elevated temperatures (at 300°C, the hydrides are expected to dissolve in the zirconium matrix) followed by slow cooling can lead to a reprecipitation of radial hydrides with an increased risk for cladding failure as a result particularly since the stress in the cladding will increase with time due to alpha decay. /Ahn et al, 1999/.

After canister failure, corrosion processes are also possible. The rate of general corrosion of Zircaloy is so slow (about 2 nm/a /Rothman, 1984/) that break-through due to corrosion is calculated to not occur until after 400,000 years. All other mechanisms, including localised corrosion and stress corrosion cracking, will only lead to local failure (i.e. holes and cracks) in an otherwise relatively intact Zircaloy cladding. In view of the difficulties to assess the probabilities for each of these mechanisms, it can be assumed in the safety analysis that the Zircaloy cladding will be present for a long time, but that it will not be capable of preventing water from reaching the fuel due to the presence of local failures in the cladding. It should be pointed out, however, that apart from initially failed cladding and failure caused by transport damages, creep failure and DHC will take time to develop although it is difficult to predict exactly how long.

### 6.3.7 Criticality

The criticality safety in a deep repository has been analysed by /Agrenius, 2002/. Agrenius' criticality calculations show that based on state of the art methods and a reasonable assessment of the uncertainties, burn-up credit is a possible way to demonstrate control of the reactivity in the canisters using a minimum set of nuclides. Additional actinides and selected fission products give more margins. There is, therefore, no need at present for more data in this field.

The results will be discussed in the SR-Can Process Report.

## 6.4 Canister issues

The SKB reference canister consists of an inner container of cast iron and a shell of copper. The cast iron insert provides mechanical stability and the copper shell protects against corrosion in the repository environment. The copper shell is 5 cm thick and the canister takes the form of an approximately 4.8 metre tall cylinder with a diameter of 1.05 metres.

The insert has channels where the fuel assemblies are placed and is available in two versions: one for 12 BWR assemblies and one for 4 PWR assemblies. The fuel channels are fabricated in the form of an array of square tubes. The walls and bottom of the inner container are then fabricated by casting spheroidal graphite iron around the channel array.

There are several options for the fabrication of copper canisters like extruding or forging to produce seamless tubes. Another option is to use the pierce and draw process to produces tubes with integrated bottom. In the case when a bottom has to be attached, this will be done by welding, using the same method and testing technique as for the sealing weld.

After fuel has been placed in the canister, the insert is closed with an O-ring-sealed lid which is fastened with a bolt. An O-ring may however not be needed if a non vacuum welding technique is used. The copper shell's lid is then attached by welding and the quality is tested using non destructive testing (NDT). The canister weighs a total of about 25 tonnes when filled with spent fuel. A canister holds about two tonnes of fuel. A total of about 4,500 canisters will be produced according to current estimates.

A critical part of the encapsulation process is the sealing of the canister lid. The welding techniques developed are electron beam welding (EBW) and friction stir welding (FSW). Both these methods are being developed in parallel and one will be chosen during 2005 for further development and use in the encapsulation plant.

### 6.4.1 Initial canister defects

The possible occurrence of initial canister defects is a key issue in the determination of initial states for the repository. This applies to all seals of the canister and in particular to the top lid seal as this is more difficult to inspect than seals made earlier in the production process.

In order to manage the situation quantitatively, two sets of requirements have been established. One is the *acceptance specifications for the seal weld*, which essentially specifies when a seal is to be regarded as defective. The other is the *design criteria for the canister production process*, which specify a maximum allowed rate of canisters with undetected, defective seals that may leave the encapsulation plant.

The acceptance specifications for the seal weld on the 50 mm thick canisters state that the largest allowed discontinuity is 35 mm in radial extension, i.e. there should be at least 15 mm intact ligament in the weld. The corrosion evaluation shows that under foreseen repository conditions, this will guarantee a service life of the canisters of at least 100,000 years and most probably of millions of years.

The design criteria for the canister production process states that the canisters must be sealed and inspected with methods that guarantee that no more than 0.1 percent of the finished canisters will contain defects larger than the acceptance specifications, i.e. at most one canister in a thousand may leave the encapsulation plant with less than 15 mm ligament anywhere in the weld.

The design criteria are used to set targets for the manufacturing process for the canisters and this process is still to be established and qualified. The manufacturing process will encompass several quality control steps, in particular NDT methods for the seal welds like radiographic testing and ultrasonic testing.

The acceptance specifications and design criteria thus essentially serve as targets when establishing the manufacturing process. The actual performance of the manufacturing process must however be demonstrated quantitatively. Two crucial factors in this demonstration are

- the actual quality of the welding system, i.e. the frequency of defects of different sizes in the produced welds and
- the actual reliability of the non-destructive testing system, i.e. the likelihood that the testing system will detect defects of different sizes.

The quality of the welding system will be determined by applying a number of destructive and non-destructive test methods to a test series and then evaluating the results statistically. The methodology for this is being developed.

The reliability of the NDT system will be determined essentially by passing a series of known defects through the system. To provide relevant defects for the study, the input parameters for the welding processes will be varied outside the normal span. The analysis will take the different test methods into account and each method as well as their combination will be analysed.

The establishing of the reliability for NDT and the quality of the welding system is expected to be finished during 2005 for both the FSW and the EBW techniques. The essential result of the project will be a so called probability of detection (POD) curve, which expresses the probability of detecting a defect as a function of the defect size. Figure 6-2 shows an example of a POD curve (the green curve). Also shown are an acceptance criterion (35 mm in this hypothetical case) and a curve of the probability of producing defects as a function of size (the red curve). The figure shows a favourable situation where *i*) the probability of detecting a defect larger than the acceptance criterion is high (between 90 and 100 per cent) and where *ii*) the probability of producing defects larger than the acceptance criterion is low (below 0.4 per cent). In this hypothetical situation it could be concluded from the details of the two curves that the probability of delivering a canister with an undetected defect larger than the acceptance criterion is around $10^{-4}$. This system would thus fulfil a design criterion which stated that the probability of delivering such a canister should be below $10^{-3}$. Note also that the above discussion is simplified and does not include e.g. effects of potential clustering of small defects.

When the quality of the welding system and the reliability of the NDT system have been satisfactorily determined, they can be combined to derive assumptions regarding the frequency of undetected welding defects for the ensemble of canisters to be deposited in the repository.

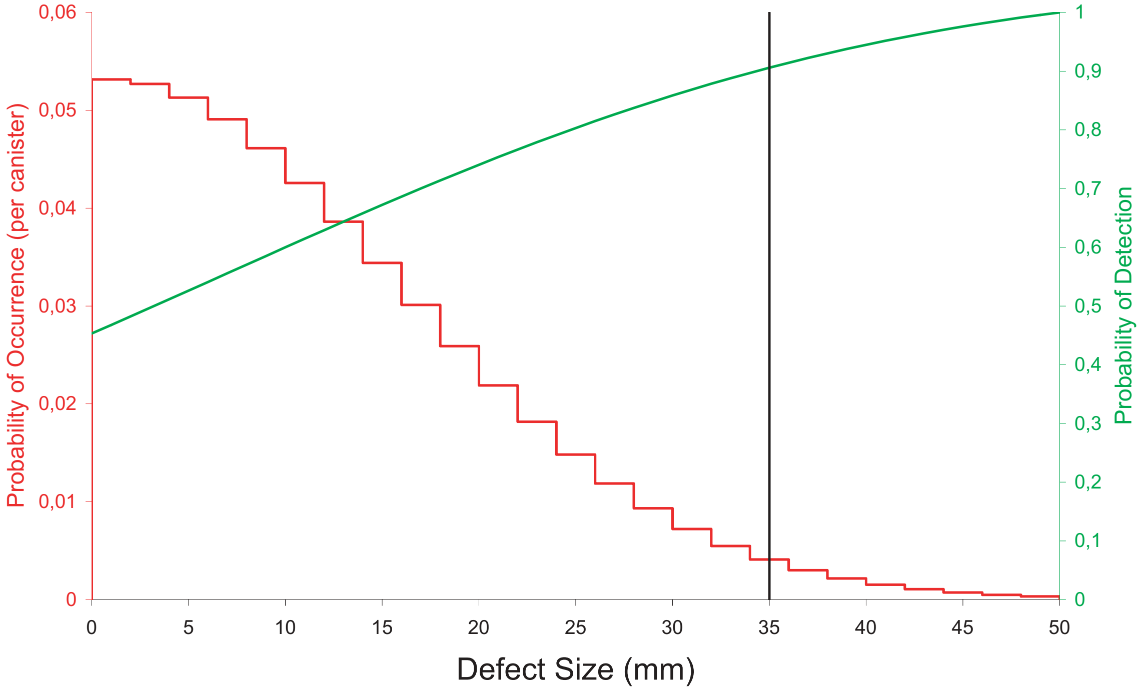

***Figure 6-2.*** *POD for the NDT system (green), probability of producing defects as a function of size (red, referring to a single canister seal) and the acceptance criterion (black vertical line).*

### *Input data for SR-Can*

A dialogue with the project described above will be maintained throughout the SR-Can project in order to follow the progress and to ensure that the results are on a suitable format to serve as input to the safety assessment. If useful data emerge in due time for the completion of SR-Can, these will be used as input to the safety assessment. Until such data is available, it could tentatively be assumed that the design critera will be *just met* by the manufacturing process. This would thus mean that on the average one deposited canister in a thousand would have weld defects with less than 15 mm ligament in the weld. The actual number of defective canisters could be assumed to be a binomial distribution with an average of $10^{-3}$ times the number of deposited canisters. This was done in e.g. /Hedin, 2002b/ and has subsequently also been mentioned as a possible way of managing the situation by /Hora, 2002/.

## 6.4.2 The further evolution of defective seals

It is likely that also canisters that do not meet the acceptance criteria will have a considerable service life. An early failure can however not be excluded. The type and form of such a defect that remains undetected is impossible to ascertain. The experience to date from the canister laboratory will, however, give some basis for a well-founded assumption.

/Ronneteg, 2001/ has extensively analysed 43 discontinuities in electron beam welds and compared indications from digital radiography and ultrasonic testing with microscopy of the discontinuities. The majority of the discontinuities are relatively small, less than 10 mm in radial extension with highest frequency for 3–5 mm. The circumferential extension is generally only a few millimetres. Since the detectability is expected to be better the larger the discontinuity, it is reasonable to assume that discontinuities that remain undetected are relatively small. A train of relatively small discontinuities, a few millimetres each, separated only with a thin ligament seems to be the most reasonable cause of an early canister failure. The probability for this is however likely to be very small.

Assume for example that the weld contains one large detected discontinuity, close to the largest acceptable size, but also several smaller, undetected, discontinuities. This could be, say, one 35 mm pore and three 4 mm pores. Thus, the weld will have about 3 mm intact ligament. In this scenario, there is no initial fully penetration defect. In the LOT experiment /Karnland et al, 2000/ the short-term corrosion rate was measured to be about 3 µm per year during the oxic period. If one, very pessimistically, assumes that this corrosion rate would prevail for an extended period of time, penetration would occur after 1,000 years. In the electrochemical noise measurements performed in the LOT experiment, the corrosion rates are a few years after burial estimated to be 0.7 µm per year. This would lead to penetration after about 4,000 years. In the lifetime predictions cited by /King et al, 2001/, conservative estimates for corrosion depths in one million years range from 1.3 mm to 18 mm, i.e. a 3 mm ligament would give a lifetime larger than 100,000 years. Even with very pessimistic assumptions, there should be no likelihood of a fully penetration defect to develop in shorter time than 1,000 years.
It remains to develop the above discussion so that the further evolution of defective seals can be treated in a consistent and defensible manner in SR-Can.

### 6.4.3 Internal evolution of damaged canister

The internal evolution of a canister with a penetrating defect depends on a number of factors like defect size, groundwater pressure, internal canister geometry, cast iron corrosion etc. Several of these factors are associated with considerable uncertainties. The following is *one* example of a conceivable evolution, assuming a 4 mm diameter hole in the copper shell.

Once the copper canister has been penetrated, water can intrude. The intrusion rate of water will be determined by the pressure difference between the far field and the interior of the canister since the flow resistance of the hole is much smaller than flow resistance of the bentonite /Bond et al, 1997; Takase et al, 1999/. At a pressure difference of 4.9 MPa, corresponding to 5 MPa hydrostatic pressure in the far field and 0.1 MPa pressure in the canister, the rate of water inflow will be $2 \cdot 10^{-5}$ $m^3$ per year for a 4 mm diameter hole.

The rate of anaerobic corrosion of cast iron is expected to be less than 0.1 µm per year, corresponding to a hydrogen production rate of about 0.2 $dm^3$ per $m^2$ and year /Smart et al, 2002b/. A possible galvanic enhancement due the cast iron-copper coupling will at the most double this rate. Even if the corrosion occurs over the full cast iron area (about 14.4 $m^2$), this corrosion rate will be too low to consume all the water that initially enters. Consequently, the annulus will slowly fill with water at the same time as the hydrogen pressure inside the canister will increase resulting in a decrease in the rate of water inflow. More elaborate calculations performed by both /Bond et al, 1997/ and /Takase et al, 1999/ show that in this scenario the loss of water due to corrosion will exceed the water inflow after about 300 years and all water is expelled after about 600 years. After that time, the corrosion will be caused by water vapour only, which means that there will be no galvanic enhancement of the corrosion rate. The corrosion will then also be evenly distributed over the whole insert area. The time to fill the annulus with magnetite will be between 10,000 and 20,000 years, depending on the manufacturing tolerances for the insert and copper canister /Takase et al, 1999/.

The most likely development after the annulus is filled with magnetite seems to be that the corrosion rate will drop to virtually zero. The experimental studies at Serco give no indication that continued corrosion has lead to strong forces created by the growth of corrosion products /Smart et al, 2001/. Nor do analogue studies support such a development /Smart et al, 2003/.

If one would assume that corrosion by water vapour is, for some reason, capable of continuing on the entire surface area of the insert after the annulus is filled, this would lead to a slow deterioration of the mechanical stability of the canister. After 50,000 to 100,000 years, the insert would collapse under the additional load from a glaciation. After that, there will be a continuous water path from the fuel to the near field.

In any situation where the canister is assumed to be partially or fully filled with water, it is critical to assess the partial pressure of hydrogen gas. As discussed in section 6.3.1, the rate of fuel dissolution in a water filled canister will likely depend strongly on this entity.

As mentioned, the above are only a few of several conceivable internal evolutions of canisters with penetrating defects. For example, also release of hydrogen gas from the canister through the buffer and increasing groundwater pressures during a glaciation will have to be considered in a more developed discussion. The area will have to be carefully evaluated so that defensible assumptions for e.g. radionuclide transport modelling can be formulated in SR-Can.

### 6.4.4 Isostatic collapse load

A project on probabilistic analysis of the mechanical stability of the disposal canisters under isostatic load has been initiated. The project includes mechanical testing of cast iron inserts, probabilistic analysis of the canister stability based on the data obtained from the mechanical testing and mechanical testing of model canisters for model validation. Results from the project will be available for SR-Can by the end of 2003 or early 2004. It is thus expected that the project will yield isostatic collapse loads of BWR and PWR canister inserts for realistic material properties and also a thorough discussion of uncertainties affecting the results.

### 6.4.5 Corrosion

Both copper corrosion and, in the case of defective copper canisters, anaerobic iron corrosion are essential processes in the repository evolution.

#### *Copper corrosion*

In /King et al, 2001/ it is shown that although much new information and data on copper corrosion have been collected over the past twenty years, nothing has been discovered that will have a major impact on the evaluation of the corrosion attack on the copper canister. What has emerged rather supports previous assessments than contradicts them. Consequently, the treatment of the copper corrosion will be essentially the same as in SR 97.

As part of the preliminary assessments of SR-Can (section 2.9), a number of bounding calculations on copper corrosion will be made using the newly developed system evolution model (section 8.1). The purpose is to put issues like corrosion due to oxygen from glacial melt water or due to sulphide produced by sulphate reducing bacteria in perspective. Also the effects of the statistical variation of flow rates at repository depth, the importance of the buffer as a barrier against advective transport and of pyrite as a reducing agent in the buffer will be analysed from the point of view of copper corrosion.

### *Anaerobic iron corrosion*

Since SR 97 more data on the anaerobic corrosion of iron has been collected and analysed. The results have also been published in a peer reviewed journal /Smart et al, 2002a, b/. The data supports the corrosion rates used in SR 97 and a similar approach to the evaluation of the iron corrosion will, therefore, be used in SR-Can.

## 6.5 Buffer and backfill issues

### 6.5.1 Introduction

Two different buffer materials and three different backfill concepts will be analysed in SR-Can. Existing and emerging experimental data on material properties will be compiled and used in analyses of the buffer and backfill evolution, first for a number of stylised situations and later in the project for the analyses of the chosen scenarios.

There are a number of safety related properties of the buffer and backfill that need to be evaluated as a function of time in the analysis of the repository evolution. For the buffer, the most important properties are the density and the hydraulic conductivity which in turn require a certain swelling pressure. For the backfill the hydraulic conductivity, requiring a certain swelling pressure, and the compression properties, notably the compression module, play key roles for safety. All these properties are however more or less linked through the intrinsic properties of the material chosen and, for a given material, a requirement on one physical property will lead to restrictions on also the others.

Both the buffer and the backfill will undergo a relatively rapid (tens to a few hundreds of years) hydraulic saturation phase at the end of which a certain amount of swelling of the buffer and an accompanying compression of the backfill is expected. After this phase the long-term evolution will mainly be caused by chemical processes as the solid phases of the buffer and the backfill react with the groundwater constituents. These processes are however, in particular for the buffer, very slow due to both the limited groundwater flux and to the fact that diffusion is the dominating transport process.

The general approach to the study of the buffer and backfill evolution will be to evaluate the saturation phase in separate modelling exercises yielding essentially the buffer and backfill densities and swelling pressures after saturation, and thereafter analyse the chemical long-term evolution for the obtained densities.

The key safety related properties mentioned above are in general not obtained directly from the modelling, but rather through known empirical relationships between modelled properties and the safety related entities. This is e.g. the case for the buffer swelling pressure which is derived through empirical relationships from buffer density and pore water composition, in particular the ionic strength. The buffer hydraulic conductivity is derived from density, temperature, ionic strength and adsorbed ion species. The backfill compression module is derived from principally the density whereas the backfill hydraulic conductivity is critically dependent on a certain minimum swelling pressure to ensure homogeneity and also on density, adsorbed ionic species and temperature.

The following is a brief outline of some key issues and the plan for their management in SR-Can.

### 6.5.2 Choice of buffer and backfill materials to be analysed

For the buffer, a naturally occurring sodium bentonite from Wyoming (Mx-80) and a Ca bentonite from Milos will be used in SR-Can. Both these have been well characterised from the point of view of material composition and up-to-date reports will be produced in September 2003 for Mx-80 and in October 2003 for the Milos clay.

Three backfill concepts will be analysed in SR-Can:

1. A 30/70 percent (dry mass) homogeneous mixture of the chosen buffer bentonite and crushed rock, compacted to a realistic density according to currently available technique,
2. 30/70 percent (dry mass) sandwiched layers of the chosen buffer bentonite and crushed rock,
3. A swelling clay; either the chosen buffer bentonite or Friedland clay, of a density to be determined and in accordance with currently available technique.

In the third case, MX-80 is not seen as a cost effective alternative. Rather, it is included since it is a well characterised representative of sodium bentonites.

A compilation of available data for Friedland clay (material composition and physical material properties) will be produced in September 2003.

It is evident that the number of possible combinations of buffer materials and backfill concepts implied above is large and that, likely, a few representative combinations will have to be used e.g. in the definitions of scenarios in order to keep the number of variants in the analysis manageable.

### 6.5.3 Available and emerging data on physical material properties

A number of material tests for the Wyoming and Milos clays will be carried out during 2003 and reported at the end of the year. Swelling pressures and hydraulic conductivities for the two materials will be determined for combinations of clay densities between 1.5 and 2.2 g/cm$^3$ at saturation and salinities up to 1 M. All these combinations will be studied for both sodium and calcium cations, meaning that the effects of complete ion exchanges for a naturally occurring sodium bentonite from Wyoming to a calcium state and of the calcium bentonite from Milos to a sodium state will be investigated. The experiments will thus yield empirical data on

- Buffer hydraulic conductivity as a function of density and ionic strength (both $Ca^{2+}$ and $Na^+$).
- Buffer swelling pressure as a function of density and ionic strength (both $Ca^{2+}$ and $Na^+$).

Regarding the key backfill properties, the hydraulic conductivity and the compression module, the following is in general true:

- For the swelling clay concept and the bentonite layers of the sandwiched concept, hydraulic conductivities and swelling pressures are obtained from the same set of data as for the corresponding buffer materials.

- The hydraulic conductivity and the swelling pressure of a well homogenised mixture of bentonite and crushed rock, is obtained by applying the above relationships for the values corresponding to the same montmorillonite density as that of the clay component of the mixture. For less well homogenised mixtures, the relationships must be used with caution.
- The backfill compression module depends on density and less on the chemical state of the backfill.

Within an ongoing SKB backfill project, available backfill data for the chosen concepts are being compiled and will later be evaluated against the empirical relationships emerging from the above described activities. The compiled data will be assessed within the SR-Can project and feedback will be given to the backfill project as to whether these are sufficient for evaluations of long-term safety or if more investigations are required.

#### *Understanding the empirical relationships*

A model based on osmosis that describes the swelling pressure given the cation exchange capacity and the density of the buffer and the ionic strength of the pore water is available /Karnland et al, 2002/ and is being further developed. The model will be referred to in the SR-Can Process Report and used in the system evolution model, see section 8.1.

An unambiguous and detailed understanding of how the hydraulic conductivities of the clay materials depend on the material characteristics is not available. This is an issue for an ongoing SKB research project entitled "Physical properties, correlation between mineralogy and swelling pressure/hydraulic conductivity" (Clay Technology AB).

The understanding of how the compression module of the backfill materials consideration depends on its material characteristics is relatively good.

### 6.5.4 Initial THM modelling of buffer and backfill

Neither the buffer nor the backfill are fully water saturated when deposited in the repository. As groundwater contacts the buffer and backfill, these will gradually reach full water saturation and eventually a swelling pressure is expected to develop as further water uptake is prevented by the surrounding host rock. The swelling pressure developed in the buffer is higher than that in the backfill resulting in an upward expansion of the buffer and a corresponding compression of the backfill. This results in a reduced buffer density which needs to be quantified in the safety assessment.

The initial saturation phase of the buffer and the resulting swelling was modelled in SR 97 for a number of parameter combinations. The modelling cases will be reviewed and additional cases including also the saturation of the backfill will be modelled. One such case will consider saturation of the buffer with water supplied through the backfill, simulating a deposition hole with no water influx.

A plan for the modelling will be established and included in the SR-Can time plan in August 2003.

In the final state of the initial THM modelling, the swelling tendency of the buffer is balanced both by compression of the backfill and by friction against the deposition hole. The latter effect could however be partly neutralised by long-term creep of the buffer material, resulting in additional swelling of the buffer and hence a further decrease of buffer density. This effect can be assessed by e.g. a bounding calculation assuming that there is no friction against the deposition hole in the initial THM modelling. It can also be assessed in the integrated system evolution model, see section 8.1. The effect will be considered in the further planning of initial THM calculations.

### 6.5.5 Long-term chemical evolution modelling of buffer and backfill

The long-term chemical evolution of the buffer was studied using a mixed tank model /Bruno et al, 1999/ in SR 97. The model has since been developed and now includes more buffer reactions and a more detailed description of transport in the buffer.

The improved model will be used in SR-Can to study a number of cases of groundwater/buffer/backfill chemical interactions. Groundwater types to be studied include reference waters from the investigation sites, high salinity and low ionic strength groundwaters and possibly also cement leachate water. A plan for the model studies has been established. The first modelling results are expected during the autumn of 2003. The time plan for the modelling project will be merged with that of SR-Can.

Regarding the validity of the model, discrepancies between recent experimental results /Karnland et al, 2000/ and modelling efforts /Domènech et al, 2003/ on ion exchange reactions remain to be explained.

### 6.5.6 Radionuclide transport properties

The key radionuclide transport properties for the buffer, given that diffusion is the dominating transport process are buffer density, effective diffusivity and distribution coefficients ($K_d$-values) where the two latter depend on density, on the chemical status of the buffer and the temperature. Buffer density will be derived as discussed above; diffusivities and distribution coefficients will be determined for a number of possible conditions of the buffer as part of the plan for input data compilation for SR-Can, see section 2.11. These properties are important also for the backfill, but also additional properties in the case that advection is a significant transport mechanism in the backfill.

### 6.5.7 Colloid formation/erosion from buffer/backfill for low ionic strength groundwaters

Colloid formation and thus erosion of the buffer or backfill will be evaluated taking recent experimental results /Wold, 2003/ into consideration. The experiments show colloid formation at 1 mM of divalent cations in natural Mx-80 bentonite. Completely $Ca^{2+}$ exchanged clay do however not show colloid formation.

### 6.5.8 Gas issues

Gas issues in general in safety assessments will be discussed in an upcoming report from the EC GASNET project. The treatment in SR-Can will be largely based on that report.

Gas is only an issue if there is a defect in the copper canister, when hydrogen is generated from iron corrosion. The evaluation of gas issues will be done in a number of steps:

1. Gas generation. What is the corrosion rate of the iron insert? What is the available surface area for corrosion? Will the corrosion be limited by availability of water? Etc. This will give the gas production rate inside the canister.

2. Gas migration. The gas generation will lead to a pressure increase within the canister. If the production rate is low the gas may be able to escape by diffusion, but more like pathways will be opened in the buffer. The effects of this process will be evaluated using the most recent experimental data /Harrington and Horseman, 2003/.

3. Consequences of gas generation. The possible impacts of gas generation in the repository are as follows:

   - Overpressurisation because of gas generation and the associated potential damage to the repository and host rock.
   - Effects on the groundwater movement. Gas could potentially push contaminated water out from canister or the repository.
   - The gas phase itself can rapidly transfer gaseous radionuclides to the biosphere, or even be a flammability hazard.
   - Hydrogen gas may also have effects on the chemistry in the near field (fuel chapter).

### 6.5.9 Canister sinking

Canister sinking has been investigated and reported. A creep theory based on laboratory tests was developed /Börgesson et al, 1995/ and used for calculations of the total canister displacement in a deposition hole (actually for two canisters in one hole) /Börgesson, 1993/. There are two concerns about these results:

1. Only deviatoric creep has been considered, meaning that the buffer is assumed not to change its volume due to creep. Volumetric creep is thus not considered. There have been plans for looking at volumetric creep, but so far no tests have been done. There is actually a strong argument for disregarding volumetric creep: It is very small and will not contribute to a reduction of the total mass of bentonite between the canister and the rock since it only compacts the bentonite. Thus the loss in buffer thickness is compensated by an increased density.

2. The theories and mathematical model are empirical and based on creep tests that are run during a limited time. It is thus difficult to prove that these models are valid for 100,000 years. The tests have been run for about 12 days (then the rate is so small that we have measuring problems) and can thus be shown to be valid between 1 and $10^6$ seconds, but the theory is extrapolated to be valid for $10^{13}$ seconds. There are two ways to increase the reliability:

   A. Make creep tests that last for up to 3 years. However, the measuring problems are very severe and a technique to overcome these must be developed. This could be very costly. And in the end we still have the problems with extrapolation.

   B. Try to find natural analogs with e.g. blocks or big stones in a bentonite deposit. However, it may be difficult to prove that those stones have been sinking less than a decimeter.

It is thus difficult to find a method to increase the credibility of the work that has been done so far. Possibly, a scenario variant where the consequences of canister sinking are assessed will be included in SR-Can.

# 7 Intrusion issues

This chapter describes how intrusion issues will be handled in SR-Can. The suggested handling is largely the same as that in SR 97.

## 7.1 Regulatory requirements and recommendations

The recommendations to SKIFS 2002:1, mention in the group "less probable scenarios", those "that take into account the impact of future human activities such as damage inflicted on barriers", whereas "damage to humans intruding into the repository is illustrated by residual scenarios".

In SSI FS 1998:1 intrusion is defined as "human intrusion into a repository which can affect its protective capability". 9§ of SSI's regulation states: "The consequences of intrusion into a repository shall be reported for the different time periods specified in 11–12 §§. The protective capability of the repository after intrusion shall be described." In 11–12 §§, special emphasis is on the first 1,000 years.

It is also important to note that the background document to SSI FS 1998:1 clearly state that intrusion scenarios should not be included in the risk calculations.

The background document also states "An important premise in discussions concerning requirements connected to intrusion is the responsibility of society for its own conscious actions. Therefore, it is not necessary, in connection with an application, to investigate issues concerning intentional intrusion into a repository which is sanctioned by society…"

"The essential point is not to describe the chain of events that leads to the intrusion, but to study the ability of the repository to isolate and retain the radioactive substances after an intrusion…"

## 7.2 Treatment in SR-Can

Future human actions in SR-Can will be restricted to actions that:

- are carried out after the sealing of the repository,
- take place at or close to the repository site,
- are unintentional and
- impair the performance of the repository's barriers.

Human actions that take place before closure of the repository and that impair the barrier functions are handled in other scenarios, as is the case of incomplete sealing of the repository. Ongoing or future human actions causing large scale or global changes, such as emission of green house gases are also excluded from the treatment but may be handled elsewhere in SR-Can.

Swedish regulation states that the responsibility of conscious intrusions into the repository lies on the society authorising the action. This standpoint is internationally accepted /NEA, 1995/. Thus only inadvertent actions that impair the functions of the repository are considered in SR-Can. An action is considered to be inadvertent if the location of the repository is unknown, its purpose forgotten and the consequences of the action are unknown.

### 7.2.1 Method

The analyses of future human actions that impair the performance of the repository will be divided into the following four parts;

1. Technical analysis.
2. Analysis of societal factors.
3. Choice of representative scenarios.
4. Analysis of the chosen scenarios.

#### *Technical analysis*

The identification of actions that may impair the repository will be based on a description of the repository system and on current technical knowledge and practise. A list of conceivable human actions that impair the repository performance will be drawn up. This will include a review of all FEP's related to intrusion in the SR-Can FEP database. The actions are described, justified and explained in technical terms.

#### *Analysis of societal factors*

Prevailing societal conditions are of importance both for the possible occurrence of inadvertent human actions impairing repository safety and for the judgement of their consequences. Important issues are why the disruptive action is being carried out and contemporary societal conditions such as general knowledge and regulations. These primarily humanistic and socio-economic questions were analysed in SR 97 /Morén et al, 1998/ and the SR-Can analysis will be based on the same reference.

#### *Choice of representative scenarios*

The results of the technical and socio-economic analyses are put together and a few scenarios that illustrate how some future human actions may affect the repository are chosen.

### *Analysis of chosen scenarios*

The analysis of the chosen scenarios consist of three parts;

- Purpose and realisation of the scenario;
  Background to why and how the action is carried out.
- Probability that the scenario will occur;
  Discussion about, and if possible, estimation of the probability of the scenario.
- Radiological consequences and risk;
  The impact on barrier performance is described and the radiological consequences are estimated based on a description on what the intruders may do when they detect the repository.

Dose calculations mainly concern people that are unaware of the action and at a later stage are exposed to radionuclides escaping from the impaired repository. Doses to the persons involved in the action are also estimated.

## 7.2.2 Plan

Findings from the work with the SR-Can FEP database will be included in the technical analysis and the following choice of representative scenarios. The analysis of the chosen scenarios will be deepened in comparison to the treatment in SR 97. In all other parts the analysis of future human actions will be based on the same references as that SR 97.

A preliminary account of intrusion scenarios will be given in the SR-Can interim report.

# 8 Integrated modelling

## 8.1 System evolution

The system of coupled processes responsible for the long-term evolution is complex. In the mathematical modelling of the repository evolution, the process system is therefore studied with a number of different process models, each illustrating certain aspects of the total evolution. Frequently, the focus in these models is on either thermal, hydraulic, mechanical or chemical processes. The full integration of all aspects of the evolution is normally done by reasoning around the process model results in a safety report.

Recently, a system model, consisting of several integrated sub-models, each mimicking a process model, has been developed /Hedin, 2003b/. The system of processes treated is by necessity simplified, excluding e.g. the short-term saturation phase of the buffer where couplings between processes are strong and detailed hydromodelling of the heterogeneous, fractured host rock.

The first version of the system model is therefore not concerned with radionuclide releases and transport. A simplified description of also these phenomena exists, see section 8.2, and can possibly be incorporated in future versions of the system model.

A main reason for the development of the system evolution model is to obtain an integrated treatment of the most significant processes in the long-term repository evolution, ensuring that a consistent input database is used in modelling all aspects of the evolution and that time dependent output from one sub-model can be used directly as input to another model. Furthermore, the integrated modelling tool is controlled directly by the safety analyst rather than by a number of different, distributed expert groups. A number of measures have been taken to increase calculation speed. This allows for rapid evaluation of a number of different sets of input data and also for probabilistic evaluations. The model can be executed probabilistically, but so far only deterministic results have been produced since the database for probabilistic calculations is still insufficient.

Other reasons for the development are to gain insight into the relative importance of various processes at a holistic level and to provide quality assurance through an independent set of models for crucial aspects of the repository evolution. The ambition sis however not to replace the more detailed process models. These will always be needed to fully account for all details in the mechanisms behind individual processes and as a necessary basis for the development of simplified models. Also, the expertise behind the development of the process models will always be required to describe and justify the common scientific basis for both types of models.

Figure 8-1 shows the set of process models that have been included as sub-models in the system model and how the sub-models are linked.

Further descriptions of the different sub-models, benchmarking results etc are provided in /Hedin, 2003b/. A more detailed and updated report will be produced within the SR-Can project.

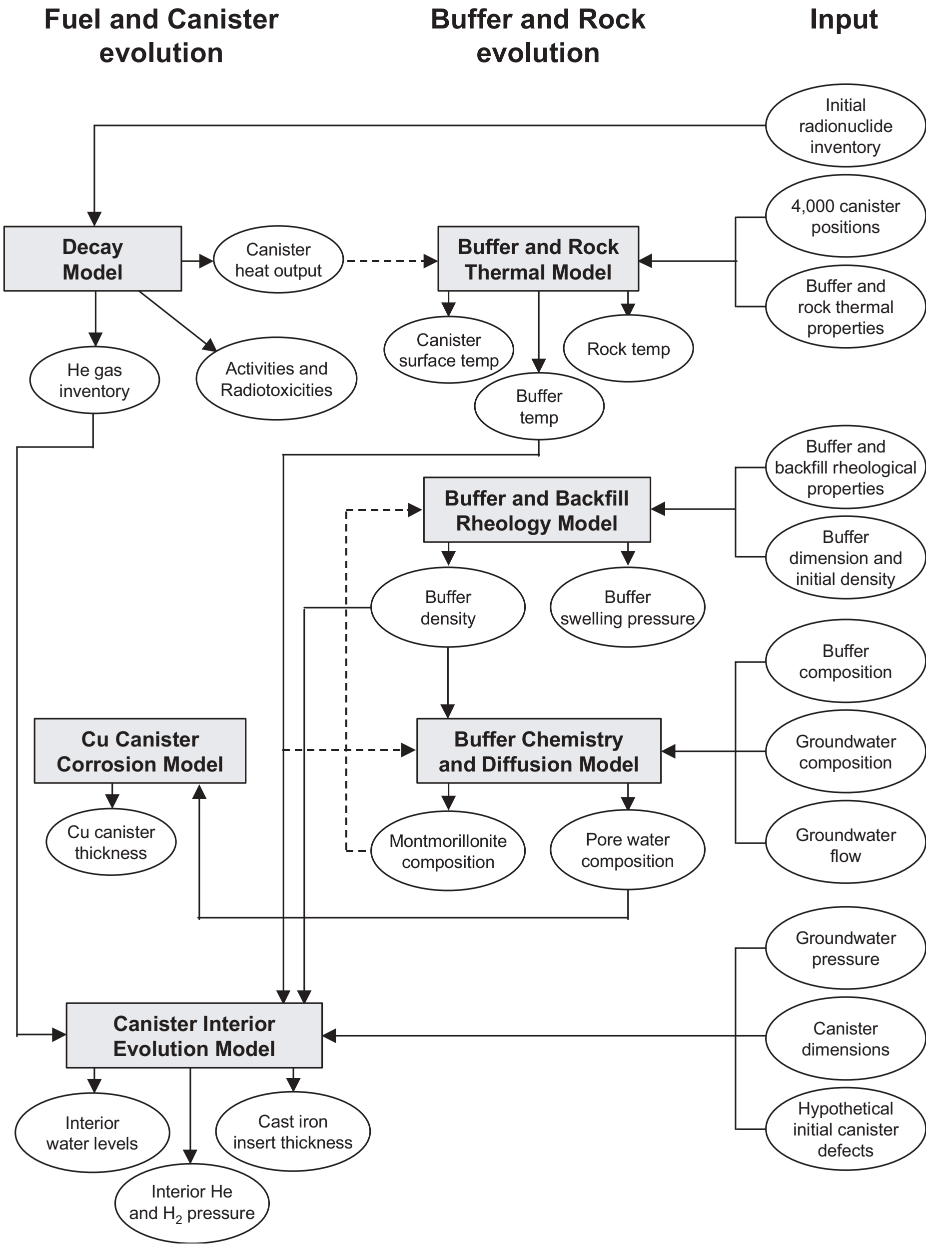

***Figure 8-1.*** *The system model with sub-models represented as rectangles; input data and time dependent calculation results as ellipses. Dashed lines represent couplings which have not yet been fully implemented.*

The process mapping in Table 2-1 gives an indication of which processes are included in the model today. The development of the model will continue with the aim of incorporating as many processes as possible early in the SR-Can project. The model will be used as one of several tools with which the general system evolution will be studied in SR-Can.

## 8.2 Radionuclide transport and dose calculations

Radionuclide transport calculations are performed in order to estimate the risk from a repository. As many of the parameters in this kind of calculation either have a natural variability or may to some degree be unknown, probabilistic calculations, where the model parameters are allowed to vary according to some sort of prescribed probability distribution, are necessary. Traditionally, in safety assessments at SKB, the transport calculations have been executed using a probabilistic computational chain which includes transport through the near field, the far field and the biosphere where also the dose is estimated. These probabilistic calculations have been supported by other simulations that generate the necessary parameters. Figure 8-2 shows how the different models intended for use in the SR-Can computations interact, besides the calculation modules for the transport calculation (for the near field, the far field and the biosphere). The figure also shows how these modules are connected to other calculation tools and what data the different models require, which for most input parameters may be given as probability distributions. These probability distributions may be based on e.g. experimental data or the result of a previously performed calculation that, for different reasons, may not be suitable to run in the probabilistic transport calculation chain.

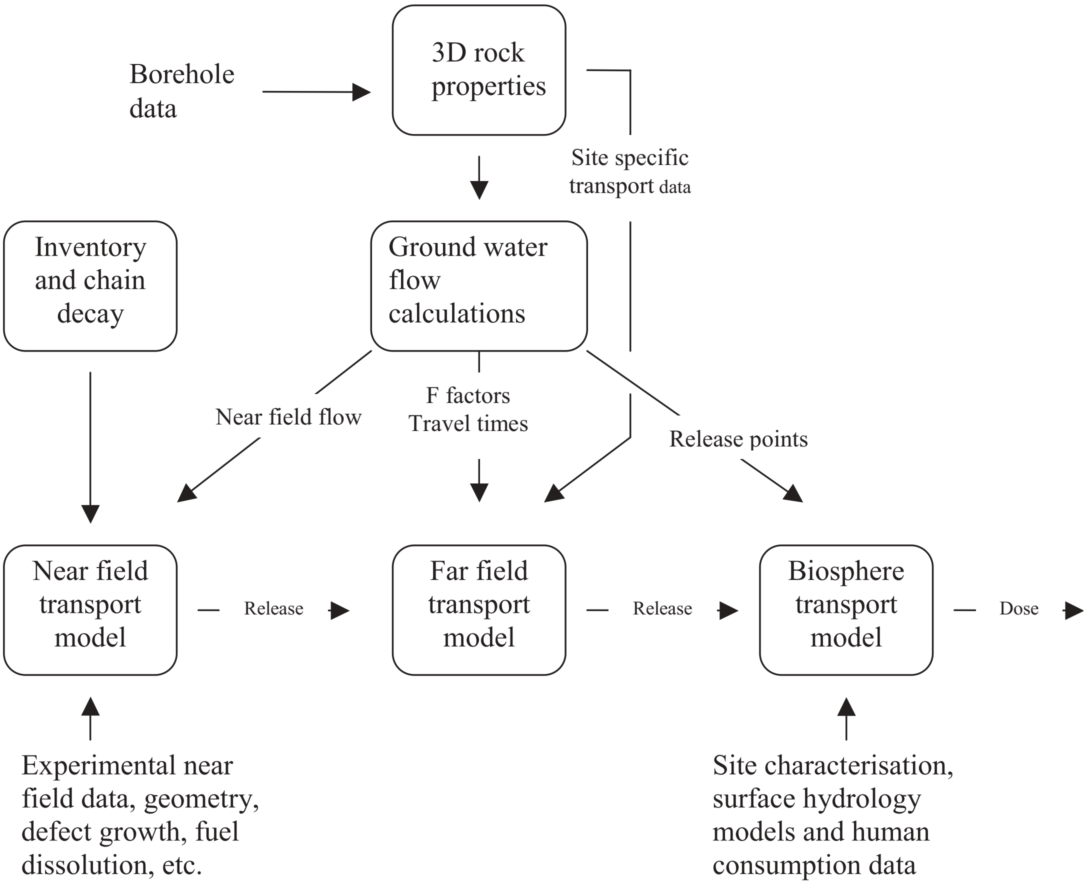

***Figure 8-2.** Schematic view of the different sub-models in the radionuclide transport calculation.*

The ground water flow calculations based on interpretations and modelling of site specific borehole data will be performed in a separate code (CONNECTFLOW or DarcyTool, see section 5.2) and are used by the transport models in different ways. These groundwater flow calculations are time consuming, and carried out in advance. Therefore, correlated probability distributions from the flow calculations are used as input data for the radionuclide transport models for the near field, the far field and the biosphere.

Recently, analytical simplified versions of the near and far field transport models have been developed /Hedin, 2002a/. These models use the same input data as the corresponding numerical models and doses are calculated by ecosystem specific dose conversion factors. The models may be executed probabilistically and yield results in good agreement with the deterministic and probabilistic calculation cases in SR 97. A single realisation with the analytical models executes on around 0.1 second on a 2 GHz Personal Computer, making them well suited for massive probabilistic calculations. The analytical models will be used as a complement to the numerical models in the SR-Can project, in particular for early scoping calculations and for complementary probabilistic calculations.

The following sections briefly describe the platforms for the numerical radionuclide transport calculations and the numerical models of the near field, the far field and the biosphere.

### 8.2.1 Platforms for radionuclide transport calculations

Radionuclide transport calculations in SKB's safety assessments have been performed with the Proper system [SKB 91, SR 95 and SR 97]. The Proper package, written in Fortran 77, consists of a number of sub-modules handling the transport calculation, see Figure 8-2. The near field transport calculation is handled by the Proper sub-module COMP23 /Romero, 1995/, the far field by FARF31 /Norman and Kjellbert, 1990/ and the biosphere transport by BIO42. The Proper environment provides, beside a centralised communication between the different modules, routines to perform deterministic simulations and libraries to provide additional tools for numerical calculations (NUMLIB). In addition, sub modules for communication with the groundwater flow model, weighting and summation of time series (SUM41) and communication with ASCII files outside Proper (TS01 and PICK51) are provided by the environment.

As a complement to the Proper package, an alternative code that runs on a desktop PC is under development and is planned to be used in parallel to the Fortran77/UNIX version in the SR-Can safety assessment calculations. The PC version, which is based on the same conceptual models as the Proper package, has been developed separately from the Fortran77/UNIX version and is written as Matlab programs. Matlab is a commonly used tool in computational engineering and provides a large number of mathematical functions, a script language and a graphical environment, Simulink, where models may be easily built and allow for different sub modules to be connected in a simple way.

Presently, the near field calculation has been fully implemented in Matlab and Simulink, thus calculations corresponding to those handled by the COMP23 sub-module can be performed in the alternative code. Work on implementing the far-field calculation is in progress. For that, the existing Fortran77 code is used and interfaces are written so that the code may be used as a Matlab function. The biosphere module has been developed into a considerably more versatile tool. While the Proper module uses dose conversion factors calculated by an external code, the Matlab version can either calculate dose conversion factors in advance or perform time dependent biosphere calculations as part of the probabilistic computational chain.

In addition to the Matlab package, the PC version can use the commercially available risk analysis code @Risk for the probability analysis. @Risk can generate a large number of probability distribution functions, can perform probabilistic simulations and may run external programs like Matlab. Moreover, the combination Matlab/@Risk provides a transparent environment for safety assessment calculations.

At present, the computational time for a single COMP23 realisation with the Fortran77/UNIX version (on the 400 MHz Sun Enterprise 450 that was used in SR97) and the Matlab/PC version (on an Intel 1700 MHz Compaq Deskpro workstation) is of the same magnitude (a couple of minutes) for runs with the 9 nuclides used in the SR97 probabilistic calculations. For the deterministic 32 nuclides simulations performed in SR97, the computational time on the Fortran77/UNIX version is however much shorter. Deterministic runs with a large number of nuclides on the present Matlab/PC version require hence some sort of optimisation (different chains may for instance be run separately). Due to the high portability of Matlab code (Matlab is available on a large number of platforms) the Matlab implementation can, with limited efforts, be run on another platform if, for any reason, the capacity of the PC platform is regarded as insufficient. The far field and biosphere modules have insignificant realisation times in comparison to the near field model.

### 8.2.2 The near field model

The near-field model COMP 23 will be used in SR-Can. This is the same model as used in SR 97 and it was originally developed from the NUCTRAN-code /Romero, 1995; Romero et al, 1999/. COMP23 is a multiple path model that calculates transient nuclide transport in the near field of a repository as occurring through a network of resistances and capacitances coupled together in analogy with an electrical circuit network. Analytical solutions instead of fine discretisation at sensitive zones, for example at the exit point of the canister hole and at the entrance to fractures, are embedded to speed up the calculations. While the COMP23 model used in SR 97 only was able to handle nuclide transport through diffusion, the present version has been modified so that also advective transport can be simulated. A further development since SR 97 is that all nuclides of a certain element can now share the elemental solubility inside the canister, where solubility limitations are imposed on radionuclide concentrations.

Figure 8-3 shows the how the canister deposition hole and the backfill was modelled in SR 97. In that model four different flow paths, Q1–Q4, was used for the near field far field interface.

To represent the barrier system, through which the species are transported, COMP23 makes use of the integrated finite difference method and of the concept of compartments.

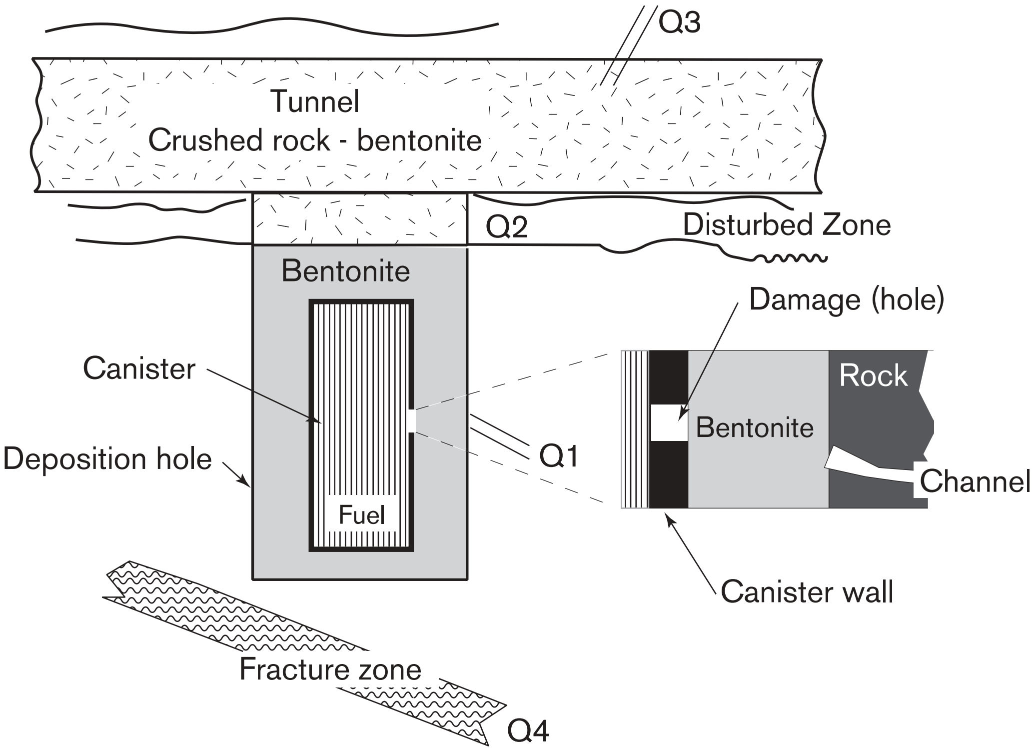

***Figure 8-3.*** *Schematic view of the near field, with the transport paths used in SR 97.*

### 8.2.3 The far field model

The far field model to be used in SR-Can is similar to that used in SR 97. This model, FARF31, /Norman and Kjellbert, 1990/ calculates the transport of dissolved radio-nuclides through the fractured rock, the retention caused by interactions between the nuclides and the rock matrix, and the radioactive chain decay, see further section 5.3.

### 8.2.4 The biosphere model

Radionuclide transport through the biosphere and doses to man was handled by the Proper sub module BIO42 in SR 97. This module was based on nuclide and ecosystem specific dose conversion factors (EDFs) which convert nuclide releases to an ecosystem into doses. In SR 97, the EDFs for the six ecosystems considered (well, lake, river, peat, soil, coast) were calculated in a separate code /Bergström et al, 1999/ using generic data for the ecosystem parameters. The different ecosystems were represented by compartment models where each compartment corresponded to a distinct part of an ecosystem. Figure 8-4 shows the example of a peat bog modelled as two compartments, representing nuclides dissolved in the water and nuclides sorbed to organic and/or solid material respectively. The nuclide exchange between the two compartments was modelled using ecosystem and element specific distribution coefficients ($K_d$ coefficients). In the modelled peat bog, Figure 8-4, both nuclide inflow and outflow will be through the soluble phase and will hence be governed by the water balance. Depending on the water exchange at the studied site, the in- and outflow may either be to other ecosystem models, inflow from the exit points of the geosphere stream tubes or an outflow of nuclides from the model domain. However, in SR 97, only single ecosystems were considered with inflow only from the exit points of the stream tubes.

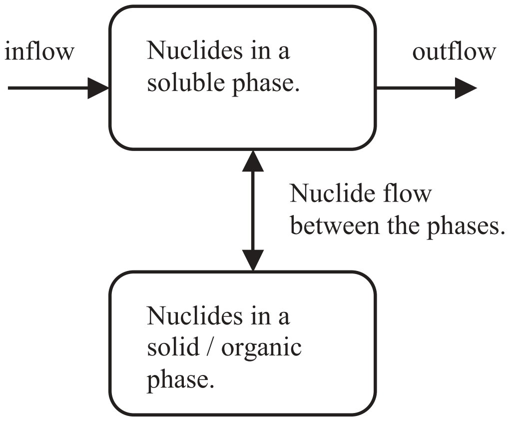

***Figure 8-4.** Compartment model of a peat bog.*

### Biosphere calculations in SR-Can

In SR-Can the site will be better known and the basis for modelling the ecosystem and the interaction between different ecosystems will be improved. Figure 8-5 shows how a downstream nuclide transport may be handled in the biosphere model if the water flow at the site is known. In the sketch, nuclides are assumed to enter a peat bog, which can be modelled as indicated in Figure 8-4, through the groundwater. The radionuclide outflow from this model will appear as inflow in, for instance a running water model and further to a lake model etc In contrast to the models used in SR 97, humans may be exposed to nuclides from all modelled ecosystems at the same time, e.g. to radionuclides from peat combustion, irrigation of agricultural land by stream water and consumption of aquatic foodstuff from a lake.

While the biosphere calculations in SR 97 were performed in a separate code and imported to the Proper package as probability distributions, the intention in SR-Can is to perform the biosphere transport calculation in the Matlab/Simulink version of the safety assessment code. The biosphere simulations will either be performed as part of the probabilistic computational chain or separately with nuclide releases taken from each realisation of the near and far field modules.

As a complement to the compartment based biosphere models used in SR 97 there is an ongoing work of implementing so called process models in the biosphere simulation tool, see section 4.5. These models are based on energy and nutrition balance and may also be used to generate input data for the compartment models. Using the Matlab/Simulink package for the simulation enables the use of these models in combination with the pre-existing compartment models and hence to perform more complex simulations.

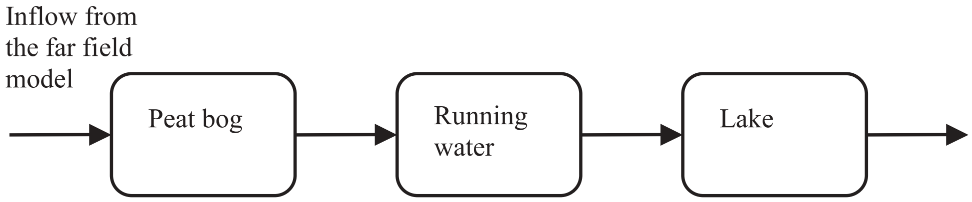

***Figure 8-5.** Connecting models to model a downstream radionuclide transport.*

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# Appendix A

# Applicable regulations and SKB's implementation of these in the safety assessment SR-Can

This Appendix contains regulatory texts issued by SKI and SSI applicable to a safety assessment for nuclear waste repositories. References to SKB's plan for implementing the regulations, as presented mainly in Chapter 2, have been inserted in italics at relevant places in sections A.1.1 (SKIFS 2002:1) and A.2.1 (SSI FS 1998:1).

## A.1 SKI's Regulations and General Recommendations

SKI has issued *i*) Regulations concerning Safety in connection with the Disposal of Nuclear Material and Nuclear Waste (SKIFS 2002:1) and *ii*) General Recommendations concerning the application of those Regulations.

Whereas the Regulations have a clear legal status, General Recommendations are described in 1 § Ordinance on Regulatory Codes (1976:725) as: Such general recommendations on the application of regulations that stipulate how someone can or should act in a certain respect.

### A.1.1 SKIFS 2002:1

**The Swedish Nuclear Power Inspectorate's Regulations concerning Safety in connection with the Disposal of Nuclear Material and Nuclear Waste**

decided on October 24, 2001

On the basis of 20 a and 21 §§ of the Ordinance (1984:14) on Nuclear Activities, the Swedish Nuclear Power Inspectorate has issued the following regulations and decided on the following general recommendations.

#### Application

**1 §** These regulations apply to facilities for the disposal of spent nuclear fuel and waste (repositories). The regulations do not apply to facilities for landfill disposal of low-level nuclear waste in accordance with 19 § of the Ordinance (1984:14) on Nuclear Activities.

The regulations contain supplementary provisions to the Swedish Nuclear Power Inspectorate's regulations (SKIFS 1998:1) concerning Safety in Certain Nuclear Facilities.

#### Barriers and their Functions

**2 §** Safety after the closure of a repository shall be maintained through a system of passive barriers.

**3 §** The function of each barrier shall be to, in one or several ways, contribute to the containment, prevention or retention of dispersion of radioactive substances, either directly, or indirectly by protecting other barriers in the barrier system.

**4 §** A deficiency in any of the repository's barrier functions that is detected during the construction or operational surveillance of the repository and that can lead to a deterioration in safety after closure in addition to that anticipated in the safety report[2], shall be reported to the Swedish Nuclear Power Inspectorate without delay[3]. The same applies if such a deficiency is suspected to occur or if the possibility that such a deficiency can occur in the future is suspected.

### Design and Construction

**5 §** The barrier system shall be able to withstand such features, events and processes that can affect the post-closure performance of the barriers.

**6 §** The barrier system shall be designed and constructed taking into account the best available technique[4].

**7 §** The barrier system shall comprise several barriers so that, as far as possible, the necessary safety is maintained in spite of a single deficiency in a barrier.

***Handling in SR-Can:*** *This may be demonstrated e.g. through some of the bounding calculation cases in section 2.12.1.*

**8 §** The impact on safety of such measures that are adopted to facilitate the monitoring or retrieval of disposed nuclear material or nuclear waste from the repository, or to make access to the repository difficult, shall be analysed and reported to the Swedish Nuclear Power Inspectorate.

***Handling in SR-Can:*** *Presently, no such measures are planned for the repository design to be analysed in SR-Can.*

### Safety Assessment

**9 §** In addition to the provisions of Chapter 4. 1 § of the Swedish Nuclear Power Inspectorate's Regulations (SKIFS 1998:1) concerning the Safety in Certain Nuclear Facilities, the safety assessments shall also comprise features, events and processes which can lead to the dispersion of radioactive substances after closure, and such analyses shall be made before repository construction, before repository operation and before repository closure.

***Handling in SR-Can:*** *The systematic management in a database of the mentioned features, events and processes in SR-Can is discussed in section 2.5. The detailed management of many of these factors is discussed throughout the report.*

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[2] Cf Chapter 4. 2 § of the Swedish Nuclear Power Inspectorate's regulations (SKIFS 1998:1) concerning Safety in Certain Nuclear Facilities.

[3] Cf Chapter 2. 2 § of the Swedish Nuclear Power Inspectorate's regulations (SKIFS 1998:1) concerning Safety in Certain Nuclear Facilities.

[4] Cf Chapter 2. 3 § of the Swedish Environmental Code.

**10 §** A safety assessment shall comprise as long time as barrier functions are required, but at least ten thousand years.

***Handling in SR-Can:*** *The timescale for SR-Can is discussed in section 2.3.*

### Safety Report

**11 §** The safety report for a repository shall, in addition what is required in Chapter 4. **2 §** of the Swedish Nuclear Power Inspectorate´s Regulations (SKIFS 1998:1) concerning Safety in Certain Nuclear facilities, contain the information required in Appendix 1 of these regulations and which concerns the time after closure.

Prior to repository closure, the final safety assessment must be renewed and subjected to a safety review in accordance with Chapter 4. 3 § of the Swedish Nuclear Power Inspectorate's regulations (SKIFS 1998:1) Concerning Safety in Certain Nuclear Facilities and must be reviewed and approved by the Swedish Nuclear Power Inspectorate.

### Exceptions

**12 §** The Swedish Nuclear Power Inspectorate may grant exceptions, if particular grounds exist, from these regulations if this can be achieved without departing from the purpose of the regulations and on condition that safety can be maintained.

### Appendix 1

**The following shall be reported with regard to analysis methods:**

- how one or several methods have been used to describe the passive system of barriers in the repository, its performance and evolution over time; the method or methods shall contribute to providing a clear view of the features, events and processes that can affect the performance of the barriers and the links between these features, events and processes,

  ***Handling in SR-Can:*** *The format for system description is discussed in section 2.4, the description of system evolution is the task for the entire assessment and will be discussed for each scenario, see section 2.12; some aspects of system evolution modelling are discussed in section 8.1.*

- how one or several methods have been used to identify and describe relevant scenarios for sequences of events and conditions that can affect the future evolution of the repository; the scenarios shall include a main scenario that takes into account the most probable changes in the repository and its environment,

  ***Handling in SR-Can:*** *Scenario selection in SR-Can is discussed in section 2.10.*

- the applicability of models, parameter values and other conditions used for the description and quantification of repository performance as far as reasonably achievable,

  ***Handling in SR-Can:*** *This will essentially be done in the SR-Can Process and Input Data Reports, see further sections 2.7.1 and 2.11, respectively.*

- how uncertainties in the description of the functions, scenarios, calculation models and calculation parameters used in the description as well as variations in barrier properties have been handled in the safety assessment, including the reporting of a sensitivity analysis which shows how the uncertainties affect the description of barrier performance and the analysis of consequences to human health and the environment.

  ***Handling in SR-Can:*** *The management of uncertainties permeates the entire safety assessment. A plan for the management of uncertainties is given in section 2.14, sensitivity analyses are discussed in sections 2.9.5 and 2.12.2.*

**The following shall be reported with respect to the analysis of post-closure conditions:**

- the safety assessment in accordance with 9 § comprising descriptions of the evolution in the biosphere, geosphere and repository for selected scenarios; the environmental impact of the repository for selected scenarios, including the main scenario, with respect to defects in engineered barriers and other identified uncertainties.

  ***Handling in SR-Can:*** *This is essentially the reporting of the analyses of the selected scenarios, see section 2.12.*

### A.1.2 Excerpts from SKI's General Recommendations concerning SKIFS 2002:1

**The Swedish Nuclear Power Inspectorate's General Recommendations concerning the Application of the Regulations concerning Safety in connection with the Disposal of Nuclear Material and Nuclear Waste (SKIFS 2002:1)**

*The following is the unabbreviated Recommendations relevant to 7, 8, 9 and 10 §§ and Appendix of SKI FS 2002:1, i.e. those sections that concern the safety assessment:*

#### On 7 §

The provision of this paragraph can be fulfilled by showing, in the safety assessment prepared in accordance with 9 §, how different types of deficiencies in barriers and barrier performance cannot on their own lead to unacceptable risks from the dispersion of radioactive substances from the repository. It should be possible to show how this dispersion is limited by other barriers and barrier functions besides those affected by the deficiencies that have arisen. In order for the provision to be fulfilled, several barriers may be necessary, especially with respect to the final disposal of spent nuclear fuel.

***Handling in SR-Can:*** *This may be demonstrated e.g. through some of the bounding calculation cases in section 2.12.1.*

#### On 8 §

Measures can be adopted during construction and operation for the possible monitoring of a repository's integrity and its barrier performance after closure. Such measures can also be adopted to maintain safeguards. Measures can also be adopted during construction and operation with the primary aim of facilitating the retrieval of deposited nuclear materials and nuclear waste from the repository, during the operating period or after closure. Furthermore, measures can be adopted to make intrusion into the repository difficult or to caution against intrusion. The safety report for the facility, in accordance with 9 § should show that these measures either have a minor or negligible impact on repository safety, or that the measures result in an improvement of safety, compared with the situation that would arise if the measures were not adopted. These provisions are in agreement with the provisions of the Swedish Radiation Protection Authority's regulations SSIFS 1998:1.

***Handling in SR-Can:*** *Presently, no such measures are planned for the repository design to be analysed in SR-Can.*

### On 9 § and Appendix

The safety of a repository after closure is analysed quantitatively, primarily by estimating the possible dispersion of radioactive substances and how it is distributed in time for a relevant selection of future possible sequences of events (scenarios). The purpose of the safety assessment is to show, inter alia, that the risks from these scenarios are acceptable in relation to the requirements on the protection of human health and the environment issued by the Swedish Radiation Protection Authority (SSIFS 1998:1). The safety assessment should also aim at providing a basic understanding of the repository performance on different time-periods and at identifying requirements regarding the performance and design of different repository components.

A ***scenario*** in the safety assessment comprises a description of how a given combination of external and internal conditions affect repository performance. Two groups of such conditions are:

- external conditions in the form of features, events and processes which occur outside repository barriers; this includes climate changes and their consequential impact on the repository environment, such as permafrost, glaciation, land subsidence and elevation as well as the impact of human activities,
- internal conditions in the form of features, events and processes which occur inside the repository; this includes properties, including defects, of nuclear material, nuclear waste and engineered barriers and related processes as well as properties of the surrounding geological formation and related processes.

Based on an analysis of the probability of occurrence of different types of scenarios in different time-periods, scenarios with a significant impact on repository performance should be divided into different categories:

- main scenario,
- less probable scenarios,
- other scenarios or residual scenarios.

***The main scenario*** should be based on the probable evolution of external conditions and realistic, or where justified, pessimistic assumptions with respect to the internal conditions. It should comprise future external events which have a significant probability of occurrence or which cannot be shown to have a low probability of occurrence during the time covered in the safety assessment. Furthermore, it should be based, as far as possible, on credible assumptions with respect to internal conditions, including substantiated assumptions concerning the occurrence of manufacturing defects and other imperfections, and which allow for an analysis of the repository barrier functions (it is, for example, not sufficient to always base the analysis leaktight waste containers, even if this can be shown to be the most probable case). The main scenario should be used as the starting point for an analysis of the impact of uncertainties (see below), which means that the analysis of the main scenario also includes a number of calculation cases.

***Less probable scenarios*** should be prepared for the evaluation of scenario uncertainty (see also below). This includes variations on the main scenario with alternative sequences of events as well as scenarios that take into account the impact of future human activities such as damage inflicted on barriers. (Damage to humans intruding into the repository is illustrated by residual scenarios, see below). The analysis of less probable scenarios should include analyses of such uncertainties that are not evaluated within the framework of the main scenario.

***Residual scenarios*** should include sequences of events and conditions that are selected and studied independently of probabilities in order to, *inter alia*, illustrate the significance of individual barriers and barrier functions. The residual scenarios should also include cases to illustrate damage to humans intruding into the repository as well as cases to illustrate the consequences of an unclosed repository that is not monitored.

***Handling in SR-Can:*** *The definition and selection of scenarios is discussed in section 2.10.*

The lack of knowledge and other uncertainties in the calculation conditions (assumptions, models, data) is denoted in this context as uncertainties[5]. These uncertainties can be classified as follows:

- scenario uncertainty: uncertainty with respect to external and internal conditions in terms of type, degree and time sequence,
- system uncertainty: uncertainty as to the completeness of the description of the system of features, events and processes used in the analysis of both individual barrier performance and the performance of repository as a whole,
- model uncertainty: uncertainty in the calculation models used in the analysis,
- parameter uncertainty: uncertainty in the parameter values (input data) used in the calculations,
- spatial variation in the parameters used to describe the barrier performance of the rock (primarily with respect to hydraulic, mechanical and chemical conditions).

There are often no clear boundaries between the different types of uncertainties. The most important requirement is that the uncertainties should be described and handled in a consistent and structured manner.

The evaluation of uncertainties is an important part of the safety assessment. This means that uncertainties should be discussed and examined in depth when selecting calculation cases, calculation models and parameters values as well as when evaluating calculation results.

***Handling in SR-Can:*** *The management of uncertainties permeates the entire safety assessment. A plan for the management of uncertainties is given in section 2.14.*

The assumptions and calculation models used should be carefully selected with respect to the principle that the application and the selection should be justified through a discussion of alternatives and with reference to scientific data. In cases where there is doubt as to a suitable model, several models should be used to illustrate the impact of the uncertainty involved in the choice of model.

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[5] This explanation of the term uncertainty only makes sense in Swedish where the same word (säkerhet) is used to denote both certainty and safety.

***Handling in SR-Can:*** *This matter is addressed in the Process Report, see further section 2.7.1, subheading "Handling in safety assessment" and "Uncertainties".*

Both deterministic and probabilistic methods should be used so that they complement each other and, consequently, provide as comprehensive a picture of the risks as possible.

***Handling in SR-Can:*** *This is briefly discussed in the introduction of section 2.12.*

***The probabilities*** that the scenarios and calculation cases will actually occur should be estimated as far as possible in order to calculate risk. Such estimates cannot be exact. Consequently, the estimates should be substantiated through the use of several methods, for example, assessments by several independent experts. This can be done, for example, through estimates of when different events can be expected to have occurred.

***Handling in SR-Can:*** *Scenario probabilities are briefly discussed in section 2.15.3. This is however an issue that will have to be further considered as the SR-Can project progresses.*

Based on scenarios that can be shown to be especially important from the standpoint of risk, a number of ***design basis cases*** should be identified. Together with other information, such as on manufacturing method and controllability, these cases should be used to substantiate the design basis such as requirements on barrier properties.

***Handling in SR-Can:*** *See section 2.12.1.*

Particularly in the case of disposal of nuclear material, for example spent nuclear fuel, it should be shown that criticality cannot occur in the initial configuration of the nuclear material. With respect to the redistribution of the nuclear material through physical and chemical processes, which can lead to criticality, it should be shown that such a redistribution is very improbable.

***Handling in SR-Can:*** *See section 6.3.7.*

The result of calculations in the safety assessment should contain such information and should be presented in such a way that an overall judgement of safety compliance with the requirements can be made.

***Handling in SR-Can:*** *This is an overall requirement on the quality of the safety reporting, which will govern the compilation of the SR-Can report.*

The validity of assumptions used, such as models and parameter values, should be supported, for example through the citing of references to scientific literature, special investigations and research results, laboratory experiments on different scales, field experiments and studies of natural phenomena (natural analogues).

***Handling in SR-Can:*** *Justification of models and parameter values will largely be done in the Process report and the Data report, see sections 2.7 and 2.11, respectively. The use of natural analogues is addressed in section 2.12.4.*

Scientific background material and expert assessments should be documented in a traceable manner by thoroughly referring to scientific literature and other material.

***Handling in SR-Can:*** *This concerns much of the documentation of SR-Can, in particular the Process report and the Data report, see sections 2.7 and 2.11, respectively. Examples of documentation style can be seen in the corresponding reports associated with the SR 97 assessment.*

**On 10 §**

The time-period for which safety has to be maintained and demonstrated should be a starting point for the safety assessment. One way of discussing and justifying the establishment of such a time period is to start from a comparison of the hazard of the radioactive inventory of the repository with the hazard of radioactive substances occurring in nature. However, it should also be possible to take into consideration the difficulties of conducting meaningful analyses for extremely long time-periods, beyond one million years, in any other way than through showing how the hazard of the radioactive substances in the repository declines with time.

In the case of a repository for long-lived waste, the safety assessment may have to include scenarios which take into account greater expected climate changes, primarily in the form of future glaciations. For example, the next complete glacial cycle which is currently estimated to be on the order of 100,000 years, should be particularly taken into account.

***Handling in SR-Can:*** *The timescale for SR-Can is discussed in section 2.3.*

In the case of periods up to 1,000 years after closure, in accordance with the regulations of SSIFS 1998:1, the dose and risk calculated for current conditions in the biosphere constitute the basis for the assessment of repository safety and its protective capabilities.

Furthermore, in the case of longer periods, the assessment can be made using dose as one of several safety indicators. This should be taken into account in connection with the calculations as well as the presentation of analysis results. Examples of such supplementary safety indicators are the concentrations of radioactive substances from the repository which can build up in soils and near-surface groundwater or the calculated flow of radioactive substances to the biosphere.

***Handling in SR-Can:*** *The use of alternative safety indicators is discussed in section 2.12.3.*

(Compare SSIFS 1998:1 and SSI's comments on those regulations).

## A.2 SSI's Regulations

SSI has issued Regulations concerning the Protection of Human Health and the Environment in connection with the Final Management of Spent Nuclear Fuel or Nuclear Waste (SSI FS 1998:1), see section A.2.1.

SSI has also published a report with background discussions and comments to SSI FS 1998:1. Relevant excerpts form that document can be found in section A.2.2.

Furthermore, SSI is planning to issue also General Recommendations concerning the application of SSI FS 1998:1.

Whereas the Regulations have a clear legal status, General Recommendations are described in 1 § Ordinance on Regulatory Codes (1976:725) as: Such general recommendations on the application of regulations that stipulate how someone can or should act in a certain respect.

### A.2.1 SSI FS 1998:1

**The Swedish Radiation Protection Institute's Regulations concerning the Protection of Human Health and the Environment in connection with the Final Management of Spent Nuclear Fuel or Nuclear Waste;**

decided on September 28, 1998.

On the basis of 7 and 8 §§ of the Radiation Protection Ordinance (1988:293), the Swedish Radiation Protection Institute stipulates the following.

**1 §** These regulations are to be applied to the final management of spent nuclear fuel or nuclear waste. The regulations do not apply to landfills for low-level nuclear waste in accordance with 19 § of the Ordinance (1984:14) on Nuclear Activities.

#### Definitions

**2 §** In these regulations, concepts are defined as follows:

- *best available technique:* the most effective measure available to limit the release of radioactive substances and the harmful effects of the releases on human health and the environment which does not entail unreasonable costs,
- *intrusion:* human intrusion into a repository which can affect its protective capability,
- *optimisation:* keeping the radiation doses to mankind as low as reasonably achievable, economic and social factors taken into account,
- *harmful effects:* cancer (fatal and non-fatal) as well as hereditary defects in humans caused by ionising radiation in accordance with paragraphs 47–51 of the International Radiation Protection Commission's Publication 60, 1990,
- *protective capability:* the capability to protect human health and the environment from the harmful effects of ionising radiation,
- *final management:* handling, treatment, transportation, interim storage prior to, and in connection with final disposal as well as the final disposal,
- *risk:* the product of the probability of receiving a radiation dose and the harmful effects of the radiation dose.

Terms and concepts used in the Radiation Protection Act (1988:220) and the Act (1984:3) on Nuclear Activities have the same meanings in these regulations.

#### Holistic Approach etc

**3 §** Human health and the environment shall be protected from the harmful effects of ionising radiation, during the time when the various stages of the final management of spent nuclear fuel or nuclear waste are being implemented as well as in the future. The final management may not cause impacts on human health and the environment outside Sweden's borders that are more severe those accepted inside Sweden.

**4 §** Optimisation must be achieved and the best available technique shall be taken into consideration in the final management of spent nuclear fuel or nuclear waste.

The collective dose, as a result of the expected outflow of radioactive substances during a period of 1,000 years after closure of a repository for spent nuclear fuel or nuclear waste shall be estimated as the sum, over 10,000 years, of the annual collective dose. The estimate shall be reported in accordance with 10–12 §§.

***Handling in SR-Can:*** *From SKI's and SSI's joint review of SR 97 /SKI and SSI, 2001/ it is noted that optimisation and best available technique is not seen as issues for a safety assessment by the authorities (section 3.3.6). SKB shares this view and these issues will therefore not be addressed in SR-Can.*

### Protection of human health

**5 §** A repository for spent nuclear fuel or nuclear waste shall be designed so that the annual risk of harmful effects after closure does not exceed $10^{-6}$ for a representative individual in the group exposed to the greatest risk[6].

The probability of harmful effects as a result of a radiation dose shall be calculated using the probability coefficients provided in the International Radiation Protection Commission's Publication 60, 1990.

***Handling in SR-Can:*** *Estimation of risk and assessing compliance with the above criterion is one of the main purposes of SR-Can. Much of the methodology outlined in chapter 2 is aiming at this end-point. Issues directly related to the calculation of risk are discussed in section 2.15.*

### Environmental Protection

**6 §** The final management of spent nuclear fuel or nuclear waste shall be implemented so that biodiversity and the sustainable use of biological resources are protected against the harmful effects of ionising radiation.

**7 §** Biological effects of ionising radiation in living environments and ecosystems concerned shall be described. The report shall be based on available knowledge concerning the ecosystems concerned and shall take particular account of the existence of genetically distinctive populations such as isolated populations, endemic species and species threatened with extinction) and in general any organisms worth protecting.

***Handling in SR-Can:*** *This issue is briefly addressed in section 4.5, where it is noted that further discussion with or advice from SSI is required in order to develop a manageable way of handling the issue, given the limited knowledge concerning radiation effects on biota other than man.*

### Intrusion and Access

**8 §** A repository shall be primarily designed with respect to its protective capability. If measures are adopted to make access easier or to make intrusion difficult, the effects on the protective capability of the repository shall be reported.

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[6] With respect to facilities in operation, the limitations and instructions that apply are provided in the Swedish Radiation Protection Institute's regulations (SSI FS 1991:5, amended 1997:2) concerning the limitation of releases of radioactive substances from nuclear power plants and the Swedish Radiation Protection Institute's regulations (SSI FS 1994:2, amended 1997:3) concerning health physics for activities involving ionising radiation at nuclear facilities.

**9 §** The consequences of intrusion into a repository shall be reported for the different time periods specified in 11–12 §§. The protective capability of the repository after intrusion shall be described.

***Handling in SR-Can:*** *Intrusion issues are discussed in chapter 7.*

### Time Periods

**10 §** An assessment of a repository's protective capability shall be reported for two time periods of orders of magnitude specified in 11–12 §§. The description shall include a case, which is based on the assumption that the biospheric conditions which exist at the time that an application for a licence to operate the repository is submitted will not change. Uncertainties in the assumptions made shall be described and taken into account in the assessment of the protective capability.

*The first thousand years following repository closure*
**11 §** For the first thousand years following repository closure, the assessment of the repository's protective capability shall be based on quantitative analyses of the impact on human health and the environment.

*Period after the first thousand years following repository closure*
**12 §** For the period after the first thousand years following repository closure, the assessment of the repository's protective capability shall be based on various possible sequences for the development of the repository's properties, its environment and the biosphere.

***Handling in SR-Can:*** *The handling of different time scales are discussed throughout the report, e.g. in section 2.3 (time frame for the assessment), 2.9.1 (time scales in process descriptions), 2.9.7 (time scales for the repository evolution), 6.4.2 (evolution of initial canister defects), 5.5 (timescales for geochemistry), 4.2 (timescales for the biosphere treatment). It however remains to determine how the two time periods mentioned in the regulations shall be accounted for on an integrated level. Factors to consider are the different time scales on which different phenomena can be reasonably predicted and the possible absence of releases from the near field during the first 1,000 years, potentially rendering a detailed description of the biosphere less relevant on that time scale.*

### Exceptions

**13 §** If special grounds exist, the Swedish Radiation Protection Institute may announce exceptions from these regulations.

### A.2.2 Excerpts from SSI's Background and Comment document concerning SSI FS 1998:1

***Handling in SR-Can:*** *The detailed handling in SR-Can is not discussed for this document. Some issues requiring clarification have been brought to SSI's attention. When the General Recommendations concerning SSI FS 1998:1 are available from SSI, the handling of these Recommendations in SR-Can will be established and documented.*

## 2.4 Protection of Human Health (§ 5)

### 2.4.1 General

Radiation from the cosmos, the ground and from the radioactive substances naturally occurring in the body, results in a dose which is on the order of magnitude of 1 mSv (millisievert) per year. Radiation from the ground varies and human beings are also exposed to other types of radiation, e.g. from radon in indoor air and from the medical use of radiation in connection with examinations and treatment. The average value of the individual dose in Sweden, from all sources, is on the order of magnitude of 4 mSv per year.

The dose limit recommended by the ICRP for individual members of the general public as a result of activities involving radiation is 1 mSv per year. This recommendation has obtained legal status within the EU through the Council Directive 96/29/EURATOM. This directive must be implemented in the member states no later than by May, 2000. However, in Sweden, this dose limit has applied for about ten years through SSI's regulations concerning dose limits in connection with activities involving ionising radiation [SSI FS 1989:1].

A licensee cannot be responsible for the consequences of releases from facilities other than those that it owns. In order to take into account the possibility of the exposure of one and the same individual to releases from several facilities, special dose constraints can be determined for individual activities. The dose constraint is set so that individuals will not receive radiation doses exceeding the dose limit, i.e. 1 mSv per year for individual members of the general public, even if several sources should contribute to the exposure. Thus, SSI has a limited release from nuclear power plants so that normally, the dose does not have to exceed one-tenths of the dose limit, i.e. 0.1 mSv per year [SSI FS 1991:5]. This means that the licensee must demonstrate, using radio-ecological dispersion models, that individual members of the general public are not exposed to higher radiation doses than 0.1 mSv per year, as a result of releases from its own activity. The constraint concerns the dose to the group of people who, as a result of age, living habits and place of domicile, receive the highest radiation dose, i.e. the critical group [ICRP 43].

Even if ten facilities existed in the same region, it would be improbable that all of the facilities would have identical critical groups. Therefore, the constraint of one-tenths of 1 mSv/year entails a high protection level.

### 2.4.2 Protection of human health from operational activities

The same release regulations as for the operation of nuclear power plants, i.e. that the dose to the critical group should not exceed 0.1 mSv per year, apply with respect to operational activities which may be needed for the management of waste or spent nuclear fuel, such as an encapsulation plant for spent nuclear fuel. These regulations are also applicable for activities at a repository prior to closure. This is stated in the footnote to § 5. SSI is currently reviewing the relevant regulation, SSI FS 1991:5. Health physics in connection with work at the nuclear facilities is covered by SSI FS 1994:2, which is also referred to in the footnote to § 5.

In the case of these activities it must be possible, as for activities at nuclear facilities, to implement measures on a continuous basis in order to limit releases, including the measure of completely shutting down the activity.

### 2.4.3 Protection of human health from a closed repository – risk concept and level of individual protection

Unlike ongoing activities, future releases from a closed repository and the resulting damage which can arise are hypothetical, known as potential exposure [ICRP Publication 64]. This results in difficulties in using criteria which, like those for the ongoing activities, are based on “actual” doses to e.g. the critical group. These difficulties are due to the uncertainty of whether an outflow will occur and of the consequences of such an outflow. An analysis is always associated with uncertainties concerning whether and when a release occurs, the dispersion pathways that the released radionuclides have in the geosphere and in the biosphere as well as the geographical location of the exposed individuals in relation to the outflow zone and their dietary and living habits.

Due to the special uncertainties that exist in connection with potential exposure, SSI has chosen to specify the individual protection criteria (for humans) in the form of an annual risk of harmful effects as a result of ionising radiation. The use of the concept “risk” relates to other protection work and facilitates a coherent societal assessment of the dose commitment to individual members of the public.

The “risk” referred to here concerns a repository undisturbed by man. The issue of the possibility of different types of intrusion into the repository is discussed in Section 2.6 Intrusion.

The concept of “risk” is defined in these regulations as the probability of the harmful effects (fatal and non-fatal cancers as well as hereditary damage) as a result of an outflow from the repository, taking into account the probability of the individual receiving a dose as well as the probability of harmful effects arising as a result of the dose. SSI has used the ICRP’s definition of detriment [ICRP 60] in the assessment of the harmful effects of radiation. The detriment is described in greater detail in § 2 as well as in Section 2.2.4 Harmful Effects.

A repository must be designed so that no further measures have to be implemented after closure to prevent or limit the outflow of radioactive substances from the repository. Institutional control and knowledge of the location of the repository in a remote future cannot be assumed. The requirement regarding sustainable development in the 1992 Declaration of Rio means that scope must also be left for the use of other energy sources in the future, which may be environmentally hazardous. If an energy source which is used in fifty years’ time can restrict the scope of the accepted harmful effects of energy production for thousands of years, it follows that the source must be regulated by very stringent requirements. Therefore, the impact from the repository must be in balance with the time that the energy source is used. It can also be assumed that in a certain region, there are 10 repositories, each with an inventory corresponding to that which is currently expected in the case of the Swedish repository. In this case, hypothetical outflows from the various repositories could overlap with each other and result in a greater impact on the population of the region. Other forms of future energy production can also, in the same way, result in a greater impact.

In order to take into account the interaction between various future risk sources, of which the repository is one, SSI requires that the risk from the repository to individuals who are representative of an exposed group must be lower than the risk that applies to the critical group near nuclear facilities in operation. Thus, SSI has decided to specify, in these regulations, that the annual risk of harmful effects as a result of the repository must not exceed $10^{-6}$, i.e. one in a million . With ICRP’s probability coefficient for cancer and hereditary effects of 0.073 per sievert, this risk level corresponds to an annual expected dose of about 15 µSv.

### 2.4.4 Assumptions for calculations

As discussed above, risk is the product of the probability of receiving a radiation dose and the harmful effects of the radiation dose. This can be mathematically described as follows:

$$\gamma \int P(D) D dD$$

where P(D) is the annual probability of the individual receiving a dose in the dose range (D, D+dD), integrated over possible doses, multiplied by the probability of harmful effects per dose unit, $\gamma$ (0.073 per Sv).

In many cases it is not possible to calculate an “exact” risk, on the basis of this formula. Instead, the risk must be assessed from the risk picture which is obtained by weighing together consequences and probabilities for different event sequences. In this context, the concept of the risk scenario refers to calculated, or otherwise assessed, consequences and probabilities for a relevant selection of possible event sequences (scenarios). The consequences must be calculated or estimated so that they include uncertainties in the assumptions and data upon which the calculations or assessments are based. The chosen scenarios must in their entirety give a full picture of the risks attributable to the final repository.

The use of risk as a criterion does not mean that the dose calculation can be skipped over. All of the stages in the calculation must be reported. The risk measure used in the regulations can, as described above, be transformed into an expected dose, using the ICRP’s factor of 0.073 per Sv.

The proponent’s responsibility with respect to risk limitation concerns a larger group that obtains a dose from the repository. It must be ensured that representative individuals from this group are not exposed to risks greater than $10^{-6}$ per year. The group is not necessarily geographically segregated. Instead it comprises individuals who will receive the highest dose commitment from several future sources.

For releases in a remote future, calculations can only be based on “hypothetical” individuals. The hypothetical group cannot be replaced by an existing group of people whose living habits can be described and for whom both measurements and calculations can be carried out. When calculating a hypothetical dose in a remote future, it is reasonable to take into account sex and age distributions. However, beyond this, the concept of the group does not contribute anything to the line of reasoning besides the average value of the dose and risk, calculated with respect to age and sex, for a hypothetical individual.

The ICRP’s Publication 43 proposes that, in certain cases (when the ratio between the average dose to the group and the dose limitation is less than one-tenth), the group must be considered to consist of individuals who receive doses within a factor of ten, i.e. with a factor of about three on both sides of the average dose. This means that the risk has the same range. SSI has decided instead to allow the hypothetical regional group to have a risk range which is ten times greater, i.e. a factor of 100.

If the proponent wishes to perform calculations with respect to an individual who is estimated to have a high dose commitment, it may be acceptable to perform the calculations for an individual who represents the higher level within the range, instead of for an individual who is representative of the commitment of the entire group. In this way, the representative individual, according to the intention of the regulations, can have a risk that is ten times lower. The representativeness of the assumed living and consumption patterns must also be investigated with respect to probability.

Doses higher than 1 mSv in a year, which cannot be ruled out for certain scenarios, e.g. for human intrusion into the repository, imply that the limit recommended by ICRP for protection of individuals of the public is exceeded. Such scenarios must be reported, and will be evaluated, separately.

### 2.4.5 Summary of human health

- The limitation of risk has been established taking into account the fact that there shall be scope for future activities such as energy production.
- The limitation applies to a larger group of individuals who are expected to have a dispersion of a factor of one hundred between the lowest and highest risk, as a result of outflow from the repository.
- A final repository must be planned so that the dose to representative individuals in the most exposed group, as a result of outflow from the repository, is not expected to lead to risks in excess of $10^{-6}$.

## 2.5 Environmental Protection (§§ 6–7)

### 2.5.1 General

§ 1 of the Radiation Protection Act states that the "aim of this act is to protect humans, animals and the environment from the harmful effects of radiation". This means that the purview of the act has been broadened, compared to before; Bill 1987/88:88 of the New Radiation Protection Act states that a new Radiation Protection Act must not "like the current act be limited to mainly providing protection for mankind. Effects on fauna and flora should also be included in the Act, as should protection of the environment in general." "Protection of the environment in general" has not been defined in the Radiation Protection Act. In SSI's opinion, in this context, it should be understood to comprise conditions for biological life in all of its forms and organisation levels, i.e. protection of the environment aims at the protection of organisms.

The opinion which has so far been upheld within radiation protection, on the basis of the ICRP's Publications 26 and 60, has been that organisms in the environment have been protected as long as the conditions for the protection of human beings have been fulfilled

("The Commission believes that the standard of environmental control needed to protect man to the degree currently thought desirable will ensure that other species are not put at risk", ICRP 60 §16)

Since the ICRP and others formulated these assessments, the focus within the area of environmental protection in general has changed, largely as a result of the Earth Summit on the environment and development in Rio de Janeiro in 1992. The focus is now on concepts such as "biodiversity", "biological resources" and "sustainable use." So far, limited attention has been paid to these issues within radiation protection.

The Convention on Biodiversity [SÖ 1993:97] defines the concept of biodiversity as "the variability among living organisms of all sources, inter alia, terrestrial, marine and other aquatic ecosystems and the ecological complexes of which they are a part; this includes diversity within species, between species and of ecosystems." Thus, the importance of all organisms contributing to the structure of the ecosystem is emphasised. Crops, cattle etc are also included.

The importance of preserving biodiversity has been emphasised by the Government [Bill 1993/94:30]: “Action plans or measures for the preservation of biodiversity should be prepared by the Swedish Environmental Protection Agency (SNV) for follow-up of environmental targets and for an overall assessment of the need for work within the entire field as well as by the competent authority in each sector in the form of sector-specific concrete plans or programmes.” SSI has participated in the review of the national environmental targets conducted by SNV on behalf of the Government prior to the 1998 environmental bill [Bill 1997/98:145].

The Rio Convention emphasises that the environment and nature must be seen as resources which local, national or international communities must be able to use in a sustainable manner, now and in the future. In other words, current usage must not jeopardise future generations’ use of the resources. The biological resources are dependent on biodiversity, e.g. in the form of genetic material of potential value for further improvement in terms of productivity and quality. Biological resources are only used in certain contexts without intermediaries, i.e. where there is a considerable share of self-initiated conservation of resources. In most cases, the biological resources are exploited via a market. This means that the values of the market will be a part of the resource concept. There may be cases where the market value of the product is reduced due to contamination, even where the radiological significance of such contamination is insignificant. This aspect may have to be taken into consideration in descriptions of the consequences of waste management.

### 2.5.2 Comments on the regulations

The aim of §§ 6–7 is to limit the effects of ionising radiation on organisms occurring in the environment, now and in the future, and to thereby allow for a sustainable use of biological resources.

This aim is presented in § 6 of the regulations, where it is stated that the final management of spent nuclear fuel or nuclear waste shall not, in radiological terms, be detrimental to biodiversity or the sustainable use of biological resources. However, it must be emphasised that biodiversity changes with time for natural reasons. Thus, the aim cannot be to “freeze” the current state of diversity.”

In § 7, it is stated that the description should include biological effects of ionising radiation. Protection cannot be ensured if only abiotic parameters are taken into account, e.g. different types of safety indications. In order to be able to evaluate whether the protection targets are being fulfilled, the biological effects must be described. This means that an estimate of the dose contribution to relevant organisms or groups of organisms must be made.

The description must apply to organisms in the relevant habitats (i.e. the relevant environment for special organisms or groups of organisms) and ecosystems concerned. Of special interest are organisms which are genetically distinctive and which are therefore of potential special importance for the ecological processes, biodiversity and biological resources. These include populations at the margin of the species’ distribution area, isolated populations with limited gene transfer within the main area where the species sis found, endemic species (species found only in a geographically isolated area) and species threatened with extinction (i.e. where the number of individuals is a specific genetic limitation). The concept of organisms worth protecting also refers to organisms which, from a biological, cultural or economic standpoint, require special treatment.

Furthermore in § 7, it is stated that the description must be based on available knowledge, i.e. existing documentation or documentation which can be prepared in connection with the siting. This means that a detailed analysis can only be carried out in the short term. For long time-scales after the closure of a repository, it is not possible to predict which genetically distinct organisms can occur. In such cases, an evaluation must be made in accordance with the general guidelines presented in §§ 10–12 of the regulations, see also Section 2.7 Time Periods.

In §§ 6–7, it is implicit that SSI does not, at present, consider it to be possible to provide, in the form of regulations, quantitative criteria for environmental protection. This means that the precautionary principle must be applied, in accordance with the Declaration of Rio. UNSCEAR has recently compiled information [UNSCEAR 1995] on the radiosensitivity of various organisms, based on data from experiments and observed effects in the natural environment. SSI intends to investigate whether evaluation criteria can be derived from existing documentation, based on an ecotoxicological approach.

### 2.5.3 Summary of environmental protection

- Biodiversity and a sustainable use of biological resources must be protected from the harmful effects of radiation.
- Analyses and evaluations must be made of biological effects in the environment, and where possible, with particular attention to genetically distinctive organisms and organisms which are otherwise worth protecting.

## 2.6 Intrusion (§§ 8–9)

### 2.6.1 Considerations

An important premise in discussions concerning requirements connected to intrusion is the responsibility of society for its own conscious actions. Therefore, it is not necessary, in connection with an application, to investigate issues concerning intentional intrusion into a repository which is sanctioned by society. Below, intrusion refers to unintentional human actions, inside or in the immediate vicinity of the repository, which degrade the protective capability of the repository.

In the case osf a repository, the consequences of intrusion must be described. The essential point is not to describe the chain of events that leads to the intrusion, but to study the ability of the repository to isolate and retain the radioactive substances after an intrusion, in accordance with §§ 8–9 of the regulations.

In cases where the proponent proposes interim storage for a long period prior to final disposal, the question of intrusion into the interim storage facility must also be studied. Intrusion into an interim facility is an unintentional breach of the safety regulations and cannot be compared with an error, e.g. in connection with tunnel drilling in a remote future. In the case of intrusion into an interim storage facility, both the event chain and the consequences of the intrusion are of interest. SSI would like to emphasise that interim storage for long periods of time cannot be accepted as a plan for a final solution.

Questions relating to intrusion will be handled by SSI separately from the discussion concerning the undisturbed repository. Therefore, the stipulations concerning the holistic approach and optimisation in § 4 and in Section 2.3.3 shall not apply to intrusion into a repository. Estimated probabilities concerning human intrusion in the future are so uncertain that SSI does not wish to override requirements on the safety of the undisturbed repository.

On the other hand, it may help to clarify the issue if separate studies of the probability of intrusion were carried out, e.g. in order to investigate possible countermeasures. Bearing in mind the responsibility borne by society for the preservation of information concerning the repository in various archives for a long time after closure, such studies, carried out under the auspices of the competent authorities and from the particular standpoint of the authorities, can also be relevant.

Measures may also be planned and implemented by the proponent to facilitate future access, e.g. for inspection, repair or retrieval. Also in this case, SSI requires that the impact of the measures on the protective capability should be described.

The activities carried out in connection with waste management must be documented. This applies, in particular, to information concerning a repository, its location, inventory and design etc. SSI has issued a special regulation [SSI FS 1997:1] concerning documentation and document retention. The documentation which is currently kept by authorities and licensees has been prepared for purposes other than that of facilitating the understanding of a reader from a remote future. Further instructions and requirements may be formulated when it is time for SSI to adopt a position concerning an application for the construction of a repository.

### 2.6.2 Summary of intrusion

- If measures are planned to make intrusion more difficult or to make access easier, the consequences with respect to the protective capability of the repository shall be reported.
- The consequences of intrusion must be evaluated on the basis of the repository's ability to isolate and retain the waste after intrusion.

## 2.7 Time Periods (§§ 10–12)

### 2.7.1 Considerations

Human health and the environment must be given adequate protection, even over very long time-scales. SSI shares the opinion that future doses should not be considered to be less harmful than doses to which man is currently exposed. The same applies to the protection of the environment.

The reasons why individual requirements are made regarding reporting for various time periods are that the hazard of the waste decreases with time and that it is difficult to perform reliable quantitative analyses of radiation protection for a remote future. The latter particularly applies to how the biosphere may be affected by the future development of society. Thus, a discussion must be conducted concerning the protective capability of the repository to protect human health and the environment from the harmful effects of ionising radiation (protective capability) for various time periods.

The absolutely most important period taking into account the hazard of the waste is the first thousand years after repository closure. For this period, SSI is of the opinion that reliable assessments of the repository's protective capability can be made on the basis of quantitative analyses of a scenario which includes the probable development of external phenomena (e.g. climatic changes) and realistic assumptions of the internal phenomena (e.g. the performance of the engineered barriers).

The choice of the thousand-year perspective also has a legal aspect. Requirements are normally made in society with respect to time periods which are shorter than one hundred years. However, there are also examples of hundred-year time-scales. Certain legal aspects in a long-term and historical perspective are examined in SSI-rapport 94-11. In SSI's opinion, a thousand years is a reasonable upper boundary which distinguishes time-periods which can be associated with existing judicial traditions from time-periods associated with an unknown future.

The proponent applying for permission for final management must also describe what can happen to a repository over a longer time-scale, i.e. in a future beyond the initial thousand years after closure. Some very slow sequences, such as the development of geological formations, are being subjected to scientific study for long time sequences. Other aspects or sub-systems of a repository can also be studied for periods which are considerably beyond the previously mentioned thousand-year perspective. Such studies do not mean that the entire protective capability of the repository can be predicted. However, they can provide valuable information without entailing the prediction of doses to living creatures.

In order to assess how the repository's predictive capabilities change over these extended periods of time, a relevant selection of possible processes (scenarios) for the development of repository properties and the environment are described and analysed. A description is also provided which illustrates different possible processes for the development of the biosphere. The descriptions will provide a view of the repository's capability to protect human health and the environment under different postulated conditions, i.e. they will provide a comprehensive description of repository robustness. These descriptions should be based on quantitative calculations, as far as possible.

According to § 10, the description must always include a case based on the current (at the time that the application is submitted) biosphere conditions. In this context, known trends must also be taken into consideration, such as land elevation, which is important e.g. in the case of the planned expansion of SFR. It is important to once again emphasise that this does not result in a prediction of actual doses or environmental consequences in a remote future (more than one thousand years). The capability of the repository to isolate and retain the waste can instead be evaluated using safety indicators. One example of a safety indicator is the hypothetical dose to human beings, calculated using a mathematical model for dispersion after a hypothetical outflow from a repository. In the case of a remote future, it cannot be assumed that the calculation models describe the biosphere conditions and living habits correctly. However, the calculated radiation dose can still be used as an indicator of the repository's capability to fulfil its purpose. A repository design which indicates a lower dose can thus be estimated to be better than another design which indicates a higher dose, without the dose having a specific, predictive value.

Uncertainties must always be described for the different time periods (§ 10). This refers to uncertainties in e.g. calculation models, input data and parameter values. The way in which and the extent to which the uncertainties affect the assessment of the repository's protective capability must always be described.

### 2.7.2 Summary of time periods

- Estimates of the repository's protective capability (capability of protecting health and environment) must be described for two periods, i) on the order of magnitude of up to one thousand years into the future, ii) very long time-scales.
- For periods up to the first thousand years following closure, calculations must be made of risk. In the case of long time-scales, the assessment of the protective capability must be based on descriptions of possible sequences for the repository and its environment. Knowledge of sub-systems must be reported even if the biosphere and other conditions cannot be described with the same degree of reliability.
- The reporting for various time periods must include a case that is based on current biosphere conditions.

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